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Briefing: Future climate projections allow engineering planning

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It is well established that the climate is changing and much of the change is as a result of human greenhouse gas emissions. Effective strategies for adaptation or mitigation are less agreed on. From an engineering perspective, adaptation strategies require reliable expectations of the climate changes expected over the lifetime of current projects. Such projections are now possible with state-of-the-art observations and computer models that provide information over the next century and beyond. The best estimates suggest that global surface temperatures will increase by approximately 5°C (9°F) over pre-industrial temperatures or approximately 4°C (7°F) over current temperatures by the year 2100.

1. Introduction

Extensive analysis originating as far back as the mid-1800s has conclusively shown that greenhouse gas (GHG) constituents within the Earth's atmosphere create a warming effect. Superimposed on the natural greenhouse effect is a human supplement which is mainly composed of carbon dioxide from the combustion of fossil fuels but also includes methane, nitrous oxides and other gases.

What is of primary interest to engineers is the likelihood of a particular future climate and how it may stress infrastructure in a way different from the climate of today. Among the changes that have been identified by scientists are the rising sea level (Scambos and Abraham, 2015); increased precipitation, which leads to more intense flooding (Abraham *et al*., 2015); more intense storms, including hurricanes with heavier rainfall and winds (Emanuel, 2013; Kamahori *et al*., 2006; Kossin *et al*., 2007; Mann and Emanuel, 2006; Trenberth and Fasullo, 2007, 2008; Trenberth *et al*., 2007); more intense and common heat waves; changes to subsurfaces including water and soil rigidity; and added latent and sensible energy fuelling more intense storms. Many of these and other changes are already being detected, and trends towards their increase will continue for the foreseeable future. One item not often discussed is the potential for a climatologic tipping point which, if passed, may cause dramatic and rapid changes. For instance, rapid methane release from melting permafrost in the Arctic, a rapid collapse of a major ice sheet and changes to the ocean currents which redistribute heat globally are potential examples. While tipping points should be considered, they are not the topic of the present paper.

Here, a brief summary will be given of the major climate projections that are expected into the near-term future (within the current century). The projections to be given will be based on computer models; however, those models are reinforced by other independent means such as the response of the past climate to changes in atmospheric GHGs.

2. Climate projections

2.1 Global mean surface temperature observations

Perhaps the most commonly used (although not necessarily most important) climate metric is the global mean surface temperature. This refers to the air temperature near the Earth's surface; in marine locations, it involves the sea surface temperature for its determination. Global mean temperatures have been measured for many decades, and advanced tools are used to ensure that contamination of data (for instance, by the growth of cities) does not occur. Multiple data centres create these data records and, despite the differences in methodologies, the agreement is remarkable. Figure 1 shows two data sets extending from 1880 to the present year. The graph shows temperature anomalies (excursions from an average) compared to the 1951–1980 period. It is seen not only by visual inspection but also by multiple statistical analyses that there has been no cessation to warming, despite claims to the contrary in the general media (Cahill *et al*., 2015; Foster and Abraham, 2015; Karl *et al*., 2015; Lewandowsky *et al*., 2016; Trenberth and Fasullo, 2013). Rather, temperatures have risen steadily since the 1970s, with modest interdecadal variations in warming rate that are consistent with internal climate variability (Steinman *et al*., 2015).

2.2 Comparison of models with measurements

One measure of the reliability climate models is their ability to simulate past temperature changes. A comparison of models/measurements is provided in Figure 2(a). The image shows four different temperature data sets. As with Figure 1, there is excellent agreement between the measurements. The grey region shows the spread of an ensemble average of climate models with a mean provided by the solid black line. When corrections are

