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Validation of the Hogg Climate Anxiety Scale

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Abstract
As one of the biggest environmental and equality challenges of our time, climate change is causing some people to experience *climate anxiety*. To address the need for valid and reliable measurement of this construct, we adapted the Hogg Eco-Anxiety Scale to measure climate anxiety in the United Kingdom ($n=501$) and United States ($n=508$). In both samples, we found the Hogg Climate Anxiety Scale (HCAS) was comprised of four dimensions: affective symptoms, behavioural symptoms, ruminative thoughts, and anxiety about one's personal impact. The four-factor HCAS fit the data well, showed measurement invariance in these two samples, and all dimensions were internally consistent. Importantly, we also provide evidence for convergent validity by demonstrating that HCAS scores were positively correlated with an alternative measure of eco-anxiety and a more general indicator of worry in one's daily life. The dimensions of the HCAS also showed distinct associations with theoretically related constructs, for example only personal impact anxiety and rumination were significant predictors of taking collective action on climate change, and personal impact anxiety was distinctly predictive of climate inequality beliefs. We recommend the HCAS as a brief (13 item) measurement tool to capture experiences of climate anxiety.

Keywords Climate anxiety · Climate injustice · Collective action · Eco-anxiety · Eco-emotions · Efficacy · Worry

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1 Introduction

Climate change is already having negative impacts on human health and habitat and these impacts are expected to increase over time (IPCC 2023). In a recent systematic review on climate change and mental health, Cianconi et al. (2020) found that climate change-fueled extreme weather events were linked with general symptoms of distress, clinical mental health problems (e.g., depression, anxiety), and risk of suicide. Climate change and environmental changes have also been linked to strong emotional responses (e.g., Hickman & Marks et al. 2021; Leiserowitz et al. 2023), and the experience of 'climate anxiety' has emerged as a prominent component of the emotional response to climate change (Coffey et al. 2021; Pihkala 2020).

1.1 Climate anxiety

Anxiety felt in response to climate change is generally thought to be subsumed within the broader experience of eco-anxiety (Pihkala 2020). Eco-anxiety captures anxiety that is related to ecological problems in a broad sense, including ecological degradation, deforestation, global pollution, and species extinction (Hogg et al. 2021), sitting at a higher level of abstraction than climate anxiety. However, due to its accelerating impacts, climate change is currently a topic of intense global concern (IPCC 2023). The ways that climate change may lead to anxiety are diverse (Clayton & Karazsia 2020). For example, people who have experienced climate change-fueled extreme weather events, such as bushfires and floods, might have climate change top of mind when feeling anxious. People also regularly encounter the idea of climate change via ominous graphs of carbon dioxide emissions, news reports from climate disaster zones, and through stories of climate injustice (Verlie 2022).

van Valkengoed et al. (2023) recently called for action on the development of a standardised definition of climate anxiety that integrates current insights from the available literature, and which focuses on its emotional, cognitive, behavioural, and physiological aspects. van Valkengoed et al. (2023; p. 2) proposed the following working definition of climate anxiety: "persistent anxiety (apprehensiveness) and worry about climate change, that is difficult to control, and associated with…emotional, cognitive, physiological, and behavioural indicators". We note that the affective, cognitive, physiological, and behavioural features of climate anxiety do not make it inherently pathological or disordered. Instead, climate anxiety (like eco-anxiety) is considered a rational and proportional response to enormous environmental problems. At the same time, the intensity and frequency with which people experience climate anxiety varies. Some people may experience climate anxiety so intensely that it affects their functioning and wellbeing (Clayton 2020). Thus, people's experiences of climate anxiety exist on a continuum ranging from 'mild' and non-debilitating to 'significant and severe' depending on the frequency and impact of their distress (Hickman 2020; Lutz et al. 2023).

1.2 Operationalisation of climate anxiety

Sound measurement is integral to understanding the implications of a phenomenon that is both qualitatively and quantitatively complex. Until recently, climate anxiety was typically measured as the anxiety response to climate change (e.g., ratings of how 'anxious' and

'afraid' one feels in relation to climate change; Stanley et al. 2021). Such conceptualisations of climate anxiety are oversimplified and fail to capture the multifaceted nature of the phenomenon. In 2020, Clayton and Karazsia (2020) made a substantial advance to this literature by developing a multidimensional tool for climate anxiety, the Climate Anxiety Scale (CAS; sometimes also referred to as the Climate Change Anxiety Scale). Their scale indexed climate anxiety by the frequency that participants experienced 'cognitive-emotional impairments' and 'functional impairments'. The former component is characterised by difficulties concentrating, nightmares, crying, difficulties sleeping, and analysis of one's thoughts about climate change, while the latter is characterised by difficulties having fun with family and friends, completing work and/or study, and reaching individual potential. However, this measure of climate anxiety has shown inconsistent psychometric performance across studies and when used in different countries (Hogg et al. 2023).

