The debate about trends get lost in statistics...

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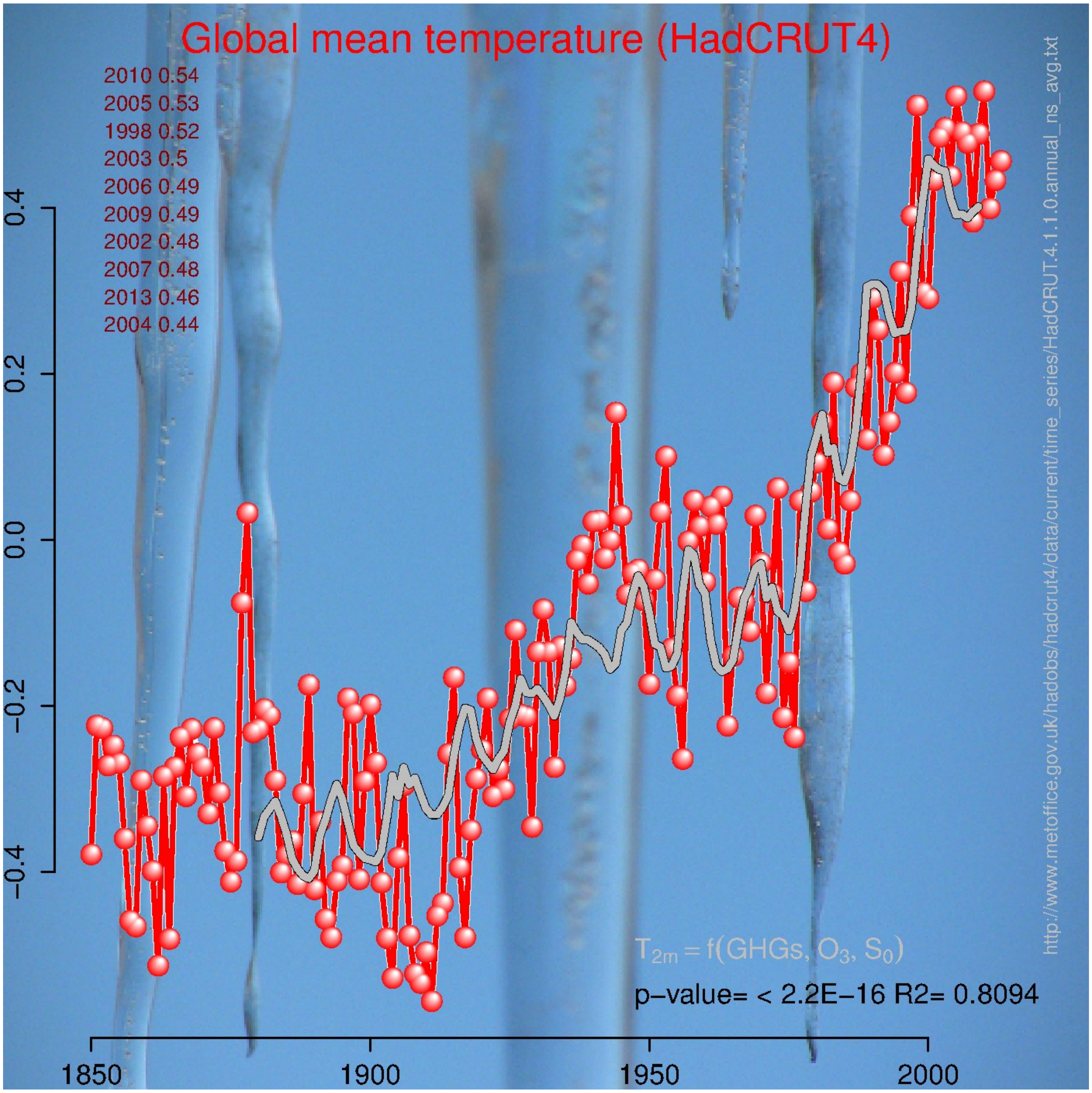

Figure 1. The recorded changes in the global mean temperature over time (red). The grey curve shows a calculation of the temperature based on greenhouse gases, ozone, and changes in the sun.

