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PERSPECTIVE

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Natural climate variability and future climate policy

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Large ensemble climate modelling experiments demonstrate the large role natural variability plays in local climate on a multi-decadal timescale. Variability in local weather and climate influences individual beliefs about climate change. To the extent that support for climate mitigation policies is determined by citizens' local experiences, natural variability will strongly influence the timescale for implementation of such policies. Under a number of illustrative threshold criteria for both national and international climate action, we show that variability-driven uncertainty about local change, even in the face of a well-constrained estimate of global change, can potentially delay the time to policy implementation by decades. Because several decades of greenhouse gas emissions can have a large impact on long-term climate outcomes, there is substantial risk associated with climate policies driven by consensus among individuals who are strongly influenced by local weather conditions.

Extreme weather events, including hurricanes Sandy and Katrina and the heatwaves experienced by much of Europe in 2010 or in the United States in 2012, spur public discussion about reducing greenhouse gas emissions — regardless of the extent to which these events can actually be attributed to past emissions. In contrast, the fact that most places have experienced relatively little warming over the past decade[1] has caused some to doubt the reality of human-induced global warming and to argue against actions to reduce greenhouse gas emissions. Natural variability and weather extremes, in particular local warming, influences people's belief in climate change and their willingness to support potentially costly climate mitigation measures[2–6]. However, climate variability and extreme events involve a fundamentally chaotic component[7,8]. Society's response to the threats posed by climate change partly depends on unpredictable meteorological events, adding another layer of uncertainty and unpredictability to policy outcomes.

Despite overwhelming scientific evidence for the impending damages caused by anthropogenic climate change, climate policy leading to substantial emissions reduction has been slow to materialize[9]. A number of recently published works in the psychological literature has shown that citizens' belief in climate change and their willingness to pay for emissions abatement are influenced by their experiences with heatwaves and other extreme local conditions[2–6]. Risk perceptions and willingness to pay for risk mitigation are influenced by local extreme events or accidents. From heatwaves and floods, to hurricanes, to nuclear power or natural gas pipeline accidents, people exhibit an availability bias[2,10] when making economic decisions impacted by environmental or disaster-related risks[11–16]. These changes in perception and willingness to pay are influenced by proximity[14] and event severity[13], and decay with time after the event[16,17].

An extreme event may therefore open a 'policy window'[18] — a limited opportunity to implement climate change policies that would lack sufficient political support in the absence of such a focusing event. While an extreme event alone is unlikely to bring about policy change[19], when aligned with hospitable political and institutional conditions it may provide a critical impetus for local policy adoption[20,21].

As global temperatures continue to rise, a confluence of natural variability and the forced response of the climate system to greenhouse gases will increase the frequency of unprecedented events, such as the 2010 heatwave in eastern Europe[22]. Although the forcing-driven component of increased extreme event frequency is to some extent predictable, the natural variability-driven component — and thus the timing and location of these events — is largely stochastic.

Large ensemble climate modelling experiments have demonstrated the important role natural variability plays in the range of regional climate change predicted for coming decades. Indeed, in many regions, the multi-decadal component of natural variability may be as large as the forced response to rising greenhouse gas concentrations over the next several decades[7,23]. Natural variability influences local meteorological conditions on timescales from days to decades[24–27]. Thus, natural variability may mask the forced response in some countries while exacerbating the forced response in others, with differential consequences for public support for climate policy in each country. Because support for climate policies is likely to be affected by the local experiences of citizens, natural variability can be expected to significantly influence the timescale for action to mitigate climate change.

Deterministic citizens in a stochastic world

There is no shortage of factors that make it difficult to predict the future evolution of complex social systems. To illustrate the influence that unpredictable extreme weather events may have on the time to reach a global agreement on climate policy, we present an analysis in which weather is the only unpredictable factor. In our simple illustrative model, deterministic citizens are confronted with a stochastic world represented by climate model projections. We analysed the output from a 40-member coupled climate model ensemble[23] to illustrate how local experiences might affect the timing of acceptance of strong climate policy measures. Each of these ensemble members are subject to identical climate forcings, yet experience different weather (see Supplementary Information for details about our analytical methods). Our analysis illustrates how timescales for domestic and international policy action will be influenced by natural variability in local weather if a nation's decision to take strong actions to abate emissions is contingent solely on the local experiences of its citizens.