An alternative measurement model is the Hogg Eco-Anxiety Scale (HEAS; Hogg et al. 2021). The HEAS was designed to delineate symptoms of a broader eco-anxiety experience, which includes climate anxiety. The HEAS dimensions were developed from an existing anxiety scale (Spitzer et al. 2006) and from qualitative responses by eco-anxious participants describing their experiences of eco-anxiety (Hogg et al. 2021). Dimensions relate to affect (worry, feelings of nervousness), behaviour (trouble sleeping or socialising), rumination (unable to stop thinking about environmental problems), and concern about one's personal contribution to environmental problems. These dimensions of eco-anxiety have been shown to differentially relate to wellbeing and pro-environmental behaviour (Hogg et al. 2024). However, despite the relevance of the HEAS to climate anxiety, its broader focus means that it is not always the right fit for researchers wishing to draw specific conclusions about climate anxiety.

To support research with a more specific scope, the HEAS was published with a series of guidelines for adapting the measure to understand other environment-related anxieties, including anxiety about specific environmental harms (e.g., pollution), and climate anxiety. To our knowledge, the HEAS has not yet been adapted for these purposes, but given the inconsistent performance of the CAS across studies (Hogg et al. 2023), we were interested in testing the performance of an adapted HEAS as an alternative measurement model for climate anxiety. In this article, we aim to adapt the HEAS (Hogg et al. 2021) to test how it performs as a measure of climate anxiety. We refer to the adapted scale hereafter as the Hogg Climate Anxiety Scale (HCAS). We adapt the instructions of the HEAS and the phrasing of the items to understand experiences of climate anxiety along affective, behavioural, ruminative, and personal impact dimensions. We speculate that for many people, their eco-anxiety may be centred on climate anxiety. As a result, we expect that the same four dimensions of eco-anxiety identified in the HEAS will reproduce as dimensions of the HCAS. An advantage of establishing the measurement of climate anxiety through the HCAS is that doing so provides an alternative measurement model to existing scales, and it does so with a comprehensive set of subscales to help researchers understand the various aspects we currently expect to make up the experiences of climate anxiety, consistent with van Valkengoed et al.'s (2023) working definition.

To investigate the convergent validity of the HCAS, we interrogate its associations with theoretically related measures, including other emotional responses people experience in relation to climate change (eco-anxiety, eco-anger, eco-depression, eco-hope) and general worry. We expect climate anxiety (as measured by the HCAS) to be positively correlated

with an alternative measure of eco-anxiety, as well as eco-anger and eco-depression. We tentatively predict heightened eco-hope scores among those with greater emotional engagement with climate change (i.e., positive correlations with HCAS scores; Ojala 2012, 2013). We expect positive associations with the tendency to experience worry, though moderate in strength to indicate separate but related constructs (i.e., associations below .80; Field 2018). We expect that the dimensions of climate anxiety will differentially relate to general worry, such that the symptomatic aspects (affective and behavioural symptoms) will more strongly predict worry, compared to rumination and personal impact anxiety (Hogg et al. 2024).

1.3 Correlates of climate anxiety

We also examine whether some groups of people, who are particularly vulnerable to the effects of climate change, also experience climate anxiety to a greater degree, and whether and how individual characteristics are related to features of climate anxiety, including climate inequality beliefs, efficacy beliefs, and climate activism.

Two groups who are vulnerable to the impacts of climate change are young people and those who are financially disadvantaged. Because climate change will continue to worsen over time, younger and future generations will bear the brunt of climate change impacts (IPCC 2023). Hickman and Marks et al. (2021) showed that *most* 16–25-year-olds who responded to their global survey from the United Kingdom (UK) and United States (US) felt anxious about climate change (UK: 60%; US: 58%). The majority also shared the view that governments were failing young people and future generations in relation to climate change. This aligns with the generational injustice inherent in climate change: young people have contributed minimally to climate change to date and future generations are yet to have any impact, and yet they will be most affected. Thus, we expected younger adults would report greater climate anxiety in our study (Clayton & Karaszia 2020). Past research has found little direct association between income and climate attitudes, although greater financial resources are associated with greater environmental efficacy (Marquart-Pyatt 2012). Financial hardship has been examined less. While a range of regional factors may affect the priorities of the financially disadvantaged, they are more vulnerable to climate impacts (Benevolenza & DeRigne 2019) and to experiencing depression and anxiety in general (Butterworth et al. 2012; Frankham et al. 2020). Therefore, and consistent with Weckroth and Ala-Mantila (2022), we expected that those experiencing greater financial hardship would experience greater climate anxiety (see Gibson et al. 2020).