From time to time, the question pops up whether the global warming recorded by a network of thermometers around the globe is a result of natural causes, or if the warming is forced by changes in the atmospheric concentrations of greenhouse gases (GHGs).

In 2005, there was a scientific paper[1] suggesting that statistical models describing random long-term persistence (LTP) could produce similar trends as seen in the global mean temperature. I wrote a comment then on this paper on RealClmate.org with the title '*Naturally trendy?*'.

More recently, another paper2 followed somewhat similar ideas, although for the Arctic temperature rather than the global mean. A discussion ensued after my posting of '*What is signal and what is noise?*' on RealClimate.org. A meeting is planned in Tromsø, Norway in the beginning of May to discuss our differences - much in the spirit of ClimateDialogue.

It is easy to make a statement about the Earth's climate, but what is the story behind the different views? And what is really the problem?

If we start from scratch, we first need to have a clear idea about what we mean by climate and climate change. Often, climate is defined as the typical weather, described by the weather statistics: what range of temperature and rainfall we can expect, and how frequently. Experts usually call this kind of statistics '*frequency distribution*' or '*probability density functions*' (pdfs).

A climate change happens when the weather statistics are shifted: *weather that was typical in the past is no longer typical*. It involves a sustained change rather than short-lived variations. New weather patterns emerge during a climate change.

At the same time, there is little doubt that some primary features of our climate involve short-lived natural 'spontaneous' fluctuations, caused by the climate itself. The natural fluctuations are distinct to a forced climate change in terms of their duration[3].

A diagnostic for climate change involves statistical analyses to assess whether the present range and frequency of temperature and precipitation are different from those of the past.

However, the presence of slower natural variations in the climate makes it difficult to make a correct diagnosis.

Long-term persistence (LTP) describes how slow physical processes change over time, where the gradual nature is due to some kind of 'memory'. This memory may involve some kind of inertia, or the time it takes for physical processes to run their course. Changes over large space take longer time than local changes.

The diffusion of heat and transport of mass and energy are subject to finite flow speeds, and the time it takes for heat to leak into the surroundings is well-understood. Often the rate decays at an exponential rate (with a negative exponent).

There may be more complex behaviour when different physical processes intervene and affect each other, such as the oceans and the atmosphere[4]. The oceans are sluggish and the density and heat capacity of water are much higher than that for the air. Hence the ocean acts like a flywheel, and once it gets moving, it will go on for a while.

There are some known examples of LTP processes, such as the ice ages, changes in the ocean circulation, and the El Niño Southern Oscillation.

We also know that the Earth's atmosphere is non-linear ('chaotic') and may settle into different states, known as 'weather regimes'[5–7]. Such behaviour may also produce LTP. Changes in the oceans through the overturning of water masses can result in different weather regimes.

It is also possible to show that LTP takes place when many processes are combined, which individually do not have LTP. For example, the river flow may exhibit some LTP characteristics, resulting from a collection of rainfall over several watersheds.

We should not forget that long-term changes in the forcing from GHGs also result in LTP behaviour[3].

The climate involves more than just observations and statistics, and like everything else in the universe, it must obey the laws of physics. From this angle, climate change is an imbalance in terms of energy and heat.

It is fairly straight-forward to measure the heat stored in the oceans, as warmer water expands. The global sea level provides an indicator for Earth's accumulation of heat over time[3].

Hence, the diagnosis ("detection") of a climate change is not purely a matter of statistics. The laws of physics sets fundamental constraints which lets us narrow down to a small number of 'suspects'.

Energy and mass budgets are central, but also the hydrological cycle is entangled with the temperatures and the oceans[8]. Modern measurements provide a comprehensive picture: we see changes in the circulation and rainfall patterns.

There are two classical mistakes made in the debate about climate change and LTP: (a) looking only at a single aspect (one single time series) isolated from the rest of Earth's climate and (b) confusing signal for noise.

The term 'signal' can have different meanings depending on the question, but here it refers to man-made climate change. 'Noise' usually means everything else, and LTP is 'noise in slow motion'.

