Our evolving climate

The climate change debate is obscured by much heat and fury. What consensus is there in the scientific community? Some years are cooler than those that went before. Is this evidence against global warming? **Ed Hawkins** summarises the situation.

Climate change is seemingly an ever-present discussion topic in mainstream media, in the blogosphere and in policy debates. Statistics is playing a central role, with increasing numbers of statisticians taking an active interest in the key scientific questions.

Entrenched and vociferous positions have been taken on all sides. Nevertheless the climate research community has reached its verdict: there is *unequivocal* evidence that the global climate has warmed over the past 150 years. The matter is beyond doubt. And it has warmed by around 0.7°C. As for the harder question of why, it is *very likely* that humans have caused most of the warming of the Earth's climate since the mid-20th century. By 'very likely' we mean that the probability is between 90% and 99%.

These findings were key conclusions of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC)[1]. In response, at the United Nations summit in Copenhagen in 2009, the world's nations agreed the aim of restricting global temperature change to a total of 2°C. Assuming 'business as usual' future greenhouse gas emissions, this threshold is projected to be crossed sometime between 2040 and 2060, although lower emissions, if we achieve them, will delay this date[2].

Climate variability

So much for the medium and long term. The attention of the climate science community is now increasingly turning to what will happen in the near term, in order to plan strategies to *adapt* to any further warming.

Over the past decade there has been a relative plateau in global temperatures, leading many to question whether the climate is indeed changing as the IPCC suggests. For instance, 1998 is still the warmest year on record, according to one key data set. Emissions have risen since then. Strong evidence, then, say climate-change sceptics, *against* a causal link. Two important questions then are: first, why is there is not an uninterrupted rise in temperatures; and second, whether a plateau such as we have had is unexpected. The latter question has significant implications for planning any adaptation response to the risks of climate change – might we expect the coming decade to also have little warming, or faster warming?

Our evolving climate is known to be influenced by many human (or anthropogenic) causes, such as greenhouse gases, and also by 'external' factors such as large volcanic eruptions and the solar cycle. Additionally, there exist naturally occurring fluctuations in climate which can temporarily mask or enhance any long-term trends for up to a decade or so, especially on continental or smaller spatial scales. Understanding and acknowledging these inherent climatic variations is important for society and policy-makers, especially if they can help explain the recent rate of warming.

What happens over the next decade depends largely on these inherent climate variations, rather than on any changes in emissions by man[3]. (This is in no way to diminish the importance of reducing emissions; but a decade is a short time in climate change.)

HMS Galatea: shot down a Zeppelin, fought at Jutland – now her logs give data of climate change

Understanding the statistics and physical causes of these variations is clearly of more than academic interest.

The climate of the past

To help address these issues it is first necessary to appreciate how the climate has varied in the past. The most commonly used indicator of climate is 'surface air temperature', which is estimated from recorded measurements taken with thermometers, typically 2 m above the ground. These point measurements must somehow be combined to reconstruct the past climate – an interesting statistical problem in itself, especially given changes in observation techniques over time.

The Central England Temperature (CET) index (see `http://www.metoffice.gov.uk/hadobs/hadcet/`) is the longest temperature record available (Figure 1). Gordon Manley (1902–1980) devoted much of his career to collecting the necessary data and producing this time series[4,5],which represents the temperatures from 1659 to the present day in a roughly triangular region enclosed by Lancashire, London and Bristol. This small regional average, representing less than 0.0005% of the Earth's surface, shows considerable year-to-year natural variability, potentially masking any long-term trend.

Measuring the temperature for such small regions is easier than for a global average. Although a few such temperature records exist for individual locations back to the 17th century, the measurements are not considered widespread enough to construct a global temperature estimate until around 1850 onwards[6]. Additionally, different regions are expected to warm more than others. For example, the land is projected to warm more than the ocean, and the Arctic will show the greatest warming as the sea ice retreats.

Among the first to attempt to estimate the global temperature was a British engineer, Guy Stewart Callendar (1898–1964). Using data from around 200 meteorological stations spread over the globe, Callendar[7] concluded in 1938 that global temperatures had risen by about 0.25°C in the previous half century, and suggested that around half of this warming was due to increases in carbon dioxide. (The infra-red radiation absorbing properties of CO_2 were first measured experimentally by John Tyndall in 1861.)

Callendar's results agree well with more recent estimates of global temperature which use thousands of observation stations[6] (see Figure 2).

