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Climate change psychological distress is associated with increased collective climate action in the U.S.



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The mental health impacts of climate change are increasingly documented; however, less research has investigated the relationship between climate change-related psychological distress and engagement with the issue. The results from two national probability samples of U.S. adults show that 16% report at least one feature of climate change psychological distress and that certain groups have higher levels of distress than others (e.g., Hispanic/Latinos, lower income adults, younger adults). Importantly, people experiencing distress are more likely to engage in collective action on climate change or express a willingness to do so, even when controlling for several correlates of environmental behavior (e.g., political ideology, collective efficacy beliefs). These findings highlight that many Americans are experiencing psychological distress from climate change, and those who do are more involved in collective climate action. People experiencing such distress may benefit from resources to support mental health and engagement with climate change.

Climate change affects human health, including mental health and well-being¹. The increased occurrence and intensity of extreme weather events, such as heat waves and floods, can produce and intensify mental health stressors. In addition, the awareness of current climate impacts and impending risks, coupled with perceived inaction, can contribute to the mental health burden of climate change². These climate impacts are felt disproportionately by more vulnerable people, including those with limited socioeconomic resources, children, older adults, pregnant women, communities of color and Indigenous peoples, people with disabilities, and those with pre-existing health conditions³. For example, in a multinational survey, 45% of children and young people aged 16–25 reported that their negative feelings about climate change affected their daily life and functioning⁴. A recent study found that climate anxiety was associated with increased levels of antenatal depression and worry among expectant mothers⁵.

Experiencing distress in response to the harsh realities of climate change is a rational and understandable reaction. However, when distress reaches severe levels, it may have detrimental effects on well-being, behavior, and day-to-day functioning^{6,7}. A notable 7% of adults in the United States report experiencing potentially serious levels of psychological distress about climate change⁸. Considering the proportion of people psychologically affected and the current strain on mental health services⁹, there is a pressing need to identify accessible resources and strategies that can support climate

adaptation and resilience. Scholars use various terms to describe the emotions, moods, and mental states associated with climate change^{10–12}. Given the overlapping nature of the current terminology in scholarly discourse and the absence of standardized definitions, this study uses “climate change psychological distress” as an umbrella term covering a spectrum of emotional and mental health responses, including features of depression and anxiety.

Additionally, people can act on climate change in many ways, ranging from individual mitigation behaviors such as reducing energy consumption and waste, to collective actions like advocating for climate policies to drive systemic change¹³. Here, we focus on collective actions, specifically social and civic/political actions like volunteerism, contacting government officials, participation in social movements, and engaging in conversations about climate change. Many of these collective actions are among the most effective ways to help address climate change^{13,14}. Actions such as these can influence government policy-making and promote the spread of pro-climate social norms that signal a shared commitment to environmental protection and climate action¹³.

Decades of mental health research indicate that problem-focused coping strategies (i.e., actively seeking and engaging in solutions to address the cause of distress) can support the psychological health of children and adolescents and adults^{15,16}. Engaging in collective actions to address climate

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change may represent a problem-focused coping strategy aimed at managing climate-related distress¹⁷. For instance, correlational research has found that participation in collective action on climate change (e.g., engaging in protests, contacting elected officials) can reduce the negative effects of climate change anxiety on the mental health of young adults in the U.S.¹⁸.

While some research suggests that experiencing distress about climate change (e.g., anxiety) can lead to maladaptive behaviors including issue avoidance and reduced engagement^{6,19,20}, several other studies indicate a positive relationship between climate-related distress and climate action (Curl et al., 2022; Hepp et al., 2023; Latkin et al., 2022; Ogunbode et al., 2022; Sangervo et al., 2022; Schwartz et al., 2022; Thomson & Roach, 2023; Verplanken et al., 2020)^{18,21–27}. For example, an international study of 32 countries found that people with higher levels of climate-related anxiety were more likely to engage in pro-environmental behaviors (e.g., saving energy at home, reducing food waste) in 24 of the countries and more likely to participate in climate protests in 12 of the countries²⁴. Interestingly, one study suggests that the positive relationship between distress and action diminishes at high levels of distress but that severe distress may impede individuals from engaging in action²³. Additionally, other research has suggested that experiencing psychological distress about climate change can promote pro-environmental behavior for some individuals, but have a negative “paralyzing” effect for others by way of decreased self-efficacy or confidence about one’s ability to make a difference²⁸. Understanding the relationship between climate-related distress and action may help identify problem-focused social and behavioral resources that can support people’s mental health and engagement with the issue.

Using two national probability samples of U.S. adults, this study tests the strength of the relationship between climate change psychological distress and engaging in collective climate action. As part of the Climate Change in the American Mind project, early exploration of this relationship suggested that such distress may have a strong, positive relationship to climate action²⁹. Compared to people with no climate change psychological distress, those who experienced at least one feature of distress reported higher levels of intentions to engage in collective action on climate change, past engagement, and discussing climate change with others. In a separate analysis, there was also evidence that Hispanics/Latinos and younger generations may have higher rates of climate change psychological distress compared with the general U.S. population⁸. However, that research included only one wave of survey data with a limited number of respondents who were distressed about climate change, and it did not statistically control for other factors that may explain the relationship between distress and climate action (e.g., political ideology, collective efficacy beliefs, perceived social norms, general levels of worry about climate change). Here, we expand on this research and include an additional wave of nationally representative survey data to investigate the strength and robustness of this relationship while controlling for several predictors of behavioral engagement with climate change. We also explore differences in climate change psychological distress across demographic and political groups. As additional exploratory analyses, we investigate whether the relationship between climate-related distress and collective climate action is non-linear, as previous research has suggested²³. Specifically, among people with at least some distress, we test whether there is decreased action among those with the highest levels of distress in comparison to those with lower levels.

Results

The data include a total of 2,118 U.S. adults (18 +), half of whom are female (50%). Most respondents are non-Hispanic White (62%), ages 35–54 (33%) or 55+ (40%), and have a Bachelor’s degree or higher (35%) or at least some college (26%; parameters are weighted; see Supplementary Material, Table S1 for all sample characteristics).

Climate change psychological distress across demographic and political groups

As shown in Fig. 1, 16% of U.S. adults reported at least one feature of climate change psychological distress (feelings of depression or anxiety) “several

days” or more often over the previous 2 weeks. Chi-square tests indicate that there are significant differences across political party ($X^2 = 149.57$, $p < 0.001$), race/ethnicity ($X^2 = 23.35$, $p < 0.001$), income ($X^2 = 28.01$, $p < 0.001$), urbanicity ($X^2 = 18.75$, $p < 0.001$), generations ($X^2 = 13.14$, $p = 0.001$), and gender ($X^2 = 6.44$, $p = 0.01$). Differences across education groups were not significant ($X^2 = 2.37$, $p = 0.31$; see Table S6 for sample sizes, margins of error, and statistical tests across subgroups). Overall, Democrats, Hispanics/Latinos, lower-income earners, urban residents, and Gen Z/ Millennials are among the groups reporting the highest levels of distress.

