Participating in a climate prediction market can increase concern about global warming

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Modifying attitudes and behaviors related to climate change is difficult, and attempts to offer information, appeal to values and norms, or enact policies have shown limited success. Here, we examine whether participation in a climate prediction market can shift attitudes by having the market act as a non-partisan arbiter of truth and by prompting participants to earn money based on their climate predictions. Across two field studies we show that betting on climate events alters participants' concern about climate change, support for remedial climate action, and knowledge about climate issues. While the effects were dependent on participants' betting performance in a highly polarized sample, they were independent of betting outcomes in a more moderate sample. Overall, our findings suggest that climate prediction markets could offer a promising path to changing people's climate-related attitudes and behavior across all levels of society.

The combined forces of social media and rise of populism have amplified the politicization of knowledge. What is considered true often depends on group membership rather than scientific evidence and facts[1–9]. This politicization is seen in numerous topics, including climate change. Overwhelming scientific evidence suggests that climate change is occurring[10], is caused by human activity[11], and is likely to result in dire consequences[12,13]. Nonetheless, actions of governments around the world lag behind what climate scientists say is needed. In some cases, this inaction is related to a lack of concern about climate change. For example, in the U.S., surveys show that over a third of the population believes that the seriousness of global warming is exaggerated[14,15], and more than half the population disagrees with the claim that climate change is caused by humans[16].

Raising concern about climate change and support for remedial action at the individual and collective level is challenging for numerous reasons. First, it is difficult to attribute a specific climate-related incident to a single cause. Second, remedial actions taken by one individual or collective often do not yield visible outcomes. Third, the cost of action is immediate whereas the benefits are distributed over long time horizons[17]. Specifically, while climate change will adversely impact future generations, for most people there is no immediate cost to rejecting its occurrence on ideological grounds[18]. Compounded by the brain's challenges in thinking about temporally- or spatially distant events[19,20], these factors make it difficult to change skeptics' views on the topic and garner support for corrective action.

However, acknowledging the role of erroneous beliefs that have no immediate cost offers a potential pathway to shifting people's climate-change related attitudes and behaviors: devise a mechanism to make maintaining false beliefs costly in the near-term. Research shows that people often behave in ways that contradict their stated beliefs when money is on the line[21]. For example,

climate skeptics publicly deny global warming but do not invest in geographic regions that will likely suffer from a rise in sea-levels[22]. Building on this, we suggest using climate prediction markets to shift attitudes towards the scientific consensus by increasing the cost of maintaining false beliefs. Simply, we encourage people to "put their money where their mouth is" by providing a financial reward (/penalty) for correct (/incorrect) predictions about soon-to-occur events that are impacted by global warming.

Traditionally, prediction markets have been implemented to crowd-source estimates about uncertain events in the future[23]. Those markets have been shown to accurately predict the outcomes of elections[24], reproducibility of scientific findings[25], spread of disease[26], or aggregation of group choices[27]. In the context of climate change, prediction markets have been suggested as a tool for aggregating views on policies[28] and as a way to provide credible signal about climate science[29–31]. However, there is no empirical evidence supporting the notion that betting on climate-related events can shift the extent to which people: 1) are concerned about the consequences of climate change, 2) support remedial action at the individual and collective level, and 3) are knowledgeable about climate topics.

Climate prediction markets

We introduce climate prediction markets as a novel intervention and report experimental findings on how participating in the markets influences people's concern about climate change, support for action, and climate change-related knowledge. Our prediction market offers individuals the opportunity to bet on future outcomes (i.e., "the average temperature in the Northern Hemisphere in the coming month will be higher than that in the equivalent time window over the last decade") and earn money if their predictions are proven right.

We implemented two different prediction markets across two field studies. In both studies participants engaged in a prediction market where they took positions on climate events over a period of several weeks and earned money based on their prediction accuracy. We term a particular prediction a "bet".

Betting topics were set by the experimenters and were released intermittently (between 1-3 days apart in Study 1 and daily in Study 2). The bets reflected both events that were dominant in the news (i.e., California wildfires, extreme heat waves, etc.) and events that were less salient to the average participant (i.e., Antarctic Sea ice extent, change in the Air Quality Index, etc.). All bets had settle date and time, and an unambiguous source for determining the outcome. For each bet, participants could decide whether they wanted to make a bet, which position to take (Yes or No), and how much money to wager.

We surveyed participants before (Pre-survey) and after (Post-survey) the period during which they engaged in the prediction market (**Fig. 1**). In both studies, we compared participants who engage in the climate prediction market to a control condition (Study 1: passive control group, Study 2: active control group that participated in a sports and entertainment prediction market prior to completing the exit survey). Comparisons with the control group allow us to account for changes that might occur naturally over time (e.g., natural variation in the salience of climate disasters which are known to impact people's attitudes about climate change[32]).

Study 1

We recruited participants using the online panel *Prolific Academic*. Participants were screened for climate beliefs (binary property: believer/skeptic) and U.S. nationality. Climate belief was defined as agreement (Yes/No) with the statement "Global warming refers to the idea that the world's average temperature has been increasing over the past 150 years and may be increasing more. Do you think that global warming is happening?" After excluding people who did not pass the attention checks, 143 participants were included in the study. Among those, 70 identified as climate change believers and 73 identified as climate change skeptics (see **supplementary table T5** for participants demographics, and **supplementary figure SI4** for the distribution of climate concerns among believers and skeptics). All participants completed two surveys, one at the beginning of the experiment (Pre-survey) and one at the conclusion of the prediction period (Post-survey). The surveys captured participants' concerns about climate change as well as variables such as demographics, political orientation, knowledge about climate and more (see **Methods** and **Supplementary Information** for details on the measures analyzed). Participants within the groups of believers and skeptics were randomly assigned to either the control (n=73) or treatment group (n=70). Each participant in the treatment group received $20 to fund their bets in the prediction market. During the prediction period participants made bets on future events (e.g., "The October average high monthly temperature in the Northern Hemisphere will exceed 20^{o}C as indicated by http://www.ncdc.noaa.gov on November 1, 2018, at 23:59 EST"; see **Supplementary Methods** for all bets). Because of the double-auction structure of the market (if one participant bet 55¢ that an event would occur, it only becomes a contract if another participant bets 45¢ that the event will not occur: see **Supplementary Methods** for details on the betting mechanism) not all bets turned into contracts. We analyzed bet offers as reflections of participants' willingness to take a position on topics. Study 1 had 4,737 interactions (stock offers, trades, etc.) with an average of 9.5 contracts/day).

