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Communication of the role of natural variability in future North American climate

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As climate models improve, decision-makers' expectations for accurate climate predictions are growing. Natural climate variability, however, poses inherent limits to climate predictability and the related goal of adaptation guidance in many places, as illustrated here for North America. Other locations with low natural variability show a more predictable future in which anthropogenic forcing can be more readily identified, even on small scales. We call for a more focused dialogue between scientists, policymakers and the public to improve communication and avoid raising expectations for accurate regional predictions everywhere.

Evidence is clear that Earth's global average climate has warmed over the past century[1]. However, a science communication challenge is to better explain where, how and how much natural climate variability may obscure anthropogenic climate change on timescales of a few decades and spatial scales smaller than continental[2–7]. (Here, the term 'natural climate variability' refers to unforced variability internal to the real or simulated climate system.) For example, natural phenomena such as the Interdecadal Pacific Oscillation and the Atlantic Multidecadal Oscillation substantially modify the rate of warming in many regions of the globe[8,9]. Despite clear evidence for the importance of such phenomena, some news articles[10] imply that uncertainties in climate change projections are due to model shortcomings, and it is sometimes confidently asserted that those can be overcome. For example, a recent modelling summit[11] concluded that "a vigorous Climate Prediction Project … would ensure that the goal of accurate climate predictions at the regional scale could begin to aid the global society in coping with the consequences of climate change". Should such assertions be more targeted, rather than global?

Uncertainty in climate projections is due to three main factors: emissions-scenario uncertainty, model-response uncertainty and natural variability[3]. The choice of emissions scenario can be specified and model-response uncertainty can potentially be reduced. But given the inherently unpredictable nature of unforced climate fluctuations beyond a few years[12] to at best a decade[13,14], uncertainty in future climate change due to natural variability is unlikely to be reduced as climate models improve or as projections of greenhouse-gas concentrations become more accurate. It is critical to consider how the amplitude of natural variability differs with location. Several recent studies[15–17] have shown that a 'signal' of locally significant summertime warming is already emerging or will emerge from the 'noise' in the next two decades in a number of tropical areas owing to low natural variability. Here we provide simple figures based on one climate model and with a specific focus on a timescale of the next 50 years to illustrate that although climate change and climate projections could be inherently uncertain in many parts of North America owing to natural variability, not all places and climate variables are subject to the same limitations, requiring a more focused approach to adaptation and science communication. North America is chosen as an example to illustrate the argument, but the conclusions qualitatively apply to all continents.

Modelling natural variability and climate change

To span the range of internal climate variability, a 40-member ensemble of climate change simulations for the period 2000–2060 was conducted with a comprehensive coupled atmosphere–ocean–sea ice–land general circulation model — the National Center for Atmospheric Research Community Climate System Model version 3 (CCSM3) — at a horizontal resolution of approximately 2.8° latitude and 2.8° longitude[4]. Each ensemble member undergoes the same external forcing, the main components of which are the *Special Report on Emissions Scenarios*[18] A1B greenhouse-gas scenario (in which carbon dioxide concentrations increase from approximately 380 ppm in 2000 to approximately 570 ppm in 2060) and stratospheric ozone recovery by 2060, as well as smaller contributions from sulphate aerosol and black-carbon changes[19]. Each ensemble member begins from identical initial conditions in the ocean, land and sea-ice model components (taken from the conditions on 1 January 2000 from a single twentieth century CCSM3 integration), and slightly different initial conditions in the atmospheric model (taken from different days during December 1999 and January 2000 from the same twentieth century CCSM3 run).

The different members of the model ensemble show how much the climate can vary in the model world as a result of random internal variations. To the extent that the model captures the relevant physical processes, its range provides insight into what could happen in the single realization that will occur in the real world. The predictability of air temperature and precipitation changes in these model runs is limited to a few years[12]. Thus, the 40 realizations are all plausible outcomes of climate change over the next 50 years. This set-up can be thought of as an idealized decadal prediction experiment in which one member is reality and the others are initialized predictions. Because all simulations are performed with the same model and are identical until 2000, twenty-first century differences cannot be ascribed to model errors, biases or initialization shocks. The spread therefore represents the irreducible uncertainty of the prediction. This 40-member ensemble of climate change realizations represents the largest such ensemble with a single state-of-the-art coupled climate model so far. The spatial patterns and magnitudes of internal climate variability on decadal and longer timescales are generally well represented by CCSM3, although some locations in North America show enhanced variability (by approximately 15–25%) compared with nature[4].