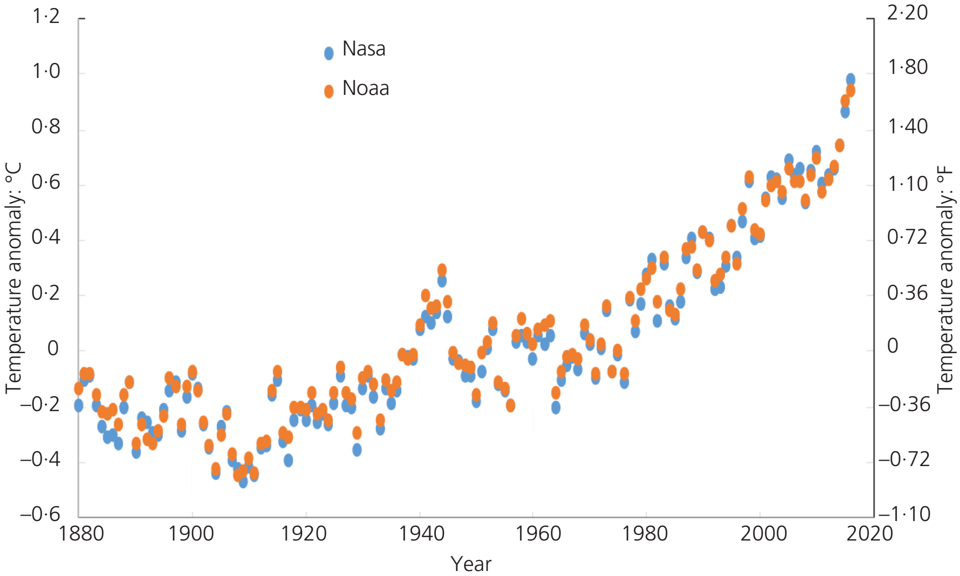

Figure 1. National Oceanic and Atmospheric Administration (Noaa) and National Aeronautics and Space Administration (Nasa) global land and ocean surface temperature anomaly record

made for changes to incoming solar energy (such as by volcanoes), the model range and mean are slightly reduced (shown by the long-dashed lines) (Santer *et al.*, 2014; Schmidt *et al.*, 2014). It is seen that 2016 is nearly identical to the central estimate from the models. For the most recent decade, the measurements have been at the lower end of the model range but within the range. The 40-year match between models and measurements gives confidence for future predictions. It should be noted that the model results in Figure 2 include both hindcast and forecast calculations.

Figure 2(b) compares temperature measurements in the oceans (upper 700 m of ocean waters). The CMIP5 model average is shown as a black line with a warming rate of 0·0053°C/year. The observations are slightly higher at 0·0061°C/year for ocean warming. Again, this excellent agreement lends support to the use of climatological models for future temperature predictions (Abraham *et al.*, 2013; Cheng *et al.*, 2015, 2016, 2017).

2.3 Future temperature projections

The most complete future temperature estimates, although perhaps slightly conservative, are from the Intergovernmental Panel on Climate Change's (IPCC) fifth report (IPCC, 2014). That report provides temperature ranges for various emissions rates (termed 'representative concentration pathways' or 'R_{CP}'). R_{CP} values represent different heat gain rates of the Earth in 2100 relative to pre-industrial values; the units of R_{CP} are Watts per square metre of the Earth's surface area. Among the potential future scenarios considered by the IPCC, an $R_{CP} = 8{\cdot}5$ can be considered a worst-case scenario, whereas $R_{CP} = 2{\cdot}6$ should be considered a best-case situation. Insofar as the current emissions are following the higher range of projections, the temperatures predicted using the R_{CP} 8·5 data are most appropriate. Figure 3 shows in graphical form the anticipated projections of global surface average temperature for the two bounding emission scenarios.

Taking advantage of Figure 3, it is seen that the two scenarios result in similar projections until approximately 2030, when divergence begins. The temperatures in the R_{CP} 8·5 case continue to rise, whereas the temperatures for R_{CP} 2·6 plateau. For comparison, the overall temperature rise in the R_{CP} 8·5 case is in excess of 4°C (7°F) above the current temperature (approximately 5°C (9°F) above the pre-industrial temperature). These would equate to temperatures not seen on Earth in at least the last 5 million years.

While it is appropriate to utilise R_{CP} 8·5 as a realistic 'no-mitigation' scenario, a significant global societal change in the utilisation and generation of power may bring real emissions more in line with the best-case scenario. In fact, the economics of renewable energy such as wind and solar power are decreasing dramatically and now are close to, or less expensive than, that of more traditional fossil fuels. Despite these positive factors, until the implementation of robust international agreements to reduce emissions is successfully completed, R_{CP} 8·5 should be considered the standard. Furthermore, the effects of temperature changes (and other climate outcomes) associated with R_{CP} 8·5 should be expected. Some of these outcomes are already being observed. For instance, sea level rise is occurring with an expected ~1 m (3 feet) rise by 2100. Ocean chemistry is changing through acidification; changes to precipitation (including increases in the most heavy precipitation events and consequent flooding) are being observed (Wang *et al.*, 2015). At the same time, changes to groundwater reservoirs and increased evapotranspiration in some areas are

