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Journal
ENVIRONMENTAL RESEARCH LETTERS, 21(15)

ISSN
1748-9326

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Publication Date
2026-08-14

DOI
10.1088/1748-9326/ae8f5a

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To cite this article: James G Larson *et al* 2026 *Environ. Res. Lett.* **21** 154031

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ACCEPTED FOR PUBLICATION
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PUBLISHED
6 August 2026

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LETTER

Climate variability introduces uncertainty into future emissions pathways

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Keywords: future emissions pathways, climate-society interactions, climate-society modeling

Supplementary material for this article is available online

Abstract

Uncertainty in long-term climate outcomes arises not only from physical processes but also from societal responses to climate variability and change. Here we embed a range of temperature anomalies into an empirically-informed, coupled climate–social model to investigate how natural temperature variability, through its influence on societal decision-making, shapes global emissions trajectories. Using Monte Carlo ensembles spanning social, political, and technological parameters, we find that anomalous mid-century warmth strengthens public support for mitigation and accelerates the timing of net-zero emissions by several years, whereas anomalous cooling delays net-zero achievement. The response scales with the magnitude and persistence of variability with stronger and longer-lasting temperature anomalies producing larger shifts in mitigation timing. Across ensembles, high-variability climates are associated with higher emissions pathways and a greater likelihood of failing to reach net zero by 2100. Externally forced cooling events, such as volcanic eruptions, produce sharp impacts, delaying net zero by nearly a decade through temporary declines in public support for climate mitigation. These findings reveal that climate variability can cascade through perception, politics, and technology adoption to alter the pace of global mitigation, highlighting the sensitivity of emissions pathways to short-term climate signals and the role of societal interpretation of those signals.

1. Introduction

The magnitude of global warming is the dominant determinant of future climate risks such as heat extremes, severe storms, and sea level rise [1]. Differences in end-of-century warming translate into divergent societal outcomes, ranging from manageable adaptation challenges to unprecedented economic and ecological damages [1, 2]. The largest source of uncertainty in long-term climate projections is not from the physical climate system itself, but rather from the future trajectory of anthropogenic greenhouse gas emissions [3, 4]. Anticipating these trajectories is profoundly challenging. Emissions are not determined by a single driver, but by the intersection of multiple domains such as economic growth, patterns of energy production and land use, technological change, political institutions, and human behavior [5, 6]. Each of these domains is complex in its own right, but when coupled together they create nonlinear feedbacks, tipping points, and path dependencies that resist simple prediction [7]. Understanding these dynamics is essential for anticipating the levels of greenhouse gas emissions that will shape the planet's future climate.

Most long-term emissions scenarios are generated by integrated assessment models, which link economic activity, energy systems, land use, and social behaviors to greenhouse gas emissions [5]. These scenarios provide the inputs that Earth system models use to simulate climate outcomes, forming the backbone of assessments by the Intergovernmental Panel on Climate Change (IPCC) and others [8, 9]. Yet this approach typically treats emissions as fixed

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inputs [5, 10], neglecting the possibility that the climate itself, through its variability and impacts, feeds back on public opinion and political action [10–12]. In doing so, it leaves unexplored how climate signals might accelerate or delay the societal momentum needed for mitigation.

A growing body of social science evidence suggests that this omission is consequential [11, 13]. Extreme weather events and short-term climate anomalies can shape public concern and political support for climate action [14, 15]. Some studies link heat waves, droughts, or wildfires to heightened concern and increased support for pro-environment candidates [13, 16]. Effects often depend on social context: perceptions are filtered through ideology, prior beliefs, and local political conditions, leading to heterogeneous societal responses [16, 17]. This indicates that climate anomalies can, under certain conditions, open so-called 'windows of opportunity' for catalyzing policy action [18].

At the same time, the physical climate system is highly variable. Internally generated fluctuations such as the El Niño–Southern Oscillation, decadal modes of variability, and externally forced events like volcanic eruptions can amplify or mask long-term warming trends [19, 20]. Such variability not only affects physical impacts but may alter societal perceptions of climate change and collective willingness to cut emissions [21, 22]. When climate trends appear to pause or reverse, even briefly, they may foster public narratives that climate change has slowed or that policies are succeeding prematurely. For example, the 'global warming hiatus' of the early 2000s illustrates this effect: despite continued greenhouse gas accumulation, a temporary slowdown in global surface warming was widely interpreted as evidence that climate change had paused. This interpretation was amplified in media coverage and political discourse, giving traction to arguments that questioned the urgency of mitigation [23, 24].

The converse dynamic may also hold. Whereas a temporary slowdown can erode perceived urgency, the record warmth of 2023 and 2024, together with emerging evidence that the rate of global warming has accelerated over the past decade [25], could heighten public concern and strengthen support for mitigation. This expectation is consistent with evidence that record-breaking heat shapes how people perceive temperature [26] and that attributing extreme weather to climate change predicts greater support for climate policies [27]. Together, these findings suggest that departures from expected climatic conditions can influence public perceptions of climate change and shift support for mitigation [14, 28].

Recent modeling and empirical works highlight the need to more explicitly integrate socio-climatic feedbacks into our understanding of emissions pathways. Ricke and Caldeira [11] showed with an illustrative model that climate variability can delay the 'time-to-action' for policy adoption by decades, emphasizing the role of stochastic signals. Beckage *et al* [7] demonstrated that behavioral feedbacks can shift end-of-century warming outcomes by several degrees, while Otto *et al* [6] identified social tipping elements that may accelerate mitigation. More recently, Moore *et al* [10] embedded social, political, and technological dynamics into a coupled model, showing how divergent realizations of these feedbacks can produce global futures ranging from 1.8 °C to 3.6 °C warming. Together, these strands of research underscore that societal and climatic processes when filtered through perceptions of variability, attribution, and political context can amplify or dampen climate outcomes via altered emissions pathways of magnitudes comparable to geophysical feedbacks.

