OCEANOGRAPHY

Has global warming stalled?

Following a period of rapid warming from the 1970s, global temperatures seem to have stalled. New analysis of the uptake of heat by the upper ocean sheds light on the cause and suggests that the slowdown could have been predicted.

Doug Smith

In 2007, when the latest Intergovernmental Panel on Climate Change assessment was published[1], the global warming debate seemed to be over. Climate models simulated the observed warming of around 0.2 °C per decade, but only if the effects of greenhouse gases were included. The observations were well within the model uncertainties and a similar rate of warming was predicted for the future. However, it is now clear that the rate of warming has slowed substantially over the past 15 years or so (Fig. 1) and the observations are very much at the lower end of model simulations. Explaining this apparent discrepancy is of high priority for climate scientists. Although many possible causes have been suggested, Guemas and co-workers[2] report in *Nature Climate Change* that redistribution of heat in the ocean is likely to have played an important role at the onset of the slowdown in global warming.

It is well established that gases such as carbon dioxide warm our planet through the 'greenhouse effect': they are relatively transparent to the incoming radiation from the sun, but trap some of the longer-wavelength radiation emitted by the Earth. However, other factors both natural and manmade can also change the temperature. For example, a cooling could be caused by a downturn of solar radiation, or an increase in the radiation reflected back to space by aerosol particles in the atmosphere. Aerosols increase temporarily after volcanic eruptions, but are also generated by pollution, especially sulphur dioxide from industry. These factors are referred to as external because they are imposed on the climate system, which consists of the oceans, atmosphere, land and cryosphere. However, climate also varies internally without any changes in external factors. Examples of such natural internal variability include the El Niño–Southern Oscillation, which causes the tropical Pacific to warm and cool every few years, and decadal variations in the strength of the ocean currents in the Atlantic Ocean. Both of these affect the climate worldwide, including globally averaged temperatures.

Global warming will therefore not proceed monotonically; indeed, the historical record (Fig. 1) shows periods where temperatures rose rapidly, such as the 1920s to 1940s and 1970s to 1990s, and periods with little warming or even cooling, such as the early twentieth century and the 1940s and 1960s. Many of these historical periods can be explained by major volcanic eruptions, changes in solar activity or anthropogenic aerosol emissions, and are well simulated by models. Although there has not been a major volcanic eruption since Mount Pinatubo in 1991, there have been several minor eruptions that may have contributed to the slowdown in warming[3]. Solar activity has also decreased[4] and decreases in stratospheric water vapour may have played a role too[5]. However, these factors are probably too small to provide a complete explanation and, in fact, anthropogenic aerosols emissions seem to have decreased[6] whereas an increase would be required to explain the recent lack of warming. It now seems that redistribution of heat below the ocean surface is likely to be important.

One way to test our understanding is to see whether we could have predicted the slowdown in warming. To do so we must take into account both external factors and natural internal variability using recently developed decadal predictions. These use the same climate models and external forcings as long-term projections, but start from the current state of the climate system to predict natural internal variability. This is the approach taken by Guemas *et al.*, who found that their decadal predictions captured the slowdown much better than standard climate projections that do not use

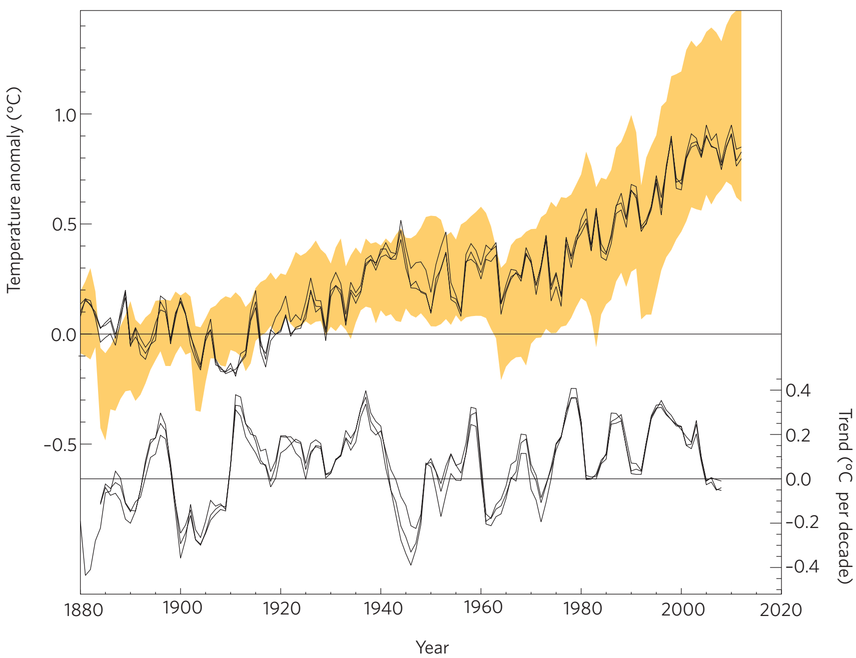

Figure 1 | The recent slowdown in surface warming. Upper: observed global mean temperature difference from the 1880 to 1919 mean (°C) from three data sets[11–13] (black curves) and 5% to 95% range from 22 Coupled Model Intercomparison Project phase 5 model simulations (shading). Lower: observed decadal temperature trends (°C per decade).

information on current ocean conditions. This might be expected simply because the initialized predictions started from a colder state, but crucially Guemas and colleagues showed that they also predicted the temperature trends better, suggesting that the relevant physical processes were captured to some degree.

