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The Earth's energy budget

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Overview

- The global energy budget is fundamental to the climate system. It is affected by external changes (solar radiation, volcanoes) and internal climate variability as well as atmospheric composition, which itself can vary both due to long-term variability of the climate and human activity, notably greenhouse gas emissions.
- More energy from the Sun has entered the top of the atmosphere than has left it in the form of infrared radiation since at least around 1970. The energy imbalance increased over 1993-2010 compared to the period 1971-2010.
- For a given energy imbalance, the oceans determine the climate response due to their relatively huge heat capacity. Ocean warming accounts for about 93 per cent of the total excess energy, with the upper 700 metres accounting for most (64 per cent) of this. The associated thermal expansion of the ocean has contributed about 40 per cent of the observed sea level rise since 1970.
- Another effect of the energy imbalance is that total mass loss from glaciers has increased significantly between 1971 and 2009. The ice mass loss from the Greenland and Antarctic Ice Sheets has accelerated dramatically over the period 2002-2011 relative to 1992-2001.
- Stabilisation of the energy imbalance would not instantaneously lead to a stabilisation of the warming. In the deep ocean, full equilibrium would be reached only after hundreds to thousands of years. Global mean sea level would continue to rise for many centuries after atmospheric temperatures stabilised.

Why is the earth's energy budget important?

In its 4.5 billion year history, the Earth has gone through periods when the poles were ice-free (hot-house) and other times when the ice-sheets reached tropical latitudes (ice-house). These dramatic climatic transitions were the result of changes to the Earth's energy budget on geological timescales. The energy budget is the amount of solar energy flowing into the Earth minus the amount of energy leaving the Earth in the form of infrared radiation. The balance of incoming and outgoing radiation determines whether the planet cools (a net loss of energy), remains in balance (zero net loss) or warms (a net gain of energy).

The amount of solar energy absorbed by the system depends on the strength of the solar radiation (which was only about 75 per cent of its current strength 4 billion years ago), the regular changes in the Earth's orbit around the sun and how much of that radiation is reflected by clouds, aerosols and the Earth's surface directly back into space. The total proportion that is reflected is called the Earth's albedo, which currently stands at around 30 per cent, but would have been significantly higher in ice-house periods.

In equilibrium, the outgoing infrared radiation emitted exactly balances the absorbed solar energy. If there were no atmosphere, this would happen when the Earth's surface was at an average temperature of minus 18°C. Fortunately, the water vapour and other greenhouse gases within the atmosphere trap some of the infrared radiation emitted from the Earth's surface. The atmosphere is also warmed by convection and evaporation of water from the surface, which then condenses and releases energy. The net result is that the warmed atmosphere emits infrared radiation both out to space, balancing the incoming solar radiation, and also to the Earth's surface, which warms further. This natural greenhouse effect increases the Earth's surface temperature by some 33°C.

The energy budget of the Earth can be unbalanced by external changes, such as changes in solar energy reaching the top of the atmosphere or sulphate aerosols ejected into the high atmosphere by volcanic eruptions. The energy balance may also be affected by internal climate variability that changes the distribution of energy among the components of the climate system, notably the surface and deep ocean.

The atmospheric concentration of major greenhouse gases such as carbon dioxide and methane has also changed - and continues to change, with a strong effect on the Earth's energy balance. These changes have been due both to natural processes and, more recently, to human activity, which has taken concentrations of carbon dioxide and methane to levels unseen in the last 800,000 years. Increased levels of atmospheric greenhouse gases create a positive net inflow of energy by trapping some of the outgoing infrared radiation emitted by the Earth. This then warms the climate system until the temperature rises sufficiently to restore the outflow of infrared radiation. Atmospheric sulphate aerosols from burning fossil fuels offset this effect, while black carbon from incomplete combustion enhances the warming.

For a given energy imbalance, the rate at which the earth warms or cools depends on the way in which energy is distributed amongst the different components of the climate system and their heat capacity. The heat capacity of the oceans is vastly greater than that of the atmosphere and land surface, so in practice it is the flow of heat into or out of the oceans that determines the climate response to warming or cooling.

The ocean covers about 71 per cent of the Earth's surface, with an average depth of 3.7 km and a total volume of 3.2 x 10^{17} cubic metres. The upper layer of the ocean – typically the first 50-100 metres – is well mixed by winds and surface cooling and has a relatively uniform temperature profile in the vertical. Except in high latitudes, below the mixed layer is a thin layer of water in which temperature and other properties change rapidly. Beneath about one kilometre in depth, there are cold, abyssal waters which are connected to the surface layer in parts of the North Atlantic and in the Southern Ocean around Antarctica. Increasing greenhouse gas induced climate change first heats up the mixed layer and then, more slowly over many decades, heats the middle and deep ocean. The rate at which the sea surface temperature changes depends on the net effect of the rate of energy flow from above and the rate at which heat is exchanged with the colder deep ocean.

What does the Fifth Assessment Report (AR5) say about observed changes to the energy budget?

AR5 assesses that:

- More energy from the Sun has entered the top of the atmosphere than has left in the form of infrared radiation since at least around 1970, when better observational data coverage became available.
- It is virtually certain that the Earth gained substantial energy from 1971-2010, estimated at 274 [196 to 351][1] x 10^{21} Joules or a heating rate of 213 x 10^{9} kW. To put this in context, this is equivalent to something like the output of more than two hundred thousand 1GW power stations. Over the period 1993-2010, AR5 reports an estimated increase in the Earth's energy of 163 [127 to 201] x 10^{21} Joules, and a higher heating rate of 275 x 10^{12} W.

