

3 The physics of climate change

REMEMBER

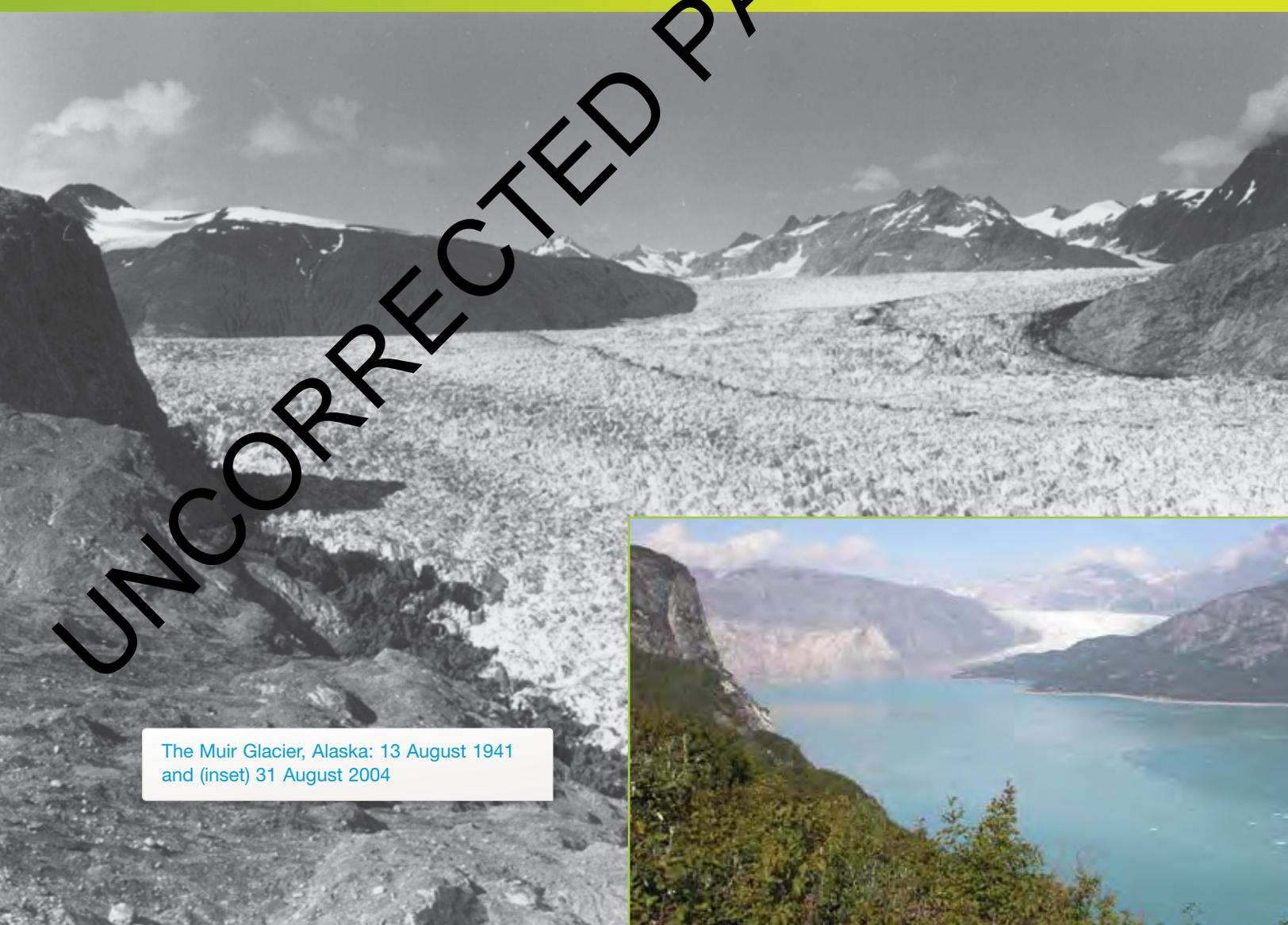
Before beginning this chapter you should be able to:

- convert temperature from degrees Celsius to Kelvin
- describe heat transfer processes by conduction, convection, radiation and evaporation
- identify regions of the electromagnetic spectrum as radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma waves
- describe the electromagnetic radiation emitted by the Sun as mainly ultraviolet, visible and infra-red.

KEY IDEAS

After completing this chapter you should be able to:

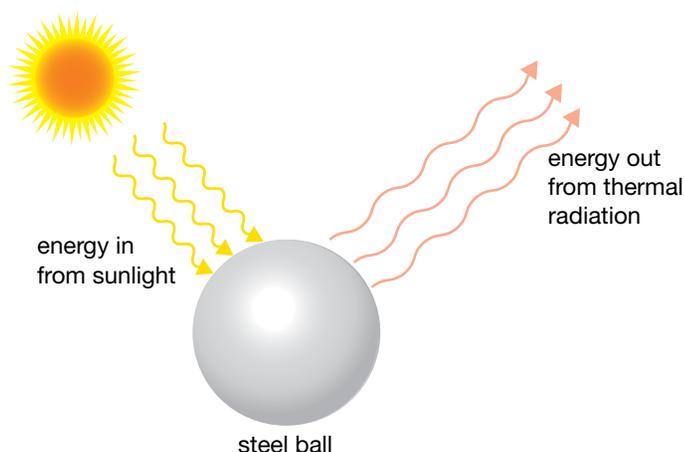
- explain how greenhouse gases (including methane, water and carbon dioxide) absorb and re-emit infra-red radiation
- model the greenhouse effect as the flow and retention of thermal energy from the Sun and the Earth's surface and atmosphere
- analyse changes in the thermal energy of the surface of the Earth and of the Earth's atmosphere
- analyse the evidence for the influence of human contributions to the enhanced greenhouse effect, including surface materials and the balance of gases in the atmosphere.



The Muir Glacier, Alaska: 13 August 1941 and (inset) 31 August 2004

Energy in balance

Every object attempts to achieve thermal equilibrium, that is, a balance between energy absorbed and energy emitted. Imagine a steel ball placed in direct sunlight as shown in the figure below.



The absorbed energy increases the temperature of the ball; the increased temperature means that the ball will radiate more thermal energy. If the amount of energy radiated is less than the amount absorbed, the temperature of the ball will continue to increase, leading to more energy being emitted, until a temperature is reached where energy in and energy out balance.