Climate change psychological distress and climate action

As displayed in Table 1, independent samples *t*-tests show that the mean differences between Americans who reported some climate change psychological distress (i.e., at least one feature of distress) versus no distress in each of the four climate action outcomes are significant (*t*-statistics range from 11.35 to 17.93, $p < 0.001$) and large³⁰. Across outcomes, Hedges’ *g* ranges from .93 (95% CI[0.81, 1.06]) to 1.27 (95% CI[1.14, 1.40]; see Tables S7–S9 for all test statistics). As shown in Fig. 2, U.S. adults who experienced some climate-related distress are much more likely than those with no distress to have engaged in collective action on climate change, or say they would engage in collective action (e.g., join a climate campaign). Additionally, people who experienced some climate-related distress are more likely to discuss global warming with their family and friends.

Regression analyses show that the relationships between climate-related distress and each of the four climate action outcomes remain positive and significant (standardized β coefficients range from .09 to .31 across models, $p < 0.001$; see Tables S10 and S11) when controlling for socio-demographics and key correlates of climate action: worry about global warming, collective efficacy beliefs, perceived social norms, political ideology, age, gender, race/ethnicity, education, annual household income, and urbanicity. This suggests that climate change psychological distress is consistently and distinctly linked to increased climate action, independent of other factors, including general levels of worry about global warming.

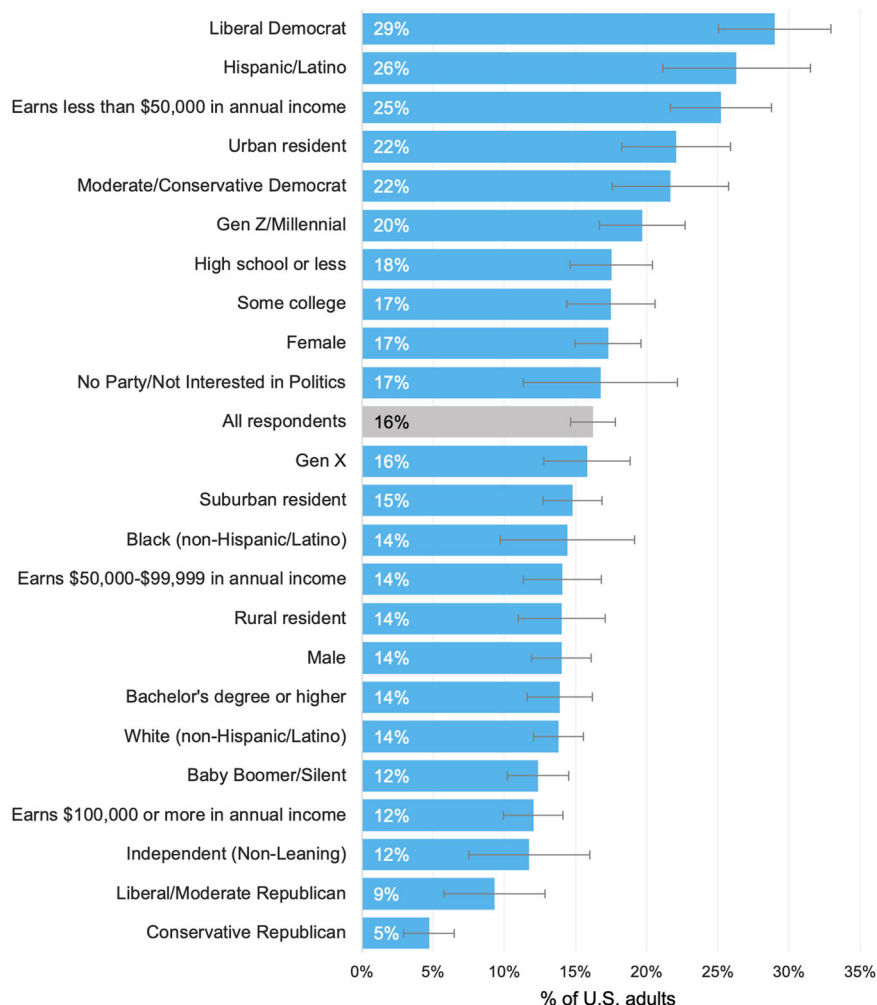
Behavioral engagement across people with varying levels of distress

Within the subgroup of people experiencing at least one feature of climate change psychological distress (feelings of depression or anxiety; $n = 327$), analyses of variance and independent samples *t*-tests show there are no significant differences between people with lower versus higher levels of distress in most measures of climate action, with the exception of past engagement among people experiencing at least some climate depression (see Fig. 3 and Table S9). As shown in Fig. 3, people experiencing higher levels of climate depression report more engagement in collective climate action in the past ($M = 2.02$, $SD = 1.16$) than people with lower levels of climate depression ($M = 1.59$, $SD = 0.77$), $t(60.57) = 2.61$, $p < 0.01$ ($g = 0.51$, 95% CI[0.21, 0.81]). However, people experiencing higher levels of climate depression report marginally less discussion about global warming with family and friends ($M = 2.59$, $SD = 1.04$) than those with lower levels of climate depression ($M = 2.87$, $SD = 0.82$), although this is not statistically significant at traditional levels $t(74.81) = -1.95$, $p = 0.06$ ($g = -0.32$, 95% CI[-0.61, -0.04]). There are no significant differences between higher versus lower levels of climate distress across the other measures of climate action. These results show that, on average, the relationship between levels of climate change psychological distress and collective climate action is non-linear and L-shaped. While there are some exceptions to these findings among people with climate-related depression, overall, the key differences in behavioral engagement are between people with no distress and those with at least one feature of distress.

Discussion

Taken together, the findings from two nationally representative cross-sectional surveys of U.S. adults show that 16% report at least one feature of climate change psychological distress (feelings of depression or anxiety) and that there is a strong, non-linear relationship between distress and increased

Fig. 1 | Percentages, by demographic group, of people who experienced at least one feature of climate change psychological distress (feelings of depression or anxiety) “several days” or more often over the previous 2 weeks. Percentages are weighted to match U.S. population parameters and margins of error are at the 95% confidence level. Refer to the Supplemental Material for sample sizes and a description of how subgroups were calculated.



climate action. People who experience at least one feature of distress are more likely to engage in collective action on climate change (e.g., contacting government officials) and express a willingness to do so (e.g., joining a climate campaign). These results align with prior correlational studies^{18,23–25,27}. However, the results show that the relationship between distress and action is L-shaped and plateaus among those with at least some distress about climate change. In support of previous research, higher levels of distress, on average, do not appear to continuously correlate with higher levels of climate action²³. Also, there is little evidence to suggest that distress at any level has a *negative* effect on engagement with climate change.

In addition, we find that certain subgroups of the U.S. population are more likely to experience climate change psychological distress, including Hispanics/Latinos, people with lower income, and younger adults. These results may be partially explained by differential vulnerability and exposure to the impacts of environmental problems like climate change, and differences in environmental concern and action. In particular, communities of color and lower income communities are disproportionately harmed by climate change impacts (e.g., extreme heat) and environmental hazards (e.g., air and water pollution, toxic waste)^{31–33}. According to the environmental deprivation hypothesis³⁴, higher levels of environmental concern among communities of color and low-income communities reflect greater exposure to environmental harms^{35,36} and social inequities, such as systemic racism, that contribute to these elevated environmental risks^{37–39}. Indeed, research has found that people of color (Hispanics/Latinos in particular) and lower-income individuals are among the groups with the highest levels of environmental concern in the U.S.⁴⁰. The greater prevalence of climate change psychological distress among U.S. Hispanics/Latinos and lower income

adults may be shaped, at least in part, by higher levels of environmental concern and exposure to environmental risks.