A pervasive theme throughout human history has seen disadvantaged groups disproportionately exposed to environmental hazards, while advantaged groups are spared the risks and enjoy more of the benefits of environmental resources. Climate change is the latest form of environmental inequality: those contributing the least to causing the problem are typically most at risk, both within countries (Chancel 2022) and across countries (IPCC 2023; van Houtan et al. 2021). The UK and US are both high emitting nations that also have substantive internal disadvantage (Chancel 2022). For example, in the US, high income earners (top 10% income bracket) each contribute close to *seven times* the emissions per year of the lower half of income earners (Chancel 2022). Qualitative research indicates that people's anxieties about the planet are tied to their perceptions of climate injustice issues. Uchendu (2022) found, when speaking with climate activists in the UK, that their anxieties about environmental problems were related to their understanding of climate injustice issues and

inequalities between countries, whereby developed nations (the very nations these activists come from) have emitted large volumes of greenhouse gases to achieve their current level of industrialisation. Qualitative research also shows that adults are worried about the impact climate change will have, not only on their current or future children, but on future generations more broadly, which is reflective of the inequalities between generations (e.g., Howard 2022). We speculated that climate inequality beliefs would therefore correlate with greater climate anxiety (Verlie 2022).

Those experiencing climate anxiety are more likely to believe that climate issues can be resolved through individual and collective action (Ojala et al. 2021; Sangervo et al. 2022), and are more likely to engage in individual and collective action (Heeren et al. 2022). Although there is limited research on the unique relationships between the dimensions of climate anxiety and efficacy beliefs, recent research by Hogg et al. (2024) found that the dimensions of eco-anxiety differentially related to pro-environmental behaviour outcomes, whereby rumination and personal impact anxiety uniquely predicted individual pro-environmental behaviour. We, therefore, speculated that efficacy beliefs (because these beliefs relate to behavioural change) and collective action would generally correlate positively with the dimensions of climate anxiety. When the climate anxiety dimensions are included together as predictors in a regression analysis, we expected rumination and personal impact anxiety would be uniquely stronger predictors of efficacy beliefs and collective action than affective and behavioural symptoms.

2 Method

2.1 Participants and procedure

We aimed to recruit 550 participants from each country and placed this number of spots on Prolific for a 10-minute survey with compensation of 1.25GBP. Data were collected between 18 and 19 October 2022. A total of 547 participants from the UK and 554 from the US completed the surveys. Participants were excluded if they failed either of two instructional attention checks ($n=16$ in UK, $n=26$ in US), or were identified as either a univariate outlier (indicated by a standardised score on the climate anxiety dimensions that were more than 3.3 standard deviations away from the mean) or multivariate outliers (indicated by significant Mahalanobis distance, $p<.001$, on the variables of interest; total number of outliers were $n=30$ in UK, $n=20$ in US)[1]. After these exclusions were applied, our final samples were comprised of 501 participants in the UK (aged 18–77 years, $M=41.89$, $SD=12.08$; 50.1% women, 48.9% men, 1% preferred another term or preferred not to say) and 508 in the US (aged 18–82 years, $M=36.25$, $SD=12.90$; 49.8% women, 48.0% men, 2.2% preferred another term or not to answer).

[1] In the main text, we present results based on data where participants who failed attention checks or were identified as outliers were excluded. Results including outliers, but excluding participants who failed attention checks, are presented in the Supplementary Materials. While there were no substantial differences between these sets of results or in the interpretation of findings, some effect sizes appeared stronger when the outliers were included in the analysis.

2.2 Measures

The Supplementary Materials include the exact wording of all items belonging to the measures described below, and the results supporting the factor structure of the measures.

Climate anxiety We modified the scale instructions and relevant items of the HEAS (Hogg et al. 2021) to refer to climate anxiety. Specifically, the instructions read:

> Over the last 2 weeks, how often have you been bothered by the following problems, when thinking about climate change?

Participants rated their experiences of affective symptoms (four items, e.g., "Worrying too much"), behavioural symptoms (three items, e.g., "Difficulty working and/or studying), ruminative thoughts (three items, e.g., "Unable to stop thinking about climate change"), and personal impact anxiety (three items, e.g., "Feeling anxious about the impact of your personal behaviours on climate change) using the response scale: 0 (*not at all*), 1 (*several of the days*), 2 (*over half the days*), 3 (*nearly every day*). See Appendix A for all items in the Hogg Climate Anxiety Scale, which is free to use without permission from the authors.