A wide range of climate risk-reduction policy options are likely to be considered simultaneously, involving a wide range

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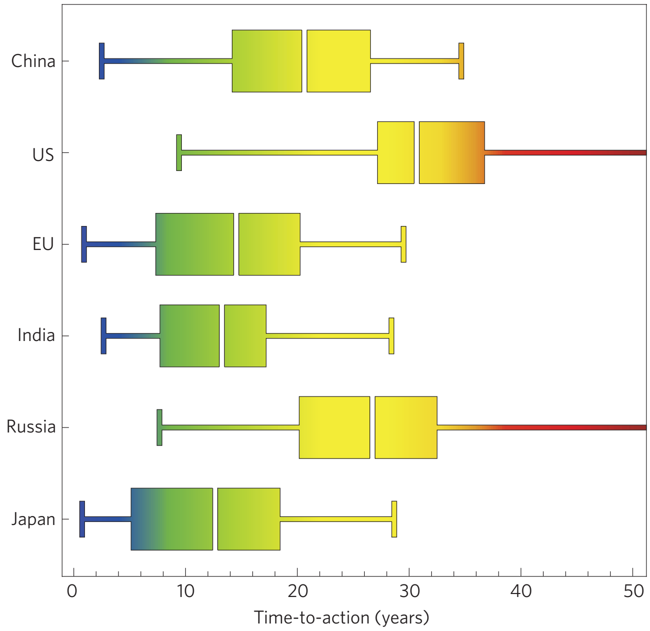

Figure 1 | Range of time-to-action (in years after 2013) for the top six carbon dioxide emitters. Time-to-action is the time it takes a country to support an international agreement. Box-and-whiskers show the median, 25–75% confidence, and maximum–minimum limits for the 40 ensemble members for each nation/economic entity.

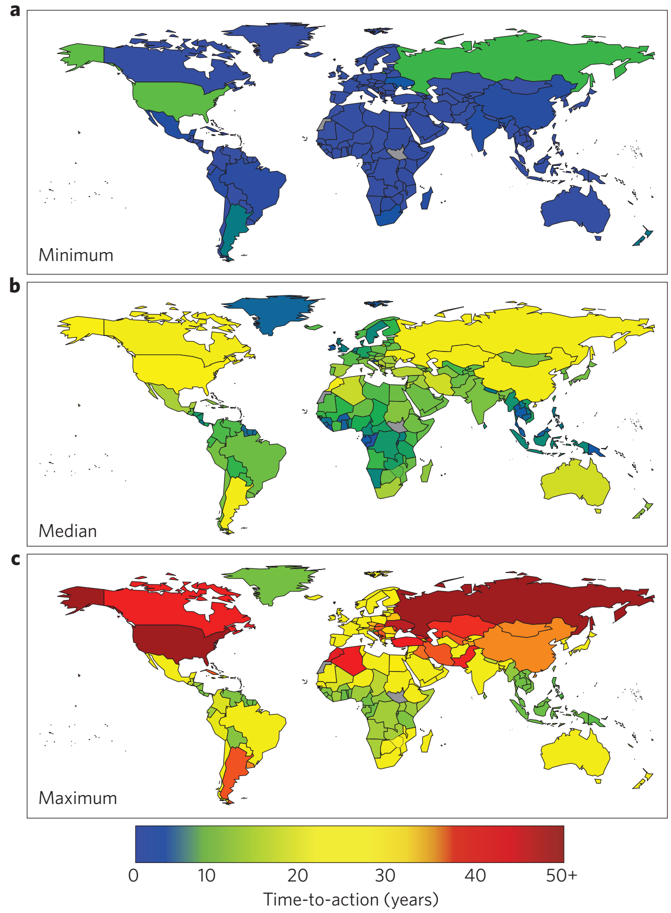

Figure 2 | Maps of the time-to-action (in years after 2013) by country. Colours indicate **a**, the ensemble minimum, **b**, the median and **c**, the maximum number of years until each country has reached the tipping point (when 50% of the population is convinced) for support of an international agreement.

of decisions, but for simplicity our illustration involves a single policy decision. Because quantitative data about the magnitude and timescale of the influence of extreme weather events on willingness to take action to mitigate climate change is limited, we draw on the broader literature about risk decision making following natural disasters (including weather-related ones) to formulate our model. In our illustration, we assume that in any given climate model grid cell[28] the fraction of the population that is convinced of the need for strong climate change risk mitigation policies is increased by unusually hot months. The fraction of the unconvinced population that becomes convinced increases with the extremity of the event. In addition, the fraction of the population previously convinced (and thus willing to pay for policy changes) decreases each month with a timescale similar to those observed in the literature about risk mitigation behaviour following natural disasters[16,17], which is consistent with timescales suggested in the more limited quantitative assessments of changes in climate risk perceptions following extreme weather events[3,5].