In a similar vein, communities of color (especially Black and Indigenous communities) historically have been key leaders at the forefront of environmental movements^{41–45}. Also, some research has found that, in the U.S., people of color (especially Hispanic/Latino Americans) are more likely to report environmental engagement compared to Whites^{46–48}. As shown in the supplemental material of the present research, compared to Whites, people of color reported higher levels of collective efficacy beliefs, intentions to engage in collective action on climate change, and worry about global warming. In addition, Hispanics/Latinos reported higher levels of past engagement. The historical and ongoing challenges experienced by communities of color, including systemic and environmental racism, have fostered a strong sense of resilience and leadership in the face of environmental problems⁴⁹. Many communities of color engage in grassroots organizing to address environmental issues and advocate for climate change mitigation policies that simultaneously address injustices^{41–44,50}. It is crucial to provide resources to strengthen resilience and support environmental engagement among groups who are disproportionately harmed and psychologically distressed by environmental problems like climate change.

Importantly, however, there may be additional factors that explain differences in climate change psychological distress across groups (e.g., mental health disparities across racial/ethnic and socioeconomic groups). Also, there may be other factors that explain the relationship between distress and climate action that we were unable to statistically control for in this analysis, including involvement in other forms of political activism or collective action (e.g., participation in other social movements) and general

Table 1 | Mean differences in climate action outcomes between people with some climate change psychological distress (i.e., at least one feature of distress) and those with no distress

Dependent variable	Climate change psychological distress	<i>n</i>	<i>M</i>	<i>SD</i>	Scale Range	<i>t</i>	Hedges' <i>g</i>
Intentions to engage in collective action	No distress	1490	1.89	0.81	1–4	16.90***	1.09 [0.96, 1.23]
	Some distress	260	2.77	0.76			
Willingness to join a climate campaign	No distress	1219	1.86	0.99	1–5	17.93***	1.23 [1.09, 1.38]
	Some distress	238	3.08	0.95			
Past engagement in collective action	No distress	1708	1.09	0.32	1–5	11.35***	1.27 [1.14, 1.40]
	Some distress	307	1.66	0.86			
Engagement in climate discussions	No distress	1758	2.00	0.88	1–4	15.70***	0.93 [0.81, 1.06]
	Some distress	327	2.82	0.87			

Note. *** $p < 0.001$. Statistical tests compare people who experienced at least one feature of climate change psychological distress (feelings of depression or anxiety) “several days” or more often over the previous 2 weeks to those who experienced no distress at all. Each dependent variable was tested separately using listwise deletion. Welch's *t*-tests were used and equal variances were not assumed due to several significant Levene's tests. Hedges' *g* effect sizes and their 95% confidence intervals (in brackets) are presented due to unequal sample sizes and variances between groups.

Intentions to Engage in Collective Action % who “definitely” or “probably” would...

Sign a petition about global warming, either online or in person

Volunteer your time to an organization working on global warming

Support an organization engaging in non-violent civil disobedience against corporate or government activities that make global warming worse

Donate money to an organization working on global warming

Meet with an elected official or their staff about global warming

Write letters, email, or phone government officials about global warming

Personally engage in non-violent civil disobedience against corporate or government activities that make global warming worse

Willingness to Join a Climate Campaign % who “definitely” or “probably” would...

Join a campaign to convince elected officials to take action to reduce global warming

Past Engagement in Collective Action % who ____ at least “once” in the last 12 months

Signed a petition about global warming, either online or in person

Donated money to an organization working on global warming

Volunteered your time to an organization working on global warming

Written letters, emailed, or phoned government officials about global warming

Engagement in Climate Discussions % who “often” or “occasionally”...

Discuss global warming with your family and friends

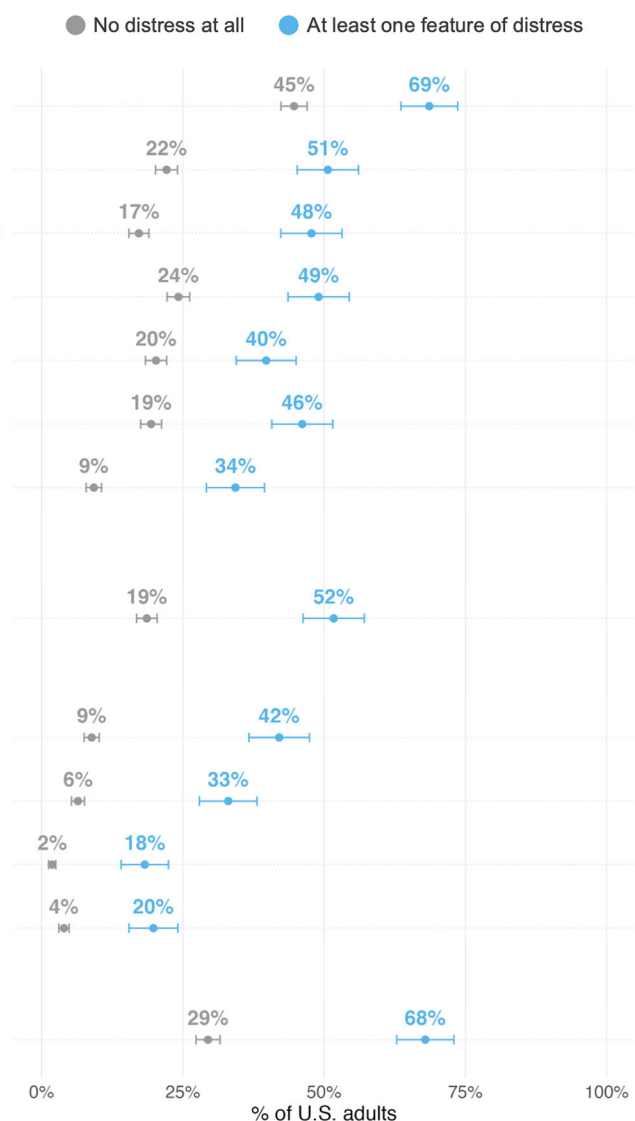


Fig. 2 | Engagement in collective climate actions across people who experienced at least one feature of climate change psychological distress and those who experienced no distress at all. Groups refer to people who experienced at least one feature of climate change psychological distress (feelings of depression or anxiety)

“several days” or more often over the previous 2 weeks ($n = 327$) versus those who experienced no distress at all ($n = 1759$). Percentages are weighted to match U.S. population parameters and margins of error are at the 95% confidence level.