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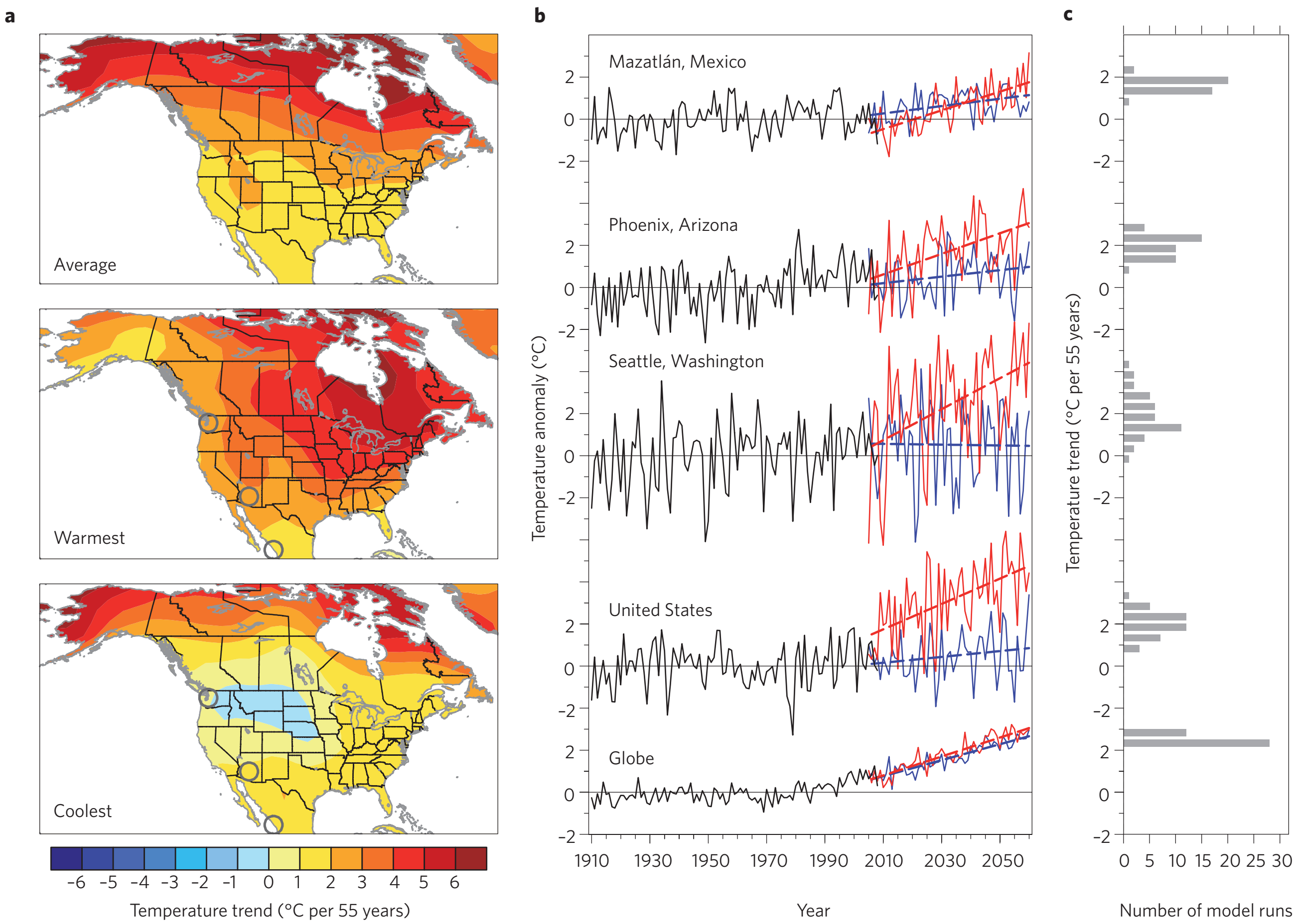

