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Near-term acceleration in the rate of temperature change

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Anthropogenically driven climate changes, which are expected to impact human and natural systems, are often expressed in terms of global-mean temperature[1]. The rate of climate change over multi-decadal scales is also important, with faster rates of change resulting in less time for human and natural systems to adapt[2]. We find that present trends in greenhouse-gas and aerosol emissions are now moving the Earth system into a regime in terms of multi-decadal rates of change that are unprecedented for at least the past 1,000 years. The rate of global-mean temperature increase in the CMIP5 (ref. 3) archive over 40-year periods increases to 0.25 ± 0.05 °C (1σ) per decade by 2020, an average greater than peak rates of change during the previous one to two millennia. Regional rates of change in Europe, North America and the Arctic are higher than the global average. Research on the impacts of such near-term rates of change is urgently needed.

Global-mean surface temperatures (GMT) are a useful indicator of the overall scale of anthropogenic climate change over time, although changes in other variables, such as local temperatures, seasonal and diurnal temperature patterns, precipitation and storm tracks, are of more direct relevance to climate impacts[1]. Although rates of climate change are implicit in all climate projections, and occasionally mentioned relative to a century timescale, sub-century rates of change have rarely been examined. O'Neill and Oppenheimer[2] stressed the importance of the rate of climate change, although we find a more constrained range of near-term rates in this updated analysis (see Supplementary Section 7). Recently Ross *et al.* examined the sensitivity of the rate of climate change to ocean heat uptake, but only as averages over the entire twenty-first century[4].

We focus here on rates of change over 40-year periods, comparing past trends with future projections. These represent background trends averaging over shorter-term internal variability. Over this timescale rates from long palaeo-climate records begin to become more reliable (or at least more consistent with model results, Supplementary Section 3.1), historical changes to date are becoming distinguishable from modelled variability (Supplementary Section 3.5), and this begins to be comparable to the lifetime of much of human infrastructure. Rates of change from a number of temperature reconstructions for Northern Hemisphere areas are shown in Fig. 1. Forty-year warming trends rarely show an average rate very much above 0.1 °C/decade for the 900 years before the twentieth century, with some reconstructions showing occasional periods with trends up to 0.2 °C/decade. Millennial-scale coupled carbon–climate model simulations show similar overall behaviour[5] (Supplementary Fig. 4). During the latter half of the twentieth century anthropogenic influences increase in importance, with the Northern Hemisphere rate of climate change now above 0.2 °C/decade. Rates of change can be larger when considered over a shorter 20-year time period, but recent rates of change are not easily distinguishable from natural variability on this timescale (Supplementary Figs 2 and 14).

Although global temperature trends are one of the most commonly used metrics of climate change, climate impacts will be driven by regional trends. Frequency distributions for regional trends before the period of strong anthropogenic influence are shown in Fig. 2 from two sources: reconstruction extending over the past 2,000 years from the PAGES 2k consortium[6] and the CMIP5 set of climate model runs[3]. Because millennial-scale model runs are not available for most climate models, we instead conduct an analysis over a shorter historical time period (1850–1930), considering one ensemble member from each model in the CMIP5 (Coupled Model Intercomparison Project phase 5) archive with consistent data (see Supplementary Information). This 'model-time' domain analysis samples over a range of internal variability and model responses, although it considers only the recent history for solar and volcanic forcings.

Both the CMIP5 and PAGES 2k analysis show distinct regional differences in the rate of change frequency distribution (Fig. 2). A number of regions show changes greater than 0.1 °C per decade in both data sets. Australasia has lower rates of change in both data sets. On average, the CMIP5 data have a 20–30% larger range than the PAGES 2k data. These differences could be due to biases in either data set, but do not alter our conclusions (see Supplementary Section 3.1).

Future rates of temperature change are examined using consistent projections of future emissions of greenhouse gases, aerosol and aerosol precursors, and other criteria pollutant emissions. Figure 3a shows the 5–95% range for rates of change in the CMIP5 archive over all 40-year periods ending between 2011 and 2020 under the RCP4.5 scenario compared with a range of rates from a historical period where anthropogenic forcing is weak. By showing the range of trends across CMIP5 models we explicitly consider the impact of internal variability over this period, at least to the extent this is captured in the models. Figure 3b shows trends for the average CMIP5 regional 40-year rate of change.