There are always physical processes driving both LTP and spontaneous changes on Earth (known as the *weather*), and these must be subject to study if we want to separate noise from signal.

If an upward trend in the temperature were to be caused by internal ocean overturning, then this would imply a movement of heat from the oceans to the air and land surface. Energy must be conserved. When the heat content increases in both the oceans9 and the air, and the ice is melting, then it is evident that the trend cannot be explained in terms of LTP.

The other mistake is neglecting the question: *What is signal and what is noise?* Some researchers have adapted statistical trend models to mimic the evolution seen in measured data[1,2]. These models must be adapted to the data by adjusting number of parameters so that they can reproduce the LTP behaviour.

In science, we often talk about a range of different types of models, and they come in all sorts of sizes and shapes. A climate model calculates the temperature, air flow, rainfall, and ocean currents over the whole globe, based on our knowledge about the physics. Statistical trend models, on the other hand, take past measurements for which they try to find statistical curves that follow the data.

Statistical models are sometimes fed random numbers in order to produce a result that looks like noise[10]. It is concluded that the measured data are a result of a noisy process if these models produce results that look the same. In other words, these models are used to establish a benchmark for assessing trends.

Statistical trend models may, however, produce misguided answers if proper care is not taken. For example, those adapted to data containing both signal and noise cannot be used to infer whether the observed trends are unusual or not. The LTP associated with GHGs can be quite substantial, and forced trends in measured temperatures will fool the statistical models which assume the LPT is due to noise.

The misapplication of statistical trend models can easily be demonstrated by subjecting them to certain tests. The statistical trend models describing LTP make use of information embedded in the data, revealed by their respective autocorrelation function (ACF).

Figure 2 below shows a comparison between two ACFs for temperature for the Arctic (area mean above 60N), taken from two different climate model simulations. One simulation represents the past (black) driven with historical changes in GHGs. The other (grey) describes a hypothetical world where the GHGs were constant, representing a ‘stable’ climate in terms of external forcings.

It is clear that the ACFs differ, and the statistical models used to assess trends and LTP rely on the shape of the ACF.

