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The carbon budget concept builds on the near-linear relationship between CO$_2$-induced global warming and total cumulative CO$_2$ emissions, which implies that additional global warming will stop when CO$_2$ emissions are zero (Figure 1).

- The global average temperature is projected to remain roughly constant after human-induced CO$_2$ emissions reach zero.
- **Why will the temperature remain constant?** If CO$_2$ emissions stop, the atmospheric CO$_2$ concentration will decrease as CO$_2$ is taken up by the ocean and land, which has a cooling effect. As the CO$_2$ concentration declines, the ocean takes up less heat, leading to additional warming, which offsets the cooling. These two effects largely balance, resulting in a stable global temperature.
- Emissions of other greenhouse gases, such as methane, contribute to additional warming.
- **Urgent action is needed** to stabilise the temperature increase and the climate system. This would require the world to stop burning fossil fuels and stop deforestation. CO$_2$ removal can also play a small role in balancing any remaining CO$_2$ emissions or warming from non-CO$_2$ emissions.

**STUDYING THE RESPONSE TO NET-ZERO EMISSIONS**

The relationship between the temperature increase and cumulative emissions varies slightly by model. Some models have different behaviour when emissions reach net zero.

To understand these variations, an experiment was set up to determine how the global mean temperature will change after emissions reach zero, which is known as the Zero Emissions Commitment (ZEC).

The ZEC Model Intercomparison Project (ZEC-MIP) brought together 18 climate models to compare how they behave under different emission pathways and thus different atmospheric CO$_2$ levels reached before net-zero emissions are achieved (e.g. 750, 1,000 or 2,000 billion tonnes of carbon) (Figure 2).

The climate models included in the simulations used these emission pathways, and the results showed the evolution in CO$_2$ concentrations and global average temperature over time [3].

**Changes in atmospheric CO$_2$ concentration**

After anthropogenic CO$_2$ emissions stop, the additional carbon already added to the atmosphere is gradually redistributed over the next centuries among the atmosphere, ocean and land.

All models project a decay in atmospheric CO$_2$ concentrations as the natural land and ocean sinks continue to take up CO$_2$ as they strive to reach equilibrium (Figure 3a) [3].
Changes in temperature

Despite the drop in atmospheric CO\(_2\) concentrations, the average temperature response across simulations shows a small increase in the first 10 years after reaching zero CO\(_2\) emissions, followed by a small gradual decline over the next 90 years across the different model simulations, although a wide range is seen in the model responses (Figure 3b).

Across the 18 climate models, the temperature response after zero CO\(_2\) emissions leads to a slight decline of \(-0.1^\circ\)C over 100 years, but there is a large spread across models, with some showing slight warming and others slight cooling [3].

Ocean heat uptake

It is evident that the temperature response does not follow the same pathway as that of CO\(_2\) concentrations (Figure 3b). The elevated CO\(_2\) concentration in the atmosphere traps additional energy from the sun, and most (~90%) of this additional energy enters the ocean. However, as the atmospheric CO\(_2\) concentration decreases after zero emissions, less of the energy (heat) is taken up by the ocean and more stays in the atmosphere. This decline in ocean heat uptake leads to a warming of the atmosphere. This warming effect counterbalances the cooling effect from the decreasing atmospheric CO\(_2\).

As a result, the atmospheric temperature remains roughly constant after zero CO\(_2\) emissions [3].

Differences between models

The different climate models all show the same processes at play, but the relative proportions of the ocean heat uptake, and the ocean and land carbon sinks vary across models. To compare these effects, they need to be translated into a unit that is comparable with the energy balance, and Watts per square meter is used here. Each model has a different climate response, scale and speed, and so the energy balance can lead to a different temperature response across models (Figure 4) [3].

The Zero Emission Commitment, where CO\(_2\) emissions reach zero, is a different concept to the ‘committed warming’ when CO\(_2\) concentrations are held constant. Constant CO\(_2\) concentrations require continued, but falling, CO\(_2\) emissions that offset the uptake of the natural carbon sinks [4].
The concepts of carbon budgets and net zero emissions have both become powerful framings for climate action. Whilst some prefer carbon budgets and others prefer net-zero emissions, the two concepts result from the same physical mechanism. Since the publication of the IPCC Special Report on Global Warming of 1.5°C [5], the concept of ‘net zero’ emissions has become prevalent. The ‘net’ term means that CO₂ emissions (e.g. burning fossil fuels) are balanced by CO₂ removals (e.g. growing new forests).

Some have argued that the ‘net’ has given an excuse for companies or countries to continue CO₂ emissions, in the hope of large-scale CO₂ removal coming at a later date [6]. Even worse, some incorrectly use ‘offsets’ (the purchase of reductions by a third-party, often not verified) as a type of CO₂ removal.

It is important to separate the physical use of net zero, the balance of emissions and removals, with the misuse of the term by some actors.

EMISSIONS BEYOND CO₂

The focus in this Science Summary is on the role of CO₂ emissions in climate warming. Other greenhouse gases also have climate impacts.

Most notably, methane has a shorter lifetime than CO₂ (about 10 years), and thus when methane emissions decline sufficiently fast, the methane-induced warming also declines. Other components, like nitrous oxide, are long lived (about 100 year lifetime) and the behaviour is more like that of CO₂ emissions. Complicating matters further are sulphur emissions, with an extremely short lifetime (weeks) but a strong cooling effect. If current sulphur emissions are stopped, motivated by reducing local air pollution, the climate may warm a few tenths of a degree.