

Planetary energy budgets

Understanding Earth's climate system can teach us about other planets.

By Sylvia Knight

Climate change and climate modelling are continually in the news. One way of testing how well we understand Earth's climate system is to see how well we can apply our knowledge to other planets with very different climates. Films like this year's *The Martian* depict other planets in our Solar System as inhospitable. What, though, are they really like and how do their atmospheric compositions affect them?

From the point of view of an individual standing on the surface, Earth's air, ice, water and soil, can seem like independent entities. However, the different elements of the climate system – atmosphere, cryosphere, oceans and land – are not isolated; they exchange huge amounts of energy and influence each other's behaviour. The fragile balance – Earth's energy budget – is calculated as the sum of all energy inputs into the climate system minus all energy leaks. If all inputs and outputs are equal, the global temperature is held constant, but if anything happens to tip the balance – such as an increase in the amount of greenhouse gases in the atmosphere – then the temperature changes (see Shallcross & Harrison, 2008).

Earth's energy

The Sun's electromagnetic radiation takes eight minutes to reach Earth, and is the major source of energy on Earth – as it is for all planets in the Solar System. As we follow the Sun's energy into Earth's atmosphere, we can see how it feeds into the planet's climate system, with its complicated energy flows and feedback loops. This information is captured in charts that have come to be known as Trenberth diagrams (figures 1, 2 and 3 on page 14; Trenberth et al, 2009).

As the Sun's radiation passes through Earth's atmosphere, much of the incoming ultraviolet radiation is absorbed by ozone in the stratosphere, approximately 10–50 km above Earth's surface. More solar radiation is then reflected and scattered by clouds and small particles in the atmosphere (known as aerosols). When dust accumulates in the

atmosphere as a consequence of huge volcanic activity, still more of the Sun's radiation is scattered away from the surface of Earth. This occurred in 1816, the year without summer, when the 1815 eruption of Mount Tambora in the Dutch East Indies (now known as Indonesia) caused a volcanic winter and major food shortages across the northern hemisphere.

Even more of the Sun's radiation is reflected by Earth's surface and is described by the albedo, which is calculated as the ratio of reflected radiation to incident radiation. Light-coloured surfaces such as ice have a higher albedo than darker ones. You can demonstrate how albedo works by using two ice cream tubs and painting the inside of one black, putting a thermometer in each tub and then covering them with clear plastic food wrap. Left in the sun, or under a lamp, the dark tub will absorb radiation and warm up while the white one will reflect the radiation and remain cooler.

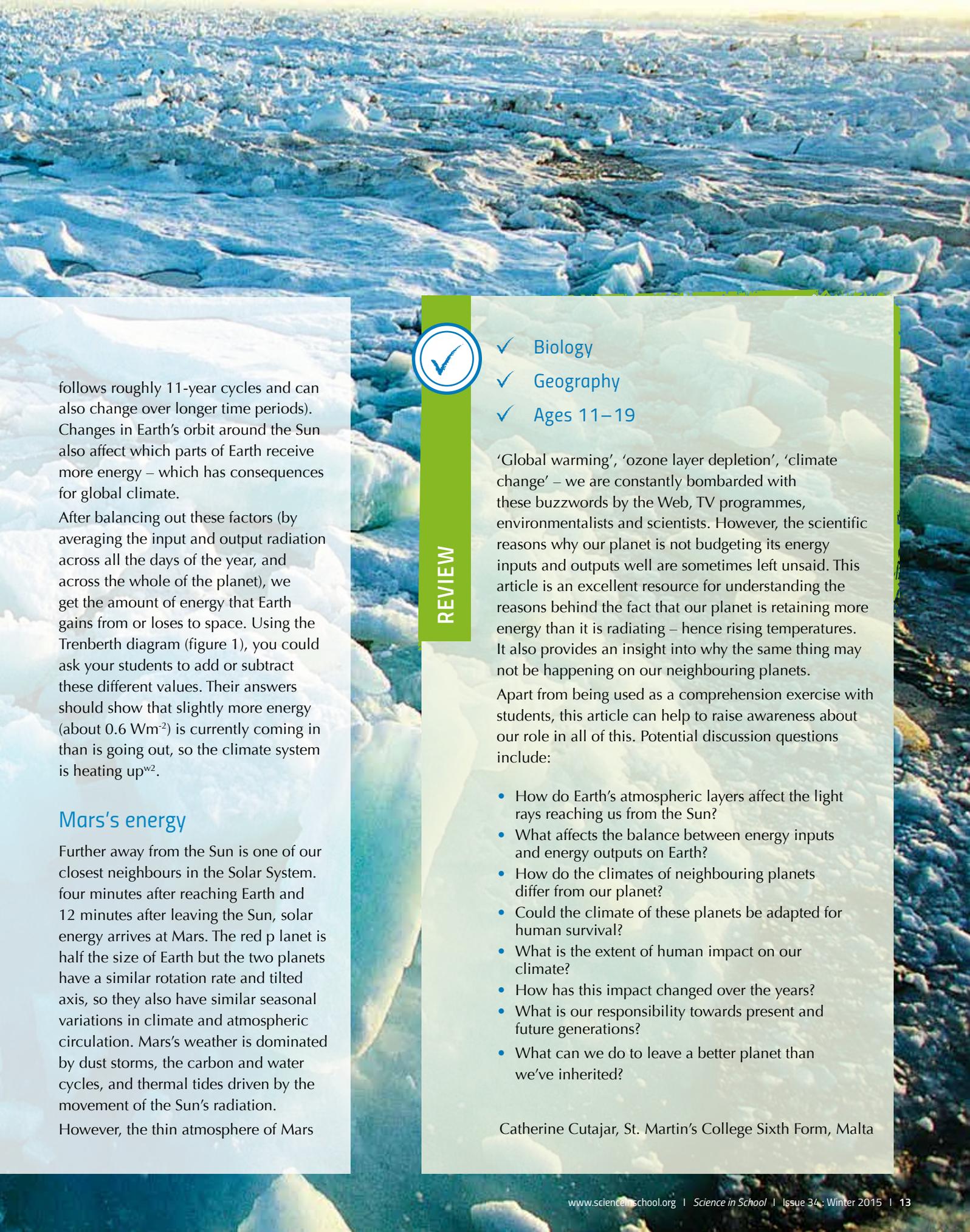
The energy that reaches the surface of Earth heats it and is re-radiated (for an explanation of black-body radiation, see Ribeiro, 2015). Some energy also returns to the atmosphere by conduction and convection as well as by the evaporation and transpiration of water – some of which later condenses in the atmosphere to form cloud droplets, releasing latent heat as it changes state.