Similarly, if a cloud moves in front of the Sun, the energy absorbed by the ball would suddenly decrease to less than the amount of energy being emitted. The temperature of the ball would drop and continue to fall until the amount of energy emitted matched the energy absorbed and a new equilibrium was reached.

The Earth as viewed from space is like the steel ball. The energy falling on the Earth from the Sun is fairly constant. At the equator, an average of about 684 joules of energy from the Sun hits each square metre of the Earth's surface every second; that is, 684 W m^{-2} , where 1 watt is a unit of power or the rate of energy delivery and equal 1 joule per second. This value varies from day to day by as much as 2 W m^{-2} , as well as having an approximate 11-year cycle of a similar magnitude.

AS A MATTER OF FACT

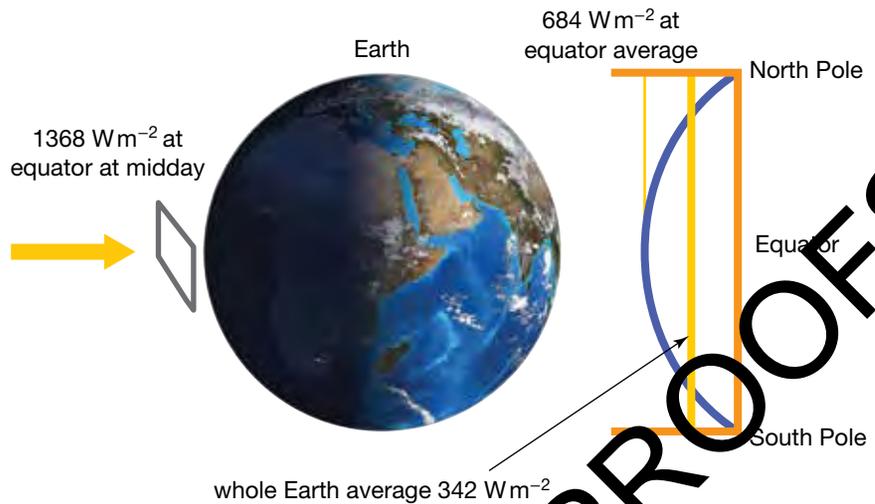
When a prisoner of war in World War I, Milutin Milankovic postulated several types of changes in the Earth's movement around the Sun that could affect the amount of solar radiation the Earth receives and its distribution. These changes can affect climate on a time span of many thousands of years and possibly explain the occurrence of ice ages. Some of the types of changes include:

- variation in the elliptical shape of the Earth's orbit with a cycle time of about 413 000 years
- precession of the Earth's axis of rotation; like any spinning top, the axis itself rotates, once every 26 000 years
- the tilt of the axis also ranges from 22° to 24.5° every 41 000 years.

All these changes are due to gravitational interactions in the solar system between the Earth, the Sun and other planets. It is thought that these factors may explain a long-term cooling trend the Earth has been in over the last 6000 years. From the slowness with which these changes occur, none can explain the unprecedented global warming in recent decades.

How hot is the Earth?

With the Stefan-Boltzmann relationship from chapter 2, it is possible to use the amount of energy the Earth radiates into space to calculate the temperature of the Earth as observed from space.



At the Earth's equator at midday, the light intensity from the Sun is 1368 W m^{-2} . The average over night and day and from pole to pole is 342 W m^{-2} .

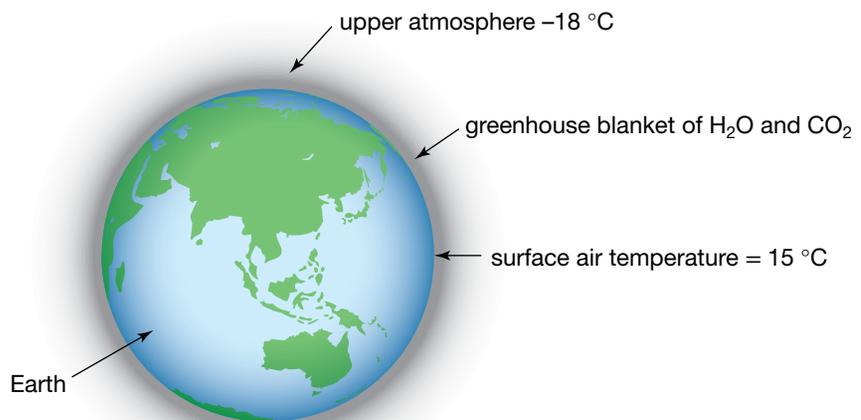
How much energy does the Earth get from the Sun?

The Sun is directly overhead the equator at midday on the equinox. At this place and time, the solar radiation is about 1368 W m^{-2} . But because the Earth turns, producing night and day, this value has to be halved. Also, the Earth is curved with the North and South Poles receiving much less light than the equator over a full year. This requires the number to be halved again. So the average solar radiation across the Earth is 342 W m^{-2} as shown in the figure above. About 100 W m^{-2} of this radiation is reflected straight back into space by the white surfaces of clouds and ice sheets. This leaves 242 W m^{-2} to heat up the Earth.

At what temperature would an object need to be to radiate 242 W m^{-2} ?

In the previous chapter, the Stefan-Boltzmann relationship, $P \propto T^4$, was described. It enables the absolute temperature of an object to be determined if you know how much energy it is radiating. For the 242 W m^{-2} that the Earth radiates, this gives a temperature of 255.6 K , that is, -18°C . This seems wrong. The Earth is not that cold! What causes the difference between this calculated temperature (which is the temperature of the Earth observed from space) and the temperature we observe at the surface? The explanation is that we ignored the greenhouse gases in the atmosphere.

The average global surface air temperature since the last ice age has been about $+15^\circ \text{C}$. This means that the greenhouse gases of water vapour (H_2O), carbon dioxide (CO_2) and others have been a blanket that has provided an extra 33°C of warmth.



The necessary temperature (-18°C) for the Earth to radiate 242 W m^{-2} actually occurs at an altitude of about 5 km above the surface. So the Earth's surface is warmed by a 5 km thick blanket!