Figure 1 | Range of future climate outcomes. a, December–January–February (DJF) temperature trends during 2005–2060. Top panel shows the average of the 40 model runs (all values are statistically significantly different from zero at the 5% confidence level); middle and bottom panels show the model runs with the largest and smallest trends for the contiguous United States as a whole, respectively. **b**, DJF temperature anomaly time series for selected cities (marked by open circles in the left panels), the contiguous United States and the globe (land areas only). Black curves show observed records from 1910 to 2008 (minus the long-term mean); red and blue curves show model projections for 2005–2060 from the realizations with the largest and smallest future trends, respectively, for each location or region. Dashed red and blue lines show the best-fit linear trends to the red and blue curves, respectively. For visual clarity, the model projections are matched to observations averaged over their common period of record 2005–2008. Thus, projected values at the end of the simulation (2060) should be regarded in relative terms (see Supplementary Information). **c**, Distribution of projected DJF temperature trends (2005–2060) across the 40 ensemble members at the locations shown in panel **b**.

A range of future climate outcomes for North America

The projected changes in winter (December–January–February) and summer (June–July–August) temperatures, when averaged over all 40 ensemble members, show familiar patterns: robust warming at all locations, with the largest amplitudes at high latitudes in winter (4–6 °C over northern Canada and Alaska compared with 1–2 °C over the southern United States and the Rocky Mountains in summer; top panels of Figs 1a and 2a, respectively). Individual realizations, however, can look very different from this average picture of climate change. For example, the model run with the most warming over the contiguous United States in winter shows the largest temperature change (4–6 °C) over northeastern North America and the smallest change (1–3 °C) over western Canada and Alaska (Fig. 1a, middle). On the other hand, the run with the least warming over the contiguous United States in winter displays temperature changes that are limited to <1 °C over much of the western United States and southwest Canada with some areas such as the northwest United States even experiencing cooling (Fig. 1a, bottom). These strikingly different climate outcomes occur despite both model runs being subjected to identical external forcings. A similar story is evident in summer: one model run shows temperature increases over the contiguous United States that are approximately twice as large as the ensemble mean (4–5 °C compared with 2–3 °C; Fig. 2a, middle), while another has only limited warming (<1 °C) over the US Midwest (Fig. 2a, bottom). The large differences between individual model realizations can be traced back to multidecadal fluctuations in large-scale atmospheric flow patterns whose patterns are similar to those observed in daily weather and in interannual variability[4].

Figures 1b and 2b offer a complementary temporal perspective on North American climate change as impacted by natural variability. Here, observed[20] temperature records for 1910–2010 are expanded with model projections to 2060 using the two ensemble members with the largest and smallest future trends for each location or region (red and blue curves, respectively). In the global terrestrial average, warming is evident over approximately the past 40 years, occurring at an average rate of 0.32 °C per decade in winter and 0.29 °C per decade in summer during 1970–2008. The model projects the rate of global warming to increase slightly over the next 55 years, with a relatively small range of uncertainty due to natural variability (0.38–0.45 °C per decade in winter and 0.35–0.42 °C per decade in summer during 2005–2060; see also Figs 1c and 2c). However, the picture is different for the contiguous United States, where it is clear that in addition to fluctuations