Eco-emotions We asked participants to mark on a sliding scale how much they experienced a series of eco-emotions from 0 (*not at all this way*) to 100 (*a great deal*). We expanded on Stanley et al.'s (2021) materials to measure each eco-emotion with four items: eco-anxiety (scared, worried, afraid, anxious: UK $\alpha = .95$, $\omega = .95$; US $\alpha = .96$, $\omega = .96$), eco-anger (frustrated, mad, irritated, angry: UK $\alpha = .92$, $\omega = .92$; US $\alpha = .96$, $\omega = .96$), eco-depression (depressed, miserable, sad, upset: UK $\alpha = .91$, $\omega = .91$; US $\alpha = .92$, $\omega = .93$), and expanded Hornsey and Fielding's (2016) measure of eco-hope (hopeful, optimistic, encouraged, determined: UK $\alpha = .89$, $\omega = .89$; US $\alpha = .88$, $\omega = .88$).

Climate inequality beliefs Participants responded to three items ("Climate change will make global inequality worse", "There is inequality in who causes climate change and who will be most affected by its consequences", and "There is inequality in who benefits from high-emission activities and who is burdened by environmental decline"; UK $\alpha = .89$, $\omega = .89$; US $\alpha = .91$, $\omega = .91$) using Likert scales from 1 (*strongly disagree*) to 7 (*strongly agree*).

Efficacy We included two items each to capture self-, collective- and participative efficacy (van Zomeren et al. 2010, 2013). Principal components analysis detailed in the Supplementary Materials (Table S1) showed that the items were clearly undifferentiated in each sample, so we combined them to create a six-item index of perceived efficacy to address climate change (UK $\alpha = .93$, $\omega = .93$; US $\alpha = .93$, $\omega = .93$).

Collective action Participants rated from 0 (*never*) to 100 (*at every opportunity*) how often in the past year they had taken eight collective actions (e.g., "Considered changing who you would vote for because of climate change matters", UK $\alpha = .81$, $\omega = .83$; US $\alpha = .84$, $\omega = .87$) from Stanley et al. (2021).

Financial hardship To assess objective financial deprivation, we included items developed by the Australian Bureau of Statistics (2000; Bray 2001). Participants answered yes (1) or no (0) to whether they experienced any of seven financial hardships since January, including "went without meals" and "was unable to heat home". A computed total score indicated that about half the sample experienced no financial hardship and therefore we created a binary measure where 0 = *no stress* and 1 = *experienced some financial hardship*.

Worry Participants responded to Topper et al.'s (2014) Penn State Worry Questionnaire (five items: e.g., "Many situations make me worry", UK α = .95, ω = .95; US α = .96, ω = .96) using the response scale: 1 (*not at all typical of me*) to 5 (*very typical of me*).

2.3 Data analysis strategy

We conducted Confirmatory Factor Analysis using Lavaan in R (Rosseel 2012) to evaluate the internal structure of the HCAS, testing one- and four-dimensional models. We used Maximum Likelihood estimation with robust standard errors (MLR estimator) to account for deviations in normality (UK: Mardia skewness = 6945.72, kurtosis = 119.16, $p < .001$; US: Mardia skewness = 6154.82, kurtosis = 126.29, $p < .001$). We follow Hu and Bentler's (1999) recommendations to evaluate the model fit: CFI and TLI values equal to or greater than .90 and .95 indicate satisfactory fit or good fit respectively, and RMSEA and SRMR values less than or equal to .08 and .06 indicate satisfactory or good fit respectively.

We conducted Multigroup Confirmatory Factor Analysis (using MLR estimation) in R to evaluate the measurement invariance (i.e., equivalence) of the HCAS across UK and US samples, and across gender in each sample. A series of nested models were tested and compared: a configural invariance model (i.e., factor structures are constrained across groups), metric invariance model (i.e., factor loadings are constrained to be equal across groups) and scalar invariance model (i.e., factor loadings and item means are constrained to be equal; Putnick & Bornstein 2016; Milfont & Fischer 2010). We evaluated overall model fit using Hu and Bentler's (1999) conventions, and the change in fit indices between the models using Chen's (2007) conventions, which is consistent with other research (Chen 2007; Milfont & Fischer 2010; Putnick & Bornstein 2016). Chen's (2007) guidelines for equal sample sizes are: ΔCFI ≤ .010, ΔRMSEA ≤ .015, ΔSRMR: metric ≤ .030, scalar ≤ .010.

Associations between the HCAS dimensions and relevant variables were tested via Pearson correlations. The unique associations between the climate anxiety dimensions and relevant variables were tested via a series of multiple linear regressions. We assessed whether there were issues with multicollinearity during regression analysis by examining the zero-order correlations between the dimensions of climate anxiety, tolerance and VIF statistics. Zero-order correlations between the dimensions (UK r's = .27 to .59; US r's = .32 to .69) were below commonly accepted levels for multicollinearity (r's > .80 may indicate issues), and all tolerance and VIF statistics were greater than 0.10 or less than 10 respectively, indicating no issues with multicollinearity in either sample (Field 2018).