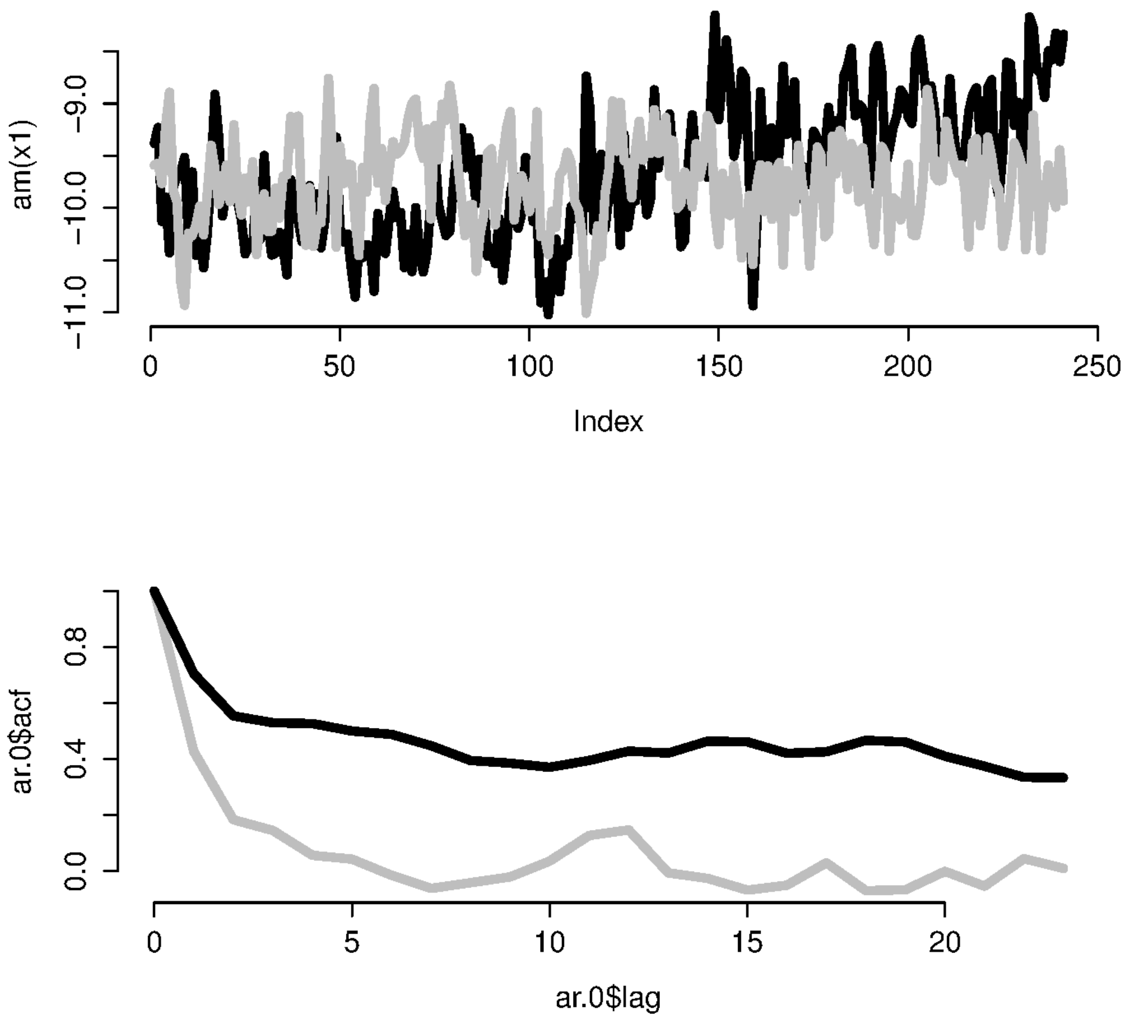

Figure 2. The upper graph shows the annual mean temperature for the Arctic simulated by a climate model. The black curve shows the year-to-year variations for a run where the model was given the observed GHG measurements. The grey curve shows a similar run, but where the GHGs do not change. The bottom panel shows the ACF, and the black curve indicates that the effect of GHGs on temperature is to increase the LTP. For the assessment of trends, the statistical models should be trained on the grey curve, for which we know there is no forced trend and where all the variations are due to changes in the oceans.

It is the way models are used that really matters, rather than the specific model itself. All models are based upon a set of assumptions, and if these are violated, then the models tend to give misleading answers. Statistical LTP-noise models used for the detection of trends involve circular reasoning if adapted to measured data. Because this data embed both signal and noise.

For real-world data, we do not know what degree of the variations are LTP-noise and what are signal.

We can nevertheless specify the degree of forcing in climate model simulations, and then use these results to test the statistical models. Even if the climate models are not completely perfect, they serve as a test bench[11].

The important assumptions are therefore that the statistical trend models, against which the data are benchmarked, really provide a reliable description of the noise.

We need more than a century-long time series to make a meaningful inference about LTP if natural variations have time scales of 70-90 years. Most thermometer records do not go much longer back in time than a century, although there are some exceptions.

It is possible to remedy the lack of thermometer records to some extent by supplementing the information with evidence based on e.g. tree rings, sediment samples, and ice cores[3,12,13]. Still, such evidence tends to be limited to temperature, whereas climate change involves a whole range of elements.

For all intents and purposes, however, it is important to account for both natural and forced climate change on these time scales. Most people would worry more about the combined effect of these components, as natural variations may be just as devastating as forced. For most people, the distinction between trend and noise is an academic question. For politicians, it's a question about cutting GHG emissions.

Another side to the story is that the magnitude of the unforced LTP variations may give us an idea about the climate's sensitivity to changing conditions. Often, such cycles are caused by delayed but reinforcing processes. Conditions which amplify an initial response are inherent to the atmosphere, and may act both on forced response (GHGs) as well as internal variations. Damping mechanisms will also tend to strangle oscillations, which is well known from many different physical systems.

The combination of statistical information and physics knowledge lead to only one plausible explanation for the observed global warming, global mean sea level rise, melting of ice, and accumulation of ocean heat. The explanation is the increased concentrations of GHGs.