Figure 1. Experimental design. **(a)** Participants first answered various questions about their

views on climate issues in a Pre-survey (see **supplementary tables T2, T4, T18,** and **T19** for survey questions). Afterwards, participants were divided into treatment (climate prediction market) and control (Study 1: no predictions, Study 2: sports/entertainment prediction market) groups. (**b)** Participants made bets continuously in a double-auction market (left), or daily (right). (**c)** Participants in Study 1 (**left**) took positions on climate bets with a price between 50¢ and 99¢ (a position less than 50¢ on a "Yes" equal to switching from "Yes" to "No" with a complementary position that is 100-30, or 70¢ on "No"). Participants in Study 2 (**right**) made one-sided bets with an amount ranging from 1-100¢. Following the prediction period, both treatment and control participants completed a Post-survey addressing climate issues as well as some assessments of their overall experience.

Participation in a climate prediction market increases concern about global warming conditional on performance

We first tested whether engaging in the climate prediction market had an impact on how concerned participants were about climate change. Specifically, we ran linear regressions to predict climate concern in the Post-survey from the experimental condition (0=control, 1=treatment), controlling for participants' concern in the Pre-survey. Contrary to our expectations, participating in the climate prediction market did not lead to an overall increase in climate concern compared to the control group (B=-0.005, SE(B)=0.015, β=-0.001, t=-0.04, p=00.976; **Fig. 2**; all results hold when using the difference between Pre- and Post-survey as the outcome).

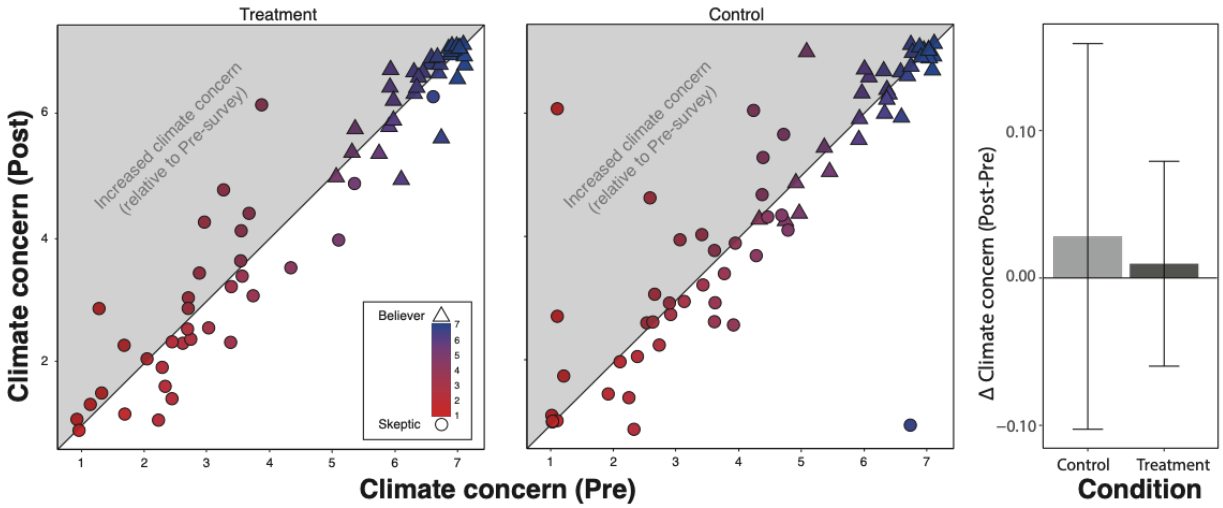

Figure 2. Distributions of climate beliefs before and after participating in the climate market. Taking the average of the three climate concern questions (**supplementary figure SI4**) we see that among the treatment (**left**) and control (**center**) groups there is no significant change in concerns following a month of waiting/betting (markers above the diagonal; shaded). Self-described believers and skeptics are marked by different symbols. Their group designation aligns with the reported answer to the survey questions with the majority of believers scattered at the top-right of the panels (see also **supplementary figure SI5**). Right panel depicts the average difference concern score among treatment and control conditions, between the Pre- and Post-surveys. Error bars depict standard errors.

However, exploratory analyses of the participants in the climate condition revealed a treatment effect conditional on participants' performance in the betting market. Specifically, we used the robust MM-type estimator[33] to regress the difference in concern between Post- and Pre-surveys (higher values indicate a shift towards more concern about climate change) onto two indicators of performance: 1) the number of bets won and 2) total earnings. The findings suggest that betting outcomes significantly and consistently predicted the change in concern (Number of bets won: B=0.007, SE(B)=0.003, t=2.44, p=0.017; Total earnings: B=0.01, SE(B)=0.005, t=2.37, p=0.021). That is, participants' concerns about climate change increased if they were accurate in their predictions but decreased when they were unsuccessful.

Finally, we tested whether the impact of the treatment varied between believers and skeptics. As before, we used the robust MM-type estimator to regress the difference in concern between Post- and Pre-surveys on the binary believer/skeptic variable. The results revealed a marginally significant effect (B=0.14, SE(B)=0.08, t=1.71, p=0.089) suggesting that the treatment was marginally more effective for believers than skeptics. However, the moderating effects of performance on concern were found to be equally strong for both believers and skeptics (B=0.001, SE(B)=0.01, t=0.11, p=0.911). That is, successful betting increased climate concern equally among both believers and skeptics.

To further explore participants' engagement with the climate prediction market, we tested for differences in betting behavior (confidence, defined as the distance from the neutral 50¢/50¢ value) and outcomes (bets won and total earnings; **Supplementary figure SI2**) between climate believers and skeptics using linear regression analyses with robust MM-type estimation.