3 Results

Data are available on the Open Science Framework: https://osf.io/pqwmb/?view_only=e1ac799cce4448839c57654bd3663ad3

3.1 Psychometric analysis of the Hogg Climate Anxiety Scale

Results showed excellent model fit of the 4-factor HCAS (Table 1). Comparatively, model fit indicators were poor for the unidimensional model (UK: $\Delta\chi^2(6)=427.56$, $p<.001$; US: $\Delta\chi^2(6)=579.13$, $p<.001$). We also tested a hierarchical model with the four climate anxiety dimensions set to predict a higher-order latent climate anxiety factor in both the UK and US (see S2 in the Supplementary Materials for specific results), however, these results did not support aggregating the four facets of climate anxiety into a single index. Factor loadings for the four dimensional model were strong across both samples (Table 2) and all dimensions of the HCAS were internally consistent: affective symptoms: UK α=.84, ω=.85, US α=.90, ω=.90; rumination: UK α=.79, ω=.80, US α=.89, ω=.89; behavioural symptoms: UK α=.70, ω=.71, US α=.84, ω=.84; personal impact anxiety: UK α=.87, ω=.87, US α=.90, ω=.90. These analyses support the multidimensionality and internal consistency of the HCAS.[2]

Multigroup Confirmatory Factor Analysis (using MLR estimation) reported in Table 3 showed that the HCAS achieved configural, metric, and scalar invariance across countries. As such, the factor structure, factor loadings, and item means for the HCAS were consistent between UK and US samples. See Supplementary Materials (Table S4) for invariance testing across binary genders in each country, where results show the factor structure, factor loadings, and item means for the HCAS were consistent across men and women in both countries.

Correlations of interest are reported in Table 4 (see Table S5 and S6 for full correlation matrices and descriptive information about each sample). These show convergent validity, with a positive association between HCAS scores and eco-anxiety (as measured by our alternative measure), eco-anger, eco-depression, and general worry. Weak positive associations indicated that people who more strongly agreed that climate change was an inequality issue tended to experience slightly greater climate anxiety, and that climate anxiety was also experienced alongside greater belief that we will address climate change, higher engagement in collective action, and (barring behavioural symptoms), greater hope.

Table 1 Model fit for 4-factor and 1-factor Hogg Climate Anxiety Scale

	χ^2 (*df*)	CFI	TLI	RMSEA	90% CI RMSEA	SRMR
UK sample						
4-factor	91.71 (59)	.98	.97	.05	[.03, .06]	.05
1-factor	519.27 (65)	.71	.65	.17	[.15, .18]	.11
US sample						
4-factor	149.91 (59)	.96	.95	.08	[.06, .09]	.05
1-factor	729.04 (65)	.71	.66	.21	[.19, .22]	.11

Note. Robust versions of χ^2, CFI, TLI, and RMSEA values are presented

[2] Supporting the validity of all measures included in our manuscript, a full measurement model also provided good fit to the data in each country (see Table S3 for further detail).

Table 2 Fully standardised factor loadings from Confirmatory Factor Analysis of the Hogg Climate Anxiety Scale

	Affective symptoms		Rumination		Behavioural symptoms		Personal impact anxiety	
	UK	US	UK	US	UK	US	UK	US
Feeling nervous, anxious or on edge	.747	.828						
Not being able to stop or control worrying	.783	.854						
Worrying too much	.852	.872						
Feeling afraid	.673	.785						
Unable to stop thinking about future climate change			.774	.882				
Unable to stop thinking about past events related to climate change			.652	.837				
Unable to stop thinking about climate change			.828	.839				
Difficulty sleeping					.605	.761		
Difficulty enjoying social situations with family and friends					.760	.793		
Difficulty working and/or studying					.683	.869		
Feeling anxious about the impact of your personal behaviours on climate change							.840	.904
Feeling anxious about your personal responsibility to help address climate change							.867	.908
Feeling anxious that your personal behaviours will do little to help fix climate change							.804	.790
M (*SD*)	0.25 (0.41)	0.37 (0.53)	0.21 (0.37)	0.29 (0.49)	0.17 (0.35)	0.27 (0.53)	0.34 (0.49)	0.43 (0.59)