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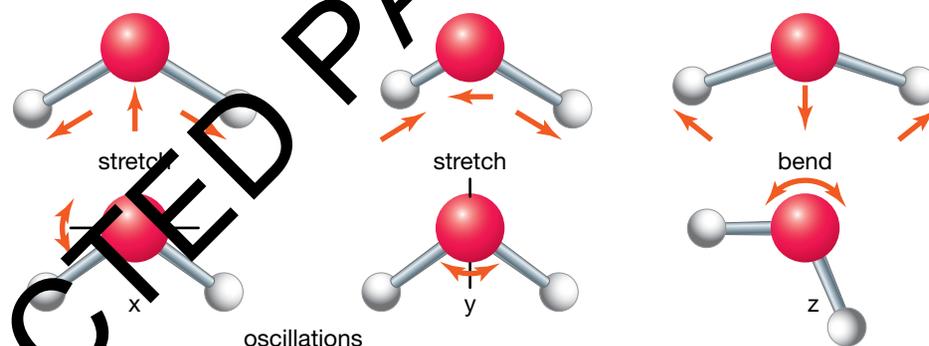
How do water vapour and carbon dioxide act as a blanket to trap heat?

If you shine a broad spectrum of light through a gas, some colours will be absorbed. The colours absorbed are specific to the substance, which means each substance produces its own unique pattern of absorption bands. These absorption bands are like fingerprints and can be used to identify molecules. The light in the absorption band has been absorbed by the molecule and then subsequently re-emitted, but in a random direction. This means the spectrum of light from the source will have gaps where absorption has occurred. The light from the other parts of the spectrum passes through the gas without a change in direction.

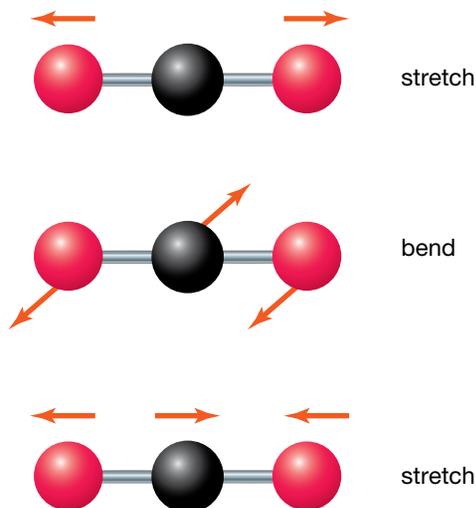
Ultraviolet light has more energy than visible light, which has more energy than infra-red, but none of them are energetic enough to break up molecules. These three types of radiation have only enough energy to stretch, twist and spin molecules. Molecules with two atoms such as nitrogen (N_2) and oxygen (O_2) have very strong bonds. When they absorb ultraviolet light, their bonds stretch. The energy of visible light and infra-red radiation is too low to affect such molecules. This means the two gases are transparent to visible light and infra-red.

Water vapour (H_2O) and carbon dioxide (CO_2) have three atoms in each molecule, so they are more flexible than N_2 and O_2 . These molecules can bend, whereas atoms with only two molecules cannot. When H_2O and CO_2 absorb infra-red light, their bonds stretch and bend. Other molecules with more than two atoms, such as methane (CH_4), absorb infra-red radiation in the same way.

The diagrams below show the different ways water vapour and carbon dioxide molecules bend and stretch.



The water molecule has three different ways of stretching or bending, as well as oscillations about three axes.



The carbon dioxide molecule has three different ways of stretching.

The oxygen atoms at the ends of the bonds in carbon dioxide are heavier than the hydrogen atoms at the ends of the bonds in water, so the bonds in the two molecules stretch and bend differently. This means each molecule will absorb different parts of the infra-red spectrum. Consequently, water vapour and carbon dioxide contribute independently to the greenhouse effect.

Once a gas molecule has absorbed infra-red radiation coming from the Earth's surface, it re-emits the radiation, but

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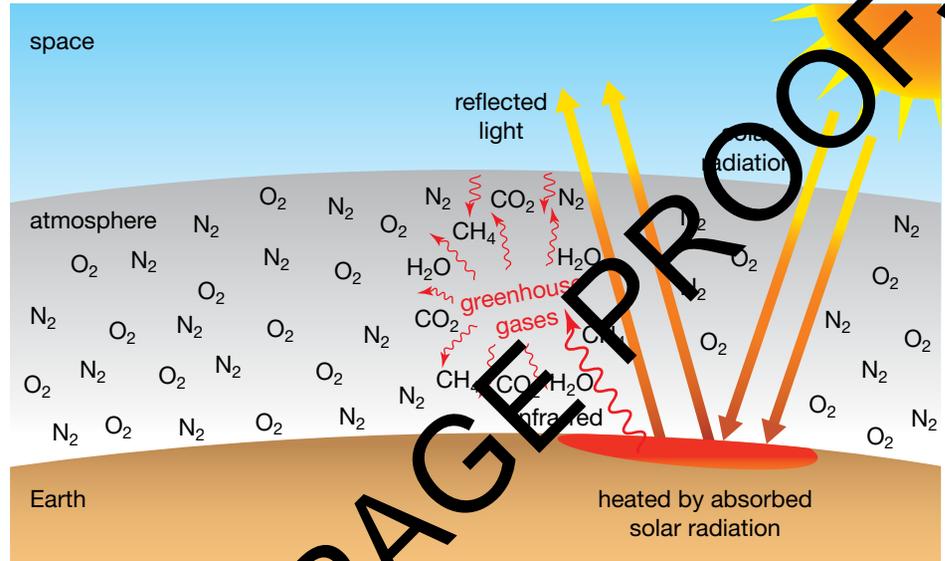
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importantly in a random direction. So, for the gas as a whole, some radiation goes back down to the Earth to increase its temperature and some is directed towards the top of the atmosphere and out into space. However, other molecules further up in the atmosphere can absorb this radiation and re-emit more back to the Earth. The overall effect is that more than half of the radiation emitted by the gas comes back to the Earth's surface.



Infra-red radiation from the Earth's surface is absorbed by greenhouse gases and re-emitted in all directions.

