

# Balancing planetary energy budgets



Energy transfer, by radiation and other processes, takes place in a planet's atmosphere and at its surface, and drives its climate system. How do these processes differ between planets?

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Figure 1 Earth's surface and atmosphere

## Exam links



The terms in **bold** link to topics in the AQA, Edexcel, OCR, WJEC and CCEA A-level specifications, as well as the IB, Pre-U and SQA exam specifications.

Energy is transferred in planetary atmospheres and surfaces by **radiation** being absorbed, reflected, scattered and emitted. Key ideas include **radiation intensity** and **black body radiation**.

The temperature of the Earth's surface and that of the atmosphere above it (Figure 1) are governed by the intricate exchange of energy between the different components of the climate system — atmosphere, cryosphere (glaciers, ice sheets or anything else involving frozen water), oceans and land. If this exchange of energy — called the Earth's *radiation budget* or *energy budget* — is in balance, the temperature of the Earth's surface stays the same. However, if anything happens to tip the balance, such as an increase

in the amount of greenhouse gases in the atmosphere, the temperature changes.

In this article and *At a glance* (pp. 16–17) we'll look at Earth's energy budget and those of other planets. The data come from a number of sources, including measurements made by spacecraft and satellites as well as by probes or instruments placed on the surface of the planets. In addition, our understanding of atmospheric physics allows us to develop powerful computer models that replicate the main features and processes of a planet and its atmosphere.

## Earth's energy budget

The Earth's energy budget is summarised in Figure 2. To read the diagram, start with the blue arrow coming in at the top. This shows radiation from the Sun entering the atmosphere. As the radiation passes through the atmosphere, it is absorbed and scattered, transferring energy to the atmosphere — the arrow gets narrower as it goes down. What's left is absorbed by the surface.

The surface also emits radiation — the red arrow leaving the ground. Again, there is absorption by the atmosphere. The atmosphere also emits radiation, increasing the width of the arrow. At the top of the diagram, the red arrow shows the energy radiated into space.

Because the Earth is considerably cooler than the Sun (288 K compared with 6000 K) its *black body radiation* is mainly in the infrared, rather than the visible and ultraviolet radiation we get from the Sun (Box 1).

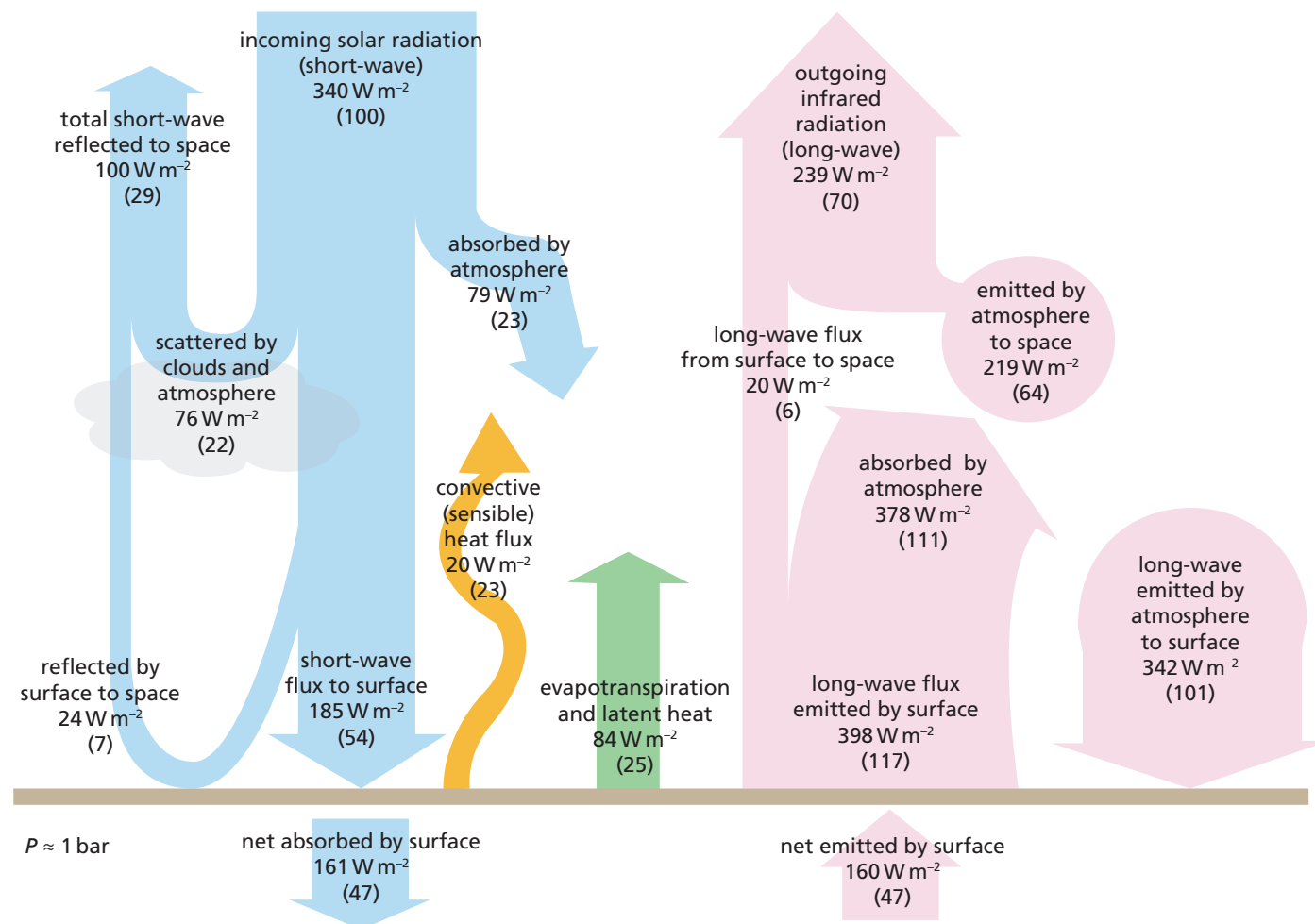
The numbers on the arrows indicate the energy flux, or *intensity* (of radiation) in  $\text{W m}^{-2}$ , averaged over the Earth's surface and over the year. The numbers in brackets express the flux as a percentage of incoming solar radiation.