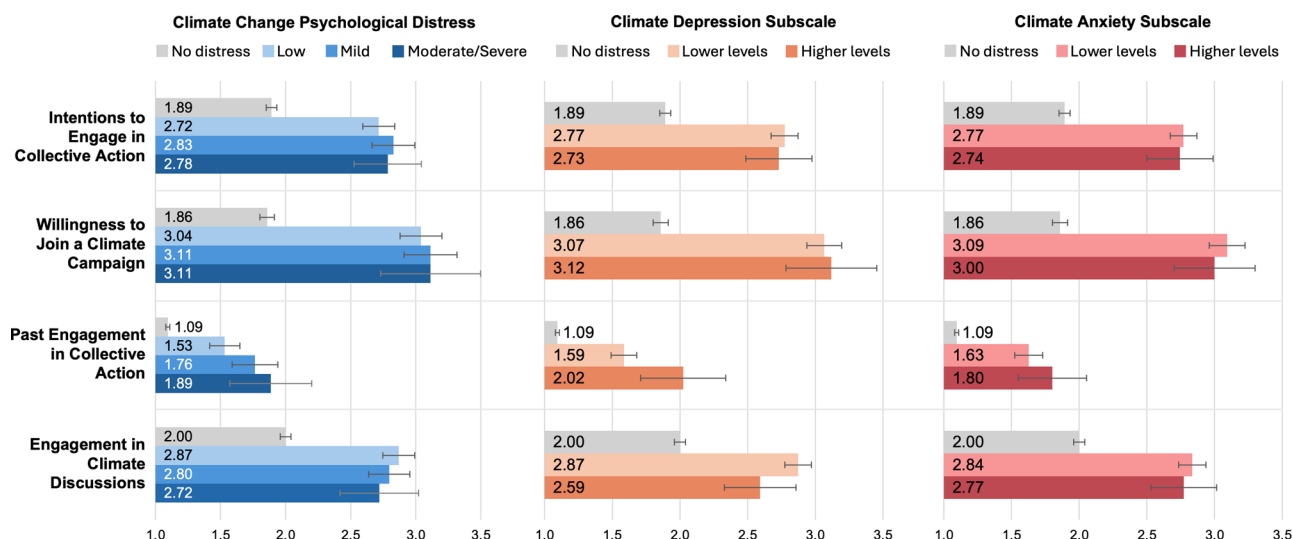


Fig. 3 | Mean differences in the four climate action outcomes across respondents with higher versus lower levels of climate change psychological distress. The four climate action outcomes are on different scales (refer to Table 1). Responses to all four climate change psychological distress items were summed to range from 0 to 12 and were categorized as “None/No distress at all” (0), “Low” (1–2), “Mild” (3–5), or “Moderate/Severe” (6–12). Among respondents who experienced at least some

climate change psychological distress, for both subscales, responses to the two depression items and two anxiety items were summed, respectively, to range from 0 to 6 and were each categorized as “Lower levels” (less than 3), or “Higher levels” (3 or higher). Error bars represent the 95% confidence interval of the mean. Refer to the Supplemental Material for sample sizes and test statistics.

levels of psychological well-being or mental health. However, several studies have found only weak relationships between measures of mental health and climate-related distress^{18,22,51,52}, and one study shows that climate-related distress significantly predicts engagement in collective action on climate change even when controlling for general symptoms of depression²³.

In addition, this study focuses on collective climate actions, not individual actions (e.g., consumer decisions, energy conservation, dietary choices). Emotional and well-being factors, including climate-related distress, may have different relationships with different forms of engagement with climate change⁵³. For instance, correlational studies have found that climate-related distress is more strongly associated with collective climate actions than with individual actions^{18,21,26}. Future research can investigate the strength of relationships between various climate actions and indicators of psychological well-being relative to climate change psychological distress. Such research can also identify potential mechanisms that may explain *why* individuals who are distressed about climate change are more (or less) likely to engage in various climate actions, including motivations and coping mechanisms.

While climate change psychological distress can have maladaptive effects on behavior and impede climate action as a way to cope with the distress^{6,19,20}, our findings are consistent with research showing that distress can serve an adaptive function and motivate engagement^{18,24,25,54,55}. However, the current research is correlational and thus we are not able to infer directional causality. For instance, there may be a bidirectional relationship between climate-related distress and action, whereby people become more worried and distressed about climate change as a result of becoming more engaged and involved with collective climate action. While this is plausible, there are theoretical perspectives and studies suggesting that constructively engaging with climate change may act as a problem-focused coping mechanism and help people manage their negative emotions and adapt to the threat^{6,17,18,25,56}. Scholars also suggest that engagement may promote a sense of empowerment (e.g., perceived efficacy and competency)⁵⁶ and other positive beliefs and emotions (e.g., happiness, hopefulness, sense of agency and meaning)^{17,57,58}. In addition, being part of climate-related movements, communities, and social groups can generate social connections, which can also facilitate positive emotions and serve as a source of resilience^{5,59}. Taken together, while this research is correlational and we cannot make causal claims, our findings contrast with the notion that climate change

psychological distress has a paralyzing effect and negatively affects behavioral engagement with the issue. More research is needed on understanding the needs, experiences, and coping mechanisms of people who are distressed about climate change, especially among those who are highly engaged with the issue. Longitudinal research can especially help scholars understand the factors that drive the relationship between distress and action. Research such as this can also help identify behavioral strategies to support the well-being of people who are vulnerable to the psychological effects of climate change.

Importantly, the measures used in this study primarily assess psychological distress stemming from an individual's perception of climate risks rather than their direct experience with climate-related events. These measures may underestimate the full extent to which climate change contributes to psychological distress, as they only assess distress that people consciously attribute to climate change. In many cases, people who experience distress as a result of extreme weather events may not associate these events with climate change. Thus, people directly exposed to climate events may have different adaptive coping mechanisms than those experiencing the features of distress measured in this study.

Additionally, the prevalence of climate-related distress in this study is lower than what has been found in other studies^{4,23,24,60}. For instance, a large global study of youth and young adults (aged 16–25 years) across 10 countries found that 62% reported feeling anxious about climate change and 39% reported feeling depressed⁴. Other research has found that 32% of U.S. adults say they feel “very” or “moderately” anxious, and 23% say they feel “very” or “moderately” depressed, when they think about global warming⁶⁰. The measures used in the current research were derived from diagnostic screening tools that assess the presence or absence of clinically significant levels symptoms of depression and anxiety, and thus, may be less likely to capture relatively mild experiences of distress compared to other self-report measures (e.g., asking people if they have ever felt anxious or depressed about climate change). Some self-report measures used in other studies may also overstate experiences of climate change psychological distress. It is important to distinguish between climate-related distress as a clinically significant mental health issue that can interfere with daily functioning versus a valid and normal (or mild) emotional response to the threat of climate change⁶⁷. Moreover, the measure used in the current research does not fully capture the broad range of distressing emotions related to climate change (e.g., anger, frustration, grief, indifference) and is limited to clinically

oriented features of depression and anxiety. There may be other emotions and feelings of distress that have different relationships with climate action. The climate change psychological distress measure used in the current research is intended to be brief and closely resemble the Patient Health Questionnaire (PHQ-4), which is validated clinical measure of psychological distress specifically assessing symptoms of depression and anxiety⁶¹. This measure needs further validation and there are other measures of climate change psychological distress that may lead to different results, including the Hogg Eco-Anxiety Scale⁶², Climate Change Anxiety Scale¹⁹, and Brief Climate Change Distress Scale²³.