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Enhanced greenhouse effect

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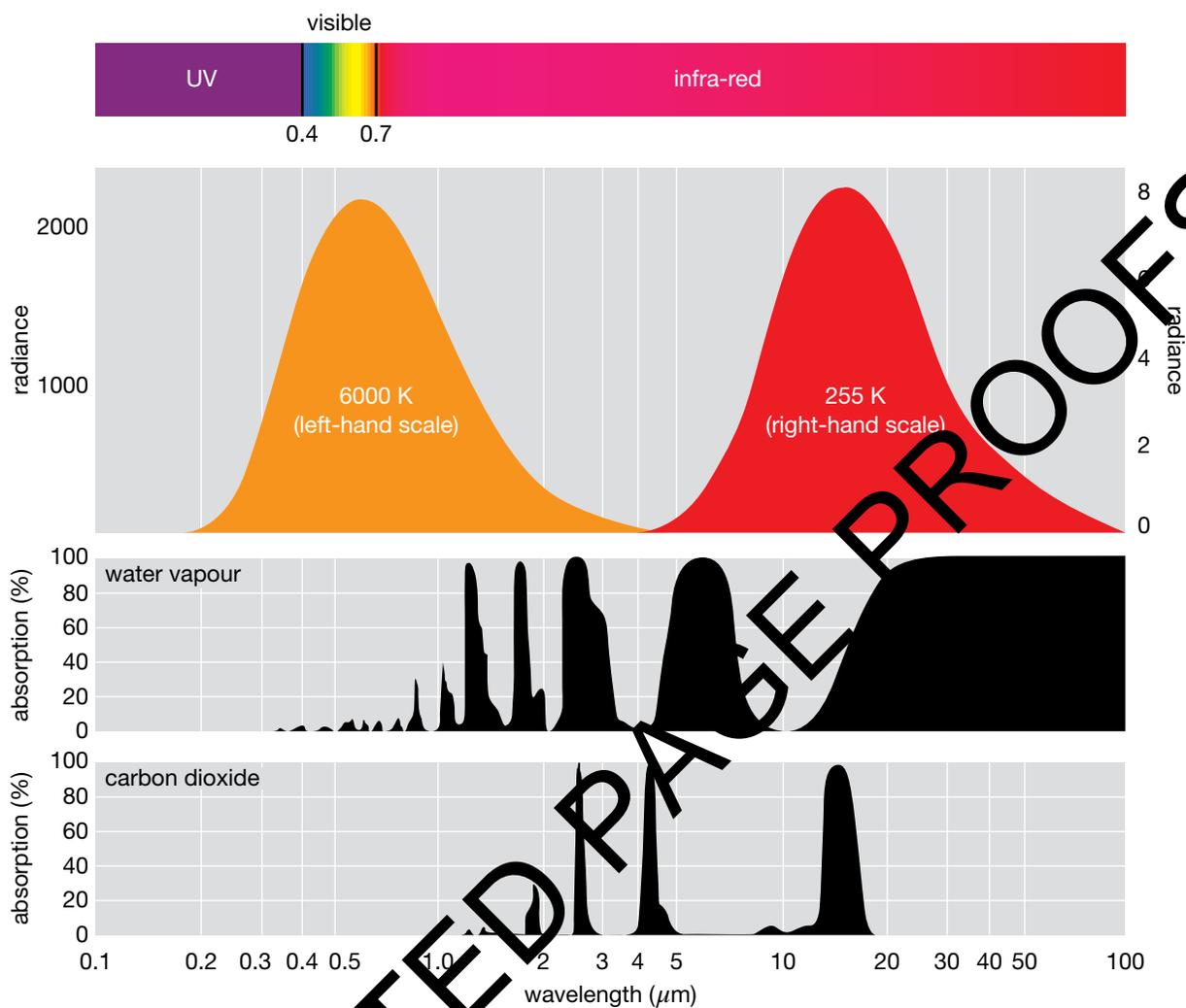
Human activities, such as the burning of fossil fuels (coal, oil and natural gas), agriculture and land clearing, are increasing the concentrations of greenhouse gases in the atmosphere. This increase is sometimes called the enhanced greenhouse effect.

Increased carbon dioxide concentration in the atmosphere means that more of the wavelengths that CO_2 absorbs will be re-emitted back to Earth, increasing the temperature of the Earth.

The next diagram shows:

- the spread of wavelengths radiated by the Sun at 6000 K (these are the wavelengths in sunlight)
- the spread of wavelengths radiated by the Earth at 255 K or -18°C . *Note:* The scale on the left is for sunlight, while the scale on the right is for the Earth's radiation. The scales are markedly different.
- the absorption spectrum for water vapour
- the absorption spectrum for carbon dioxide.

It is worth clarifying the vertical scale on the absorption spectra. The spectra show that for some wavelengths 100% of the radiation is absorbed. This means that in a container holding only that gas, no radiation of that wavelength would pass through without interacting with a molecule. However, in the atmosphere with a mixture of gases, and with CO_2 , H_2O and CH_4 at low concentrations, much of the radiation with these wavelengths has a good chance of passing through without ever hitting one of these molecules. The gases CO_2 , H_2O and CH_4 make up a very small proportion of the atmosphere, so the infra-red radiation emitted from the Earth's surface has a good chance of reaching outer space without being absorbed. However, with increased emissions of CO_2 and CH_4 , interactions are more likely to occur.



The energy spectra of the Sun (6000 K) and the Earth (255 K) with the absorption spectra of water vapour (H₂O) and carbon dioxide (CO₂)

Revision question 3.1

- Use the figures from the diagram above to determine the range of wavelengths emitted by the Earth that are absorbed by (i) CO₂ and (ii) H₂O.
- Which wavelengths emitted by the Earth are absorbed by CO₂ and not by H₂O?

Fossil fuel's fingerprints

Atoms with the same number of protons but different numbers of neutrons are called isotopes. Isotopes of an element have identical chemical behaviour because they have the same number of electrons. However, because different isotopes have different masses, their reactions may proceed at different speeds. Heavier isotopes generally react slower.

For example, carbon has two main isotopes: carbon-12 with six neutrons and carbon-13 with seven neutrons. The process of photosynthesis in plants turns carbon dioxide and water into carbohydrates. This reaction occurs more quickly with carbon-12 than it does with carbon-13. This means the proportion of carbon-13 in the plant is less than what was in the atmosphere at the time the plant was growing.

Over millions of years, dead plants are turned into fossil fuels, such as coal, oil and natural gas. When these fossil fuels are burnt, the carbon, which has relatively little carbon-13, is released back into the atmosphere. Tree rings and ice cores can be used to determine the ratio of carbon-13 to carbon-12 of the Earth's atmosphere going back thousands of years. These can then be compared to the current atmosphere.

The data shows that the ratio of carbon-13 to carbon-12 is much lower now than in the past. The ratio started to decline about 1850, around the time fossil fuel use began to increase. The low amount of carbon-13 in our atmosphere is evidence that the increased CO_2 is produced by humans using fossil fuels.

Revision question 3.2

- Which carbon dioxide molecule would move faster in the atmosphere: a lighter one with a carbon-12 atom or a heavier one with a carbon-13 atom?
- Which molecule do you think is more likely to dissolve in the ocean? Give a reason.