Table 3 Demonstrating invariance across countries

Country: UK = 501, US = 508							
	χ^2 (*df*)	CFI	ΔCFI	RMSEA	ΔRMSEA	SRMR	ΔSRMR
Configural	242.96 (118)	.970	--	.062	--	.044	--
Metric	260.94 (127)	.968	− .002	.063	.001	.051	.007
Scalar	277.18 (136)	.967	− .001	.061	− .002	.051	.000

We also identified some associations with demographic variables: in both samples, younger participants endorsed more affective symptoms and rumination, and age was negatively associated with behavioural symptoms in the UK and personal impact anxiety in the US. Gender was not significantly related to climate anxiety in the UK, but US women experienced higher HCAS scores than men (affective symptoms: men $M = 0.24$, $SD = 0.40$, women $M = 0.47$, $SD = 0.58$; rumination: men $M = 0.24$, $SD = 0.44$, women $M = 0.33$, $SD = 0.52$; behavioural symptoms: men $M = 0.19$, $SD = 0.47$, women $M = 0.33$, $SD = 0.57$; personal impact anxiety: men $M = 0.31$, $SD = 0.52$, women $M = 0.52$, $SD = 0.62$). Experienc-

Table 4 Correlations with climate anxiety dimensions

	Affective symptoms		Rumination		Behavioural symptoms		Personal impact anxiety	
	UK	US	UK	US	UK	US	UK	US
Eco-anxiety	.40***	.53***	.40***	.46***	.15***	.25***	.46***	.51***
Eco-anger	.35***	.43***	.41***	.39***	.15**	.25***	.42***	.44***
Eco-depression	.41***	.55***	.37***	.44***	.19***	.33***	.46***	.51***
Eco-hope	.15**	.11*	.26***	.16***	.05	.02	.18***	.18***
Climate inequality beliefs	.15**	.24***	.16***	.24***	.09*	.12**	.27***	.31***
Efficacy	.16***	.20***	.23***	.23***	.09*	.06	.21***	.32***
Collective action	.32***	.37***	.38***	.46***	.17***	.23***	.34***	.47***
Worry	.32***	.45***	.21***	.30***	.21***	.25***	.33***	.38***
Age	−.10*	−.22***	−.09*	−.16***	−.10*	−.09	−.02	−.20***
Gender	.05	.22***	−.03	.09*	.01	.13**	−.02	.18***
Financial hardship	.11*	.23***	.13**	.22***	.15**	.20***	.05	.25***

Note. Gender: 1=man and 2=woman. Financial hardship: 0=no financial hardship and 1=financial hardship. *$p<.05$, **$p<.01$, ***$p<.001$

Table 5 Distinct associations between climate anxiety dimensions and related constructs from multiple linear regression analyses

	Affective symptoms		Rumination		Behavioural symptoms		Personal impact anxiety	
	UK	US	UK	US	UK	US	UK	US
Eco-anxiety	.22***	.41***	.16**	.05	−.11*	−.10*	.29***	.25***
Eco-anger	.12*	.24***	.22***	.06	−.05	.00	.26***	.25***
Eco-depression	.22***	.38***	.11*	−.00	−.05	.00	.30***	.28***
Eco-hope	.02	−.02	.23***	.10	−.05	−.05	.07	.14*
Climate inequality beliefs	−.02	.07	.04	.03	.02	−.01	.26***	.25***
Efficacy	−.00	.03	.16**	.03	.01	−.06	.13*	.30***
Collective action	.11	−.04	.24***	.26***	−.02	.07	.17**	.31***
Worry	.18**	.45***	−.02	−.13*	.05	−.06	.23***	.20***

Note. *$p<.05$, **$p<.01$, ***$p<.001$

ing financial hardship was also associated with slightly higher HCAS scores in all cases except UK participants' personal impact anxiety.

Table 5 shows these associations from a series of multiple linear regression analyses where the four HCAS dimensions were entered as predictors of the other variables, revealing some distinct patterns of associations. Unique associations with negative climate emotions suggested that both affective symptoms and personal impact anxiety (and rumination in the UK only) predicted more intense climate-related anxiety, anger, and depression. Behavioural symptoms did not have distinct associations with anger and depression, and predicted lower intensity of reporting anxiety relating to climate change (using our alternative measure) while controlling for the other HCAS dimensions. Climate inequality beliefs was distinctly predicted by personal impact anxiety, and collective action by rumination and

personal impact anxiety. Worry was more strongly predicted by affective symptoms and personal impact anxiety.