Also, this study was conducted with a nationally representative sample of U.S. adults. Climate distress prevalence rates and its relationship with climate action may vary across other countries and populations (e.g., youth). For instance, global research has found significant variation in climate anxiety across countries and that its positive relationship with pro-environmental behavior is stronger in more democratic and wealthy countries that tend to have higher levels of individualistic values²⁴. Scholars have suggested that people in individualistic societies like the U.S. may be more inclined to act because of individual factors (e.g., personal beliefs and feelings), whereas those in collectivistic societies may be more motivated by social factors (e.g., complying with social norms)⁶³. Additionally, certain groups, such as those with higher socioeconomic status, may be more likely to act on their personal beliefs and feelings, in part, because of increased access to engagement opportunities⁶⁴. More research is needed on the various factors (e.g., personal, sociocultural, contextual) that shape climate-related distress, and how distress affects psychological well-being and engagement with climate change across different groups of people and cultures.

Future research can also further investigate the relationship between climate-related distress and engagement in climate discussions. As shown here, there was evidence that people experiencing higher levels of climate-related depression were marginally, but not significantly, less likely to talk about global warming with family and friends compared to those with lower levels of climate-related depression. Engaging in climate discussions is recognized as an important collective action that everyone can perform and can help people change their minds about climate change^{65,66}. However, people may feel discouraged talking about their feelings and “self-silence” for reasons such as fear of embarrassment or losing respect⁶⁷, or potentially because of emotional factors (e.g., feelings of hopelessness) as indicated by the current research. Self-silencing may contribute to feelings of isolation and impede building social connections that can support people’s mental health and resilience⁶. Providing people with opportunities to get involved with climate change and talk with others about it can be beneficial to both individual and social well-being—and to addressing climate issues. Groups that tend to experience higher levels of distress as shown here (e.g., Hispanics/Latinos, lower-income earners, younger adults) may especially benefit from climate-related mental health resources. More research is needed on the effectiveness of various interventions in helping people manage their climate-related distress.

The mental health harms of climate change are receiving increased attention, and it is important to recognize that they are multifaceted and that people have unique experiences and needs^{6,68}. Furthermore, individuals have different capacities and barriers to taking action that are influenced by several factors, like socioeconomic status or cultural values (e.g., dietary choices)^{13,24,64}. While climate change psychological distress may motivate engagement in climate action, which in turn may help some people cope, it is essential that people experiencing distress have access to effective mental health resources and support⁷. Building accessible and climate-informed mental health services is important to helping people cope, promoting positive engagement with climate change, and strengthening adaptive resilience and overall well-being in the face of these challenges.

Methods

Two nationally representative surveys of U.S. adults were conducted December 2–12, 2022 and October 20–26, 2023, and included measures of

global warming beliefs and attitudes, risk perceptions, and policy preferences. The two distinct samples are combined in the analysis ($N = 2,118$). Both samples were drawn from an online panel (the Ipsos KnowledgePanel[®]) using probability sampling methods and a combination of random digit dial and address-based sampling techniques to cover essentially all non-institutional resident phone numbers and addresses in the U.S. Prospective respondents who lacked Internet access were loaned computers and provided Internet access so they could participate. Respondents self-administered the questionnaire online. The median completion times for both surveys were 22 minutes. Key sociodemographic variables (e.g., gender, age, race, education, income) were weighted post-survey to align with U.S. Census Bureau parameters, and sampling weights were adjusted to account for sample sizes differences across waves.

Measures

Survey questions and details on missing data and how variables were coded are available in the Supplemental Material (see Table S2 for descriptives and missing data, and Table S3 for a correlation matrix).

Climate change psychological distress. Two validated brief screening tools for depression (PHQ-2)⁶¹ and general anxiety disorder (GAD-2)⁶¹ were adapted to assess distress about global warming⁸. Respondents were asked “Over the last 2 weeks, how often have you been bothered by the following problems?” and were provided with two statements measuring features of anxiety (“Feeling nervous, anxious, or on edge because of global warming” and “Not being able to stop or control worrying about global warming”) and two statements measuring features of depression (“Little interest or pleasure in doing things because of global warming” and “Feeling down, depressed, or hopeless because of global warming”). Because of the skew on this variable (see Table S4), respondents who answered “Not at all” to all four items were coded as 0 = “Not distressed” ($n = 1759$) and those who answered “Several days,” “More than half the days,” or “Nearly every day” to at least one of the statements were coded as 1 = “Distressed” ($n = 327$). Regression analyses that used a mean composite of the four items on the original 4-point scale (from 1 = “Not at all” to 4 = “Nearly every day”) were similar to analyses that used the binary variable (see Table S13). Additionally, there were no statistical differences in distress across waves (see Table S5).

Levels of climate change psychological distress. Levels of distress were assessed in three ways using the cut-offs from the Patient Health Questionnaire (PHQ-4), which includes the two subscales measuring features of depression (PHQ-2) and general anxiety (GAD-2)⁶¹. To measure degree of climate change psychological distress, responses to all four distress items were summed to range from 0 to 12 and were categorized as “None/No distress at all” (score of 0; $n = 1,759$), “Low” (scores 1–2; $n = 169$), “Mild” (scores 3–5; $n = 108$), and “Moderate/Severe” (scores 6–12; $n = 50$). To measure degree of climate-related depression and anxiety among respondents who experienced at least some climate change psychological distress, responses to the two depression items and two anxiety items were summed, respectively, to range from 0 to 6 and were each categorized as “Lower levels” (scores less than 3; depression $n = 268$; anxiety $n = 261$) or “Higher levels” (scores 3 or higher; depression $n = 59$; anxiety $n = 66$).

Intentions to engage in collective action on climate change. Respondents were asked “How likely would you be to do each of the following things if a person you like and respect asked you to?” and were provided with seven behaviors (e.g., “Meet with an elected official or their staff about global warming”). Respondents indicated how likely they would perform the behaviors on a scale from 1 = “Definitely would not” to 4 = “Definitely would” (including “Don’t know” and “Prefer not to answer” options which were coded as missing data). Responses were averaged to compute a mean score for each respondent ($M = 2.02$, $SD = 0.86$, $\alpha = 0.94$). In supplemental sensitivity analyses, we recoded the

measure to include “Don’t know” responses as the scale midpoint (overall, results were similar; see Tables S2b and S12).

Willingness to join a climate campaign. Respondents were asked a single question “How willing or unwilling would you be to join a campaign to convince elected officials to take action to reduce global warming?” on a scale from 1 = “I definitely would *not* do it” to 4 = “I definitely would do it” with an additional response option 5 = “I am participating in a campaign like this now” ($M = 2.06$, $SD = 1.09$). The “Not sure” and “Prefer not to answer” response options were coded as missing data. In supplemental sensitivity analyses, we recoded the measure to include “Not sure” responses as the scale midpoint (overall, results were similar; see Tables S2b and S12).