Let's look at each of the main processes in turn.

## Incoming solar radiation

Almost all of the energy stored in the atmosphere ultimately comes from the electromagnetic radiation emitted by the Sun. The intensity of incoming solar radiation depends on solar activity and Earth's orbit around the Sun.

There is a roughly 11-year cycle in solar activity and the number of sunspots — the more sunspots, the more intense the solar radiation. The changes in intensity through a cycle are typically less than 0.1%, which causes a global temperature change of less than  $0.03^\circ\text{C}$ . This is enough to have some impact on, for example, droughts, temperature extremes and the amount of ozone. After a period of relatively high activity at the end of the twentieth century, the Sun has recently been less active.



**Figure 2** The energy budget of the Earth. Solar radiative fluxes are shown in blue and infrared fluxes in pink; convective fluxes are shown in orange. Numbers in brackets indicate the percentage of incoming solar radiation

## Box | Black body radiation

Black body radiation is the electromagnetic radiation emitted by an object that is at uniform temperature. The amount and wavelength spectrum of its radiation is determined by its temperature.

The Stefan–Boltzmann law tells us that  $J$ , the total power per unit surface area emitted by an object, is proportional to  $T^4$ :

$$J = \sigma T^4$$

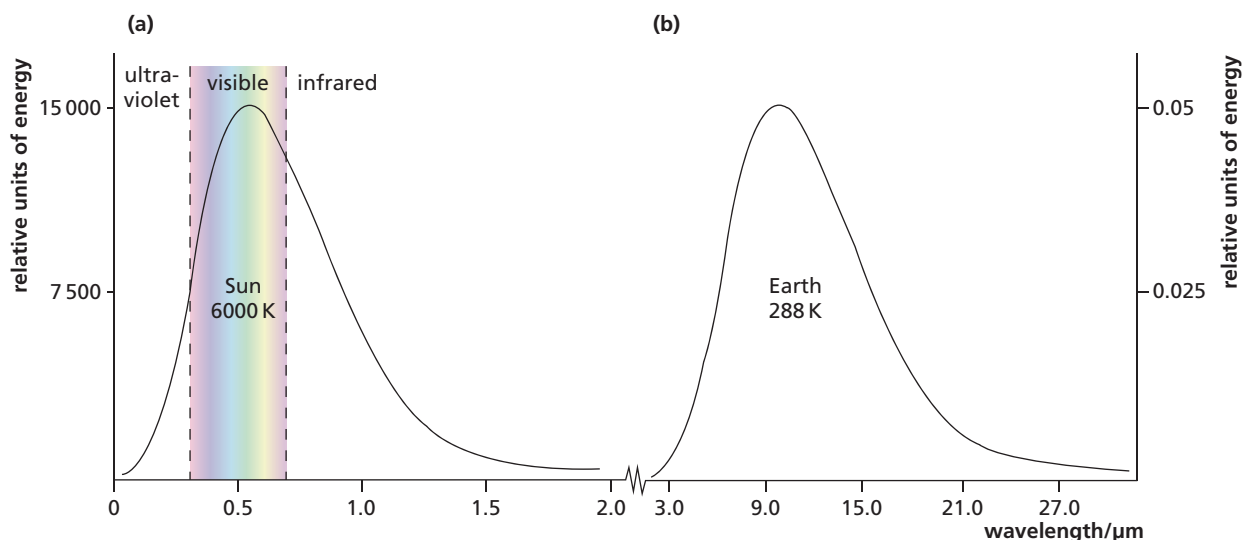
where  $T$  is its temperature in kelvin and  $\sigma$  is the Stefan–Boltzmann constant ( $\sigma = 5.670373 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ).