Despite believers being among the highest earners in our market (with the top 11% of earners being believers), believers and skeptics did not significantly differ in the number of bets won (B=0.70, SE(B)=2.01, p=0.728) or the total earnings (B=1.44, SE(B)=1.33, p=0.282). However, the bets of believers indicated marginally higher levels of confidence (B=0.48, SE(B)=0.24, p=0.053; **Supplementary figure SI6**).

Taken together, Study 1 offers suggestive evidence that prediction markets can increase concern for climate change under certain conditions (i.e., successful betting). Despite the promising results, Study 1 also suffers from a number of limitations. First, by virtue of its reliance on a real-world double auction ("two-sided") market like the one seen in public exchanges, it is hard to isolate the treatment effects (i.e., participants may have placed bets that did not turn into contracts). Second, the decision to target only individuals with polarized positions made obtaining a shift in concern challenging since believers are already at the ceiling of climate concern, while skeptics are the hardest to shift. Third, the size of our participant pool size made it impossible to detect small effects that are common in behavior change research. Fourth, the fact that we opted for a passive control group that did not engage in any meaningful task during the prediction period prevented us from testing whether the effect of successful betting on concerns was uniquely related to climate predictions or the result of participants experiencing positive outcomes.

Study 2 overcomes these limitations by: 1) testing the effects in a controlled experimental setting, 2) focusing on people who are less extreme in their beliefs about climate change, 3) recruiting a

much larger sample, and 4) having an active control group that engaged in a non-climate prediction market.

Study 2

We recruited 1,005 participants using the online panel *Prolific Academic*. Participants who did not pass the attention checks or failed to meet all study criteria (see below) were excluded. A total of 664 participants completed the entire study and were included in the final analyses. The Pre- and Post-surveys measured participants' climate concern, support, and knowledge (see **Methods** for details on the measures). Between surveys, participants were randomly assigned to either a climate prediction market (n=356, treatment) or a sports and entertainment prediction market (n=308, control, see **Methods** and **Supplementary Information** for evidence that the randomization was successful in both the initial sample and the final analysis sample). Both prediction markets ran for a period of 35 days during which one new bet was posted daily. Upon logging into the prediction market, participants saw an overview of their betting profile (i.e., amount won thus far, number of bets placed) and were informed about the outcomes of previous bets. Participants then saw the daily bet along with a visual representation of historical trends (**Fig. 1c**). Participants were asked to decide whether to bet, which position to take, and how much money to wager. Each participant received $20 at the beginning of the study. Only participants who spent at least $10 and placed at least 15 bets throughout the prediction period were analyzed. In total, the 664 participants placed 10,384 bets (an average of 15.6 bets per person).

Participation in a climate prediction market increases concern about global warming

We first tested whether engaging in the climate prediction market had an impact on how concerned participants were about climate change, how supportive they considered themselves of remedial action, and how much participants knew about climate change. Specifically, we used a series of linear regressions to predict climate concern, support, and knowledge in the Post-survey from the experimental condition (0=control, 1=treatment). All models controlled for the respective concern, support, and knowledge in the Pre-survey and included the socio-demographic variables to increase the precision of the estimates (see **Supplementary Information** for robustness checks). The treatment group showed significantly higher levels of concern (B=0.12, SE(B)=0.045, β=0.08, t=2.69, p=0.007; **Fig. 3a**), support for remedial action (B=0.13, SE(B)=0.058, β=0.09, t=2.19, p=0.029; **Fig. 3b**), and knowledge (B=1.58, SE(B)=0.22, β=0.52, t=7.15, p<0.001; **Fig. 4**) in the Post-survey compared to the control group. Specifically, participants in the treatment group, on average, scored 0.12 points higher on concern (0.08 std.), 0.13 points higher on support (0.09 std.), and answered an additional 1.58 questions (out of 20) correctly on the knowledge test (0.52 std. increase).