Past engagement with collective action on climate change. Respondents were asked “Over the past 12 months, how many times have you done the following?” and were provided with four behaviors (e.g., “Volunteered your time to an organization working on global warming”). Respondents indicated whether they had performed the behaviors on a scale from 1 = “Never” to 5 = “Many times (6 +)” (including a “Don’t know” option which was coded as missing data). Responses were averaged to compute a mean score for each respondent ($M = 1.18$, $SD = 0.49$, $\alpha = 0.79$). Because this measure was highly skewed, we also tested an alternative calculation in sensitivity analyses and included “Don’t know” responses in the measure (overall, results were similar; see Tables S2b and S12).

Engagement in climate discussions. Respondents were asked a single question “How often do you discuss global warming with your family and friends?” on a scale from 1 = “Never” to 4 = “Often” ($M = 2.13$, $SD = 0.93$).

Collective efficacy beliefs. Respondents were asked “How confident are you that people like you, working together, can...” and rated two statements (“affect what the federal government does about global warming” and “affect what corporations do about global warming”) on a scale from 1 = “Not at all confident” to 5 = “Extremely confident.” Responses were averaged to compute a mean score for each respondent ($M = 2.24$, $SD = 1.04$, $r = 0.84$).

Perceived social norms. Respondents completed two measures of perceived social norms: beliefs about what other people are doing (descriptive norms) and expect you to do (injunctive norms; Schultz et al., 2007). To assess descriptive norms, respondents were asked “How much of an effort do your family and friends make to reduce global warming?” on a scale from 1 = “No effort” to 5 = “A great deal of effort.” To measure injunctive norms, respondents were asked “How important is it to your family and friends that you take action to reduce global warming?” on a scale from 1 = “Not at all important” to 5 = “Extremely important.” Both items included a “Don’t know” option which was coded as missing data. Because perceived descriptive and injunctive norms were highly correlated ($r = 0.70$), responses to these two questions were averaged to compute a mean score for each respondent ($M = 2.33$, $SD = 1.00$). In supplemental sensitivity analyses, we recoded the measure to include “Don’t know” responses as the scale midpoint (overall, results were similar; see Tables S2b and S12).

Worry about global warming. Respondents answered a single question “How worried are you about global warming?” on a scale from 1 = “Not at all worried” to 4 = “Very worried” ($M = 2.75$, $SD = 1.04$).

Political ideology and party affiliation. Respondents indicated their political ideology by answering the question “In general, do you think of yourself as...” on a scale from 1 = “Very liberal” to 5 = “Very conservative” ($M = 3.05$, $SD = 1.09$). This single-item measure was tested as a covariate in the main regression models. Party affiliation was used for

descriptive analyses and supplemental sensitivity analyses substituting political ideology in regression models (see Table S14; results were similar to analyses controlling for political ideology). Respondents answered the question “Generally speaking, do you think of yourself as with the following response options: “Republican,” “Democrat,” “Independent,” “Other; Please specify,” and “No party/not interested in politics.” Republicans and Democrats include respondents who initially identified as either a Republican or Democrat, as well as those who do not initially identify as a Republican or Democrat but who say they “are closer to” one of those parties (i.e., “leaners”) in a follow-up question (see Table S2a for the question wording). The category “Independents” does not include any of these “leaners.” Respondents were coded as “No party” if they selected “No party/not interested in politics.” Democrats were coded as a “Liberal Democrat” if they said they were “very” or “somewhat” liberal to the political ideology question, or were coded as a “Moderate/Conservative Democrat” if they said they were “moderate, middle of the road” or “somewhat” or “very” conservative. Republicans were coded as a “Conservative Republican” if they said they were “very” or “somewhat” conservative to the political ideology question, or were coded as a “Liberal/Moderate Republican” if they said they were “moderate, middle of the road” or “somewhat” or “very” liberal (see Table S1 for sample sizes).

Sociodemographics. The following were used as covariates in regression models: gender (1 = “Male” and 2 = “Female” or “Non-binary/Other”), race/ethnicity (dummy coded with “White, non-Hispanic/Latino” as the reference group), age (continuous), education (1 = “High school or less,” 2 = “Some college,” 3 = “Bachelor’s degree or higher”), annual household income (1 = “Less than \$50,000,” 2 = “\$50,000–\$99,999,” 3 = “\$100,000 or more”), and urbanicity (1 = “Non-urban resident” and 2 = “Urban resident”). Refer to the Supplemental Material for sample sizes and details about how subgroups were calculated for both descriptive and regression analyses.

Analytic procedure

We first investigated the descriptive statistics of U.S. adults who experienced at least one feature of climate change psychological distress. For descriptive purposes, percentages were weighted to match population parameters. Chi-square tests were used to test differences in rates of climate change psychological distress across demographic and political groups using the unweighted sample sizes of each group. The data are unweighted for all statistical tests and regression models. We used two-tailed significance tests across all statistical analyses and all confidence intervals are calculated at the 95% level.

Next, we computed mean composites for the four climate action outcomes to statistically test the strength and robustness of climate distress effects on the climate action measures. For these and the following statistical tests, we followed the Bonferroni correction method and adjusted the alpha level of significance from .05 to .0125 (given the four dependent variables tested) to reduce the risk of Type 1 errors. Because there were several unequal variances across groups, Welch’s independent samples *t*-tests were used to test differences between people who had experienced distress and those who had not across each of the four dependent variables. Hedges’ *g* statistics are reported as measures of effect size. For descriptive purposes, we compared the weighted percentages for each individual climate action question across people who had experienced at least one feature of distress versus those who had not.

Multiple regression models were built using the lavaan package in R⁶⁹ to test distress effects on climate action while controlling for other predictors. We used the Robust Maximum Likelihood (MLR) and Full Information Maximum Likelihood (FIML) estimation methods to account for the missing data, skew, and non-normality of distributions. FIML imputes missing data by jointly estimating model parameters and missing values based on the likelihood function. Sociodemographics and additional variables are entered in as covariates. The Variance Inflation Factors of all variables were less than 3 across all models (see Tables S11–S14). Statistics

from the standardized solutions of models are presented in data tables. In supplementary sensitivity analyses, we tested the models by including “Don’t know” response options as the midpoint (instead of excluding the responses as missing data) for the following measures: perceived social norms, intentions to engage in collective action, willingness to join a climate campaign, and past engagement with climate action (overall, the results were similar; compare Tables S11 and S12). Additionally, we replicated models substituting (a) the continuous rating scale version of the climate change psychological distress measure for the binary measure, and (b) party affiliation for the measure of political ideology, and overall, the findings were similar (compare Table S11 with Tables S13 and S14).

Additionally, to further investigate the relationship between climate change psychological distress and climate action, we focused on the subgroup of people experiencing at least one feature of climate change psychological distress ($n = 327$) to test whether there is decreased action among those with the highest levels of distress in comparison to those with lower levels. We used analyses of variance (ANOVAs) to test mean differences in climate action across people with low, mild, or moderate/severe levels of overall distress; and Welch’s t -tests to test mean differences across people with lower versus higher levels of climate-related depression and anxiety.

Data availability

These data are proprietary, and thus restrictions apply to their availability. They may be requested from the corresponding author and will be made available upon reasonable request and with the permission of funders.