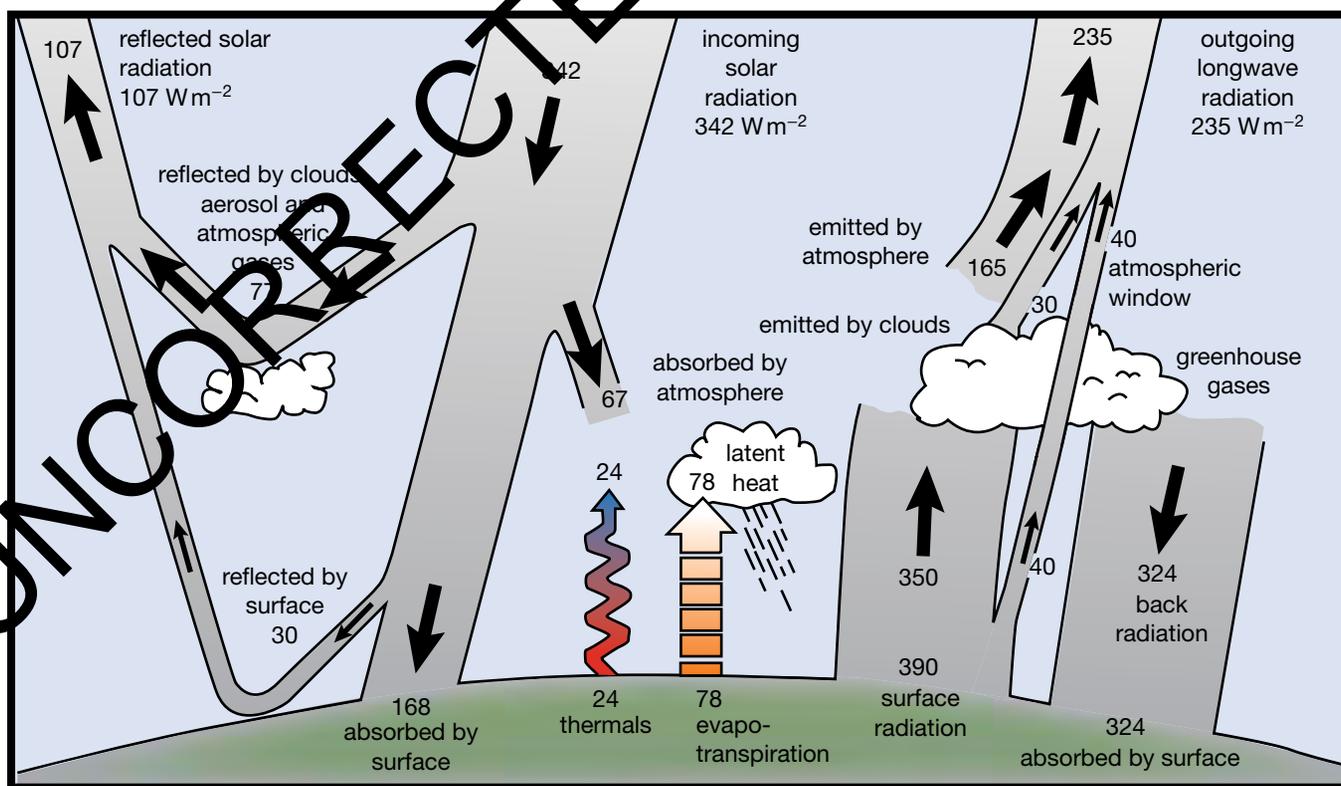
The Earth's energy budget

The Earth's energy budget is an accounting of the incoming energy from the Sun, where it goes in the atmosphere and at the surface, and how the outgoing energy leaves the Earth.

Note: This is called an energy budget, even though the numbers are measured in watts per square metre, which is actually the amount of energy passing through an area of one square metre every second.

The figure below shows all the different paths that energy takes from arriving at the Earth mainly as visible light to being emitted as longwave infra-red radiation or reflected straight back into space.

The Earth's energy budget from the International Panel on Climate Change (IPCC)



The numbers in the figure can be used to check the energy balance between energy coming in and energy going out, and not only of the whole Earth, but also of just the atmosphere, or just the Earth's surface. In each case, the energy coming in should equal the energy going out.

For example:

For the Earth as a whole:

Incoming energy = 342 W m^{-2}

Outgoing energy = $77 + 30 + 165 + 30 + 40 = 342 \text{ W m}^{-2}$

For the Earth's surface:

Incoming energy = $168 + 324 = 492 \text{ W m}^{-2}$

Outgoing energy = $24 + 78 + 350 + 40 = 492 \text{ W m}^{-2}$

Revision question 3.3

- From the figure for the Earth's energy budget, calculate the total incoming energy and total outgoing energy for the atmosphere and show that each equals 519 W m^{-2} .
- For each of the energy transfers in the figure for the Earth's energy budget, determine whether it occurs by conduction, convection, radiation or evaporation.

The table below provides a description and the contribution to the energy budget of most of the terms in the figure for the Earth's energy budget.

TABLE 3.1 Energy budget of the Earth by energy category

Energy category	Amount (W m^{-2})	Description
Incoming solar radiation	342	Visible light with some infra-red and ultraviolet from the Sun
Outgoing longwave radiation	235	Infra-red radiation from many sources heading out to space
Reflected solar radiation	107	Visible light from two sources heading out to space
Reflected by clouds, etc.	77	Visible light reflected by clouds, aerosol and atmospheric gases
Atmosphere window	40	Infra-red radiation passing through the atmosphere because it is in the part of the spectrum that is not absorbed by the main greenhouse gases
Emitted by clouds	30	Infra-red radiation from clouds heading out to space
Latent heat	165	Energy used or released when there is a change of state
Back radiation	24	Infra-red radiation emitted downwards by Greenhouse gases in the atmosphere
Absorbed by surface	168, 324	Visible light, infra-red and ultraviolet radiation from two sources absorbed by the Earth's surface
Thermals	24	Rising currents of hot air
Evapotranspiration	78	Moisture in plants released as water vapour
Surface radiation	390	Infra-red radiation emitted by the Earth's surface into the atmosphere

Sample problem 3.1

Using the figure on page 37 for the Earth's energy budget from the IPCC, find the missing amount in the table below.

Energy category	Amount (W m^{-2})	Description
Emitted by atmosphere	?	Infra-red radiation emitted upwards by greenhouse gases in the atmosphere

Solution: From the figure, the amount emitted is $165 \text{ (W m}^{-2}\text{)}$.

Revision question 3.4

Using the figure on page 37 for the Earth's energy budget from the IPCC, find the missing amount in the table below.