Although initialization is necessary to predict natural variability, improved predictions of the slowdown do not necessarily mean that natural variability is entirely responsible, because initialization can also correct errors in the model's response to external factors. Nevertheless, a successful model simulation can be further analysed to understand the physical processes at play. Guemas *et al.* did this by tracking energy changes in their model. They found that the input of energy at the top of the atmosphere remained constant during the slowdown, showing that factors that would have altered this — such as changes in aerosols, solar radiation or stratospheric water vapour — did not play an important role in their model. Instead, the slowdown was initiated by the largest uptake of heat by the upper ocean in the historical record, which warmed the ocean below the surface without affecting surface waters.

This offers a plausible explanation for the onset of the warming slowdown, although further work is needed to understand relationships between upper ocean and surface temperatures, and the processes by which heat was buried below the surface. However, the lack of warming beyond 2004 is still not understood[7]. According to observations[8], energy continues to be accumulated through the top of the atmosphere, but has not been taken up by the upper ocean. This leaves the deep ocean as the most likely destination, but this cannot be confirmed because the observational network is too sparse. There is therefore an urgent need for observations of the deep ocean, as well as continued monitoring of energy fluxes at the top of the atmosphere.

According to climate models[9,10], decades without warming are inevitable. Nevertheless, to retain confidence in long-term projections it is essential to understand why they occur and preferably predict them in advance. Guemas *et al.* have taken an important step towards this goal. ❐

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ATMOSPHERIC SCIENCE

Volcanic rain shift

The distribution of dust particles in the stratosphere affects the location of the tropical rainband. The possible implications of this for geoengineering — by injection of particles — need to be taken into account before implementation.

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The cost of natural disasters in terms of life and property is, by some measures, on the rise[1]. Climate and weather variability in the form of droughts, floods and damaging storm effects, is regularly inflicting suffering around the world, often disproportionately affecting developing countries and possibly contributing to violent regional conflicts[2]. Weather and climate scientists have been pondering the cause of such disasters and making considerable investments in methods and tools for prediction to warn society in advance of their occurrence. However, climate and weather are strongly influenced by chaotic processes, which subject predictions to errors and uncertainty. Moreover, whether by lack of proper institutions and procedures or simply because of human reluctance to act, the dire consequences of extreme events are often unavoidable even when they have been successfully predicted. Such constraints, amongst others, should be borne in mind particularly when contemplating intervention to prevent disasters through geoengineering.

Writing in *Nature Climate Change*, Jim M. Haywood and collaborators from the UK Met Office Hadley Center[3] look into the processes that affect rainfall in a world region that suffered one of the most calamitous climatic events of the twentieth century: the sub-Saharan region of the Sahel. The effects of the disastrous decades of Sahelian droughts in the 1970s and 80s are well known[4]. In their wake numerous scientific studies were conducted to identify the physical causes of the protracted retreat of summer monsoon rains southwards, which caused the drying of the region[5]. In the following years, the African summer monsoon regained a proportion of its strength over the Sahel, but not to the extent seen before the drought.

The prevailing scientific opinion is that the multi-decadal drought can be attributed to large-scale changes in sea surface temperatures, particularly temperature gradient change across the equator in the Atlantic Basin[5]. In the 1940s, 50s and 60s, the Atlantic was considerably warmer in the North than in the South, and the monsoons were spread further north, wetting the Sahel. In the 1970s the North Atlantic cooled abruptly and the rains retreated south, resulting in the drying of the Sahel.

There can be considerable interannual variability where the influence of El Niño is important and has led to the development and implementation of seasonal prediction in the region[5]. However, Haywood *et al.* propose a new forcing mechanism that seems to affect Sahel rainfall on short timescale. They hypothesize, based on observational evidence, that explosive volcanic eruptions can shift the normal summer monsoon rainfall in North Africa. This causes either a wet or dry Sahel, depending on whether the volcanic dust is loaded preferentially into the Southern or Northern Hemispheres, respectively. Such asymmetric volcanic forcing results in the cooling of the more highly aerosol-loaded hemisphere comparatively (Fig. 1), and consequently affects the northward