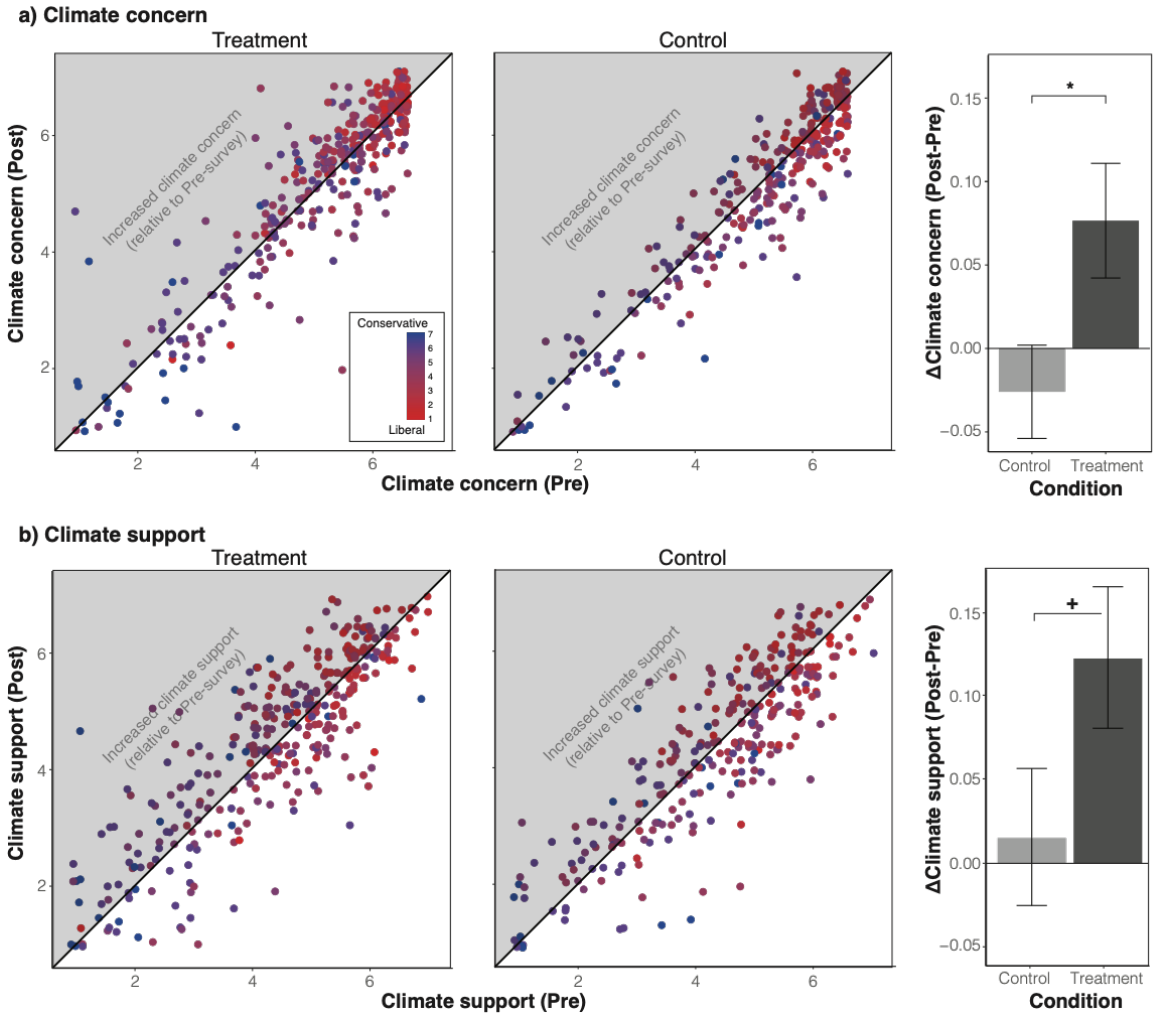

Figure 3. Effects of condition on climate concern and support. a) Participants concern, and **b)** support before (x-axis) and after (y-axis) the prediction market. Right column depicts the shifts in concern across control and treatment conditions, calculated as the average difference scores, across conditions, between the Post- and Pre-survey. Error bars depict standard errors. * $p < 0.05$, + $p < 0.1$.

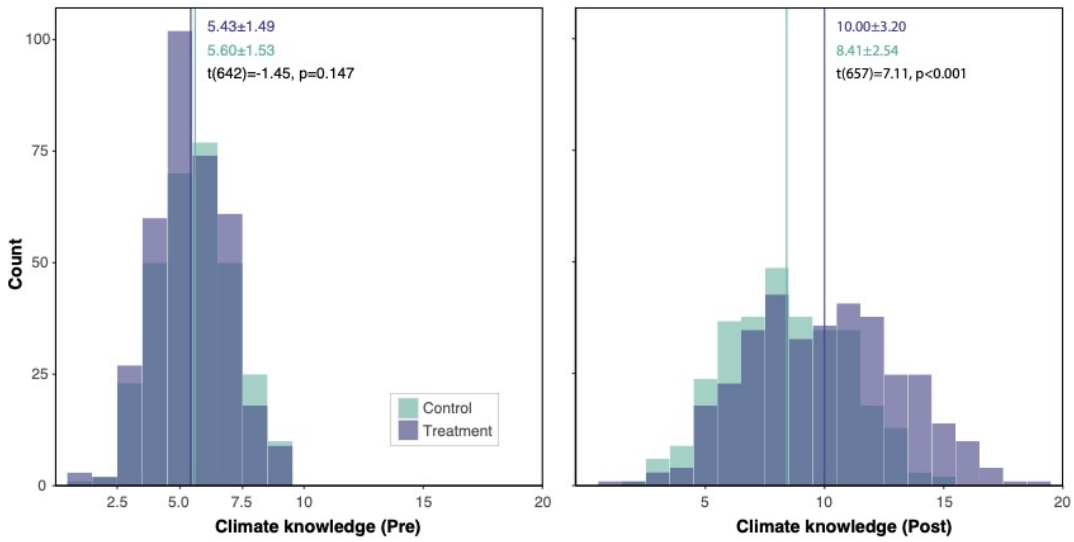

Figure 4. Climate knowledge increases after participating in a climate prediction market. Participants' knowledge was evaluated by comparing the treatment and control groups' knowledge in the Pre-survey (left; n.s.) and Post-survey (right).

Given that we asked the same question regarding concern and support in both the Pre- and Post-survey, we could directly compare participants' pre- and post- scores to better understand the underlying mechanisms of the observed effects. Participants in the treatment condition showed significantly higher levels of concern in the Post-survey than the Pre-survey (t(355)=2.23, p=0.026; *paired t-test*; **Fig. 3**) while participants in the control condition did not show such a shift (t(307)=-0.93, p=0.353; *paired t-test*). Similarly, participants in the treatment condition increased their support for remedial action (t(355)= 2.89, p=0.004; *paired t-test*) while those in the control condition did not(t(307)= 0.37, p=0.712; *paired t-test*).

In addition to testing our main hypotheses, we also conducted a series of exploratory analyses. First, we tested whether the treatment effect was stronger in certain conditions (i.e., as in Study 1, where participants only shifted their attitudes when they were successful in the market). While we did not observe significant interaction effects between the experimental condition and the amount won for climate concern (B=0.009, SE(B)=0.011, β=0.04, t=0.75, p=0.455) or support (B=0.007, SE(B)=0.014, β=0.04, t=0.55, p=0.583), we found a significant moderation for climate knowledge (B=0.182, SE(B)=0.053, β=0.41, t=3.44, p<0.001), suggesting that those who were more successful in the market gained more knowledge. Notably, we observed a significant interaction between the treatment and political ideology, such that the treatment was more effective at increasing support for remedial action among more conservative participants (B=0.077, SE(B)=0.036, β=0.13, t=2.14, p=0.033). All treatment effects were independent of initial climate concerns, suggesting that participants at all levels of climate concern were equally affected by their involvement in the climate prediction market.