Energy category	Amount (W m^{-2})	Description
Reflected by surface	?	Visible light reflected by snow, land and sea ice
Absorbed by atmosphere	?	Incoming radiation that is absorbed by gases in the atmosphere

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Albedo
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TABLE 3.2 Albedo of different materials

Material	Albedo
Water	0.08
Sea ice	0.5–0.7
Fresh snow	0.8–0.9
Clouds	0.4–0.8
Forest	0.1
Desert	0.3
Green grass	0.25

Feedback

In any complicated system with many interacting components, such as the Earth's climate, sometimes one part changes a second part, and a change in the second part can then change the first part. This is called feedback. A common audio example of feedback is when a person using a microphone walks in front of a loudspeaker. The microphone picks up the signal from the speaker, which is then amplified, fed back into the speaker, which is again picked up by the microphone, and so on, producing a loud high-pitched noise. This is called positive feedback. Negative feedback is also possible, for example, a 'governor' or control device is used in engines, where excess speed is used to reduce the input to keep the speed constant.

The climate has examples of both positive and negative feedback.

Positive feedback:

- Evaporation: Increasing sea temperatures leads to more evaporation of water, a greenhouse gas, which increases the temperature of the air and sea.

Negative feedback:

- Thermal radiation: Increasing surface temperature emits more infra-red radiation, which cools the Earth.

The risk of positive feedback is that there is a 'tipping point' beyond which the system can become unstoppable, as in the loudspeaker example above.

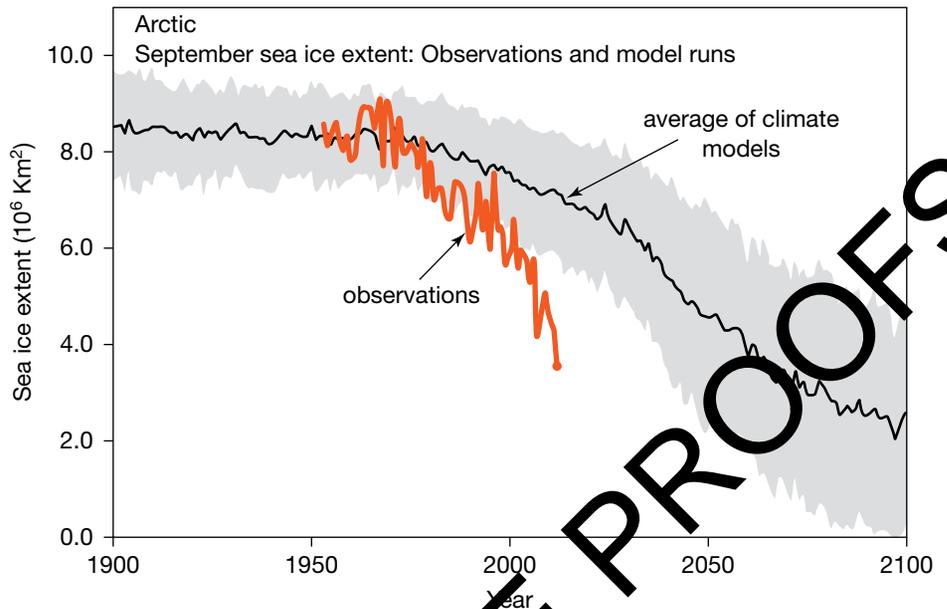
Another example of positive feedback in the Earth's climate is the physical quantity 'albedo'. Albedo is a measure of the proportion of incoming radiation that is reflected without being absorbed. It is usually expressed as a number between 0 and 1, with 1 being a perfect reflector and 0 a perfect absorber.

Revision question 3.5

- (a) Estimate the albedo of the following materials: (i) the asphalt road surface, (ii) crops, (iii) the roof of your house.
- (b) Indicate whether each of the following is an example of positive or negative feedback. Explain your reasons.
- The release of methane from melting permafrost
 - Effect of clouds

The significance of albedo for the climate is the role it plays in determining the amount of sea ice in the Arctic. Sea ice is very reflective, but the water it is floating in is not. Increased air temperature leads to more sea ice melting, which means that more of the incoming radiation hits water rather than ice and is absorbed. This increased energy absorption then heats up the atmosphere, which leads to more sea ice melting, and so the feedback loop continues.

The extent of Arctic sea ice in September each year. The solid line shows the average of climate model predictions, the shaded area is the spread of the predictions from the different models.



Revision question 3.6

- Why do you think the extent of Arctic sea ice in September is graphed?
- What factor about the sea ice other than its surface area could be important?

Climate models

The scientific principles that underlie climate have been understood since the 19th century. They include:

- Newton's laws of motion that explain the movement of gases and liquids, such as the existence of high and low pressure regions, the formation of cyclones, the flow of ocean currents
- thermodynamics principles that explain heat transfer within the atmosphere, and also between the atmosphere, the oceans and the land
- gas laws and solubility in liquids from chemistry that explain the behaviour of gases within the atmosphere and their interactions with the oceans.

These principles are precisely known with mathematical relationships, some of which you will come across in this year's or next year's courses in Physics and Chemistry. The development of the computer meant that these principles and their mathematical relationships could be applied to the biggest problem on Earth, the Earth itself.

A climate model is an attempt to apply these relationships to the atmosphere of the whole Earth as well as the surface features of land, ice and sea. The model attempts to calculate aspects of the climate that are important to humans, such as rainfall and humidity, sea level rise, ocean acidity, wind strength and, of course, air temperature.

Climate models are also able to calculate future trends in these aspects of climate and then investigate the effect on these trends of changes such as reducing greenhouse gas emissions or aerosol use.

How to know if a climate model is accurate?