Greenhouse gases also absorb some wavelengths of the infrared radiation emitted from the surface of Earth. Some of this is then emitted upwards and lost to space, but most is directed back towards Earth's surface. Other wavelengths of outgoing infrared radiation are not absorbed by any atmospheric gas and escape to space unhindered.

The balance

Earth's energy budget explains how the global temperature can change in one direction or another. Noticeably, the total amount of solar radiation reaching Earth is not always the same because of changes in the activity of the Sun (which

Sea ice plays a central role in our climate and global ocean circulation.



follows roughly 11-year cycles and can also change over longer time periods). Changes in Earth's orbit around the Sun also affect which parts of Earth receive more energy – which has consequences for global climate.

After balancing out these factors (by averaging the input and output radiation across all the days of the year, and across the whole of the planet), we get the amount of energy that Earth gains from or loses to space. Using the Trenberth diagram (figure 1), you could ask your students to add or subtract these different values. Their answers should show that slightly more energy (about 0.6 Wm^{-2}) is currently coming in than is going out, so the climate system is heating up^{w2}.

Mars's energy

Further away from the Sun is one of our closest neighbours in the Solar System. four minutes after reaching Earth and 12 minutes after leaving the Sun, solar energy arrives at Mars. The red planet is half the size of Earth but the two planets have a similar rotation rate and tilted axis, so they also have similar seasonal variations in climate and atmospheric circulation. Mars's weather is dominated by dust storms, the carbon and water cycles, and thermal tides driven by the movement of the Sun's radiation.

However, the thin atmosphere of Mars



REVIEW

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'Global warming', 'ozone layer depletion', 'climate change' – we are constantly bombarded with these buzzwords by the Web, TV programmes, environmentalists and scientists. However, the scientific reasons why our planet is not budgeting its energy inputs and outputs well are sometimes left unsaid. This article is an excellent resource for understanding the reasons behind the fact that our planet is retaining more energy than it is radiating – hence rising temperatures. It also provides an insight into why the same thing may not be happening on our neighbouring planets.

Apart from being used as a comprehension exercise with students, this article can help to raise awareness about our role in all of this. Potential discussion questions include:

- How do Earth's atmospheric layers affect the light rays reaching us from the Sun?
- What affects the balance between energy inputs and energy outputs on Earth?
- How do the climates of neighbouring planets differ from our planet?
- Could the climate of these planets be adapted for human survival?
- What is the extent of human impact on our climate?
- How has this impact changed over the years?
- What is our responsibility towards present and future generations?
- What can we do to leave a better planet than we've inherited?