Here we build on this body of work to ask how natural climate variability may shape modeled emissions pathways through social and political feedbacks. Specifically, we investigate: whether variability in temperature anomalies influences mitigation trajectories; how the impact depends on the timescale of variability, from annual to decadal; and how a period of externally forced cooling, such as that induced by volcanic activity, might alter motivation to cut emissions. By embedding a range of temperature variability into a coupled climate–social model, we assess how climate fluctuations can cascade through opinion and policy to affect the long-term path toward net-zero emissions.

2. Methods

2.1. Coupled climate–social model framework

To investigate the influence of natural climate variability on future emissions pathways, we use the coupled climate–social model developed by Moore *et al* [10], which integrates social, political, technological, and climatic processes into a single dynamical system. The model represents feedbacks among six primary components: cognition, opinion, adoption, policy, emissions, and climate (figure 1). Greenhouse gas emissions determine the forced climate response, which contributes to global mean temperature change. In parallel, natural climate variability is prescribed as an exogenous, temperature anomaly sequence. These temperature signals feed into individual cognition, which shapes the distribution of public opinion and support for climate policy (figure 1). Changes in support affect political responsiveness and the pace of technology deployment, which in turn alter emissions trajectories. The pathway linking temperature variability to future emissions is the focus of this study and is highlighted by bold arrows in figure 1.

Interactions among model components occur through temporally lagged feedbacks that introduce inertia and nonlinear dynamics. Changes in perceived

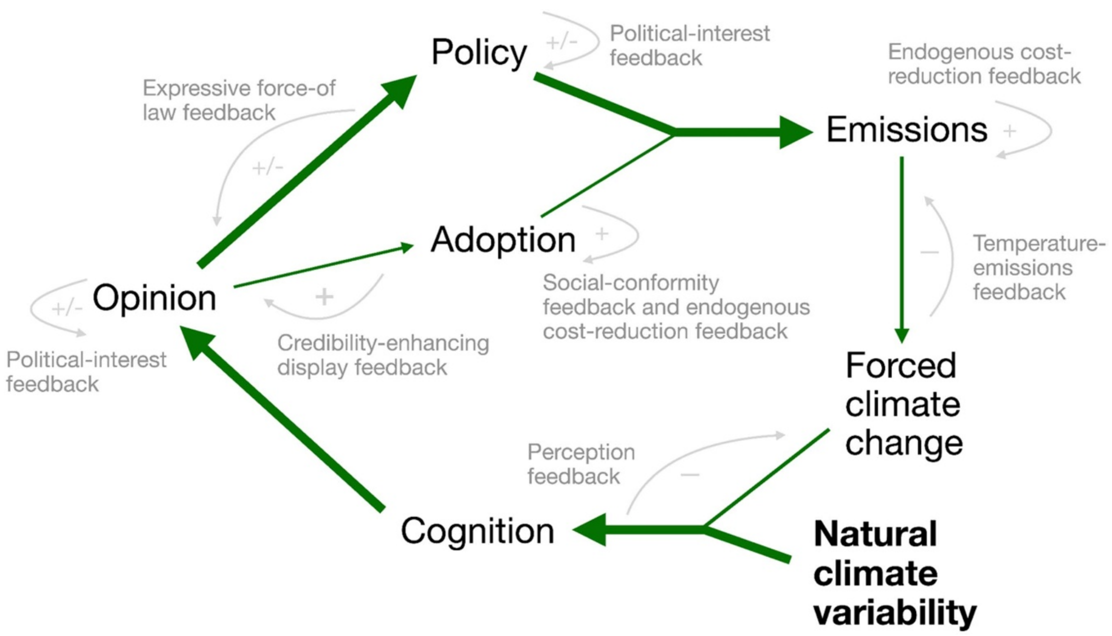

Figure 1. Diagram of the integrated climate–social system, highlighting the pathway from natural climate variability to global annual emissions. Adapted from Moore *et al* [10]. Main modules are shown in black and feedback processes in grey. Bold text and arrows emphasize the pathway examined in this study, linking temperature variability to emissions through cognition, opinion, and policy dynamics.

climate signals influence opinion only gradually through social persuasion, motivated reasoning, and shifting baselines, meaning that the effect of a temperature anomaly on policy support may unfold over multiple years. Policy responses are further moderated by institutional status quo bias, which requires sufficiently large opinion majorities before policy adjusts and slows the rate at which policy responds before thresholds are crossed. Additional delays arise in the emissions module, where mitigation driven by policy produces persistent but gradually decaying emissions reductions as energy infrastructure and technologies turn over. Together, these lags allow short-lived climate signals to propagate through the system in nonlinear ways, producing delayed or amplified responses across cognition, opinion, policy, and emissions.

Within the cognition component, perceived temperature anomalies are calculated relative to either a fixed historical reference or a shifting baseline defined by a weighted average of the previous eight years of temperatures, capturing the tendency for recent conditions to reset what is considered 'normal' [29]. The cognition module therefore reflects two competing mechanisms: the emergence of a climate-change signal from rising temperatures and the obscuration of that signal by natural temperature variability. It is not known *a priori* which mechanism dominates, over what timescales, or how persistent its effects may be once downstream policy and technology feedbacks are activated.