By 2020, both the range in the rate of change, and the average value, is substantially higher than in the historical period (Fig. 3). For most regions, there is only a small overlap between the lowest 5% of CMIP5 rates of change in this decade and the 95% point from the 1891–1910 period (see also Supplementary Section 3.2). This implies that there is a relatively small chance that 40-year temperature trends over the 2011–2020 decade for 40-year periods will be within pre-industrial bounds. We find that rates of change, relative to inter-regional differences, generally do not have a strong dependence on the size of the analysis region or the ocean fraction (Supplementary Fig. 10).

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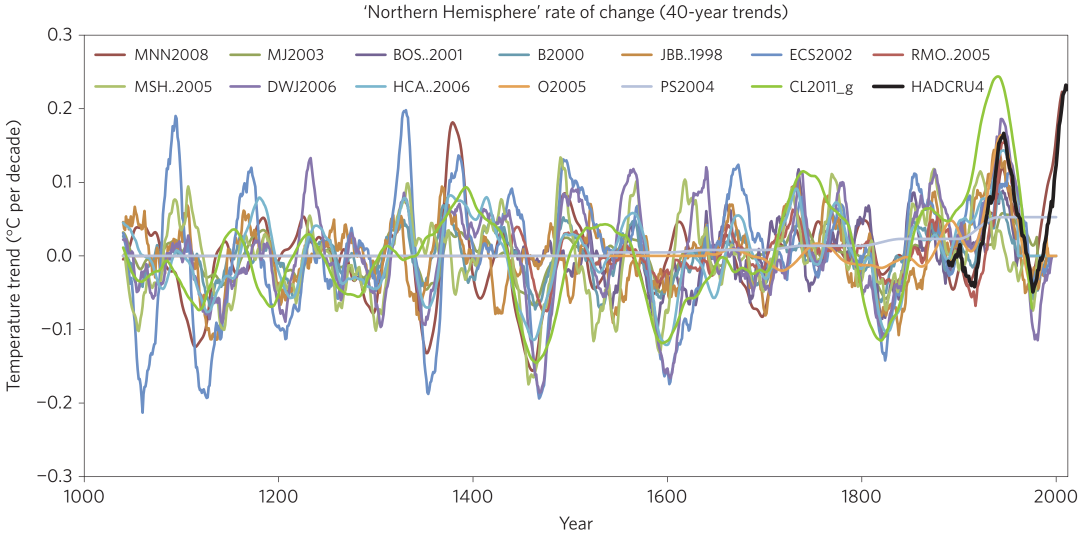

Figure 1 | Rates of temperature change over 40-year periods for a number of climate reconstructions that cover various Northern Hemisphere areas. Areas are land and ocean, land, and land 20°–90°, see Supplementary Information. The thick black line shows the corresponding rate of change of Northern Hemisphere temperature from the HADCRU4 data set[13]. Trends are linear fits ending at the year shown. Note that the proxy and historical records over the twentieth century are generally not independent, because proxy records are often calibrated to the historical temperature record. Global rates of change are about 20% smaller than Northern Hemisphere land + ocean rates of change in the CMIP5 archive (Supplementary Section 3.4).

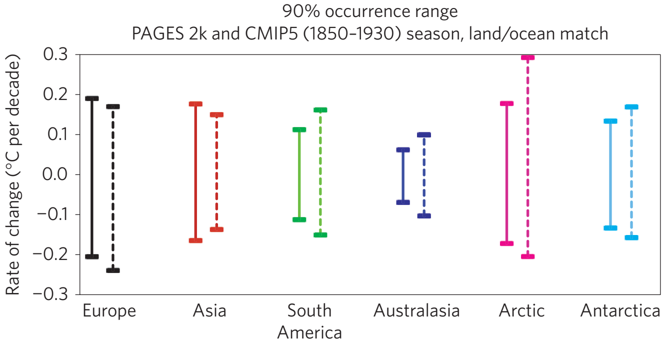

Figure 2 | 40-year rates of change from the PAGES 2k reconstructions up to 1900 and the CMIP5 climate model archive for the period 1850–1930. The bars (solid—PAGES 2k reconstruction, dotted—CMIP5 data) show the 5–95% range of occurrence for rates of change within each data set. The CMIP5 data were processed to match the seasonal and spatial (land + ocean or land only) coverage of the PAGES 2k reconstruction target for each region (Supplementary Table 2).