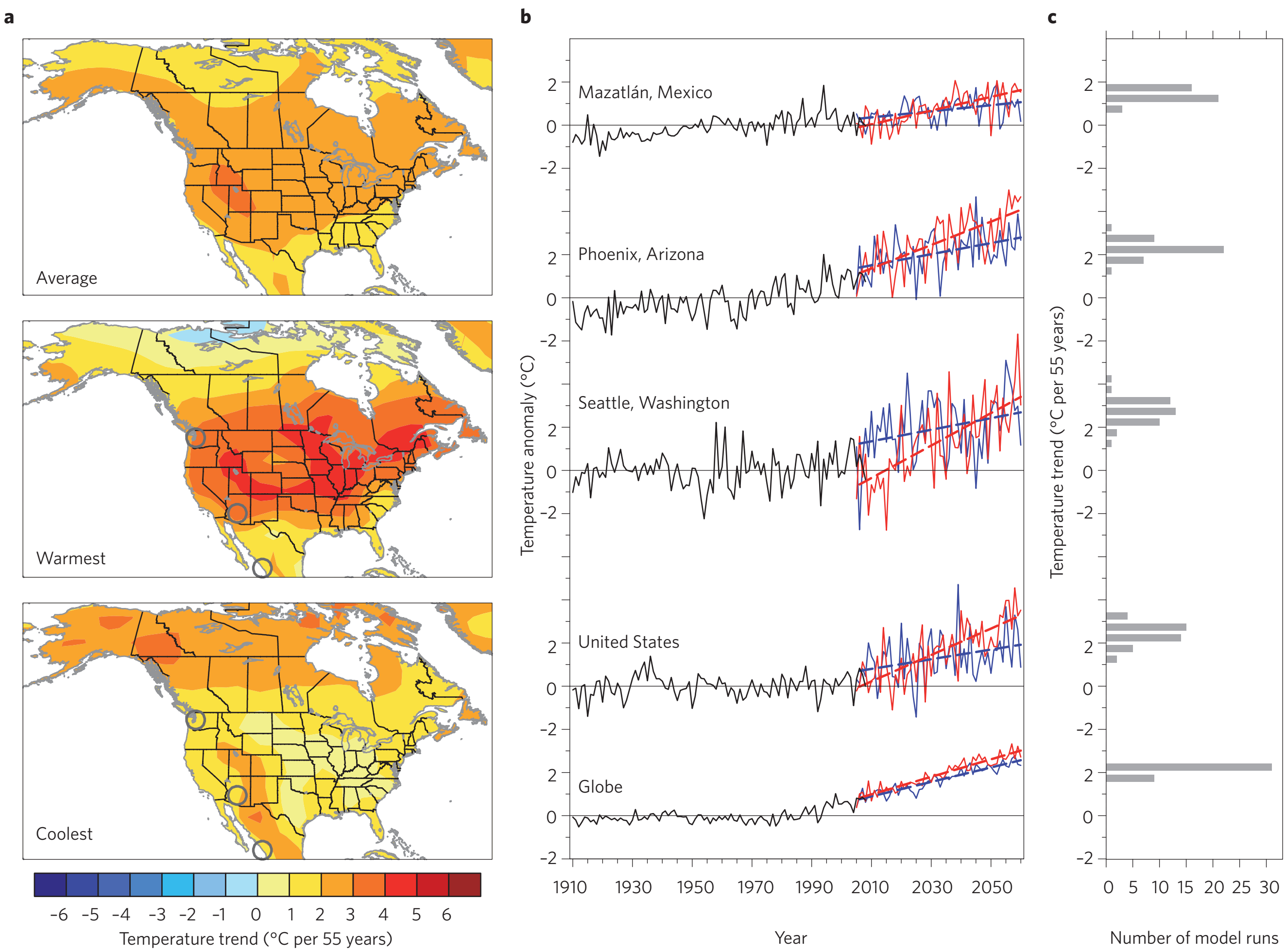

Figure 2 | Range of future climate outcomes. As in Fig. 1 but for June–July–August.

on interannual-to-decadal timescales, even trends over 50 years are subject to considerable uncertainty owing to natural variability. For the contiguous United States as a whole, future (2005–2060) warming ranges from 0.8 °C to 3.4 °C in winter and 1.3 °C to 3.4 °C in summer (recall the corresponding maps in Figs 1 and 2). The distribution of trends in Figs 1c and 2c shows the probability of warming of a particular magnitude. Higher warming over the contiguous United States is compensated for by weaker warming in other parts of the globe, particularly Canada, China and portions of the tropical eastern Pacific Ocean, and vice versa (not shown).

Simulated temperature records at three selected western North American cities (Mazatlan in Mexico, Phoenix in Arizona and Seattle in Washington) illustrate the latitudinal dependence of uncertainty in the magnitude of future warming due to natural variability (Figs 1 and 2). A single model grid box is used for each city location. At Mazatlan, where both the interannual variability and relative uncertainty in future trends are smallest, projected warming ranges from 1.0 °C to 2.5 °C in winter and 0.8 °C to 1.8 °C in summer over the period 2005–2060. In comparison, Seattle shows the largest interannual variability and greatest range of uncertainty in future trends, with projected temperature changes varying from −0.1 °C (that is, cooling) to as much as 4.1 °C in winter and from 1.5 °C to 4.2 °C in summer. The interannual variability and range of future trends at Phoenix (0.9–2.7 °C in winter and 1.4–3.0 °C in summer) lie in between those of Mazatlan and Seattle. The histograms shown in the figures illustrate how these extreme cases relate to the range of the results across all realizations, demonstrating for example the narrowness of the distribution of results for Mazatlan, and the much broader spread across realizations for Seattle and the mean across the United States. These results illustrate that at many locations within North America and even at the regional scale of the contiguous United States, natural variability of temperature trends over the next 55 years in both winter and summer should be expected to be substantial. However, some places in the southwestern United States and Mexico are less subject to natural variability and may therefore be more predictable than other locations or even the United States as a whole: in other words, regional averaging does not necessarily reduce the uncertainty in climate change projections. Smaller levels of variability are generally found in summer compared with winter, and at lower latitudes compared with higher latitudes; previous studies have shown such behaviour to hold not only in a range of climate models but also in observations[16–18].