Perceived temperature anomalies influence support for climate policy, with asymmetric effects across opinion groups governed by a bias-assimilation parameter. This reflects evidence that individuals tend to place greater weight on information consistent with their prior beliefs, meaning that warm anomalies are overweighted by supporters and underweighted by opponents of climate policy, with the reverse occurring for cool anomalies [28]. Acting together, these cognitive filters mean that transient cool excursions can dampen pro-policy support and reinforce the status quo. Through the model's coupled feedbacks, these shifts in opinion can delay policy adoption and the development of energy-system technologies, potentially producing long-term effects on climate outcomes.

2.2. Monte Carlo ensemble design

The Monte Carlo ensemble method provides the basis for our analysis. By sampling parameter values across a range of empirically informed distributions, we generate large sets of plausible futures that span uncertainty in social, political, and technological processes. We conduct several Monte Carlo experiments that differ in how natural variability is generated and prescribed to the model. These experiments are described in the sections that follow and summarized in supplementary table S1. In each experiment, runs propagate their prescribed temperature variability through the cognition–opinion–policy loop, yielding annual time series of emissions, temperature, and opinion group distributions. This approach enables us to analyze distributions of outcomes rather than single trajectories without having to rely on the potential shortcomings of any single parameterization.

Parameter ranges follow Moore *et al* [10], where model parameters were informed by published empirical estimates from the psychology, political science, and energy systems literature where available, and further evaluated through hindcasting exercises. In these exercises, Monte Carlo simulations of the opinion and policy modules were compared with observed time series of public opinion and carbon prices across several OECD countries. Parameter combinations that better reproduced these historical patterns were given greater weight, partially constraining the model parameter space.

We introduce one modification to the initialization of public opinion. The original model calibrated the initial share of climate policy supporters to Pew Research Center survey data, yielding a strong pro-policy majority of 71%. Pulling on a range of current global estimates of support for climate policy [30–32], we modify the initialization to instead draw the initial supporter fraction from a truncated skew-normal distribution centered on 0.5 (i.e. 50% policy support, see supplemental figure 2). This allows some realizations to begin with pro-policy majorities and others with oppositional majorities.

2.3. Construction of natural temperature variability

We consider three distinct approaches to prescribing natural temperature variability. Across all experiments, variability sequences are pre-generated and exogenous to emissions decisions within each run.

2.3.1. Spectrally generated global variability

In baseline experiments, the default temperature variability scheme is used, where annual global mean temperature anomalies are generated by a stochastic process designed to preserve the frequency structure of Earth's natural climate oscillations [10, 33]. Specifically, the random temperature time series are constructed by matching the spectral decomposition of 1500 years of pre-industrial global mean temperature from the Last Millennium Reanalysis (LMR) [34], a paleoclimate reconstruction that assimilates proxy records to estimate global temperature over the past two millennia. The resulting sequences are zero-mean and temporally autocorrelated, ensuring that variability contains realistic persistence without being influenced by transient emissions within the simulation.

2.3.2. Local variability from CESM pre-industrial control

To represent geographically heterogeneous climate signals from around the world, we replace the stochastic generator with temperature anomaly time series sampled directly from a high-resolution pre-industrial control simulation of the Community Earth System Model (CESM) [35, 36]. We use the Understanding the Role of MESoscale Atmosphere-Ocean Interactions in Seasonal-to-Decadal CLImate Prediction (MESACLIP) configuration of CESM version 1.3, run at a nominal 0.25° horizontal resolution in the atmosphere and land and 0.1° in the ocean and sea ice [36, 37]. At these resolutions, the model broadly reproduces the observed amplitude of the El Niño–Southern Oscillation and improves the representation of the Pacific decadal oscillation and Atlantic multidecadal variability relative to standard-resolution configurations [36]. We sample land grid cells globally using latitude weighting and extract 81 year segments of annual 2-meter temperature anomalies, corresponding to the 2020–2100 period of the coupled climate–social simulations.

2.3.3. Volcanic variability from CESM last millennium

To examine externally forced cooling events, we draw 81 year segments of annual 2-meter temperature anomalies from across the CESM Last Millennium Ensemble (LME) [38]. The LME uses CESM version 1.1 at a nominal 2° resolution in the atmosphere and land and 1° in the ocean and sea ice, and prescribes transient last-millennium forcings, including volcanic aerosols derived from ice-core reconstructions. We draw from the volcanic-forced ensemble members, selecting segments so that the cooling associated with the 1815 Tambora eruption occurs in model year 2030. The simulated 2-meter global cooling anomaly over land from Tambora peaked at about 1 °C (supplemental figure 3). This experiment allows us to evaluate abrupt, short-lived cooling shocks embedded within the coupled social–climate system.

3. Results

We begin with a hypothetical future scenario: what if natural temperature variability in 2025–2034 led to especially warm or cool global conditions? How might these temperature anomalies lead to downstream impacts on support for climate policy and emissions trajectories? This recalls the 'climate hiatus' of the early 2000s, which was widely used to question the reality of global warming [23, 24]. To test this concept, we compute each run's mean prescribed temperature anomaly over 2025–2034, rank all runs by this decadal-average value, and group them into deciles. We then compare the hottest and coldest deciles against the median fraction of climate-policy supporters (figure 2(a)) and the median emissions pathway (figure 2(b)). Here, the underlying Monte Carlo ensemble utilizes the default temperature variability scheme, as described in Methods 2.3.1.