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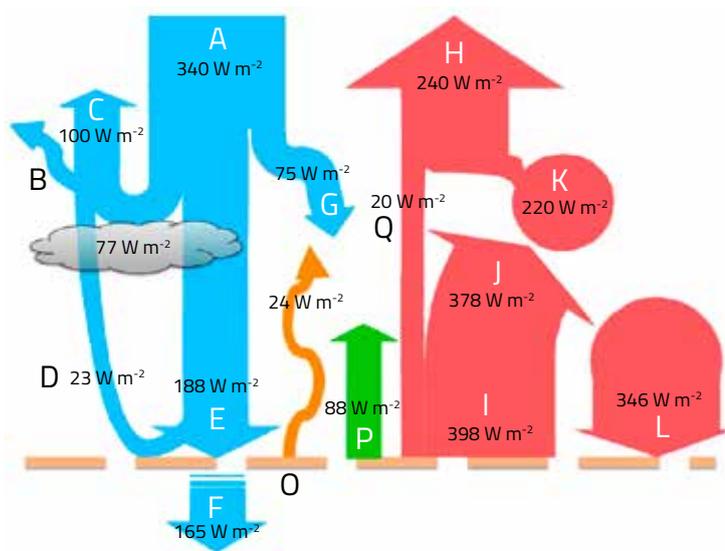


Figure 1: The energy budget of Earth, averaged over Earth's surface and over the year. Solar radiative fluxes are shown in blue and infrared fluxes in pink; convective fluxes are shown in orange.

- A: Incoming solar radiation;
- B: Scattered by clouds and atmosphere;
- C: Total shortwave radiation reflected to space;
- D: Reflected by surface;
- E: Shortwave radiation that reaches surface;
- F: Shortwave radiation absorbed by surface;
- G: Shortwave radiation Absorbed by atmosphere;
- H: Total outgoing infrared (longwave) radiation;
- I: Longwave radiation emitted by surface;
- J: Longwave radiation absorbed by the surface;
- K: Longwave radiation emitted by atmosphere to space;
- L: Longwave radiation emitted by atmosphere to surface;
- O: Thermals;
- P: Evapotranspiration;
- Q: Longwave flux from surface to space.

Images courtesy of Sylvia Knight

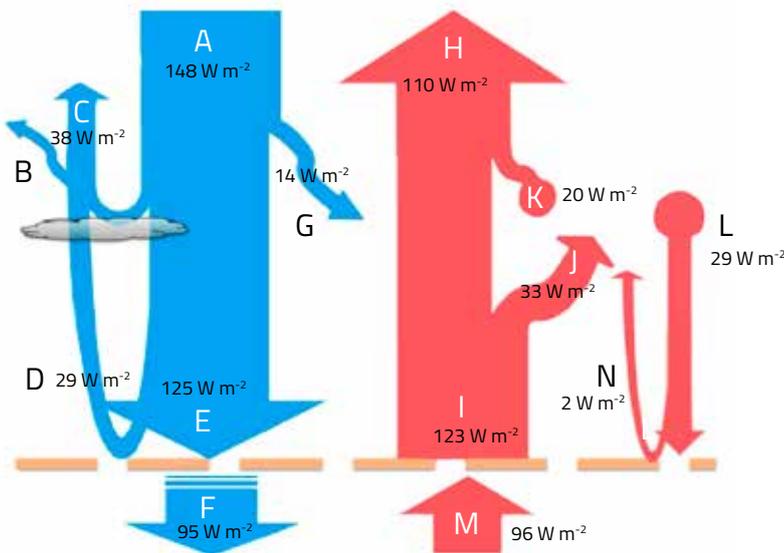


Figure 2: Mars's energy budget under relatively low dust conditions. When there isn't a dust storm, Mars's atmosphere has very little impact on the flow of energy into and out of the planet.

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- I: Longwave radiation emitted by surface;
- J: Longwave radiation absorbed by the surface;
- K: Longwave radiation emitted by atmosphere to space;
- L: Longwave radiation emitted by atmosphere to surface;
- M: Longwave radiation emitted by surface;
- N: Longwave radiation reflected by the surface.