A climate model starts as hundreds of mathematical equations that describe all the physical and chemical interactions within the atmosphere, and between the atmosphere, the land, sea and ice. These equations are applied to a model of the Earth's atmosphere as it was at an earlier time, say 1900, to calculate the expected climate conditions for the next 100 years. These calculations are

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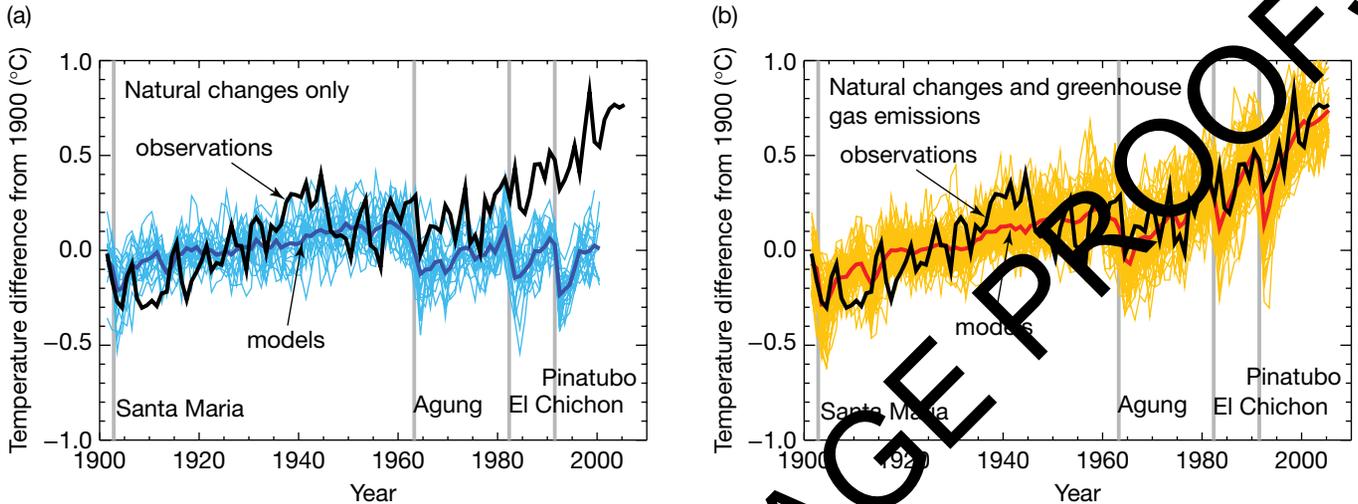
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then compared with the actual climate conditions to see how close the climate model comes to reality.

If the model is out, then it is back to the drawing board to redesign the model. If the model is accurate, it can be used to calculate the future climate. Different countries and scientific organisations each produce their own climate models. The basic scientific principles are the same, but the models vary in their subtlety and complexity, and the available computing power.



Model comparisons against actual temperature from 1900 to 2000
Source: IPCC.

The solid black line in each graph above is the global average surface air temperature from 1900 until 2000. The models were run twice:

- The first run assumed the carbon dioxide concentration stayed constant at its value in 1900. This produced the blue graph on the left. The solid blue line is the average of all the different models.
- The second run included the actual carbon dioxide concentration over the century. This produced the red graph on the right. Again the solid red line is the average of all the different models.

The red line in the graph on the right is a close fit to the actual observed temperature change. It is apparent from comparing the two graphs that increased carbon dioxide concentration has led to an increase in the global temperature.

The close match of the red graph with the observations validates the design of the climate models and gives confidence about what the models might predict for the decades and centuries ahead. The models can also be used to investigate how long the Earth's atmosphere would take to respond to a significant reduction in CO₂ emissions.

With this information, governments can act together to bring about change. The models not only produce a global average, but also specific information for each region of the Earth. So local responses to climate change can be planned.

Revision question 3.7

Use the graphs above to answer the following questions.

- (a) Pinatubo, El Chichon, Agung and Santa Maria are all volcanic eruptions.
- What was the effect of the eruptions on the average global surface air temperature?
 - Suggest a mechanism for this effect.
- (b) There are some stretches of a number of years where the models and the actual temperature data differ significantly.
- Identify those stretches of years.
 - Thinking of the history of each of those years, is there a possibility that the collection of temperature data to obtain a global average may have been unreliable?

- (c) Looking at the two graphs, when do you think the increased carbon dioxide concentrations started to affect the global average surface air temperature?
- (d) The Earth's surface is made up of solid rock, liquid oceans and a gaseous atmosphere.
 - (i) Which do you think would be better to use to measure the temperature of the Earth's surface?
 - (ii) Why do you think the air temperature is used?

Climate models can be used to investigate the long-term effects of international agreements on controlling greenhouse emissions on surface air temperature, sea level rise and rainfall.

Investigating a simple climate model

The energy budget shown in the figure on page 37 has been converted into a rudimentary spreadsheet model of the climate, which you can use to investigate the effect of future scenarios such as:

- a decrease in sea ice, leading to a reduction in the amount of radiation reflected straight back into space
- increased atmospheric CO₂ concentration, leading to a lesser proportion of infra-red radiation from the atmosphere being emitted into space and more being emitted back to Earth.

Issues related to thermodynamics

You have studied many aspects of thermodynamics in the last three chapters that affect our lives in many ways, including:

- preparing food
- designing our homes, as well as heating and cooling them
- keeping our bodies at an even temperature
- selecting energy sources for our economy and, most important of all,
- understanding and addressing climate change.

It is therefore appropriate that you explore an issue in some depth, to identify the thermodynamic principles in use and to evaluate relevant public policy and social commentary for their scientific accuracy.

The Resources section of your eBookPLUS has an extensive list of possible topics to research, each with supporting documents and useful weblinks, as well as suggestions for how to present your findings.

Some possible topics for you to research are listed below.

- Compare domestic heating and cooling technologies. Are the brochures and advertising physically plausible?
- Investigate the design of energy efficient houses. How do building materials differ? Are star ratings reliable? Should design features such as double glazing and orientation in relation to the Sun be mandatory?
- Compare appliances by their technology, efficiency and emissions. Are the energy ratings useful?
- Research solar thermal technology. Is generating electricity by solar thermal technology a feasible alternative for Australia?
- Investigate geo-engineering solutions to tackle climate change. Are any of them feasible?
- Examine the treatments for hypothermia (body core temperature < 35 °C) and hyperthermia (body core temperature > 38 °C). How have they changed over time and how do they work?
- Compare different technologies for food preparation, e.g. microwave oven vs convection oven as well as different fuel options.

These broad topics may need to be narrowed down to focus on a specific aspect if the task is to be manageable.

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A simple climate change model

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Evaluating resources

When collecting information from the internet or elsewhere, it is important to determine how reliable and accurate the information is. Each item should be evaluated to see how useful it will be.

Some aspects worth considering are:

Reliability

- Relevant: Is the information central to your purpose?
- Up to date: When was the information produced? Has it been superseded by new information?
- Expertise: Is the information produced by someone with appropriate qualifications? Do they know what they are talking about?
- Source: Where did the author obtain their information?
- Audience: Who is the intended audience and is the resource suited to your purpose?
- Bias: Is there evidence of overstatement, selective quoting or other tricks designed to mislead?