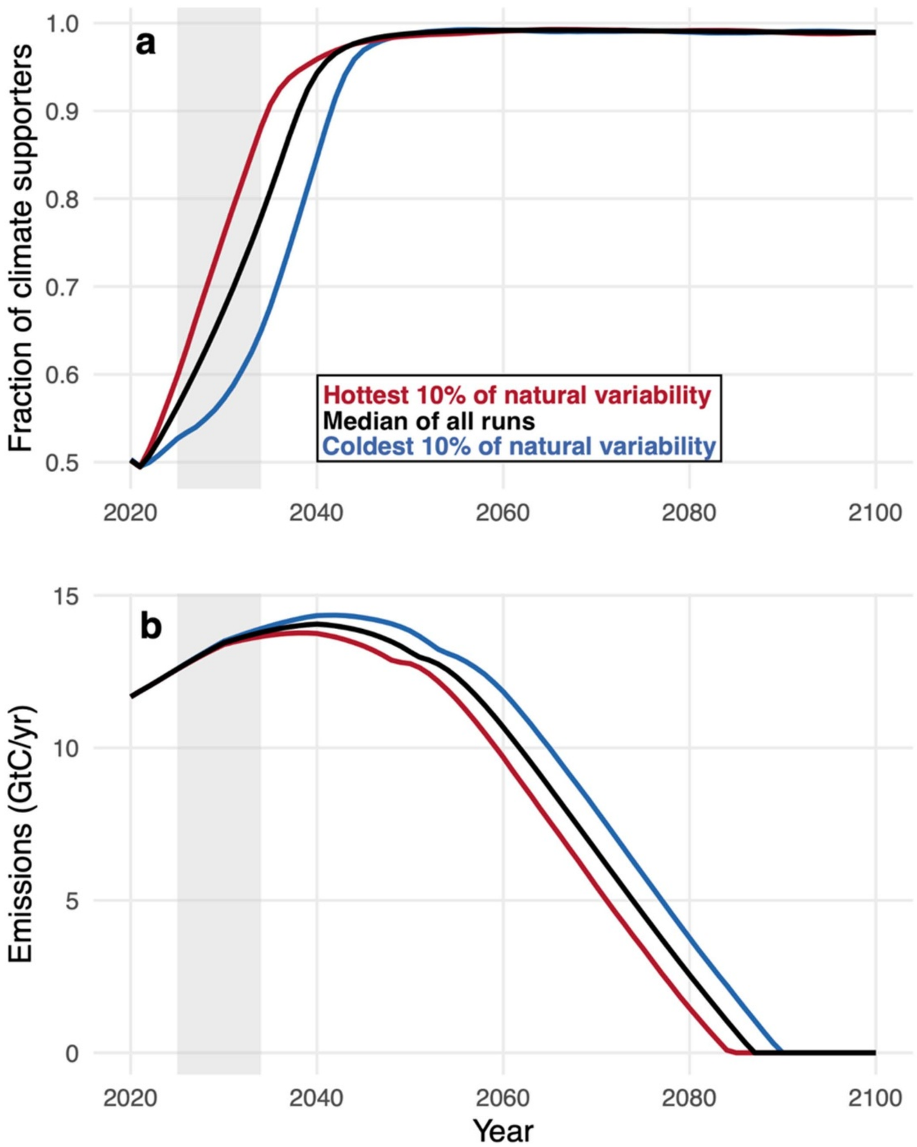

Figure 2. The coldest and hottest decadal temperature variability influences support for climate mitigation and median emissions pathways. Two-panel comparison of median trajectories from the Monte Carlo ensemble: (a) fraction of the population supporting climate policy and (b) annual carbon emissions (GtC yr^{-1}). Lines show medians for the coldest 10% (blue) and hottest 10% of runs (red) by average natural temperature variability in 2025–2034 and the median of all runs (black). The shaded band marks the 2025–2034 window over which the natural temperature variability used to define the hottest and coldest deciles is averaged.

Deviations in the fraction of climate policy supporters emerge quickly in the 2020s, with hot temperatures raising support for climate action and cold temperatures reducing it (figure 2(a)). Nearing 2040, the cold and hot deciles converge toward stable pro-policy majorities. Emissions show a similar, albeit delayed behavior, with hotter temperatures leading to an accelerated decline in global emissions. After about 2045, the emissions pathways remain parallel until they eventually reach net zero. The overall impact is a timing shift in the achievement of net-zero emissions by about ± 3 years relative to the ensemble median: earlier for 'hot-2030s,' later for 'cold-2030s' (figure 2(b)). These outcomes illustrate how temporary temperature excursions can have a long-term, persistent effect on emissions trajectories by influencing path-dependent, coupled feedbacks operating through public opinion, policy, and the energy system.

To generalize beyond single scenarios, we systematically explore the magnitude and persistence of temperature variability. We bin simulations by the mean temperature anomaly over windows ranging from 1 to 20 years, with each window beginning in 2025. This range of window sizes spans variability timescales from interannual to multi-decadal fluctuations. For each bin we calculate the median emissions trajectory and record the year it achieved net-zero. As before, the underlying Monte Carlo ensemble for this analysis utilizes the default temperature variability scheme, as described in section 2.3.1.