In this model, the fraction of the population (f) convinced to pay for mitigation policy is represented by the following equation:

$$\frac{df}{dt} = (1-f)\,\frac{N}{k+N} - \frac{f}{\tau}$$

where N represents the extremity of the event (as in a 1-in-N hot month) relative to a baseline period. N is calculated in terms of the month's temperature as measured in standard deviations (σ) from an early twenty-first century baseline: $N = 1/(1 - \mathrm{erf}(\sigma/\sqrt{2}))$. The parameter k represents the sensitivity of the unconvinced population to extremes, and τ is the time constant according to which supporters of policy action lose their willingness to support those policies (Supplementary Methods and Supplementary Fig. 1).

In our model, a national tipping point for the policy action occurs when half of the country's population is convinced. We refer to the time that this social tipping point is reached for a particular country as the 'time-to-action' for that country. Because populations' sensitivities to extremes are uncertain, natural variability could delay action by more or less than indicated by our analysis. The point of this exercise is to illustrate the potential interplay of natural variability and the forced climate response in influencing public perceptions and climate policies within the confines of the available dataset. Therefore, other aspects of our model are kept as transparent and simple as possible.

To the extent that climate policies are driven by the weather experienced by a country's citizens, variability in weather will result in significantly disparate times-to-action. The spread of the model results for each country is entirely due to internal climate variability — our modelled social system is deterministic and the only differences between simulation ensemble members are small perturbations in the initial conditions of the atmosphere. For the top six global CO_2 emitters, natural climate variability results in a range of times-to-action spanning several decades (Fig. 1). Furthermore, the times-to-action for these large emitters are not strongly correlated (Supplementary Table 1). The potential range of outcomes is narrower and the median times-to-action are nearer-term for the European Union, India and Japan than for China and, in particular, the United States and Russia.

Figure 2 shows that countries that tend to reach time-to-action sooner also have a narrower range of expected time-to-action (see the outcomes in each individual ensemble member in Supplementary Fig. 2). Tropical nations are more likely to reach their time-to-action sooner, consistent with other work that shows the signal of low-latitude temperature change emerging early from the noise of natural variability as global temperatures increase[23,29]. Other explanatory factors, beyond general climatological ones, account for the uncertainty associated with a country's time-to-action. On average, the larger the country the more variability it has in reaching its time-to-action. To trigger action in the largest countries, decadal trends and interannual variability must combine to manifest exceptional extremes in close temporal proximity in multiple climatological zones. In contrast, for a small country one extreme event will often push the entire population past a tipping point.

While the results in Figs 1 and 2 are based on monthly temperatures, the patterns are qualitatively the same for any climate indicator with a strong stochastic component. The results are not dependent on the particular model of social tipping points (for example, see Supplementary Information and Supplementary Fig. 3). The same analysis conducted using precipitation, a combination of temperature and precipitation or even staple crop yields, shows similar patterns and ranges of outcomes (Supplementary Figs 4–6).

Ratcheting open an international policy window

Climatologically effective emissions abatement will be contingent on widespread international adoption of abatement policies. Like domestic policy tipping points, policies at the international scale also have a documented, but highly uncertain, tendency to propagate after reaching certain thresholds. Once large-scale changes to economic and social norms (such as the reduction of trade barriers, universal suffrage, women's rights and international human rights standards) are adopted by an unpredictable 'critical mass' of states or actors, adoption by many more follows in a relatively short period of time[30,31]. Diffusion of policies can take place in national[32], international[33] or even sectoral contexts[34]. Such policies may be eventually codified in formal international legal agreements, but such binding agreements are not necessarily required for these norms to be effective[35,36]. Therefore, large-scale international action to mitigate climate change could potentially occur if enough powerful international actors adopt new norms, which would ultimately induce near-global adoption. Such norm adoption need not necessarily be codified through the UNFCCC process, although it could be.