We can also use another statistical technique for diagnosing a cause,11 which is also used in medical sciences and known as ‘regression analysis’. Figure 1 shows the results of a multiple regression analyses with inputs representing expected physical connections to Earth’s climate. In this case, the regression analysis used GHGs, ozone and changes in the sun’s intensity as inputs, and the results followed the HadCRUT4 data closely.

The probability that this fit is accidental is practically zero if we assume that that the temperature variations from year-to-year are independent of each other. LTP and the oceans inertia will imply that the degrees of freedom is lower than the number of data points, making it somewhat more likely to happen even by chance.

Furthermore, taking paleoclimatic information into account, there is no evidence that there have been similar temperature excursion in the past ~1000 years[12,14]. If the present warming were a result of natural fluctuations, it would imply a high climate sensitivity, and similar variations in the past. Moreover, it would suggest that any known forcing, such as GHGs, would be amplified accordingly. The climate sensitivity may be a common denominator for natural fluctuations and forced trends (Figure 3).

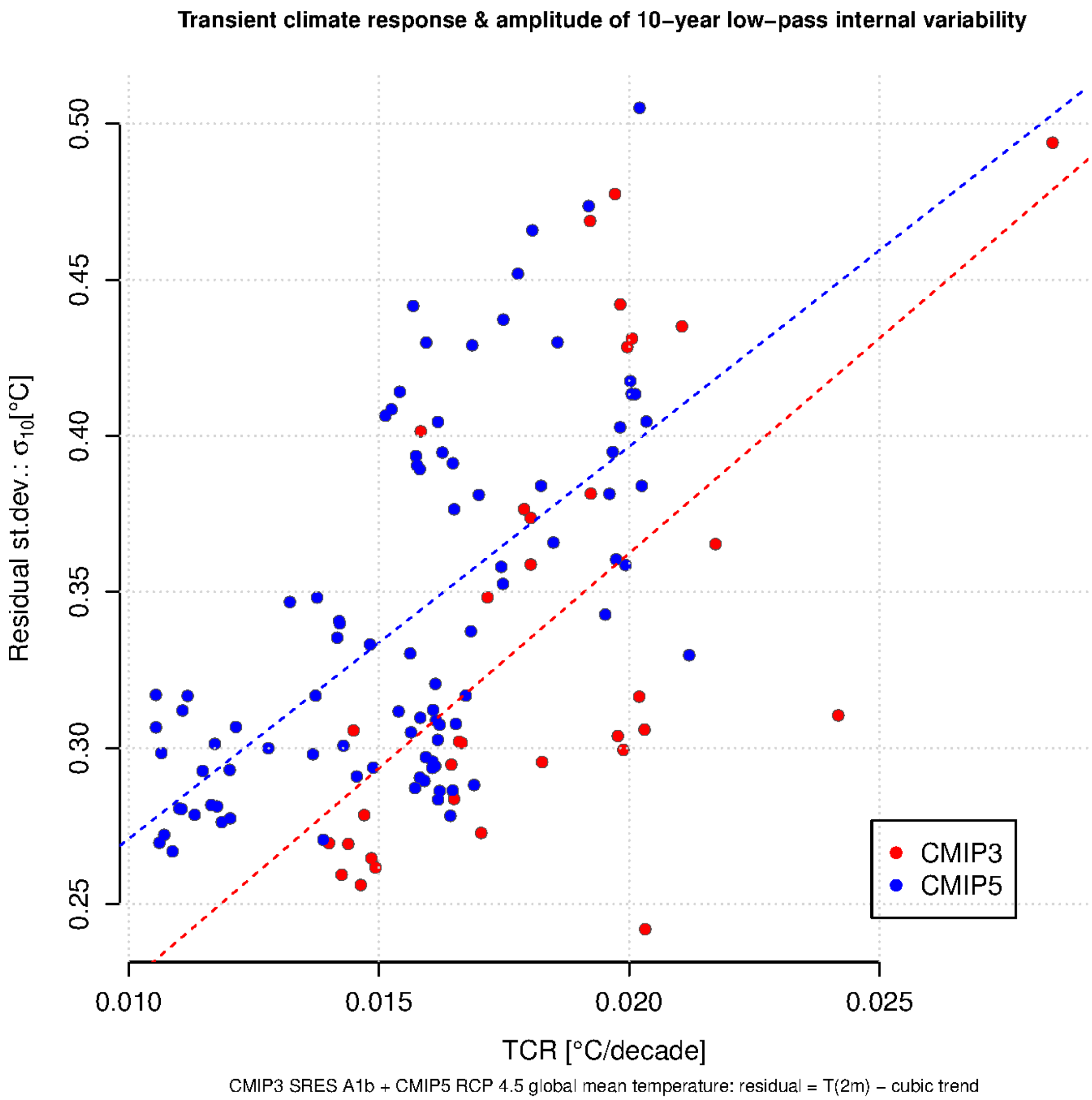

Figure 3. Comparison between trend estimates and the amplitude of 10-year low-passed internal variability in state-of-the-art global climate models.

There may be some irony here: The warming 'hiatus' during last decade is due to LPT-noise15,16; however, when the undulations from such natural processes mask the GHG-driven trend, it may in fact suggest a high climate sensitivity – because such natural variations would not be so pronounced without a strong amplification from feedback mechanisms. Figure 3 shows that such natural variations in the climate models are more pronounced for the models with stronger transient climate response (TCR; a rough indicator for climate sensitivity).

For complete probability assessment, we need to take into account both the statistics and the physics-based information, such as the fact that GHGs absorb infrared light and thus affect the vertical energy flow through the atmosphere.