The resulting heatmap (figure 3) reveals a pattern consistent with figure 2(b), that warm anomalies lead to a more rapid achievement of net-zero

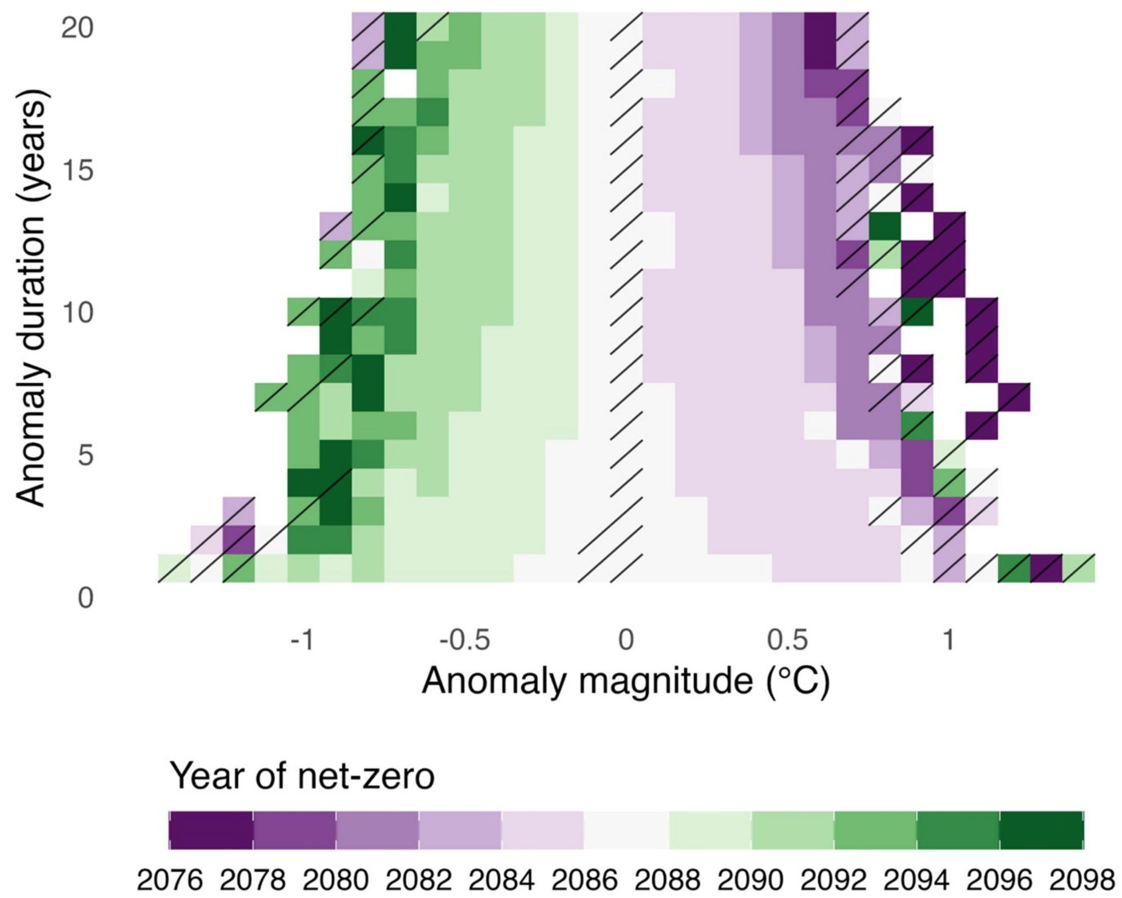

Figure 3. The year of achievement of net-zero emissions depends on the severity and duration of temperature anomalies. Median year of net-zero emissions as a function of the average magnitude and duration of natural temperature variability across the Monte Carlo ensemble (see Methods). The color scale is centered on 2087, the year the median trajectory for all runs first reaches net-zero, and runs from earlier net-zero years (purple) to later ones (green). Hatching marks bins whose difference from the ensemble median is not statistically significant ($p > 0.01$, Mann–Whitney U test). Blank bins contain too few runs for a reliable median.

emissions, while cool anomalies delay. The size of this shift depends on both the duration and magnitude of the temperature anomaly, with stronger and longer-lasting anomalies leading to a greater shift. Cold temperature anomalies exert a somewhat stronger influence on emissions trajectories, with some anomalies nudging the net-zero achievement year by up to two more years than hot anomalies of similar duration and magnitude. This asymmetry partly reflects model mechanics, where support for climate policy tends to rise over time due to a warming climate, leaving limited headroom for additional acceleration during warm periods, while cooling can still erode support and slow policy.

Most bins differ significantly from the ensemble median. Non-significant bins ($p > 0.01$; Methods) are hatched and occur mainly near zero magnitude anomalies or along the figure edges where sample sizes are small due to the rarity of temperature extremes. The significance hatching in figure 3 is determined as follows: for each magnitude–duration bin we compute the per-run 'year of net-zero', defined as the first year an individual run's annual emissions reaches net-zero emissions. We then test whether the distribution of net zero years in that bin differs from the distribution across the full ensemble using a Mann–Whitney U test, also known as a two-sided Wilcoxon rank-sum test [39, 40]. Runs that do not reach net zero by 2100 are excluded.

So far, our analysis has treated variability in terms of global mean temperature. In reality, individuals do not experience the global mean, rather they feel local temperature variability which is not uniform across regions. Tropical regions exhibit relatively little year-to-year fluctuation, whereas the mid-latitudes and poles experience larger swings. To capture a broader range of signals, we replace the temperature anomaly generator in Moore *et al* [10] with draws of temperature anomalies from a high-resolution version of CESM, capturing climate variability from around the world, which we then propagate through a new Monte Carlo ensemble (see Methods 2.3.2).