The wavelength  $\lambda_{\text{max}}$  at which most energy is emitted is inversely proportional to temperature, shown by Wien's displacement law:

$$\lambda_{\text{max}} = \frac{b}{T}$$

where  $b$  is Wien's displacement constant ( $b = 2.8977721 \times 10^{-3} \text{ m K}$ ).

Figure 1.1 shows the spectra of the solar radiation reaching Earth and the Earth's own radiation.



**Figure 1.1** The black body spectra of (a) incoming solar radiation and (b) Earth's emitted radiation

The combined gravitational pull of the Sun, Saturn, Jupiter and other planets causes the shape of the Earth's orbit to vary from its most elliptical to almost circular on a 110 000-year timescale. The Earth is currently closer to the Sun in the northern hemisphere winter than in the southern hemisphere winter. The angle of obliquity of the Earth's axis also varies, and the axis precesses ('wobbles') over a roughly 26 000-year cycle (PHYSICS REVIEW Vol. 24, No. 4, pp. 6–9). These processes affect which part of the Earth's surface gets most energy. The greater land surface area in the northern hemisphere compared with the south has an impact on the global climate.

### Reflected solar radiation

This is the combined radiation reflected by the atmosphere, clouds, small particles in the atmosphere ('aerosols') and the Earth's surface. The fraction of energy reflected is called the *albedo*; typical values are given in Table 1.

Huge explosive volcanic eruptions in the tropics, energetic enough to push sulfur gases up into the upper atmosphere where they condense into aerosols, can have a cooling effect on climate by increasing the albedo. This effect can last a couple of years. The combined eruptions of La Soufrière (1812), Mayon (1814) and Tambora (1815) had catastrophic global effects, leading to a 'year with no summer' in 1816.

**Table 1** Typical albedo values

Surface	Albedo
Clouds	0.15–0.8
Snow and ice	0.8–0.9
Forests and cities	0.1–0.2
Desert	0.35
Water	0.05–0.5

### Radiation absorbed by the Earth's surface

All the solar radiation that avoids being reflected or absorbed before it reaches the surface of the Earth, as well as the radiation that is emitted back towards the Earth by the atmosphere, is absorbed by the surface. This warms the ground and the oceans.

### Conduction, convection, evaporation and surface radiation

The warm surface of the Earth returns energy to the atmosphere by:

- warming the air directly above it by conduction and convection

## Box 2 Latent heat

When a substance changes state (from solid to liquid or liquid to gas) it requires an input of energy that increases the molecules' potential energy without raising the temperature. This energy is known as latent ('hidden') heat. As the substance liquefies or solidifies, this same energy is given out while the temperature remains at the melting or boiling point.