Compared with temperature, precipitation projections are even more subject to natural variability (Fig. 3). Although the ensemble mean shows the familiar pattern of future precipitation increases at high latitudes and decreases at low latitudes over North America in winter, the changes over the midsection of the United States (indicated by stippling in the figure) do not exceed the range of modelled natural variability. As for temperature, individual realizations depict a very different future for winter precipitation than that conveyed by the ensemble mean. For example, one model run shows a wet future for much of the contiguous United States, with trends exceeding 20–30% of the 2005–2060 mean over much of the southwest and Kansas; whereas another shows a dry future with the largest rainfall

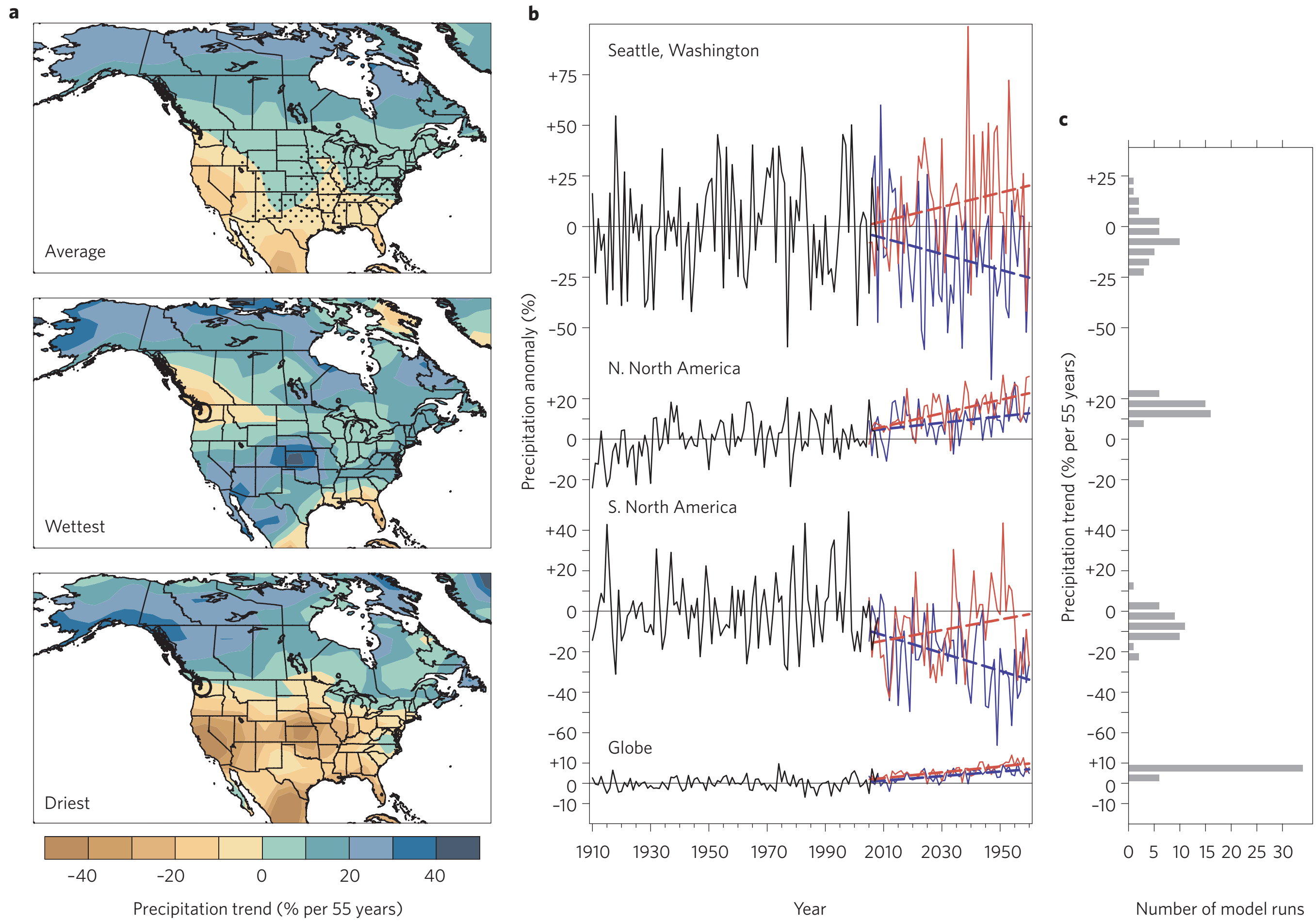

Figure 3 | | Range of future climate outcomes. a, As in Fig. 1 but for December–January–February (DJF) precipitation trends, expressed as a percentage of the model's ensemble-mean climatology for 2005–2060. Top panel shows the average of the 40 model runs, with stippling where the values are not statistically significantly different from zero at the 5% confidence level. The middle and bottom panels are based on the model runs with the wettest and driest trends for the southern half of North America (south of 42° N), respectively. **b**, DJF precipitation anomaly time series, expressed as a percentage of the observed mean during 1910–2008 minus 100%. Northern and southern North American regions refer to averages north of 50° N and south of 42° N, respectively. **c**, Distribution of projected DJF precipitation trends (2005–2060) across the 40 ensemble members at the locations shown in panel **b**.

deficits (30–40%) in California, Nevada, Kansas and parts of Mexico (Fig. 3a, middle and bottom).

The winter precipitation records[21] shown in Fig. 3b illustrate the high levels of uncertainty in future rainfall both locally and regionally. For example, individual locations such as Seattle (also Phoenix and Mazatlan; not shown) and areas as large as the southern half of North America may experience wetter or drier conditions in the future, with trends ranging from approximately −23% to +17% of the 1910–2008 observed mean, in addition to considerable interannual variability. Winter precipitation over northern North America, on the other hand, is projected to increase in all ensemble members, with changes ranging from +9% to +18% of the 1910–2008 observed mean. As for temperature, the range of future terrestrial precipitation increases at the global scale is small (+6 to +8% over the period 2005–2060). Although the minimum-to-maximum trend ranges given above depend on the ensemble size, qualitatively similar results are obtained using ranges based on 95% confidence level estimates (for example, as Fig. 3c illustrates).