To assess how long-term variability influences mitigation outcomes, we bin simulations by the standard deviation of their temperature anomalies over the full run and plot the corresponding median emissions trajectories (figure 4). Median trajectories demonstrate that persistently elevated emissions and

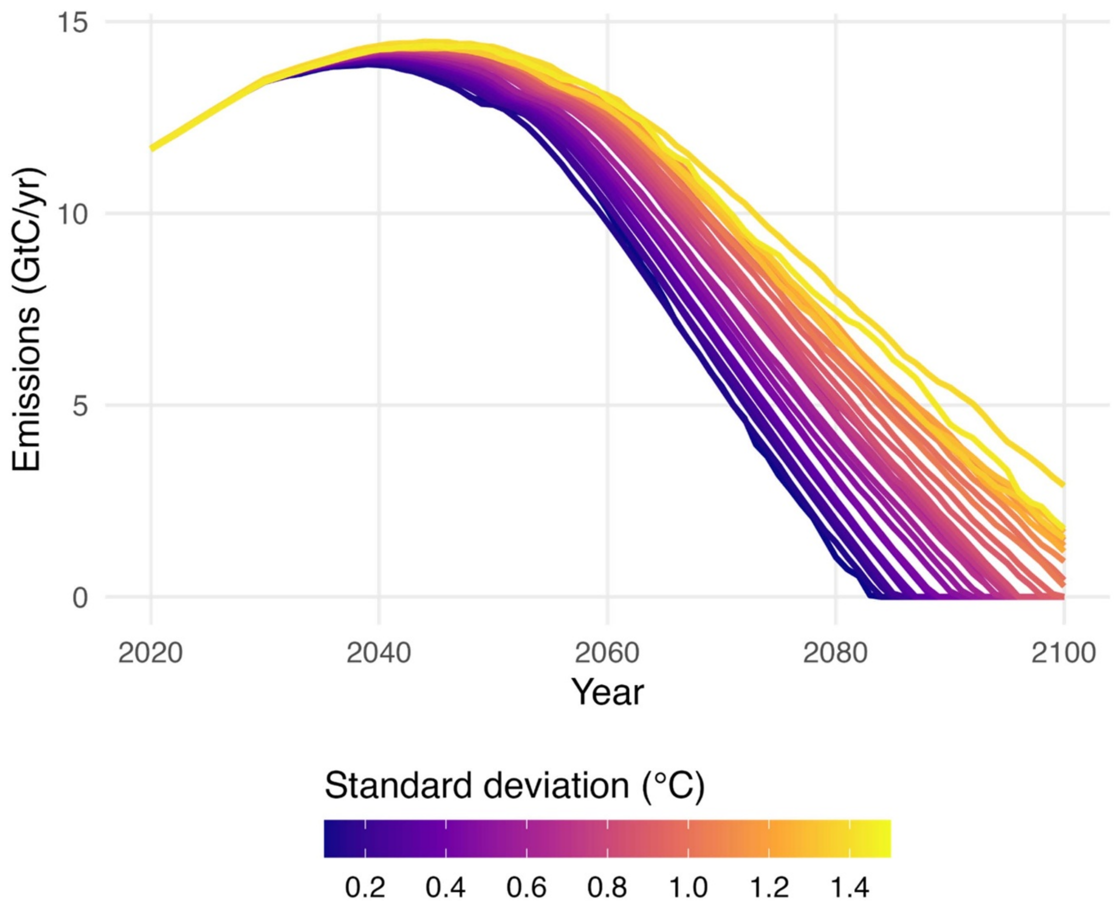

Figure 4. Large temperature variability can mask warming due to climate change, delaying climate mitigation action. Median emissions trajectories (GtC yr^{-1}) for Monte Carlo runs binned by the standard deviation (°C) of each run's full natural temperature variability time series. Each line shows the median emissions across runs within each bin; the color indicates the bin center. The natural variability of the underlying Monte Carlo ensemble comes from land-based, gridpoint 2-meter temperature anomalies sampled from a high-resolution pre-industrial control simulation of CESM (see Methods).

slower approaches to net zero are associated with higher temperature variability, whereas faster mitigation pathways are associated with lower variability. In the model, larger temperature variability produces more frequent cool deviations around the warming trend. When filtered through the shifting-baseline and motivated-reasoning components of the cognition and opinion modules, these cool excursions dampen support for climate policy. Reduced support slows policy-driven technology deployment and the associated learning-by-doing in the mitigation system, reinforcing the status quo. In contrast, smoother climates with fewer cool excursions sustain stronger support and faster emissions reductions. Notably, a substantial share of runs in the higher-variability bins do not achieve net zero by 2100, underscoring that variability can prevent decarbonization within the century.

Volcanic eruptions represent some of the most powerful perturbations to the climate system, producing sharp and temporary global cooling through the injection of reflective aerosols into the stratosphere which decrease the amount of sunlight reaching the Earth's surface. For example, the 1815 eruption of Mount Tambora produced the 'Year Without a Summer,' inducing widespread crop failures, food shortages, and social disruption across Europe, Asia, and North America [41, 42]. Motivated by these historical records, we test how externally forced cooling events might propagate through this coupled climate–social system, shaping public opinion, policy momentum, and ultimately emissions trajectories. We conduct a Monte Carlo ensemble driven by temperature anomalies sampled from the CESM Last Millennium simulations [38], which include representations of volcanic eruptions of varying magnitudes. We focus in particular on cooling anomalies attributed to the Tambora eruption, which we impose in the model year 2030 (see Methods), to assess its influence on mitigation dynamics.