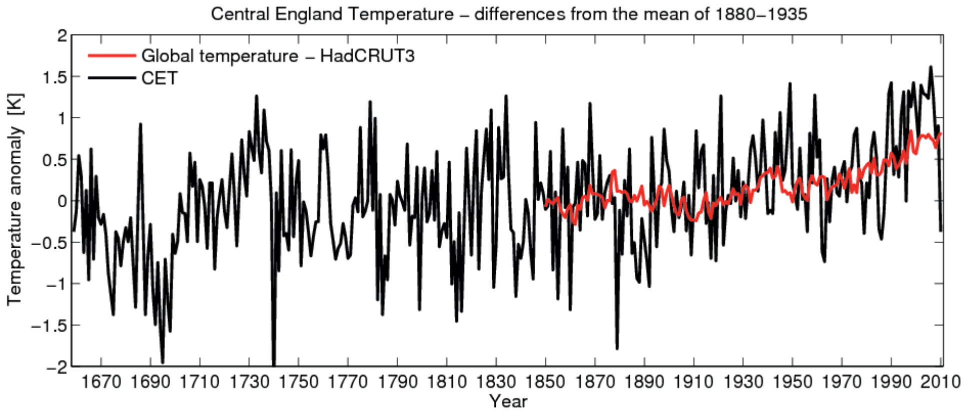

Figure 1: Historical temperature reconstructions of Central England Temperature (1659–2010, black)[4,5] and global mean temperature (red)[6]. Note the larger variability for the small region

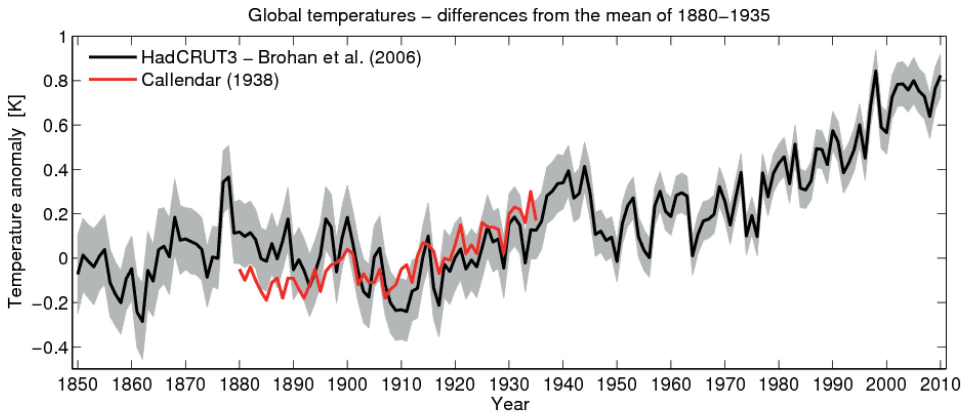

Figure 2: Historical temperature reconstructions of global mean temperature (1850–2010) from Callendar[7] (red) and Brohan *et al.*[6] (black, with 5–95% confidence levels in grey); data available from `http://www.metoffice.gov.uk/hadobs/hadcrut3/`

There is much ongoing effort to improve such temperature reconstructions and there are at least five different groups producing their own versions of historical global temperatures.

Although it is obviously not possible to travel back in time to make additional measurements, researchers are finding ever more inventive ways of recovering extra historical weather observations. It is now even possible for anyone to contribute to improving the reconstructions. The 'Old Weather' project (`http://www.oldweather.org`) has put thousands of British Royal Navy ship logbooks online, with a neat interface to allow an easy digital transcription of the handwritten weather data, which were taken every 4 hours onboard ship. The transcription of the initial collection of logbooks covering a 10-year period around World War I was completed entirely by online volunteers in late 2011, adding several million additional observations to the historical measurement archives, with many more to come. Phase 2, involving more ship's logs is already underway.

Additionally, weather forecast computer models are now being used to fill in the gaps between the available observations, potentially allowing a much clearer picture of day-to-day weather back to the late 19th century, along with the associated uncertainties[8].

The next decade

These reconstructions of past climate provide a long-timescale reference for considering the nature of the temperatures over the most recent decade. To start, it is helpful to consider the question: what is the chance of one year being warmer than the last?

For instance, during the 20th century, global temperatures rose by around 0.7°C, but with 53 years being warmer than the previous one, and 47 being cooler. For the coming century, climate model projections (such as those assessed by the IPCC) suggest that around 60% of years will show an increase in global temperatures over the previous year.

However, for smaller continental scales, the variability is far larger and the odds are smaller. For instance, just 52% of years will be warmer than the previous one for Europe (Figure 3). So the odds of the temperature in Europe being warmer or cooler than in the previous year differ very little from the odds of a coin falling heads or tails. This may seem quite counter-intuitive given that the climate is warming. One year is clearly not a reliable guide to any long-term trend – but what about a decade?

When considering longer-timescale trends, the odds change because of the gradual rise in temperatures. Even so, several decades with particularly strong negative trends, as well as decades with positive ones, are seen in the historical global observations (Figure 2). These decades demonstrate that even 10 years is not necessarily indicative of any longer-term trend. There are potentially other causes for some of the historical cooling decades, such as emissions of particulate sulphate aerosols in the 1950s and sporadic large volcanic eruptions. Because of such variability, 30 years are typically used to define trends.

For a small regional average, such as the CET index, the situation is even more extreme, with many periods of extremely strong trends in temperature. This is a vivid depiction of the fact that local climate is not necessarily a reliable guide to what is happening globally, and why observations are needed from widespread locations to determine the global picture.