In line with prior findings on motivated reasoning[2,7,9], we observed a marginally significant relationship between political ideology and the percentage of bets placed on "Yes" such that more conservative participants were less likely to place bets that superficially align with climate change (r=-0.10, t=-1.90, p=0.058). We also performed tests for correlations between political ideology

and: 1) betting behaviors (total bets placed, r=-0.01, p=0.828; and total amount spent, r=0.05, p=0.192), 2) outcomes (number of bets won, r=-0.02, p=0.526; and total amount earned, r=-0.004, p=0.921). However, we did not observe any significant correlations (**supplementary figure SI8)**. This suggests that political ideology did not influence participants' engagement with the markets, confidence in their bets, or prediction accuracy.

Discussion

In line with existing theoretical arguments about the power of climate prediction markets[34], our findings from two field studies suggest that participating in a climate prediction market can influence people's attitudes towards climate change. Specifically, we show that compared to a control group, participants who bet on climate-related events reported higher levels of concern about the impact of climate change, showed higher levels of support for remedial action, and had higher levels of knowledge on climate issues. While the positive impact of our intervention on attitudes was conditional on betting success in Study 1, it was unrelated to earnings in Study 2. This discrepancy might, in part, be explained by the fact that the participants pool recruited in Study 1 was selected to be highly polarized with respect to their views on climate change.

The effects of our intervention are small, with our experimental condition explaining between 1-7% of the variance in the Post-survey responses regarding concern, support, and knowledge. However, we argue that our intervention offers a meaningful tool for behavior change despite these small effect sizes. First, prior work has suggested that, when considered at scale, small effects can turn into highly impactful outcomes[35]. For example, a small shift in concern or support for climate change among thousands of people could result in more public support for policy changes. Second, our intervention results in positive attitude shifts across the entire political spectrum. Neither political ideology nor the extent to which people were concerned about climate change prior to the intervention consistently moderated the effect. The only exception to this lack of moderation by political ideology was the shift in climate support in Study 2, where the intervention was stronger among more conservative participants. The success of the intervention is promising given that prior works have reported adverse reactive behavior among climate skeptics targeted with interventions aimed at shifting their concern about climate change[16,36–39]. Further, we propose that even if the participation in a climate prediction market is limited, the media accounts about market valuations, the prediction outcomes, and the dissemination of knowledge that is derived from the markets may yield an increased shift in concerns in the larger population.

While it is difficult to translate the effects in field studies to population-level outcomes, there are some quantifiable metrics that could be impacted by interventions like ours. For example, if the prediction market in Study 1 was scaled to 1,000,000 climate believers and skeptics, and all believers decided to invest their annual earnings from, say, $500 in market money ($25, on average, if applied to our results) into countering climate change, this would result in an estimated $25,000,000 of additional funding for climate solutions. Note that this amount could quickly increase when considering highly motivated players that might have far greater yields than the 5% earnings observed for the average believer in Study 1. Similarly, given that participation in climate markets such as the one in Study 2 yields an increase in climate concern, support, and knowledge, then such intervention among a representative subset of the population could yield a shift in attitudes among millions[14,16] of individuals.

The majority of previous attempts at getting people to update their existing position on climate change focused on highlighting scientific consensus[39–43], neutralizing partisan conflict[36–39], or appealing to norms[7,44–47]. The success of a number of those efforts was driven primarily by increasing knowledge and providing information, which in turn helped shift perspectives. Some of the challenges in previous works have been attributed to: 1) motivated reasoning (i.e., rejection of new information that contradicts standing beliefs[9]), 2) the desire to signal social identity within a group by clinging to information that fosters collective homogeneity[48], and 3) active attempts to foster uncertainty about climate science by various organizations[49]. Our intervention offers a solution to all three of these challenges by: 1) making motivated reasoning costly, 2) anonymizing people's individual decisions (thereby protecting their position within a group of climate skeptics, for example) while conveying aggregated public opinion, and 3) creating higher levels of certainty by having people actively engage with scientific sources. Additionally, since the change in attitudes is intrinsically driven, it has the potential to be less threatening to one's identity and hence more sustainable. Together, these features might allow people to engage with climate change-related topics in a way that is less prone to a partisan interpretation of climate information and hence less polarizing[6,36–39].

Our findings contribute to the existing knowledge on behavior change, both inside and outside of the climate domain. First, they align with existing empirical findings on how betting can serve as a tool for boosting engagement and driving behavior change. For example, participating in sports prediction markets was shown to drive engagement with the topic[50], and data on financial investment markets have highlighted that trading stocks of a company increases people's consumption of news related to that company[51]. Second, the findings speak to a growing body of work suggesting that reducing the "distance" to the problem of climate change—psychologically, temporally, or spatially—can lead to positive shifts in attitudes and behaviors[39,52,53]. For example, people who live closer to coastlines, where the effect of climate change is more concrete, expressed greater concern about climate change and higher support for regulating carbon emissions[54], although unlike our intervention this may not hold for skeptics[55]. While our intervention does not change the physical setting of participants, continuous engagement with very tangible climate-related events may reduce the psychological distance to climate change and make its effects appear more imminent. Third, our findings also align with simulations suggesting that participation in climate prediction markets should foster alignment with the scientific climate consensus[34].

Study limitations

Our studies were associated with a number of limitations. First, given that our studies were field experiments that involved real-time responses, the results are impacted by ongoing events (i.e., actions taken by other participants, news cycle, or saliency of climate-related events). In Study 2, for example, climate events dominated the news during our Pre-survey period (including a 50-year record high heatwave in Europe), which is likely to have impacted our baseline levels of climate concern and support. This might have made it harder to see bigger increases in concern in the Post-survey. Although our study therefore produces findings of high ecological validity, this also suggests that the effects might vary depending on when the study is conducted. We suggest that future climate prediction market studies should replicate our findings across multiple time windows to corroborate the generalizability of results above and beyond our specific time window.

Second, given that the participants were recruited solely based on location and climate beliefs, our results reflect the behavior of U.S. participants and may not generalize to the world population. Indeed, the political polarization of U.S. citizens with respect to climate change is larger than that in other countries[56]. On the one hand, this deep ideological polarization might make it more difficult to shift concerns through prediction market interventions in the U.S, but on the other hand, the U.S. might experience larger effects because there are more people who show at least moderate levels of skepticism.