The eruption produces a sharp decline in support for climate policy, with public backing requiring roughly five years to recover to pre-eruption levels (figure 5(a)). Additional eruptions in the ensemble, occurring in model years 2023, 2046, and 2098 (supplementary figure 3), generate similar cooling responses and associated dips in support. Although support recovers as the cooling anomalies subside,

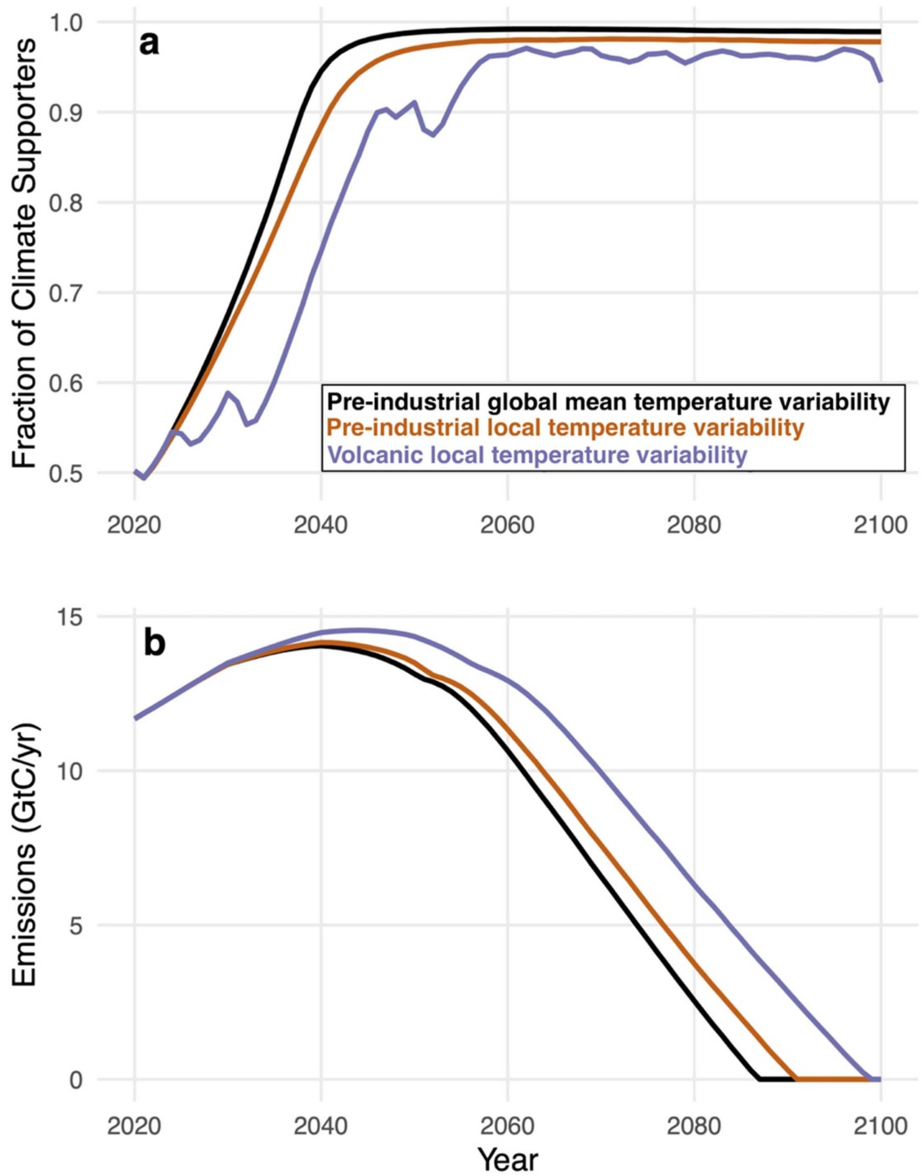

Figure 5. External cooling due to volcanoes causes sharp opinion drops and long-lived emissions delays. Two-panel comparison of median trajectories from three Monte Carlo ensembles of (top) median fraction of the population supporting climate policy and (bottom) median annual carbon emissions (GtC yr^{-1}). Lines show medians across runs for each dataset: pre-industrial global mean temperature variability (black), pre-industrial local temperature variability (orange), and volcanic local temperature variability (purple).

the median emissions remain elevated relative to non-volcanic experiments, and the achievement of net-zero is delayed by nearly a decade. These findings suggest that externally forced cooling events can generate a temporary loss of mitigation momentum in the cognition–opinion–policy pathway, leaving lasting imprints on long-term emissions outcomes.

4. Discussion

These conclusions extend earlier work by Ricke and Caldeira [11], who used an illustrative model to argue that local climate variability could delay the 'time-to-action' for nations by decades. Their model emphasized how people living in a stochastic world may hesitate to implement climate mitigation measures until local weather conditions cross thresholds. Our analysis confirms this insight but advances it in two important ways.

First, we examine these dynamics within a more fully coupled climate–social framework that explicitly represents interactions among public opinion, political institutions, and technological change [10]. In this framework, climate signals influence public perception, which alters support for climate policy and in turn affects policy enactment and technology deployment. These interactions occur through temporally lagged feedbacks that introduce inertia and nonlinear dynamics into the system. As a result, natural temperature anomalies can propagate through multiple modules of the model and generate deviations in emissions trajectories years down the road.

Second, rather than focusing on time-to-policy thresholds, our results evaluate how climate variability alters the trajectory and timing of mitigation itself, including the achievement of net-zero emissions. This metric directly connects social–climate feedbacks to long-term climate outcomes and enables comparison with emissions pathways produced by integrated assessment models. In this sense, temperature variability acts not just as a delay to policy adoption, but as a driver of mitigation pathways themselves. Reinforcing feedbacks and path dependencies in the model can amplify delays in policy adoption, leading to even larger cumulative effects in global emissions in this coupled system.