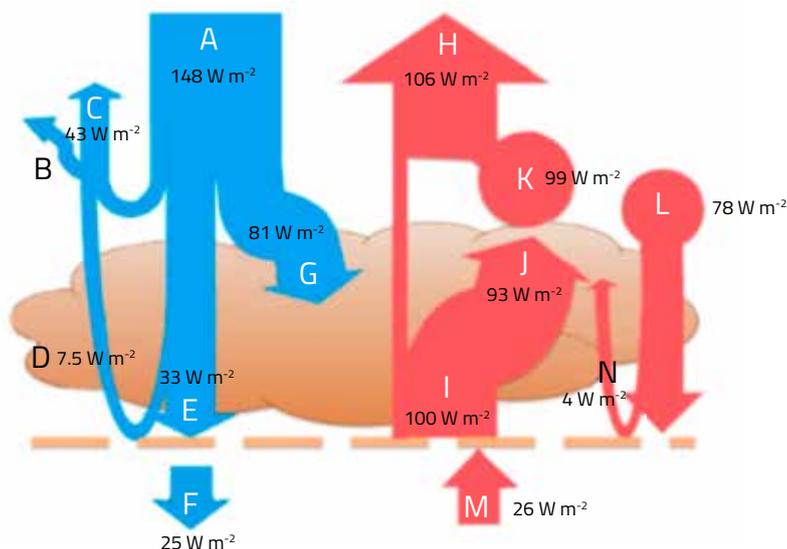


Figure 3 Mars's energy budget during major dust storms. The dust absorbs much of the incoming sunlight and creates an anti-greenhouse effect, with more heat escaping from the top of the atmosphere than leaves the surface.

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Image courtesy of ESA/DLR/FU Berlin



The south pole of Mars, capped with frozen water and carbon dioxide

has little effect on radiation passing through it. This means that almost all the incoming radiation reaches the planet's surface, but then almost all its emitted radiation escapes to space. This is due to the fact that the Martian atmosphere contains much more carbon dioxide than Earth's, and hardly any other greenhouse gases. Whilst the relatively narrow band of emitted radiation at a wavelength of $15\ \mu\text{m}$ is almost entirely absorbed by the carbon dioxide in the atmosphere, the rest of Mars's black body emission escapes and Mars's greenhouse effect only warms the planet's surface by 5 K. In the typical Martian winter, temperatures can be low enough (140 K) for carbon dioxide to condense, forming snow around both its poles and further increasing the planet's albedo. Things change dramatically in the Martian atmosphere every 3–5 years when a major dust storm leaves the sky a reddish-brown and dust clouds reflect or absorb up to 78% of the Sun's radiation. The absorbed solar radiation is emitted as heat in the atmosphere,

producing an anti-greenhouse effect as more infrared radiation is lost from the top of the atmosphere than is emitted by the surface. The atmosphere warms as the surface cools; as the surface cools, surface winds fall and low-level convection switches off, removing the source of dust and triggering the storm's decay.

The importance of our atmosphere

The energy flows through planetary atmospheres in our Solar System are as different as the planets themselves (a description of the climate of Venus, Titan and Jupiter can be downloaded from the *Science in School* website^{w3}). Planets such as Earth and Venus have gases that produce a greenhouse effect, which has a significant influence on their climate; other planets, such as Mars (when dusty) and Jupiter, have an anti-greenhouse effect. Together with liquid water and a living ecosystem, we humans complicate Earth's climate system further. However, although

we are slowly altering the energy balance on Earth, we would not be able to survive without our atmosphere trapping the solar energy and warming up our little blue planet. The more we understand how these complicated systems work, the closer we can come to understanding our impact on Earth.

References

Ribeiro CI (2015) Starlight inside a light bulb. *Science in School* **31**: 37–42. www.scienceinschool.org/2015/issue31/black_body

Shallcross D, Harrison T (2008) Climate change modelling in the classroom. *Science in School* **9**: 28–33. www.scienceinschool.org/2008/issue9/climate

Trenberth KE, Fasullo JT, Kiehl J (2009) Earth's global energy budget. *Bulletin of the American Meteorological Society* **90**: 311–323. doi: 10.1175/2008BAMS2634.1

Web references

- w1 You can learn more about how Earth generates its own heat by reading *National Geographic's* education web page on geothermal energy. See: <http://education.nationalgeographic.com/encyclopedia/geothermal-energy>
- w2 The Metlink website provides support and materials for teaching weather and science. For updates on the 2013 Intergovernmental Panel on Climate Change report for science teachers, see: www.metlink.org/climate/pcc-updates-science-teachers/#1
- w3 A description of the climates of Venus, Titan and Jupiter can be downloaded from the *Science in School* website. See: www.scienceinschool.org/2015/issue34energy

Resources

The MetLink website is full of teaching resources and activities for teachers. The 'Why is the sky blue', 'Scatter UV light' and 'Reflective surfaces' activities all support this article and can be found at <http://www.metlink.org/experimentsdemonstrations>

For a series of *Science in School* articles about climate change, see: www.scienceinschool.org/climatechange

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