Third, we cannot speak to the exact mechanisms of our effects. In fact, betting behavior is the reflection of a complex combination of factors, including 1) participants' view/knowledge on topics, 2) their confidence in their prediction, 3) their level of risk tolerance, 4) their understanding of the market forces, 5) the amount of time they have to do research and place bets, 6) the availability of funds, 7) the likelihood that others would take the opposite position of a prediction (in Study 1), and 8) the available information on the outcomes (i.e., more data were available as the outcome date approached, in Study 1) among numerous other psychological mechanisms that impact the betting behaviors. Future research could aim to understand the mechanisms driving the betting patterns.

Fourth, our limited study duration imposed a stringent cap on the temporal horizon of predictions that aligns poorly with the longer time scale of climate change. We could not, for example, look into notable changes in Earth's temperature within the time limit. This limitation forced us to focus on climate predictions with large spatial domains (i.e., multiple cities) or comparison to historical events (i.e., average temperature in October 2018 higher than that of the average of October 2012-2017). Further, the uncertain relationship between near-term events eligible for use in the prediction market and events causally related to global warming according to climate attribution science inevitably caused some of our markets to reflect weather events rather than climate change events. However, we made an effort to include numerous markets that were broad to ensure that our participants could weigh in on both shorter and longer temporal/spatial horizons. An implementation of the climate prediction market on a longer period (i.e., years) would both allow for long-term predictions as well as understanding of the effect of new information on predictions, irrespective of the temporal horizon (i.e., predictions about the year 2100 can be updated far ahead of their settle date if new information at, say, 2025 suggests a need for change of bet values). In fact, when Study 2 concluded, we asked participants to make predictions that span years into the future (**supplementary table T19**) which could be analyzed when they settle (data available along with our **Supplementary Information**).

Fifth, our studies were limited to a financial allotment of $20 per participant, capping motivation and outcomes. Participants were limited to using their allotted amount (i.e., they could not increase their funds upon using all of them on predictions) and, correspondingly, unsuccessful participants who lost much of their income early were effectively excluded from further activity (and presumably were less engaged with the study). In addition, the fact that participants did not invest their own money may have changed their overall motivation compared to prediction markets in public exchanges. However, prior work has suggested that playing with virtual money may be as effective as playing with real money, especially given that the virtual earnings translate to real money at the end of the experiment[57]. Further, we argue that this limitation may indicate that a real-world prediction market could in fact amplify the outcomes we identified.

Taken together, these limitations suggest that while our work provides an initial feasibility test for climate prediction markets, further research should examine the markets' ability to shift attitudes persistently across a more diverse set of samples. Specifically, future work should investigate whether changes in concern, support and knowledge are sustained long-term and whether continuous participation in climate markets solidifies those changes. Additionally, further analyses of the bets could investigate the positions taken by an individual as dependent observations and test whether certain outcomes affect future bets (i.e., losing multiple bets in sequence leading to less extreme bets) or attitudes.

Finally, we strongly advocate for a replication of our results using a large-scale prediction market, implemented over a longer period (ideally, years) in an open, non-experimental setting. This would allow market forces to strengthen the effects and could lead to widespread attitude change. Existing public prediction markets could offer a starting point.

Applications

Climate prediction markets can be a useful tool for financial policy estimation[30], for evaluation of public opinion[28], and for aggregation of views and signals about the future[29–31]. Importantly, by making false beliefs costly, climate prediction markets are likely to present a more accurate reflection of people's expectations about climate change. As such, they might help overcome politically motivated skepticism and gradually shift attitudes by highlighting that concern about climate change is more widespread than surveys suggest. Importantly, as one key attribute of any prediction market is its reliance on an accurate arbiter of truth, the power of prediction markets is that participants, upon entry, agree on the resource they will use to determine the outcome. Practically, prediction markets are effectively projecting the reality constraints by which parties will operate.

An additional advantage of climate prediction markets is that they make it possible to quantify probabilities about future events long before the outcomes are manifested. In Study 1, for example, participants traded positions with different values far before the contract settle date. This indicates that the additional information about the future manifested itself in people's present behavior, regardless of the ultimate outcome. As a parallel, while outcomes of electoral bets (say, the winner of a presidential election in Brazil) may be determined months ahead, new information about current events and policies might change the bets position values in ways that are captured by the probability estimates.

Taken together, these make the application of climate prediction markets at scale (i.e., under a federally regulated authority) a promising instrument in the arsenal of climate policy makers. As current direct financial incentives — e.g., tax credits or government subsidies — produce limited (and short-term) results with respect to shifting concerns on climate[58], climate prediction markets can act as a complementary instrument for climate policy. The introduction of large-scale prediction markets for climate change could create a new sector of the financial information industry, where climate attribution and prediction modeling would grow from a small academic enterprise to one that can help numerous governmental and private sector entities plan for the manifold effects of climate change.

Finally, it is noteworthy that implementing multiple climate prediction markets over the course of this work has highlighted the importance of market makers (i.e., the individuals generating the bets) in the process. For example, the selection of market topics or market launch times may influence market activity by nudging participants towards engagement with a specific topic. Similarly, setting markets that are realistic and fair requires effort and knowledge on the topic. Bets that are too extreme in any direction make all participants act in unison irrespective of their personal opinions. For example, the thresholds we chose for settling the first set of markets in Study 2 led to almost all bets settling in favor of predictions that aligned with climate skepticism. Although this did not impact the effect on climate concern and support, it resulted in a general shift among participants towards more conservative bets in subsequent markets (supported by anecdotal evidence from debriefs of participants; see **Supplementary Information** for examination of this effect). The impact that such choice of markets can have on the outcomes (and associated attitude change) raises concerns about potential market manipulation. While prior work has explicitly suggested market manipulation as a means to subsidize certain positions, encourage informed traders, and reward accuracy[28,59], our experience suggests that this is not necessary for concern shift. Put simply, engaging in climate prediction markets without any manipulation yields increase in support for climate action. The unfortunate reality of climate change means that *any* randomly chosen period of time we selected for our studies had an abundance of salient climate anomalies that yielded an increase in concern about climate change.