Code availability

The analysis code is available on the Open Science Framework at <https://osf.io/59v6g/>.

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References

- Intergovernmental Panel on Climate Change (IPCC). Climate change 2022 – impacts, adaptation and vulnerability: working group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). *Cambridge University Press* <https://doi.org/10.1017/97810093258442> (2023).
- Crimmins, A., J. et al. The impacts of climate change on human health in the United States: A scientific assessment. *U.S. Global Change Research Program, Washington, DC* <https://doi.org/10.7930/JOR49NQX> (2016).
- White, B. P. et al. Mental health impacts of climate change among vulnerable populations globally: An integrative review. *Ann. Glob. Health* **89**, 66 (2023).
- Hickman, C. et al. Climate anxiety in children and young people and their beliefs about government responses to climate change: A global survey. *The Lancet Plan. Health* **5**, e863–e873 (2021).
- Lykins, A. D., Bonich, M., Sundaraja, C. & Cosh, S. Climate change anxiety positively predicts antenatal distress in expectant female parents. *J. Anx. Dis.* **101**, 102801 (2024).
- Clayton, S. Climate anxiety: Psychological responses to climate change. *J. Anx. Dis.* **74**, 102263 (2020).
- van Valkengoed, A. M. Climate anxiety is not a mental health problem. But we should still treat it as one. *Bull. Atom. Sci.* **79**, 385–387 (2023).
- Uppalapati, S. et al. The prevalence of climate change psychological distress among American adults. *Yale Program on Climate Change Communication* <https://climatecommunication.yale.edu/publications/climate-change-psychological-distress-prevalence/> (2023).
- American Psychological Association. Psychologists reaching their limits as patients present with worsening symptoms year after year: 2023 Practitioner Pulse Survey. American Psychological Association <https://www.apa.org/pubs/reports/practitioner/2023-psychologist-reach-limits> (2023).
- Coffey, Y., Bhullar, N., Durkin, J., Islam, M. S. & Usher, K. Understanding eco-anxiety: A systematic scoping review of current literature and identified knowledge gaps. *J. Clim. Change Health* **3**, 100047 (2021).
- Koder, J., Dunk, J. & Rhodes, P. Climate distress: A review of current psychological research and practice. *Sust* **15**, 8115 (2023).
- Pihkala, P. Toward a taxonomy of climate emotions. *Front. Clim.* **3**, 738154 (2022).
- Constantino, S. M. et al. Scaling up change: a critical review and practical guide to harnessing social norms for climate action. *Psych. Sci. Pub. Int.* **23**, 50–97 (2022).
- Ockwell, D., Whitmarsh, L. & O’Neill, S. Reorienting climate change communication for effective mitigation: forcing people to be green or fostering grass-roots engagement? *Sci. Comm.* **30**, 305–327 (2009).
- Clarke, A. T. Coping with interpersonal stress and psychosocial health among children and adolescents: A meta-analysis. *J. Youth Adol.* **35**, 10–23 (2006).
- Penley, J. A., Tomaka, J. & Wiebe, J. S. The association of coping to physical and psychological health outcomes: A meta-analytic review. *J. Beh. Med.* **25**, 551–603 (2002).
- Ojala, M. How do children cope with global climate change? Coping strategies, engagement, and well-being. *J. Env. Psych.* **32**, 225–233 (2012).
- Schwartz, S. E. O. et al. Climate change anxiety and mental health: Environmental activism as buffer. *Curr. Psych.* **42**, 16708–16721 (2023).
- Clayton, S. & Karazsia, B. T. Development and validation of a measure of climate change anxiety. *J. Env. Psych.* **69**, 101434 (2020).
- Stanley, S. K., Hogg, T. L., Leviston, Z. & Walker, I. From anger to action: Differential impacts of eco-anxiety, eco-depression, and eco-anger on climate action and wellbeing. *J. Clim. Change Health* **1**, 100003 (2021).
- Curl, S. L., Stanley, S. K., Brown, P. M. & O’Brien, L. V. Nature connectedness in the climate change context: Implications for climate action and mental health. *Trans. Iss. Psych. Sci.* **8**, 448–460 (2022).
- Hepp, J., Klein, S. A., Horsten, L. K., Urbild, J. & Lane, S. P. Introduction and behavioral validation of the climate change distress and impairment scale. *Sci. Rep.* **13**, 11272 (2023).
- Latkin, C., Dayton, L., Scherkoske, M., Countess, K. & Thrul, J. What predicts climate change activism?: An examination of how depressive symptoms, climate change distress, and social norms are associated with climate change activism. *J. Clim. Change Health* **8**, 100146 (2022).
- Ogunbode, C. et al. Climate anxiety, pro-environmental action and wellbeing: Antecedents and outcomes of negative emotional responses to climate change in 28 countries. *J. Env. Psych.* **84**, 1–13 (2022).
- Sangervo, J., Jylhä, K. M. & Pihkala, P. Climate anxiety: Conceptual considerations, and connections with climate hope and action. *Glob. Env. Change* **76**, 102569 (2022).
- Thomson, E. E. & Roach, S. P. The relationships among nature connectedness, climate anxiety, climate action, climate knowledge, and mental health. *Front. Psych.* **14**, 1241400 (2023).
- Verplanken, B., Marks, E. & Dobromir, A. I. On the nature of eco-anxiety: How constructive or unconstructive is habitual worry about global warming? *J. Env. Psych.* **72**, 101528 (2020).
- Innocenti, M. et al. How can climate change anxiety induce both pro-environmental behaviours and eco-paralysis? The mediating role of general self-efficacy. *International J. Env. Research Pub. Health* **20**, 3085 (2023).
- Ballew, M. et al. Is distress about climate change associated with climate action? *Yale Program on Climate Change Communication*