In summary, we do not really know what the LTP in the real world would be like without GHG forcings, and we don't know the real degrees of freedom in the measured data record. The lack of such information limits our ability to make a statistics-based probability estimate. On the other hand, we know from past reconstructions and physical reasoning that present warming is highly unusual.

1. Cohn, T. A. & Lins, H. F. Nature's style: Naturally trendy. *Geophys. Res. Lett.* **32,** n/a–n/a (2005).
2. Franzke, C. On the statistical significance of surface air temperature trends in the Eurasian Arctic region. *Geophys. Res. Lett.* **39,** n/a–n/a (2012).
3. *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2007).
4. Anderson, D. L. T. & McCreary, J. P. Slowly Propagating Disturbances in a Coupled Ocean-Atmosphere Model. *J. Atmospheric Sci.* **42,** 615–629 (1985).
5. Gleick, J. *Chaos*. (Cardinal, 1987).
6. Lorenz, E. Deterministic nonperiodic flow. *J. Atmospheric Sci.* **20,** 130–141 (1963).
7. Shukla, J. Predicatability in the Mids of Chaos: A scientific Basis for climate forecasting. *Science* **282,** 728–733 (1998).
8. Durack, P. J., Wijffels, S. E. & Matear, R. J. Ocean Salinities REveal Strong Global Water Cycle Intensification During 1950 to 2000. *Science* **336,** 455–458 (2012).
9. Balmaseda, M. A., Trenberth, K. E. & Källén, E. Distinctive climate signals in reanalysis of global ocean heat content. *Geophys. Res. Lett.* n/a–n/a (2013). doi:10.1002/grl.50382
10. Paeth, H. & Hense, A. Sensitivity of climate change signals deduced from multi-model Monte Carlo experiments. *Clim. Res.* **22,** 189–204 (2002).
11. Benestad, R. E. & Schmidt, G. A. Solar Trends and Global Warming. *JGR* **114,** D14101 (2009).
12. Mann, M. E., Bradley, R. S. & Hughes, M. K. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392,** 779–787 (1998).
13. Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M. & Karlén, W. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433,** 613–617 (2005).
14. Marcott, S. A., Shakun, J. D., Clark, P. U. & Mix, A. C. A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science* **339,** 1198–1201 (2013).
15. Easterling, D. R. & Wehner, M. F. Is the climate warming or cooling? *Geophys Res Lett* **36,** L08706 (2009).
16. Foster, G. & Rahmstorf, S. Global temperature evolution 1979–2010. *Environ. Res. Lett.* **6,** 044022 (2011).