For water at normal atmospheric pressure:

specific latent heat of fusion (melting) =  $3.34 \times 10^5 \text{ J kg}^{-1}$

specific latent heat of evaporation =  $2.26 \times 10^6 \text{ J kg}^{-1}$

- water vapour condensing to form cloud droplets, releasing energy (latent heat — Box 2) and warming the atmosphere
- water vapour entering the atmosphere through:
  - the evaporation of water from oceans, lakes etc.
  - plants transpiring
- the Earth's surface radiating upwards

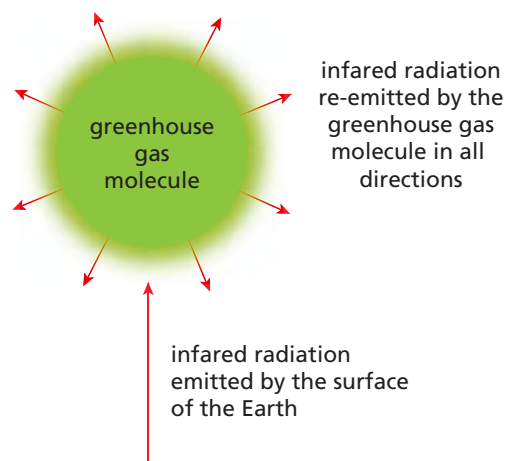
### Radiation absorbed by the atmosphere

Some incoming solar radiation is absorbed by the atmosphere. Most importantly for us, stratospheric ozone absorbs much of the incoming ultraviolet radiation, protecting all living things from potential damage.

In 1859 John Tyndall's laboratory experiments showed that certain gases absorb infrared radiation; these are collectively known as greenhouse gases. They include water vapour (the most important), carbon dioxide, methane and nitrous oxide.

These gases absorb much of the long-wave radiation emitted by the surface of the Earth. Without this *greenhouse effect*, the surface of the Earth would be about 33 K cooler.

Each molecule absorbs radiation coming at it from one direction and re-emits it in all directions (Figure 3). So, if the radiation it absorbed was heading upwards initially, half of it will end up heading downwards once it is re-emitted. The net effect of this happening over and over again is that the warm atmosphere radiates energy in two directions — some upwards, so that it is lost to space, but more downwards, back towards the surface of the Earth.



**Figure 3** A molecule absorbs and re-emits radiation

Some wavelengths of radiation are not absorbed by any atmospheric gas, and therefore pass through the atmosphere unhindered. The wavelength ranges in which this happens are known as *atmospheric windows*.

### Outgoing long-wave radiation

This outgoing radiation transfers energy from Earth into space. In Figure 2, the relationship between energy fluxes is:

$$\begin{array}{ccccc} \text{reflected} & & \text{outgoing} & & \text{incoming} \\ \text{solar} & + & \text{long-wave} & \approx & \text{solar} \\ \text{radiation} & & \text{radiation} & & \text{radiation} \end{array}$$

with slightly more (about  $0.6 \text{ W m}^{-2}$ ) coming in than going out, implying that energy is collecting in the climate system, heating it up. Scientists understand that this is due to the fact that the concentration of greenhouse gases in the atmosphere is increasing, as people burn fossil fuels and change land use.

### Other planets and moons

It is interesting to compare Earth's energy budget with other bodies in the solar system (Table 2). We'll look at Mars, Venus, Jupiter and Titan (Saturn's largest moon). The planetary budgets for these bodies are displayed on pp. 16–17.

#### Mars

Mars (1, p. 16) rotates at almost exactly the same rate as the Earth and with a similarly tilted axis. It has only around half the diameter of Earth, with no oceans and a thin atmosphere composed almost entirely of  $\text{CO}_2$ . Many scientists have studied Mars and its atmosphere is well understood. Martian weather is dominated by dust storms, the carbon and water cycles and thermal 'tides' driven by the movement of the surface in and out of the Sun's radiation.

The Martian energy budget under relatively low dust conditions is shown on p. 16 (2). The *P* value shows the pressure of the atmosphere at the surface: 600 Pa = 0.006 bar, where 1 bar ( $10^5 \text{ Pa}$ ) is the average atmospheric pressure on the surface of the Earth.

In the Martian winter, temperatures can be low enough (140–145 K) for  $\text{CO}_2$  to condense, forming snow and cloud around the pole. This doesn't have much of an effect on the latent heat fluxes, but does affect the planet's albedo.

Unlike in the Earth's atmosphere, very little incoming or outgoing radiation is absorbed by the Martian atmosphere. Mars has much more  $\text{CO}_2$  than the Earth, but hardly any other greenhouse gases, meaning that whilst one wavelength band is almost entirely absorbed by the atmosphere, the rest of Mars's blackbody emission escapes to space. Mars's greenhouse effect only warms the planet's surface by 5 K. This means that, when there isn't a dust storm blowing, Mars's atmosphere doesn't have a big effect on the planet's energy budget.