Climate change uncertainty and natural variability

Model projections are inherently uncertain. But the results shown here suggest that often models may disagree because future changes are within the natural variability[22]. Such natural fluctuations in climate should be expected to occur, and these will augment or reduce the magnitude of climate change due to anthropogenic forcing in many parts of the world. Such intrinsic climate fluctuations occur not only on interannual-to-decadal timescales but also over periods as long as 50 years. Through an examination of a large ensemble of twenty-first century projections produced by the CCSM3 climate model, we have illustrated that even over the next 55 years, natural variability contributes substantial uncertainty to temperature and precipitation trends over North America on local, regional and continental scales, especially in winter at mid and high latitudes. Such uncertainty and regional variation in projected climate change is largely a consequence of the chaotic nature of large-scale atmospheric circulation patterns, and as such is unlikely to be reduced as models improve or as greenhouse-gas trajectories become more certain[4]. Perhaps surprisingly, regional averaging does not necessarily reduce uncertainty due to natural variability: the range of temperature change from one ensemble member to another over the next 55 years is larger for the contiguous United States as a whole than for a number of specific locations within the southwestern United States in summer and parts of Mexico in both winter and summer. It is worth noting that downscaled information derived statistically or dynamically from global climate model output will add local detail, but remains dependent on the overlying larger-scale field, and cannot mitigate the uncertainty of projected climate trends due to natural climate variability.

Planning for the future

Planning for future climate change thus requires not simply the application of regional or temporal averaging, but depends on a deeper understanding of what drives the climate and its variability. Improvements in global and regional models are undoubtedly critical, and will help climate prediction in many respects, and for some places (such as parts of Mexico) better information on local climate change and adaptation can be expected as models improve. But to guide decisions in some locations, for example, the diameter of Seattle's storm drain-pipes[10], the models probably cannot be expected to provide accurate projections. Whether projections subject to large and irreducible uncertainties remain helpful needs careful examination by the user[23,24].

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Additional information

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