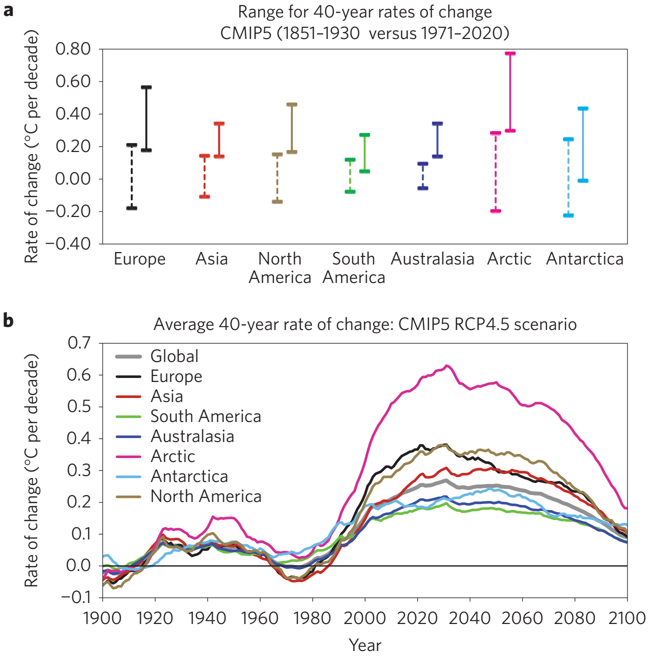

Figure 3 | Past and future regional rates of change from CMIP5. a, 5–95% occurrence range of the decadal rate of change over 40-year periods from the CMIP5 archive over a time with small anthropogenic influences (1851–1930, dotted lines) and a period centred on the present (40-year periods ending in 2011–2020, solid lines) from the RCP4.5 scenario. Because the CMIP5 archive is a 'sample of convenience', these percentages should not be interpreted as probabilities. **b**, Average over CMIP5 models for the regional rate of change. Rates of change in this figure are annual averages over land + ocean areas in each region.

This is consistent with findings that recent temperature extremes in high northern latitudes are unprecedented when compared with the past six centuries[7]. We note that Antarctica stands out with a lower rate of change signal relative to the inter-model variation, indicating less agreement for modelled trends in this region (Supplementary Fig. 6).

A simple climate model is used to diagnose the primary drivers of the forced component of these rates of change. In each future emissions scenario considered, we examine the impact of uncertainties in the equilibrium climate sensitivity and the assumed strength of aerosol forcing in the absence of internal variability by varying the values for each of these parameters (see Supplementary Information). Climate sensitivity is varied between 1.5 and 4.5 °C/CO_2-doubling, which a likely range of climate sensitivity from the IPCC AR5 (ref. 8). We vary total aerosol forcing between -0.4 and $-1.4\ \mathrm{W\ m^{-2}}$ in 2000, which we judge to cover a comparable probability range. All combinations of parameters are examined to explore the range. Aerosols at present provide a net cooling effect and the imposition of pollution controls around the world have been reducing emissions, particularly of sulphur dioxide[9,10], resulting in a net warming.

Figure 4 shows the 40-year global rate of change for two future scenarios used to drive the CMIP5 climate models, RCP4.5 and