The majority of this additional energy is stored in the ocean as heat. Ocean warming also accounts for about 93 per cent of the total heating rate, with the upper 700 metres accounting for most (64 per cent) of this. The associated thermal expansion of the ocean has contributed about 40 per cent of the observed sea level rise since 1970. The rate of ocean warming in the first 700 metres in some estimates was lower from 2003-10 than in the previous decade. However, warming in the deeper layer between 700-2000 metres has likely continued unabated during this period.

Another manifestation of this additional energy is the melting of ice. Total mass loss from glaciers (excluding those on the periphery of ice sheets) very likely increased significantly from 226 [91 to 361] Gt per year in the period 1971-2009, to 275 [140 to 410] Gt per year in 1993-2009 and 301 [166 to 436] Gt per year between 2005 and 2009. The ice mass loss from the Greenland Ice Sheet has very likely increased by a factor of more than six, from 34 Gt per year over the period 1992-2001 to 215 Gt per year over the period 2002-2011. The average rate of ice loss from the Antarctic Ice Sheet also increased over the same period by almost a factor of five.

The net incoming energy also warms the continents and the atmosphere. Observations indicate that because of the relatively small heat capacity of the atmosphere, decades of steady or even decreasing mean surface temperature can occur in a warming world.

The available independent estimates of effective radiative forcing, observed heat storage and of surface warming give an energy budget for the Earth that is consistent with the assessed likely range of equilibrium climate sensitivity to a doubling of carbon dioxide concentrations in the atmosphere of 1.5 to 4.5°C.

What does AR5 say about projected changes to the energy budget?

AR5 uses four scenarios with widely differing greenhouse gas emissions pathways, reflecting differing levels of success in tackling climate change. Of these Representative Concentration Pathways (RCP) scenarios, the lowest, RCP2.6 is a very strong mitigation scenario, with CO_2

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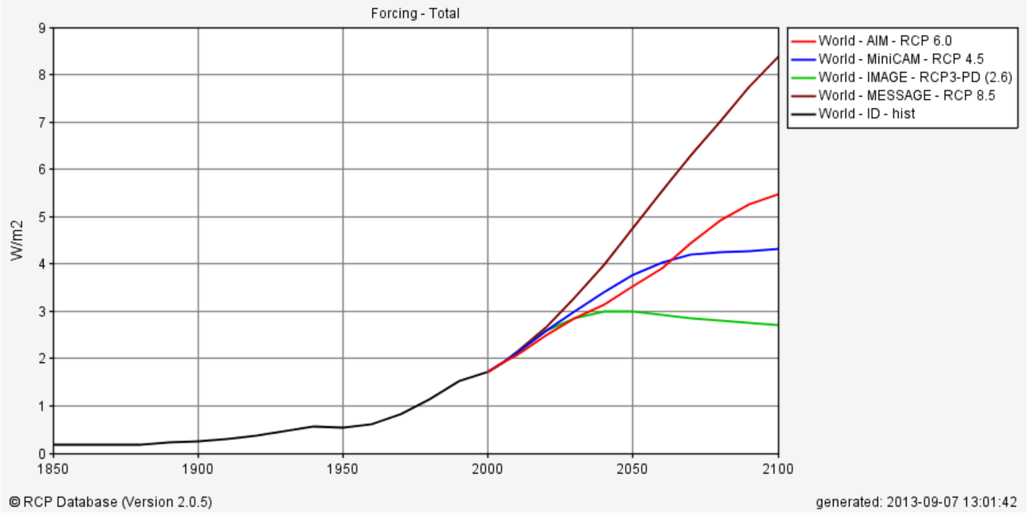
[1] The range in square brackets is the 90% uncertainty interval. This is expected to have a 90% likelihood of covering the value being estimated. There is an estimated 5% likelihood that the value could be above the range given and 5% likelihood that the value could be below that range. A best estimate of the value is given where available. Uncertainty intervals are not necessarily symmetric about the corresponding best estimate.

levels peaking by 2050 at ~443ppmv. RCP4.5 has a continuing rise in CO_2 concentrations to the end of the century, when they reach ~538ppmv. In RCP6.0, CO_2 concentrations rise more rapidly, reaching ~670ppmv by 2100. RCP8.5 continues current rapidly increasing CO_2 emission trends with CO_2 concentration reaching 936ppmv by 2100.

Differences in the radiative forcing – a measure of the energy imbalance in units of Wm^{-2} – between the four RCP scenarios are relatively small up to 2030 but become very large by the end of the century (see Figure 1 below). The RCP emissions scenarios are <u>not</u> predictions and are not assigned probabilities; they are plausible future scenarios to be used as a benchmark for scientific research and for policy discussions.

Stabilisation of the energy imbalance would not instantaneously lead to a stabilisation of the warming. The fraction of realised surface temperature warming at a time when the energy imbalance stabilises would be around 75-85 per cent of the projected equilibrium warming. In the deep ocean, full equilibrium would be reached only after hundreds to thousands of years. Global mean sea level rise depends on the pathway of carbon dioxide emissions, not only on the cumulative total, but would continue for many centuries after atmospheric temperatures stabilised.

Figure 1: Radiative forcing for the RCPs over the 21st Century and historically (Source: RCP Database)



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