Conclusion

This study offers empirical evidence for the ability of climate prediction markets to change people's attitudes about climate change. The engagement with climate prediction markets in a domain that is less polarizing than politics and more uniformly quantitative could not only support existing methods to change climate concerns[6,17,53,60] but also act as an ultimate polling tool to help scientists, activists, and politicians aggregate public opinion about climate trends, policy preferences, and future scientific predictions. It has not escaped our notice that the powerful financial instrument proposed here could be used in other topics of controversy where an independent arbiter of truth could allow individuals to reflect their views through market economics rather than public stated opinions.

Methods

Study 1

Participants

A total of 160 participants were recruited for the study. Participants were recruited online using *Prolific Academic* and through the *Reddit* "Climate Change skeptics" group. Participants were screened online using two questions: 1) "What is your nationality?" (only participants who answered "United States" to this question were eligible to participate), and 2) "Do you believe in climate change?" (an equal number of people saying "Yes" and "No" were recruited). Participants' location within the United States varied, and spanned areas that are deemed high and low for their support for climate change science[61] (**supplementary figure SI1**).

Seventeen participants were excluded from the analysis, broken down as follows: three were excluded because they did not complete the required surveys, five since they failed an attention check question in either the Pre-/Post-survey, and nine since they did not fulfill the requirement to use the entirety of the allotted $20. Of the 143 remaining participants, 73 were used as controls (35 believers, 38 skeptics) and the remaining 70 were used as the treatment group (35 believers, 35 skeptics). See **supplementary table T5** for a breakdown of all participants' demographics.

Participants in the control group received $5 for completing the Pre-survey, and an additional $5 for completing the Post-survey. Participants in the treatment group received the same renumeration for these surveys, along with additional $20 to spend in the climate prediction market (see **supplementary figure SI3** for bet topics distribution). Participants were instructed to use the full amount for climate predictions. At the end of the study, participants received their earnings in the climate prediction market. Participants who lost all their $20 allotment during the betting period received only a $10 participation fee. In total, participants in the treatment group could earn anything from $10 (participation fee) to a maximum of $650 (participation fee and their earning from bet wins).

All participants signed an online consent form upon initial engagement with the Pre-survey. The study protocols were approved by Northwestern University's Institutional Review Board (STU00206273).

Experimental procedure

On the day of the study initiation, participants received a message instructing them to complete a Pre-survey. At the end of the survey, they were given a personalized link to a web-based online climate betting site. Upon logging in to the site, they were presented with a number of climate betting markets and could take a position on any number of them (**Fig, 1**). In addition, participants could choose to trade a position with other participants. The number of available markets changed daily based on old markets closing and new markets opening. Participants could place multiple bets on the same market and could trade continuously as long as the market did not settle.

During the betting period, participants could log in to the prediction market site whenever they wished, monitor their currently available funds, view the available markets, make bets, or trade positions. The market mechanism was "double-action" (see **Supplementary Information** for

details) which required two participants to take opposite bets such that the sum of two bets was $1 (i.e., if one participant chose to wager 60¢ that a "Yes" bet will occur, only when another participant wagered 40¢ that a "No" on the outcome would a contract be initiated). If no participant was willing to take the opposite wager, the offer remained pending until the participant making the offer chose to revoke it). The manifested value of each market at any given moment was that of the last "Yes" transaction to occur. That is, if a participant made a bet for 82¢ that the average Methane level in October 2018 will be the highest on record and another participant took the opposite position at 12¢, then all participants saw the current market value as 82. Accordingly, the values of markets represented the aggregated stable amount of money people were agreeing to wager on each topic. Naturally, as the settlement date of markets had approached, the bets were likely to converge to the probability (0…100) of the correct outcome (i.e., if the market asked whether the number of disasters in a certain location be more than 10 by a certain date, and a few days before the closing time a number of disasters already reached 9, the likelihood of a "Yes" bet was higher). The betting period was initiated on September 9, 2018, and lasted until November 11, 2018. When the betting period was complete, participants were instructed to complete a Post-survey. Once participants completed the Post-survey they were paid for their participation in the entire study. The Pre- and Post-surveys included a variety of questions (see **Supplementary Information** for all questions), but the main focus of the study was the subset of questions pertaining to the concern about climate change.

To ensure the site's robustness to large-scale use and to reduce the risk of technical issues jeopardizing the real-time experiment, we ran a pilot test of the site for two months prior to the experiment on a smaller group of participants

Study 2 was similar to Study 1 in its design, with the following deviations: 1) the criteria for exclusion in Study 1 was stricter (i.e., participants were asked to use the full amount of money allotted to them), 2) the betting period in Study 1 was longer and bets were not released daily but rather intermittently, 3) the participant population for Study 1 was selected such that the pool was more polarized, 4) the control group for Study 1 did not participate in an alternative prediction market, 5) the treatment group's bets in Study 1 occurred in a double auction, which pitted the believer and skeptics against each other with predictions occurring only when two participants claimed opposite sides of a bet such that the sum of the positions was $1 (see **Supplementary Information** for explanation of the double auction fulfillment method), 6) participants in Study 1 could trade their bets in the market as the settle date was approaching based on the value of the trade at the time, 7) participants in Study 1 did not have to take a position on a bet as soon as it appeared on the portal, but could choose to make a decision to enter as more information became available (the option price presumably reflected the information availability and outcome certainty), 8) participants in Study 1 could take contrary positions on the same bet, or hedge their bets with variety of positions.

Study 2

Participants

Participants were recruited through an online panel, *Prolific Academic*. Our target sample for the start of the study was 1,000 participants with anticipated attrition rates of approximately 30-40% over the course of the entire assessment period. To obtain this initial sample, we recruited 1,754

Prolific workers whose native language was English and who currently resided within the U.S. We excluded all participants who took less than two minutes to complete the survey and who failed an attention check embedded in the survey (n=134).