Validity

- Accuracy: Are physics concepts correctly used?
- Argument: Is the argument logical, sound and strong? Are deceptive strategies used, e.g. oversimplification or false choices?
- Analysis: Are physics relationships applied correctly?

Uncertainty

- Graphs: Are the graphs misleading?
- Data: Does the data lack precision? Is only selected data used?

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Chapter review

Summary

- The Earth on average, over the day and across the globe, receives about 342 joules of energy every second in each square metre.
- About 100 joules of this energy the Earth receives is reflected back into space by ice, snow and clouds.
- Without greenhouse gases in the atmosphere, the surface temperature of the Earth would be -18°C .
- Most of the radiation emitted by the Earth is infra-red radiation.
- The main greenhouse gases are water vapour (H_2O) and carbon dioxide (CO_2), with methane (CH_4) making a small contribution along with other molecules with more than two atoms.
- The relative flexibility of the greenhouse gas molecules allows them to absorb the infra-red radiation emitted by the Earth's surface. After absorbing the infra-red radiation, the greenhouse gases re-emit it in all directions; some upwards out into space, but most back down to the Earth to heat the surface.
- Some of the wavelengths absorbed by the greenhouse gases are common to each, but each particular gas absorbs some wavelengths that are unique to that gas.
- The energy that comes to the Earth from the Sun is balanced by the energy the Earth radiates back into space.
- The energy from the Sun is absorbed by the atmosphere, the land surface and the oceans. The energy absorbed by the land and sea is transferred by conduction, convection, radiation and evaporation to the atmosphere. Some of this energy returns to the Earth's surface after being emitted by the greenhouse gases and increases the surface temperature.
- Climate models are based on the scientific principles of motion, thermodynamics and the chemistry of gases and liquids.
- Climate model calculations are very consistent with the historical record.
- Climate model calculations show that the increase in global average surface air temperature in recent decades is explained by the increased atmospheric CO_2 concentration.
- The albedo of a surface is the proportion of incoming radiation that is reflected with no change in wavelength.
- Feedback mechanisms are processes in complex systems where the output from the system can affect an input to the system. The feedback can be either positive or negative. Both types occur in the Earth's atmosphere.

Questions

1. Why doesn't all of the radiation from the Sun that enters the Earth's atmosphere reach the surface?
2. List the features of the Earth that influence its climate.
3. Describe the properties of water that cause the variation in climate over the Earth's surface.
4. What is the enhanced greenhouse effect and why is it a threat to life on Earth?
5. Is the majority of the heating of the Earth's atmosphere due to the transfer of radiant energy from the Sun or from the Earth's surface?
6. Why do the atmosphere and surface of the Earth emit infra-red radiation?
7. Why does water take much longer to increase in temperature due to exposure to sunlight than the same mass of soil in an identical container?
8. Why does air cool as it rises even though it is getting closer to the Sun?
9. The intensity of the Sun's radiation on the Earth's surface at latitudes of 60° is about half of that near the equator. Give two reasons for this difference.
10. Use the Earth's energy budget illustrated in the figure on page 37 to show that the total amount of energy entering the atmosphere is equal to the total amount of energy leaving it.
11. Why is so little heat transferred from the Earth's surface to its atmosphere by conduction?
12. All of the energy transferred from the Earth's surface and atmosphere into space is transferred by radiation. Why is there no transfer by conduction or convection?
13. In the tropical regions of the Earth, more radiant energy is received from space than is lost. At the poles, more radiant energy is lost than is received. This would suggest that average temperatures in the tropics should be continually increasing while the average temperatures at the poles should be continually decreasing. Explain why this doesn't happen.
14. Although the IPCC graphs on page 41 show that long-term global warming is occurring, the temperature increase is not steady. What factors make the increase so erratic?
15. What is the major cause of the greenhouse effect?
 - A. Gases in the atmosphere absorb heat from the Earth's surface.
 - B. Gases in the ozone layer absorb heat from the Earth's surface.

- C. Gases in the ozone layer absorb heat from the Sun.
- D. Gases in the atmosphere absorb heat from the Sun.
16. It has been falsely argued that since the bulk of the greenhouse effect is caused by water, the other greenhouse gases are insignificant. Use the absorption spectra of CO_2 to show that this is not the case.
17. Indicate whether each of the following is an example of positive or negative feedback and explain why.
- Carbon cycle: Carbon atoms in CO_2 are absorbed by plants, which are either eaten as food or used as fuel, which produce CO_2 .
 - Warmer oceans absorb less CO_2 .
18. What are the similarities and differences between the energy from the Sun that is absorbed by the Earth and the energy the Earth radiates into space?
19. Why can the low carbon-13 to carbon-12 ratio in our atmosphere be described as fossil fuels' fingerprints?
20. The specific heat capacity of water is over four times that of sand.
- What effect does this have on the heating and cooling of water and sand?
 - Explain why, on a hot day, sand is too hot to stand on in bare feet while the water in the sea can be too cold for some people.
 - Why is the temperature of the sand of an inland desert almost always greater than that of the sand on a beach at the same latitude?
21. At night, still water cools by conduction, convection, radiation and evaporation. However, during the day, convection takes no part in its warming. Why not?
22. When the Sun is directly overhead, each square metre of the Earth's surface receives 1368 J of radiant energy each second. On a typical winter's

weekday, Victoria consumes about 4500 MW of electrical energy. What area of solar collectors (of 15 per cent efficiency) would be needed to provide energy at the same rate while the Sun is directly overhead?

23. Estimate the quantity of radiant energy that would fall on your body if you were to lie in the afternoon sun on the beach for 30 minutes. Assume that each square metre is receiving radiant energy at the rate of 1200 W. Explain any additional assumptions that you have made in making your estimate.

More of a challenge

24. The table below compares the specific heat capacities as well as reflection and absorption properties of water and dry sand.

Property	Water	Dry sand
Specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)	4200	820
Reflectivity (%)	3	15
Depth to which 50% of the radiant energy is absorbed	11 m	1 mm

When the Sun is directly overhead, each square metre of the Earth's surface receives radiant energy at the rate of 1368 W. Assuming that all of the energy that is not reflected is absorbed, what average temperature increase would be expected during a period of 1 hour in:

- water to a depth of 11 m
- sand to a depth of 1 mm?

The density of water is 1000 kg m^{-3} while the density of dry sand is 2400 kg m^{-3} .

25. On a warm sunny day, the Sun's radiation melts very little snow on the slopes of an alpine ski resort. Why?