4 Discussion

We show that the Hogg Climate Anxiety Scale is a valid and internally consistent multidimensional measure of climate anxiety in these UK and US samples. While climate anxiety sits within the broader experience of eco-anxiety (Hogg et al. 2021; Lutz et al. 2023; Passmore et al. 2022; Pihkala 2020), our findings show that climate- and eco-anxiety share common features as identified in the HCAS and HEAS: affective and behavioural symptoms, rumination, and anxiety about one's personal impact on the planet. As such, the primary distinction between these scale versions is the environmental condition(s) each scale targets. The HCAS serves as an alternative measurement model to Clayton and Karazsia's (2020) CAS and the brief nature of the HCAS (13 items) makes it a useful tool that can easily be administered in survey research. Based on our findings, we recommend that those who use the HCAS treat the four climate anxiety dimensions as distinct facets and avoid aggregating participant responses on these dimensions into a single score for climate anxiety (unless their data supports an alternative factor structure).

Consistent with previous research on associations with general mental health (e.g., Clayton & Karazsia 2020; Hogg et al. 2021), we found that climate anxiety was related to, though distinct from, feelings of worry. Some people who experience climate- and eco-anxiety do not simultaneously experience symptoms of poor mental health (Hogg et al. 2021), and may continue to seek information about environmental problems (Gunasiri et al. 2022; Hogg et al. 2023) and engage in environmental solutions (Heeren et al. 2022; Ogunbode et al. 2022).

We found that most dimensions of climate anxiety were felt more strongly among younger adults, those experiencing greater financial hardship, and in the US, among women. These demographic groups are more vulnerable to lower psychological wellbeing in general (WHO 2014), potentially explaining their heightened climate anxiety. However, a recent meta-analysis found that gender did not moderate the relationship between climate anxiety (as measured by the CAS) and wellbeing, which suggests that climate anxiety is not a greater threat to general wellbeing for women as compared to men (Gago et al. 2023). Alternatively, these associations may reflect greater climate anxiety among those more vulnerable to climate change itself. The inequity of climate change means that more vulnerable members of society, including women and people facing economic disadvantage, are more vulnerable to its effects, as well as younger generations who will experience more substantial increases in warming throughout their lifetimes (IPCC 2023). This explanation warrants further investigation, especially since our results add to the inconsistent gender-climate anxiety findings in the extant literature (Clayton & Karazsia 2020; Larionow et al. 2022; Wullenkord et al. 2021), which may indicate that gendered aspects of climate anxiety are context dependent. Further research is required to better understand the gendered aspects of climate anxiety.

In pursuing further research, we suggest moving beyond a focus on emotional responses to climate change as an individual-level phenomenon to acknowledge that climate anxiety is situated within a system-level problem. Consistent with this approach, we identified that those who held stronger beliefs that there is inequality inherent in the issue of climate change were more anxious about their personal contribution to climate change. A greater

appreciation of the disparity in vulnerability to, versus responsibility for, causing climate change could underlie some experiences of climate anxiety, alongside responses like moral outrage (Antadze 2020).

Regression analysis showed that specific dimensions of climate anxiety were associated with climate action: personal impact anxiety and rumination. This aligns with previous research showing that these dimensions of eco-anxiety predict greater engagement with pro-environmental behaviour (Hogg et al. 2024). Although it must be verified with longitudinal evidence, these distinct associations could suggest that the motivational drive is coming from the thoughts enmeshed in the experience of climate anxiety, rather than the affective experience. It may be that dwelling on the nature of climate change and one's own role in it creates a readiness to act in response to the risk. Alternatively, those who take climate action may be more likely to think about it. Further research is needed to identify the causal relationships, which are probably recursive.

It is also striking that the associations climate anxiety has with collective action and worry were similar (Table 4). Thus, while climate anxiety has implications for mental health, we show there are also positive implications for planetary health. Consistent with past research, eco-anger was the strongest correlate of climate action in the current study (Table S5 and S6; Stanley et al. 2021). But the relationships we identified between dimensions of climate anxiety and pro-environmental behaviour suggest that climate-anxiety should not simply be treated as a net-negative individual experience. Additionally, when examining causal pathways in future research, it would be worth clarifying the role of efficacy, which has been shown to be an important predictor of collective action (van Zomeren et al. 2010) and was here associated with both collective action, anger, and all dimensions of climate anxiety except behavioural symptoms.

We propose that climate anxiety should be conceptualised as both a challenge to personal wellbeing and an opportunity for climate action (Lutz et al. 2023), which is consistent with the positive associations between climate anxiety and indicators of mental wellbeing and pro-environmental behaviour (Heeren et al. 2022; Wullenkord et al. 2021). However, this is speculation and not based on our data, since both our samples on average reported low levels of climate anxiety, which is consistent with other research (Clayton & Karazsia 2020; Whitmarsh et al. 2022; Wullenkord et al. 2021). These low scores indicate a floor effect, with fewer data points at the top end of the climate anxiety scales, and thus we cannot know how very high levels of climate anxiety would relate to the variables examined here. As the climate crisis worsens, it is likely that climate anxiety will increase and/or intensify, and thus, future research should aim to recruit samples with higher levels of climate anxiety to provide further insight into the nature of the relationships between climate anxiety and mental wellbeing and pro-environmental behaviour beyond these typical low levels.