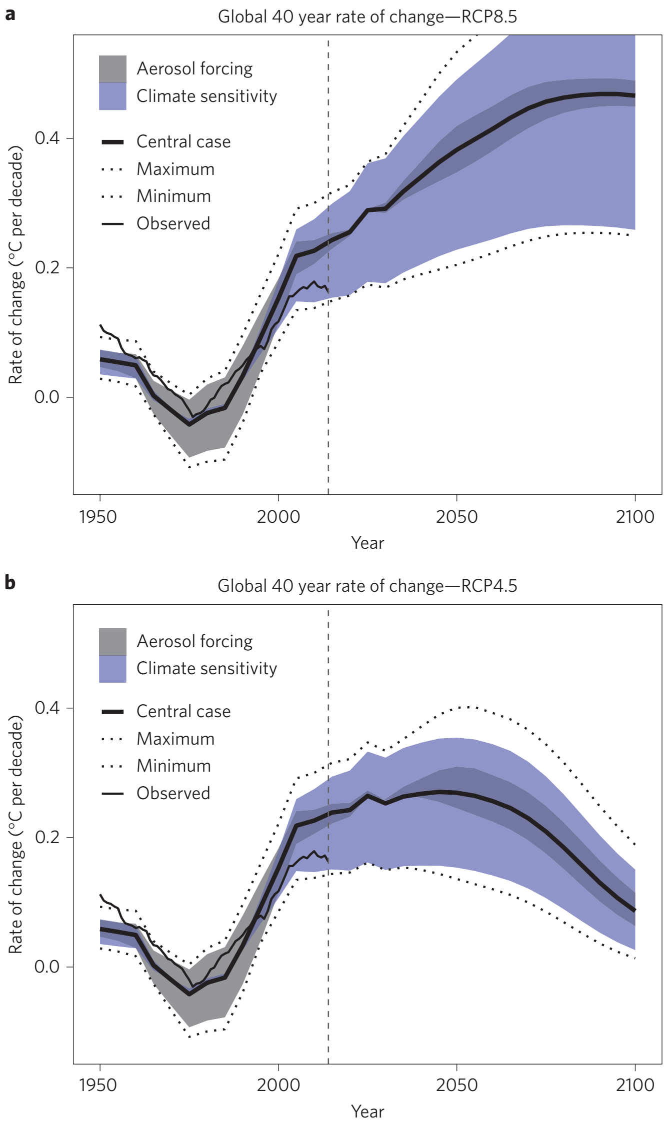

Figure 4 | Decomposition of global rates of temperature change from the MAGICC model. a,**b**, Forty-year rates of change for periods the RCP 8.5 scenario (**a**) and the GCAM 4.5 W m^{-2} climate stabilization scenario (**b**). Results are shown for: central climate assumptions (thick solid line), range due to uncertainty in aerosol forcing (grey shading), and range due to uncertainty in climate sensitivity (blue shading). The outer bounding cases are shown as dotted lines. The thin solid black line shows the historical rate of change using the HADCRU4 observational data. The vertical dashed line indicates 2014.

RCP8.5. The RCP4.5 scenario represents a world where global actions are taken to limit greenhouse gas concentrations[11], whereas the RCP8.5 examines a contrasting case where greenhouse gas emissions remain at high levels throughout the century[12]. Also shown, for reference, is the historical rate of change derived from the HADCRU4 record[13]. By 2030, the 40-year rate of change spans 0.15 to 0.33 °C/decade. The range in future rates of change from the simple model are comparable to the CMIP5 range (Supplementary Fig. 17). A number of the CMIP5 models, however, do not reproduce the historical drop in the rate of change seen in both the simple model and the HADCRU record.

Aerosol forcing assumptions strongly impact the rate of change until near the end of the twentieth century, but have a much smaller relative impact over the twenty-first century. By 2010, most of the spread in results is due to the assumed range in climate sensitivity. The spread in results in the twenty-first century is dominated by the assumed climate sensitivity, with a smaller impact for aerosol assumptions. The near-term rates of change are not very sensitive to the emissions scenario, with almost no difference out to 2025 (Fig. 4 and Supplementary Fig. 16), and successively larger differences after this point.

During the historical period, a range of assumptions impact rates of change, including internal (unforced) variability, solar and volcanic forcings, and anthropogenic forcings, particularly those for aerosols. Aerosol forcing has a particularly large impact in the twentieth century because these occur predominantly over land, which has a faster response to forcing than forcing over oceans.

The above analyses show that the world is at present in the midst of a transition to a regime where the rate of climate change on both global and regional scales will be dominated by the impact of increasing greenhouse gas forcing[14]. In this regime, assumptions for the magnitude of the climate sensitivity, which is still poorly constrained, has a dominant effect on rate of climate change over those of aerosol forcing assumptions (Fig. 4).

A climate policy that limits total radiative forcing to 4.5 W m^{-2} by the end of the century (Fig. 4b) limits the potential rate of change in the long term, but does not appreciably alter global-mean temperatures over the next few decades. This is due to both the impact of ocean thermal inertia and the fact that net aerosol cooling declines in the near-term as climate policy is implemented[15,16]. Under the 4.5 W m^{-2} stabilization scenario, rates of global-mean temperature change are still above 0.2 °C/decade until after the mid twenty-first century unless the climate sensitivity is low (for example, $\leq$2.0 °C/CO$_2$-doubling).