- <https://climatecommunication.yale.edu/publications/distress-about-climate-change-and-climate-action/> (2023).
30. Cohen J. Statistical power analysis for the behavioral sciences (Routledge Academic, 1988).
 31. Brulle, R. J. & Pellow, D. N. Environmental justice: human health and environmental inequalities. *Ann. Rev. Pub. Health* **27**, 103–124 (2006).
 32. U.S. Environmental Protection Agency. Climate change and social vulnerability in the United States: a focus on six impacts. *U.S. Environmental Protection Agency* www.epa.gov/cira/social-vulnerability-report (2021).
 33. Mohai, P., Pellow, D. & Roberts, J. T. Environmental justice. *Ann. Rev. Env. Res.* **34**, 405–430 (2009).
 34. Mohai, P. & Bryant, B. Is there a “race” effect on concern for environmental quality? *Pub. Op. Quart.* **62**, 475–505 (1998).
 35. Bullard, R. D., Mohai, P., Saha, R. & Wright, B. Toxic wastes and race at twenty: Why race still matters after all of these years. *Env. Law* **38**, 371–411 (2008).
 36. Tessum, C. W. et al. Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proc. Nat. Acad. Sci.* **116**, 6001–6006 (2019).
 37. Macias, T. Environmental risk perception among race and ethnic groups in the United States. *Eth* **16**, 111–129 (2016).
 38. Satterfield, T. A., Mertz, C. K. & Slovic, P. Discrimination, vulnerability, and justice in the face of risk. *Risk Anal* **24**, 115–129 (2004).
 39. Shonkoff, S. B., Morello-Frosch, R., Pastor, M. & Sadd, J. The climate gap: environmental health and equity implications of climate change and mitigation policies in California—a review of the literature. *Clim. Change* **109**, 485–503 (2011).
 40. Pearson, A. R., Schuldt, J. P., Romero-Canyas, R., Ballew, M. T. & Larson-Konar, D. Diverse segments of the US public underestimate the environmental concerns of minority and low-income Americans. *Proc. Nat. Acad. Sci.* **115**, 12429–12434 (2018).
 41. Bullard, R. D. Dumping in Dixie: Race, class, and environmental quality (Routledge, 2018).
 42. Figueroa, R. M. Indigenous peoples and cultural losses in The Oxford handbook of climate change and society (eds. Dryzek, J. S. et al.) 232–249 (Oxford University Press, 2011).
 43. Martinez-Alier, J., Temper, L., Del Bene, D. & Scheidel, A. Is there a global environmental justice movement? *Journal Peas. Stud.* **43**, 731–755 (2016).
 44. Schlosberg, D. & Collins, L. B. From environmental to climate justice: climate change and the discourse of environmental justice. *Wil. Int. Rev.: Clim. Change* **5**, 359–374 (2014).
 45. Thomas, L. The intersectional environmentalist: How to dismantle systems of oppression to protect people + planet (Souvenir Press, 2022).
 46. Ballew, M. T., Goldberg, M. H., Rosenthal, S. A., Cutler, M. J. & Leiserowitz, A. Climate change activism among Latino and White Americans. *Front. Comm.* **3**, 58 (2019).
 47. Ballew, M. et al. Which racial/ethnic groups care most about climate change? *Yale Program on Climate Change Communication* <https://climatecommunication.yale.edu/publications/race-and-climate-change/> (2020).
 48. Whittaker, M., Segura, G. M. & Bowler, S. Racial/ethnic group attitudes toward environmental protection in California: is “environmentalism” still a white phenomenon? *Pol. Res. Quart.* **58**, 435–447 (2005).
 49. Lorenzen, J. A. & Drew, E. We Need Communities of Color’: How Coalitions Can Move from Climate Action to Climate Justice. *Soc. Just. Res.* **36**, 103–131 (2023).
 50. Taylor, D. E. American environmentalism: the role of race, class and gender in shaping activism 1820–1995. *Race, Gen. Class* **5**, 16–62 (1997).
 51. Parmentier, M. L. et al. The influence of environmental crisis perception and trait anxiety on the level of eco-worry and climate anxiety. *J. Anx. Dis.* **101**, 102799 (2024).
 52. Whitmarsh, L. et al. Climate anxiety: What predicts it and how is it related to climate action? *J. Env. Psych.* **83**, 101866 (2022).
 53. Zawadzki, S. J., Steg, L. & Bouman, T. Meta-analytic evidence for a robust and positive association between individuals’ pro-environmental behaviors and their subjective wellbeing. *Env. Res. Lett.* **15**, 123007 (2020).
 54. Urbild, J., Zauner, K. & Hepp, J. Panic internally, act sustainably: Climate change distress predicts pro-environmental behavior in a modified work for environmental protection task and a dictator game. *Curr. Res. Eco. Soc. Psych.* **4**, 100099 (2023).
 55. Wullenkord, M. C., Tröger, J., Hamann, K. R. S., Loy, L. S. & Reese, G. Anxiety and climate change: A validation of the Climate Anxiety Scale in a German-speaking quota sample and an investigation of psychological correlates. *Clim. Change* **168**, 20 (2021).
 56. Doherty, T. Mental health impacts in Climate change and public health (eds. Levy, B. & Patz, J.) 195–214 (Oxford University Press, 2015).
 57. Corral-Verdugo, V., Mireles-Acosta, J. F., Tapia-Fonllem, C. & Fraijo-Sing, B. Happiness as correlate of sustainable behavior: A study of pro-ecological, frugal, equitable and altruistic actions that promote subjective wellbeing. *Hum. Eco. Rev.* **18**, 95–104 (2011).
 58. Gunasiri, H. et al. Hope, coping and eco-anxiety: Young people’s mental health in a climate-impacted Australia. *Int. J. Env. Res. Pub. Health* **19**, 5528 (2022).
 59. Bamberg, S., Rees, J. H., & Schulte, M. Environmental protection through societal change: What psychology knows about collective climate action—and what it needs to find out in Psychology and climate change (eds. Clayton, S. & Manning, C.) 185–213 (Academic Press, 2018).
 60. Leiserowitz, A. et al. Climate Change in the American Mind: Beliefs & Attitudes, December 2022. *Yale Program on Climate Change Communication* <https://climatecommunication.yale.edu/publications/climate-change-in-the-american-mind-beliefs-attitudes-december-2022> (2023).
 61. Kroenke, K., Spitzer, R. L., Williams, J. B. W. & Löwe, B. An ultra-brief screening scale for anxiety and depression: The PHQ-4. *Psychosom* **50**, 613–621 (2009).
 62. Hogg, T. L., Stanley, S. K., O’Brien, L. V., Wilson, M. S. & Watsford, C. R. The Hogg Eco-Anxiety Scale: Development and validation of a multidimensional scale. *Glob. Env. Change* **71**, 102391 (2021).
 63. Eom, K., Kim, H. S., Sherman, D. K. & Ishii, K. Cultural variability in the link between environmental concern and support for environmental action. *Psych. Sci.* **27**, 1331–1339 (2016).
 64. Eom, K., Kim, H. S. & Sherman, D. K. Social class, control, and action: Socioeconomic status differences in antecedents of support for pro-environmental action. *J. Exp. Soc. Psych.* **77**, 60–75 (2018).
 65. Goldberg, M. H., van der Linden, S., Maibach, E. & Leiserowitz, A. Discussing global warming leads to greater acceptance of climate science. *Proc. Nat. Acad. Sci.* **116**, 14804–14805 (2019).
 66. Hayhoe, K. Saving us: A climate scientist’s case for hope and healing in a divided world (Simon and Schuster, 2021).
 67. Geiger, N. & Swim, J. K. Climate of silence: Pluralistic ignorance as a barrier to climate change discussion. *J. Env. Psych.* **47**, 79–90 (2016).
 68. Doherty, T. J. & Clayton, S. The psychological impacts of global climate change. *Am. Psych.* **66**, 265–276 (2011).
 69. Rosseel, Y. Lavaan: An R package for structural equation modeling. *J. Stat. Soft.* **48**, 1–36 (2012).

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Author contributions

MB developed the research design, analyzed the data, and wrote the manuscript. SU assisted with the development of measures and writing

the manuscript. TM and JM assisted with the development of the research design and measures. EC and SR assisted with the development of measures. JK, AL, and EM led the development of measures and assisted with the research design. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethics

The survey research this study received an exemption determination from the Human Research Protection Program, Institutional Review Board at Yale University (IRB Protocol Number: 2000028451). All respondents gave electronic informed consent to complete the online survey.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s44168-024-00172-8>.

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