We emphasize that our findings should not be interpreted as predictions of specific emissions pathways. The Monte Carlo ensembles employed here are designed to probe underlying mechanisms and sensitivities, not to forecast the timing of policy change or net-zero achievement. The social module represents opinion and policy dynamics as globally uniform, abstracting away the substantial cultural, institutional, and political heterogeneity that shapes how different societies perceive and respond to climate signals. The model also uses temperature as the mediating variable between climate and society and does not represent the non-thermal impacts—such as floods, wildfires, ecosystem collapse, and storms—that in many cases catalyzes public attention and political action more so than gradual warming. While many of these indicators are connected to changes in global mean temperature, the relationship is neither simple nor uniform.

Together, these simplifications mean the effects we identify are mechanistic illustrations: they demonstrate that a plausible, empirically grounded pathway exists through which natural temperature variability can cascade into long-term emissions outcomes, not that specific timing shifts will materialize in the real world. The quantitative estimates of net-zero delay or acceleration should be read as indicative of the direction and order of magnitude of effects rather than as forecasts. Still, the consistent direction of results across ensembles and experimental designs offers an important qualitative insight: cool periods tend to dampen mitigation momentum, while warm periods accelerate it.

An important feature of our results is the asymmetric influence on emissions pathways between runs forced with high- and low-temperature variability. Simulations with muted variability, which are characteristic of tropical regions, achieve net-zero sooner while those with larger swings, typical of midlatitude climates, are delayed. This juxtaposition highlights a geographic discrepancy: regions with the least temperature variability, often in the Global South, are among the most vulnerable to climate impacts and contribute the least to global emissions [43, 44]. Conversely, geopolitically powerful, high-emitting nations at higher latitudes experience greater masking of the warming signal due to larger swings in temperature [19, 44], which in our model sustains opposition to climate policy and slows mitigation. This paradigm underscores how the global distribution of temperature variability intersects with the inequitable representation within climate governance, echoing concerns that those most exposed to clear climate signals are least empowered in global decision-making [45].

Our volcanic experiments underscore the role externally forced events may play. Even though the direct cooling from eruptions subsides within a few years, the coupled opinion–policy–technology system produces a lasting legacy: emissions remain higher for decades and net-zero is delayed by nearly ten years. This suggests that temporary disruptions, whether natural or externally forced, can have disproportionately long-lived consequences for mitigation trajectories. While the scenarios are hypothetical, they clarify how abrupt shocks can intersect with social and institutional dynamics to slow decarbonization. While we focus on volcanic forcing, future changes in anthropogenic aerosol emissions could similarly modulate near-term warming trends and societal perceptions of climate change, potentially affecting mitigation trajectories.

A limitation of this study concerns the fidelity and assumed stationarity of the prescribed natural variability, which we draw from a long pre-industrial control simulation of the CESM. While CESM is a state-of-the-art Earth system model that reproduces natural climate variability well, its representation is not perfect, and the character of its biases depends on the specific mode, timescale, and model in question [46]. If real-world variability differs meaningfully from what CESM produces, the effects we identify in figure 4 could differ in magnitude from our results. A second concern is stationarity: because we draw variability from pre-industrial control simulations and prescribe those sequences to future model years, we implicitly assume that the statistical properties of internal variability remain unchanged across the 21st century. Future work could address this assumption by sampling variability from transient future climate projections rather than pre-industrial controls.

Several extensions could build on this modeling framework. Incorporating regional and cultural heterogeneity into the social module would allow the coupled dynamics to vary across political and institutional contexts rather than operating through a single global population. Representing extreme weather and natural hazards such as floods, wildfires, and storms could capture drivers of public attention that temperature alone does not. Additionally, introducing more forms of human intervention in the climate system, such as intentional cooling through stratospheric aerosol injection, would broaden the range of questions this modeling framework can address. Together, such efforts would help move this class of coupled climate–social experiments from mechanistic illustration toward a more realistic representation of how a variable climate shapes the path to net-zero.

5. Conclusion

Our results demonstrate that natural climate variability can modulate the trajectory of global emissions in a coupled climate–social model. Periods of anomalous warmth accelerate the timing of net-zero by strengthening public support for mitigation, while anomalous cool periods delay it by reducing momentum. These effects are dependent on the character of the temperature variability, being influenced by the magnitude and persistence of anomalies, as well as by their timing and frequency of occurrence. Temperature anomalies due to externally forced cooling events, such as volcanic eruptions, reduce societal motivation to cut emissions, leaving lasting effects on modeled emissions pathways. Together, these findings highlight that natural fluctuations in the climate system can cascade through public perception, political processes, and technology adoption to alter the pace of global decarbonization by years to decades.

These findings point to the value of insulating climate policy from the weather and climatic fluctuations arising from natural variability. Communication strategies and governance institutions that emphasize long-term trajectories rather than short-term fluctuations are critical to maintaining steady progress. The key lesson is not that net zero will be reached earlier or later by a fixed number of years, but that variability introduces uncertainty into the emissions pathway itself.

Acknowledgments

J G L and P W K acknowledge funding support from Quadrature Climate Foundation.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/records/17716310#:~:text=10.5281/zenodo.17716309 [47].

Supplemental figures & table available at: https://doi.org/10.1088/1748-9326/ae8f5a/data1.

Code availability

Code to reproduce the analysis in this article is provided in an online repository: https://doi.org/10.5281/zenodo.17716309.

Conflict of interest

The authors declare no conflicts of interest.

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Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

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