If the climate sensitivity is as low as 1.5 °C/CO$_2$-doubling, then the rate of change stabilizes around 0.15 °C/decade. In contrast, if the climate sensitivity is as high as 4.5 °C, then the rate of change exceeds 0.4 °C/decade by 2030 to 2040, although there is some evidence that the very high end of this range may not be consistent with observed warming to date[17].

Although the rate of change slows under a 4.5 W m^{-2} policy, global temperatures still increase throughout the century. Only a much stronger climate policy, such as a 2.6 W m^{-2} peak and decline scenario (Supplementary Fig. 16), can begin to reduce global-mean temperatures by the end of the century. Even under such strong climate mitigation, rates of climate change are above historical values until mid-century. In contrast, a reference scenario with higher greenhouse gas emissions, such as the RCP8.5, leads to much higher rates of change throughout the century (Fig. 4).

Like the projections from more complex models, these results do not capture the recently observed decrease in the rate of warming. Owing to internal variability, such a temporary slow-down is neither unusual nor unexpected[8,18,19], and is consistent with our analysis of historical rates of change where recent warming does not stand out when examined over 20-year time periods (Supplementary Fig. 2). The specific mechanisms at work are still a subject of research[20,21].

Global temperatures, with the impacts of natural variability subtracted, are close to, or may have already reached, a 0.2 °C/decade rate of change[22] (Supplementary Fig. 15). Continued research on near-term climate prediction[21,23,24], including resolving the physical mechanisms behind observed temperature changes over the past several decades, is needed to improve our understanding of potential rates of climate change over the next two to four decades. Improved methodologies for separating the impacts of natural variability from anthropogenic influences would also aid in the observational verification of anthropogenic climate changes over time[22]. Natural variability will play a key role in determining when increases in the rate of change would be observable. Note that both internal variability and changes in external forcings (solar and volcanic) have been found to play a role in determining 50–100-year trends in the absence of anthropogenic forcing changes[25].

The large shift over the coming decades relative to the historical period of both occurrences of high rates of change and the average rates of change indicates that the world is now entering a regime where background rates of climate change will be well above historical averages until at least mid-century. The impacts of an extended period of increasing rates of change are unclear. Little research has been conducted specifically on impacts associated with differing rates of climate change over a timescale of two to four decades. Specific impacts, including in natural systems, may be sensitive to changes over different timescales. Those impacts that are sensitive to changes over 40-year periods would now be on the cusp of experiencing unprecedented rates of change. The accelerated rates of change noted here mean that impacts related to rates of change will intensify over the coming decades. Research on such impacts, and also on potential adaptation measures, is urgently needed to guide adaptation. Adaptation to these changes, as well as detection and attribution of impacts[26], will be necessary as these rates of change will be sustained for some decades even under substantial emission mitigation efforts (Figs 4 and Supplementary Information 16). Mitigation of greenhouse gas emissions would be needed to limit the duration and magnitude of high rates of change over the long term.

Methods

CMIP5 data were processed for the first ensemble member of every model for which the required data was available over the time span of the analysis. Regional data were averaged over rectangular regions consistent with those from the PAGES 2k palaeo-climate analysis (see Supplementary Information).

We examine the factors contributing to these twenty-first century changes by using the MAGICC simple climate model[27,28] as implemented in the Global Change Assessment Model (GCAM; Supplementary Section 5). The MAGICC model is a four-box energy balance model with an upwelling diffusion representation of ocean heat transport that has been shown to be able to reproduce the global-mean temperature results of more complex models[29]. The results shown here incorporate a comprehensive suite of future anthropogenic forcing agents, including well-mixed greenhouse gases, sulphate and carbonaceous aerosols, and ozone. Because the model produces trends without natural variability, realized trends would have a variable component superimposed on the model results as shown. We limit the MAGICC sensitivity analysis to two primary variables (climate sensitivity and aerosol forcing) for clarity and because these are known to be particularly important in this context. Varying other model assumptions, such as the long-term rate of ocean heat uptake[4], would widen the range of results.

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Author contributions

S.J.S., J.E. and K.C. designed research. S.J.S., C.A.H. and A.M. conducted research. All authors wrote paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.