All participants were asked a series of questions about their concerns pertaining to climate change, their support for climate action, and their knowledge on basic climate-related topics (see **Measures**). We excluded participants who were already at ceiling with respect to climate concern and support (n=615; see **Supplementary Information**).

A total of 1,005 participants met all inclusion criteria. Participants were randomly assigned to a treatment (n=524) or control condition (n=481; **Supplementary table T6**). Participants in the treatment condition were told that they would participate in a 4-week long climate prediction market, while participants in the control condition were told about their participation in a sports and entertainment prediction market (see **supplementary table T6** for evidence that the treatment and control groups randomization assignments did not significantly differ from one another).

Each participant was allotted $20 to use for bets throughout the study. We considered participants' study records complete if they: 1) placed at least 15 bets and spent at least $10 from their allocated wages during the prediction period, 2) completed the Post-survey at the end of the study which included the same climate-related measures (i.e., concern, support, and knowledge) as the Pre-survey. After excluding participants who did not meet these criteria, we were left with an analysis sample consisting of 664 participants (34% overall attrition rate; 32% in the treatment group, 36% in the control; $x^2(2)=1.71$, p=0.191, n.s.). Participants were compensated with a fixed sum of $11 for completing the Pre- and Post-surveys and a variable additional amount depending on their earnings in the prediction period.

All participants signed an online consent form upon initial engagement with the Pre-survey. The study protocol was approved by Columbia University's Institutional Review Board (AAAU2501).

Experimental procedure

The study consisted of three main building blocks: 1) The Pre-survey that measured participants concern about climate change (climate concern), their support for possible solutions (climate support), and their knowledge on climate issues (climate knowledge) prior to the intervention, 2) a 5-week long prediction market, and 3) a Post-survey that captured climate concern, support and knowledge following the intervention. Participants were recruited between July 17 and July 21, 2022, and completed the Pre-survey as part of the initial screening procedure. After exclusion, participants were randomly assigned to the five-week climate (treatment) or sports/entertainment (control) prediction markets. The betting period started on August 1, 2022, and concluded on September 4, 2022. The final bet was settled on September 6, 2022. The Post-survey was sent to participants on September 8, 2022, and was closed on September 14, 2022, at which point all participants were paid (**Fig. 1**).

Each participant received a unique login identifier that allowed them to use a personalized version of study surveys. Every day at 10:00 EST all participants received an email through the study messaging system indicating that a new bet was available on the prediction portal. The message included a link to the prediction portal.

Upon receipt of the daily reminder, participants had 20 hours to enter the portal (**Fig. 1**), look at that day's bet, and decide whether to make a prediction. Once participants logged in to the portal they were greeted with their personal identification and a summary of their personal study metrics. The metrics were: how many bets they had already placed, how much money they currently held in their wallet, how much money they had in bets escrow (i.e., bets awaiting resolution), and their total earnings up to that point. Below the metrics, participants saw a summary of the bets that already materialized and their outcome. Below this information, participants saw the day's new bet (i.e., "Will the number of wildfires in California exceed 5,500 by August 8, 2022?") alongside the bet's settle date (i.e., "August 8, 2022, 23:59 EST"), the source for determining the outcome (i.e., "https://www.fire.ca.gov/incidents/2022"), and where possible a graph of the history of the variable being bet on, showing settle date of the current bet with respect to that graph.

Participants were then asked to indicate whether they wanted to abstain from betting, predict "Yes", or predict "No". If participants elected to make a Yes/No prediction, they advanced to the next screen where they were asked to select the bet amount. Depending on their level of confidence, participants could bet any amount between 1¢ and 100¢. After participants determined their position and bet wager, they were asked to confirm their decision or restart their decision. Once the participants confirmed their decision, the bet was locked for the day and they were not able to alter their bet.

Measures

Climate concern. We measured people's concern about climate change in both the Pre- and Post-survey using the following four items: 1) "Do you think that global warming/climate change is happening?" (Definitely not—Definitely yes, 2) "Do you think global warming/climate change is the result of human activities?" (Definitely not—Definitely yes), 3) "How much risk do you believe global warming/climate change poses to humanity's health, safety and prosperity?" (None at all—Extremely high), and 4) "Some people say that global warming/climate change is simply a scam. What do you think about this?" (Strongly disagree—strongly agree; reverse coded). The measure was adopted from work by Weber and colleagues[62]. Responses were recorded on a 7-point scale. With a Cronbach's alpha of 0.93 in both the Pre- and Post-surveys, the internal consistency of our measure was found to be excellent.

Support for climate change solutions. We measured people's support for climate change solutions in both the Pre- and Post-survey using the following three items: 1) "Addressing global warming/climate change should be a priority of the government" (Strongly disagree—Strongly agree), 2) "I feel personally responsible to help slow down global warming/climate change" (e.g., by making changes to my lifestyle or paying higher taxes) (Strongly disagree—Strongly agree), and 3) "Some people say that climate change is real, but that the cost of fixing it today might not be worth the investment (i.e., that the cost of fixing it today is higher than the cost of the damages caused by it)" (Strongly disagree—Strongly agree). Responses were recorded on a 7-point scale. With a Cronbach's alpha of 0.84 in the Pre- and 0.87 in the Post-Survey, the internal consistency of our measure was found to be good.

Climate knowledge. The questions for climate knowledge differed between Pre- and Post-survey. The Pre-survey asked 10 relatively generic multiple-choice questions (i.e., "How many major

layers does Earth's atmosphere have?" Or "What is the primary effect of greenhouse gasses?". The Post-survey, on the other hand, asked a more comprehensive set of questions that were directly related to knowledge about climate change (i.e., "When does a tropical disturbance become a tropical storm and gains a name?" or "What percentage of heat from global warming has the ocean absorbed in the past 40 years?"; see **supplementary tables T2, T4, T18, and T19** for all questions).

Sociodemographic control variables. We collected information about a wide range of participants' socio-demographic characteristics. These included: age, gender, ethnicity, education, employment status, income, religious beliefs, political ideology, and number of children (**supplementary tables T18** and **T19**).

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Author Contributions
All authors equally designed the research, performed the research, analyzed the data, and wrote the paper.

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