We consider the timescales for effective international action under two different institutional constraints on reaching an agreement, which reflect some of the potential differences in international policy processes. Under the first, stricter constraint ('simultaneous consensus'), a window for effective international action will only open when a quorum of nations is simultaneously convinced to take action. Under the second, looser constraint ('incremental consensus'), a nation permanently buys into an international agreement at the time its own population is convinced to take action, and the international agreement then enters into force when a quorum is reached. Under this constraint, national policies are passed when a national-scale policy window opens, and an international policy window is also partially propped open. In effect, this incremental approach ratchets an international policy window open state by state.

We also examine timescales for agreement under three hypothetical international tipping points representing different international power schemes: (1) majority population, (2) majority economic output and (3) consensus among the US and China. We refer to the time to reaching effective international-scale action as the 'years-until-agreement', for which 'agreement' may refer to anything from a formal binding one to a substantive normative one.

Under the simultaneous consensus constraint, in which international agreements are not reached until all relevant parties have reached the tipping point simultaneously (dark-bordered bars in Fig. 3), the median years-until-agreement is considerably larger

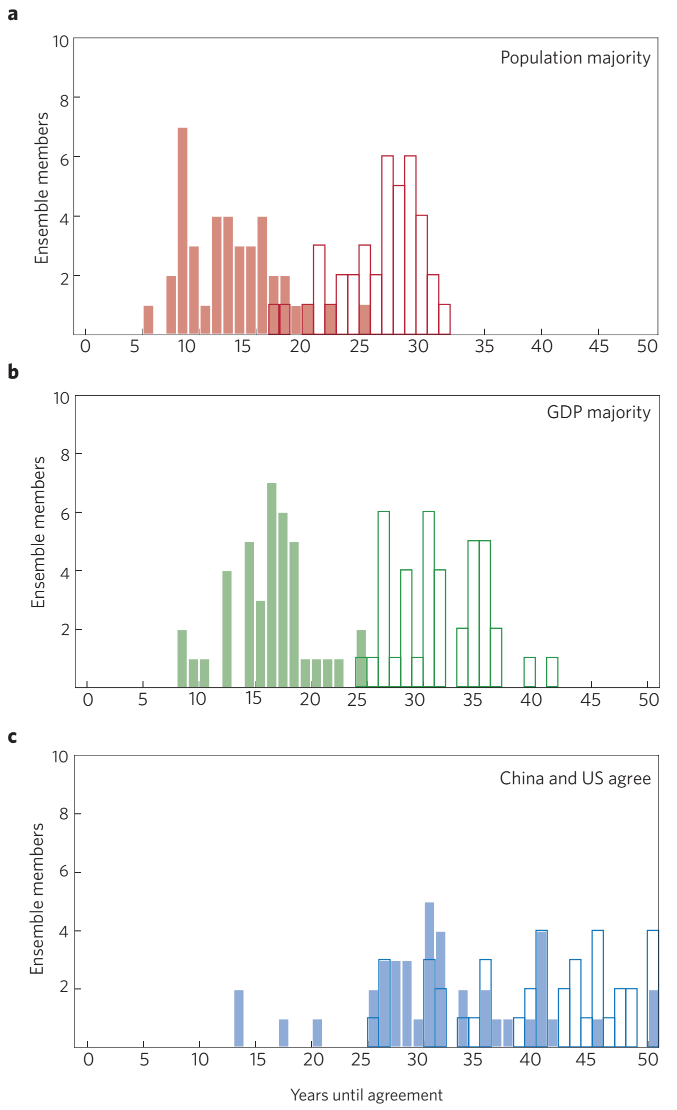

Figure 3 | Years until an international agreement is reached by world power scheme and policy approach. Histograms of years until **a**, countries representing more than 50% of world population have agreed to take action, **b**, countries representing more than 50% of world GDP have agreed to take action, and **c**, both China and the US have agreed to take action. Empty bars illustrate results under the simultaneous consensus constraint and light, solid bars show results for the incremental consensus constraint. For the ensemble members shown by the rightmost bar in panel **c**, the criterion for agreement is never met.

than under the incremental consensus constraint (light, solid bars in Fig. 3). Even if national-scale commitments are not effective at reducing emissions, but only effective at maintaining national support for eventual emissions reductions, such commitments serve to reduce long-term risk if they ratchet open an international policy window. The median 'ratcheting effect' of national policies is a decade or more reduction of the years-until-agreement under all international power schemes.