However, every 3–5 years things change significantly when there is a major dust storm. Up to 78% of the Sun's radiation can be reflected or absorbed, never reaching the planet's surface, leaving the sky a reddish brown. The absorbed solar radiation is emitted as heat in the atmosphere, producing a sort of anti-greenhouse effect, warming the atmosphere but cooling the surface (3, p. 16).



**Table 2** Solar system bodies

Body	Average distance from the Sun/AU (1 AU = $1.496 \times 10^{11}$ km)	Average surface temperature/K (range in brackets)	Radius/km	Major constituents of atmosphere
Earth	1.000	288 (240–310)	6 378	Nitrogen (78%) Oxygen (21%) Water vapour (1%)
Mars	1.52	216 (140–290)	3 396	Carbon dioxide (95%) Nitrogen (2.7%) Argon (1.6%)
Venus	0.723	730 (720–740)	6 052	Carbon dioxide (96%) Nitrogen (3.5%)
Titan	9.55	93	2 575	Nitrogen (90%) Methane (1.5%) Argon (?)
Jupiter	5.2	270 (250–280)	71 492	Hydrogen (90%) Helium (10%)

### Venus

Venus (4, p. 17) is the Earth's other near neighbour. In many ways Venus is even more like the Earth than Mars. It is almost the same size as the Earth and composed of similar solid materials. Its atmosphere and orbit, however, are radically different from Earth's with an atmosphere composed mostly of CO<sub>2</sub> and exerting a pressure on its surface about 90 times that on the Earth.

Venus's lower atmosphere is filled with dense clouds, thought to be made of sulfuric acid droplets. These clouds reflect much of the Sun's radiation so that, even though it is closer to the Sun than the Earth, the planet's surface receives less energy (5, p. 17). However, the huge amount of CO<sub>2</sub> in the atmosphere leads to a major greenhouse effect — the average surface temperature is around 730 K, a massive 500 K warmer than it would be without its atmospheric blanket.

### Titan

Titan (6, p. 17) is the largest moon of Saturn and is the only natural satellite of another planet known to host a substantial atmosphere. Titan itself is around the size of Mercury — 50% larger than the Earth's moon — but is almost certainly composed of a mixture of rock and ices, which gives it a mean density of only  $1.88 \times 10^3 \text{ kg m}^{-3}$ .

The combination of very low surface gravity and low surface temperature gives Titan a relatively deep atmosphere, composed mostly of nitrogen and small amounts of methane and other hydrocarbons. With a mean surface pressure of 1.45 bars, this exerts a greater pressure than the Earth's atmosphere.

Although Saturn and therefore Titan are a long way from the Sun, and therefore don't receive much solar radiation, enough reaches Titan's atmosphere to drive a methane cycle very similar to the water cycle on Earth. Large lakes of methane are found near Titan's poles. Convection forms large methane clouds in the atmosphere.

The upper atmosphere (stratosphere), between 250 km and 300 km, is hazy with aerosols, which prevent the Sun's radiation from reaching Titan's surface. However, the methane and hydrogen in the lower atmosphere generate a greenhouse effect, warming the surface (7, p. 17).

### Jupiter

Jupiter (8, p. 17) is a gas giant planet, without a solid surface to absorb the Sun's radiation. Instead, the radiation carries on being scattered and absorbed as it travels deeper into the planet.

Jupiter generates about as much energy internally as it receives from the Sun. As the planet slowly shrinks under its own gravity, the gases gain kinetic energy as they lose gravitational potential energy. This increases the random kinetic energy of the gas molecules — in other words, the temperature rises. This heating drives convection, meaning there is an upward energy flux. Jupiter's 'surface' can be defined as the level where the downward solar radiation flux is equal to the upward energy flux due to convection.

A third of the Sun's radiation is scattered or reflected back to space by haze particles and ammonia ice cloud layers (9, p. 17). The rest is absorbed by Jupiter's upper atmosphere and, combining with the heat emerging from within the planet, is lost to space. Before it escapes, however, it fuels the movement of Jupiter's atmosphere, producing belts of fast easterlies and westerlies, and complex eddies where they meet — for example, the Great Red Spot.

### Conclusion

The energy transfers through the atmospheres of the different planets in the solar system are as different as the planets themselves. Whereas Earth and Venus have gases that produce a greenhouse effect with a significant effect on their climate, other planets such as Mars (when dusty) and Jupiter have an anti-greenhouse effect.

The Earth's climate system is probably unique among all the planets we've looked at: liquid water and a living ecosystem make things quite a lot more complicated. There is still much interesting work to be done as we try to understand our own planet.

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