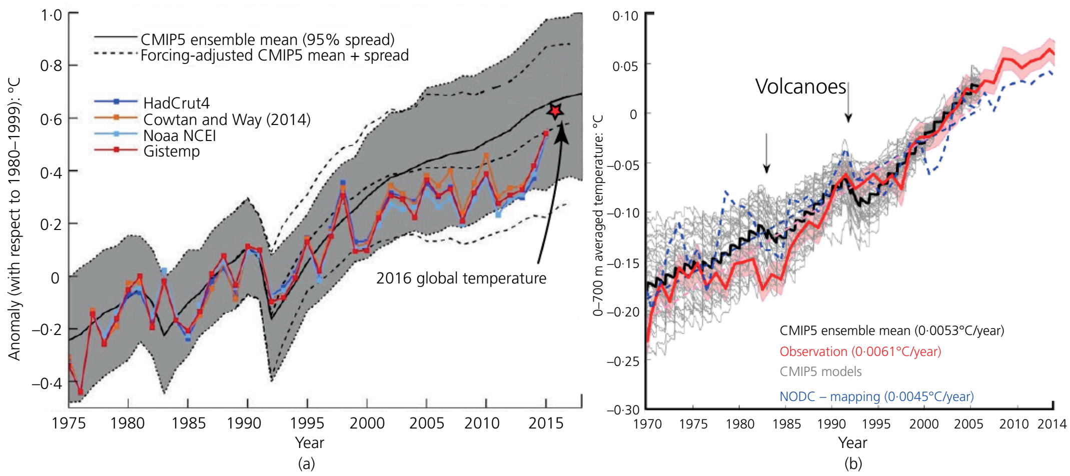

Figure 2. Comparison of temperature measurements with climate model predictions: (a) global surface temperatures and (b) upper 700 m ocean temperatures. Credits: (a) graph provided by Dr Gavin Schmidt; modified by J. Abraham, April 2017; (b) adapted from Cheng *et al.* (2015). CMIP5, Climate Model Intercomparison Project; HadCrut4, Hadley Centre of the UK Met Office and the Climatic Research Unit of the University of East Anglia; Noaa, National Oceanic and Atmospheric Administration; NCEI, National Centers for Environmental Information; Gistemp, Goddard Institute for Space Studies

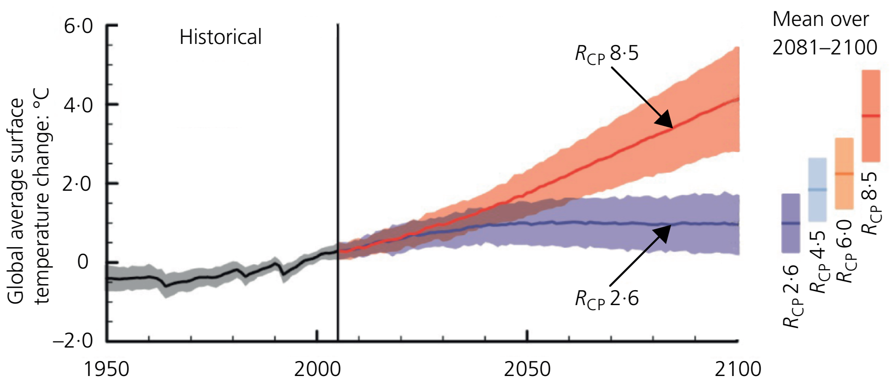

Figure 3. Temperature anomaly projections until 2100 using best- and worst-case emissions scenarios (IPCC's fifth assessment report (IPCC, 2014))

making droughts and other weather patterns more severe and more frequent (Horton *et al.*, 2015; Mazdiyasni and AghaKouchak, 2015; Trenberth *et al.*, 2015). There has also been an increase in the intensity of some storms, including Atlantic hurricanes' destructive wind power and rainfall (Emanuel, 2013; Kamahori *et al.*, 2006; Kossin *et al.*, 2007; Mann and Emanuel, 2006; Trenberth and Fasullo, 2007, 2008; Trenberth *et al.*, 2007).

For businesses and individuals in the construction industry in particular, careful thought should be given as to how or whether these changes will affect engineering projects. In some cases, the effects will be negligible, while in other cases the effects will be manageable with adaptive strategies. There will also be some scenarios where adaptation is not possible or is too expensive to justify the adaptation costs.

Simply put, enough is known to plan for the future. The best plans should account for the increase in the intensity of extreme weather-related climate changes. On a business-as-usual path, the changes by the end of the century will make tomorrow's weather very different from today's.

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