But what about the future: how often might we expect plateaus, or even cooling, in global temperatures? The climate model simulations suggest that such decades are expected to occur occasionally – about 5% of overlapping decades – during the 21st century. In other words we might expect to find 5 periods of 10 years between now and the end of the century in which the globe apparently cools, assuming no dramatic reductions in emissions. The most recent decade is therefore not unexpected. The simulations also suggest that a global cooling trend of more than about 15 years is unlikely. However, for Europe, around a quarter of future decades are expected to show a cooling trend, due to increased levels of natural variability (Figure 3).

These issues can be easily demonstrated at home. Take a shuffled pack of playing cards, with red cards representing 'warm' years and black cards 'cool' years. When dealing out the pack there will be times when several warm or cool years appear together. Next, remove some black cards from the pack, and reshuffle. This pack now represents a changed 'climate' with fewer cool years. When dealing the pack for a second time, there will be more periods of warm years, but probably periods of cool years as well.

In summary, over the course of the next century, the traditional adage of the stock market will be particularly appropriate: temperatures *will* go down, as well as up. We should therefore not be surprised to see plateaus in temperatures – in fact, we should expect them.

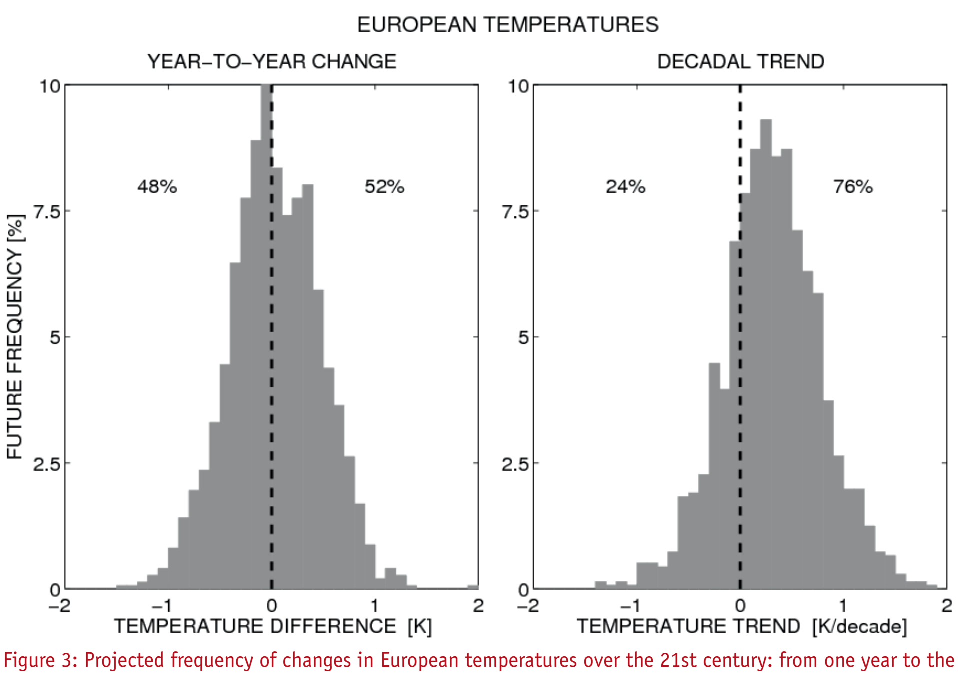

Figure 3: Projected frequency of changes in European temperatures over the 21st century: from one year to the next (left), and 10-year trends (right)

References

1. IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds). Cambdge and New York: Cambridge University Press. (Available from: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html.)

2. Joshi, M. *et al*. (2011) Estimating when global temperatures will cross policy-relevant thresholds. *Nature Climate Change*, **1**, 407–412, doi: 10.1038/nclimate1261.

3. Hawkins, E. and Sutton, R. (2009) The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, **90**, 1095–1107.

4. Manley, G. (1953) The mean temperature of central England, 1698-1952. *Quarterly Journal of the Royal Meteorological Society*, **79**, 242–261. (Available from: http://www.rmets.org/pdf/qj53manley.pdf.)

5. Manley, G. (1974) Central England temperatures: monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society*, **100**, 389–405. (Available from: http://www.rmets.org/pdf/qj74manley.pdf.)

6. Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B. and Jones, P. D. (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *Journal of Geophysical Research*, **111**, D12106. (Available from: http://www.metoffice.gov.uk/hadobs/hadcrut3/HadCRUT3_accepted.pdf.)

7. Callendar, G. S. (1938) The artificial production of carbon dioxide and its influence on climate. *Quarterly Journal of the Royal Meteorological Society*, **64**, 223–240. (Available from: http://www.rmets.org/pdf/qjcallender38.pdf.)

8. Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D. *et al*. (2011) The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society*, **137**, 1–28.

Ed Hawkins is an Advanced Research Fellow in the National Centre for Atmospheric Science (NCAS) at the University of Reading, funded by the Natural Environment Research Council. Follow him on Twitter (@ed_hawkins) or read his 'Open lab-book' blog (http://www.met.reading.ac.uk/~ed/blog).