Impacts of a global outlook

The more inequitable the world power scheme, the larger the influence of natural variability. If an agreement is reached when countries representing more than 50% of the world's population reach their time-to-action (Fig. 3a), then agreement is reached, on average five years sooner than when countries representing more than 50%

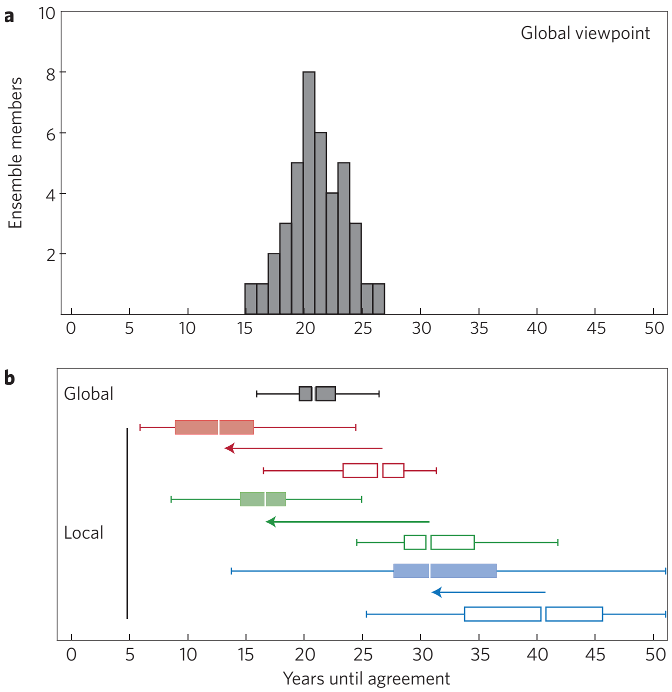

Figure 4 | Years until an international agreement is reached by worldview, power scheme and policy approach. a, Histogram of the years until an international agreement is reached if citizens weight the experiences of all mankind equally. **b**, Box-and-whiskers for all three power schemes and policy processes (colours as in Fig. 3) in comparison with the global result (black). Arrows illustrate the 'ratcheting effect' of an incremental international policy process.

of the world GDP reach their time-to-action (Fig. 3b). Few think that an international coalition will be both effective and viable without the participation of the United States and China. The timescale for an agreement in which both China and the US have passed the threshold is more uncertain, and more than a decade longer, on average, than other more inclusive schemes (Fig. 3c).

One might imagine that decisions based on global perspective, rather than on local conditions, would shorten timescales for policy action. When policy enactments are based on not only how convincing weather is locally, but how convincing it is if citizens adopted a global viewpoint (caring equally about the weather each person on Earth is experiencing) then timescales associated with all power schemes and both institutional constraints converge to the same distribution (that is, distributions in Fig. 3a–c all converge to that in Fig. 4a). If simultaneous consensus is necessary to achieve effective global emissions reductions, a global perspective will always reduce both uncertainty and the number of years until agreement (Fig. 4b, bordered box-and-whiskers). However, in a world with policy-window-ratcheting, an emphasis on global-scale impacts may have a mixed effect. Uncertainty is still always reduced, but not necessarily the timescales for international agreement.

Effective international climate change mitigation policy will continue to be difficult to enact without the participation of powerful large emitters such as the US and China. If effective international policy cannot occur before the US and China both agree, then increasing the global awareness and global mindedness of citizens in these countries will decrease years-until-agreement (blue versus solid black in Fig. 4b) regardless of the policy process. This result is contingent on the climatology in the climate model used (in which China and the US are empirically less at risk of heat extremes than many other countries and regions). However, under the more equitable international decision making regimes with an incremental international policy process, sensitivity to local extremes has some potential utility in decreasing the amount of time needed to reach international agreement (solid red and green versus solid black in Fig. 4b).

Risks when weather influences policy

Our model demonstrates risks presented by allowing local weather to drive policy. However, we counsel against reading too much into our precise quantitative analysis. As with many simple models of complex systems, the one we present omits many significant components of the system for the sake of mechanistic transparency. Our model represents naive views of human psychology and national and international politics. We aim to illustrate the large potential influence that natural variability has on policy when support for policies is contingent on local phenomena. Our analysis is not intended to provide quantitative predictions for the range of times to international agreement on emissions abatement. The social tipping points that we explore, while qualitatively supported by the behavioural science literature, are quantitatively arbitrary.

One could imagine any number of different events, trends or conditions that trigger public support for emissions abatement and other climate risk mitigation policies. While we use extremely hot weather in our illustrative example, extreme precipitation events undoubtedly play a role in people's perceptions as well. Our model assumes a common baseline for all nations, but contemporary public concern about climate change and public support for policy actions vary considerably from country to country[37]. In reality, the population of each country has its own set of social and cultural conditions that would cause them to respond differentially to extreme weather events[38–40].

It is well documented that a 'focusing event', such as an extreme weather event, is not in itself a guarantee that a policy window will open, nor is the opening of a policy window a guarantee for a policy's enactment[18,19]. Other political, institutional and social factors, unrelated to recent extreme weather events, will play significant roles in determining whether climate change mitigation policies are adopted in the future. For example, focusing events may not lead to policy changes if minority interests are strong enough to stop or substantially weaken action.

In addition, even if such focusing events do provide impetus for policy change, such policies may not be focused on mitigation, but could be targeted towards other types of risk reduction, such as adaptation. For small nations convinced to take action sooner than the rest of the world, the direct local benefits of adaptation may well make it the more appealing investment.

Despite these caveats, our example illustrates several robust results. First, natural variability in the climate system may affect the time to reach an effective global agreement to reduce greenhouse gas emissions by decades. Second, more highly concentrated power results in an increase in policy uncertainty caused by climate variability, because concentrated power places a lot of weight on extreme weather events occurring in a relatively limited spatial domain. The more wealthy and powerful countries tend to be in the middle to high latitudes where the signal of climate change is more difficult to detect, whereas many of the most populous countries are located closer to the equator where the signal of climate change is easier to detect against the background natural variability. Scenarios in which more power is held by people in the richest countries take longer to reach global agreement for action on climate change.

Finally, inasmuch as local extremes can result in the adoption of enduring national policies, decisions that are based on local conditions do not necessarily extend the timescale for effective international action. While basing risk mitigation policies on global conditions rather than on local ones always reduces variability-driven uncertainty, timescales for international agreements may well be increased. If policies are adopted at a national scale when salient, the policy window for international action is incrementally propped open as more nations build the institutions required for eventual emissions reductions. Even if national policies are not implemented effectively until an international quorum is reached, their existence reduces both the time until an agreement is reached and the variability-driven uncertainty in the timescale. On the other hand, if large countries that are convinced to act early pursue an incremental consensus and actually implement emissions reduction policies, this could create a feedback that further delays the policy window of the remaining nations.

It does little good to recommend an international policy process that gives equal weight to all countries if such a process is incompatible with international political reality — however, encouraging policy entrepreneurs to push through national-level policies that commit countries to implementing emissions reductions after some international quorum is met will reduce long-term risk without forcing countries to lose out to free-riders.

The component of local change that is driven by natural variability results in a broad range of timescales for policy outcomes, even in the face of well-constrained projections for global-mean change (Supplementary Fig. 7). In our example, variability in local weather results in decades of variation in the projected time required to achieve international agreement. Several decades of delay can mean several more decades of expansion of a CO_2-emitting energy infrastructure, paralleled by an increase in greenhouse gas emissions. Thus, delays of just a few decades in reaching an agreement can have a profound influence on future atmospheric greenhouse gas concentrations and climate[41]. The effects of near-term climate variability, interacting with nonlinear social systems, can therefore have important consequences for long-term risks associated with 'dangerous interference in the climate system'.

Long-term outcomes under all ensemble members are similar; within fifty years nearly everyone will experience extreme weather. However, the time until a majority of people in each country experiences enough extreme weather to convince them to pay for strong risk mitigation policies is influenced by stochastic elements — and in some cases, this natural variability can delay action by decades. Policy responses based on sound science, rather than local experience, would lead to more predictable outcomes and would be more effective at reducing long-term risk of climate damage associated with variability-driven delay in policy enactment. In any democratic society, public opinion will influence the political viability of a policy and, thus, political agenda setting. It may be tempting to wait for nature to take its course before making the large investments required to transform our energy system, but there are great risks in allowing local weather to drive national and global climate policies.

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Author Contributions

Both authors contributed to the design of the study. K.L.R. conducted the data analyses. Both authors contributed to writing the manuscript.

Additional Information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K. L. R.

Competing financial interests

The authors declare no competing financial interests.