We provide evidence of cross-cultural equivalence between respondents in the US and UK, suggesting that climate anxiety means the same thing for both US and UK samples, and for men and women within these nations. Our findings, however, are limited to two English-speaking industrialised nations with high historical emissions, and therefore, our results cannot speak to whether climate anxiety dimensions differ in other samples. Climate anxiety may be contingent on culture and/or context, and may manifest differently across countries and/or populations. This may be especially true in nations where the impacts of climate change are more pervasive and closely linked to people's livelihoods and financial security, and their connection to culture and ancestry,

and where prominence is placed on holistic and relational wellness (Gibson et al. 2019). Research by Gibson and colleagues (2020) found that for people from the Pacific Island, Tuvalu, their anxiety about climate change was also related to deep worries about being forced to leave Tuvalu due to the impacts of climate change, such as rising sea levels and natural disasters (see also research from other regions of Polynesia; Asugeni et al. 2015; Orr & Krishnan 2022). Climate anxiety may for some include specific worried cognitions about being displaced from climate change, and/or losing connection to culture and ancestry. Further research is needed to better understand the nature of climate anxiety across cultures and time.

5 Conclusions

We present the Hogg Climate Anxiety Scale as a valid, reliable, and economical (13 item) measure of climate anxiety with four dimensions: affective and behavioural symptoms, rumination, and personal impact anxiety. Importantly, we demonstrate how to adapt the Hogg Eco-Anxiety Scale to measure anxiety relating to specific environmental conditions, such as pollution and ecological degradation (see the Supplementary Materials for Hogg et al. 2021 for instructions on how to adapt original scale), which future research can follow. Further evidence about the HCAS could come from formal comparisons with alternative models of climate anxiety (such as the CAS, Clayton & Karaszia 2020), and from validations with diverse samples, including youth and child samples (Coffey et al. 2021). Since younger people are at greater risk of experiencing higher levels of climate anxiety, educational institutions could play an important role in helping young people understand the climate problem and manage both their emotional and behavioural responses to it. Further, when deciding how best to support and engage young people, the HCAS is one of the tools that could help educational institutions understand their ongoing experiences of climate change.

Appendix A

Hogg Climate Anxiety Scale

Instructions: Over the last 2 weeks, how often have you been bothered by the following problems, when thinking about climate change?

Affective symptoms:

1. Feeling nervous, anxious or on edge.
2. Not being able to stop or control worrying.
3. Worrying too much.
4. Feeling afraid.

Rumination:

5. Unable to stop thinking about future climate change.
6. Unable to stop thinking about past events related to climate change.
7. Unable to stop thinking about climate change.

Behavioural symptoms:

8. Difficulty sleeping.
9. Difficulty enjoying social situations with family and friends.
10. Difficulty working and/or studying.

Personal impact anxiety:

11. Feeling anxious about the impact of your personal behaviours on climate change.
12. Feeling anxious about your personal responsibility to help address climate change.
13. Feeling anxious that your personal behaviours will do little to help fix climate change.

Response options: 0 (*not at all*), 1 (*several of the days*), 2 (*over half the days*), 3 (*nearly every day*).

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Declarations

Ethics approval Ethical approval was granted by the Australian National University Human Research Ethics Committee (protocol 2020/429).

Informed consent All participants read a detailed information sheet about the study content, voluntary nature of participation (including that they could withdraw at any time before submitting responses), and completed the survey only if they consented to take part, thus providing passive consent.

Consent to publish The participant information sheet clearly outlined how the data would be used, including for publication in academic journals and for de-identified data to be made publicly available. Thus, participants were agreeing to this by consenting to participate.

Competing interests The authors declare no conflicts of interest.

References

Antadze N (2020) Moral outrage as the emotional response to climate injustice. Environ Justice 13(1):21–26. https://doi.org/10.1089/env.2019.0038

Asugeni J, MacLaren D, Massey PD, Speare R (2015) Mental health issues from rising sea level in a remote coastal region of the Solomon Islands: current and future. Australasian Psychiatry 23(6suppl):22–25. https://doi.org/10.1177/1039856215609767

Australian Bureau of Statistics (2000) Household Expenditure Survey Australia, user guide 1998–99. Australian Bureau of Statistics, Canberra

Benevolenza MA, DeRigne L (2019) The impact of climate change and natural disasters on vulnerable populations: a systematic review of literature. J Hum Behav Social Environ 29(2):266–281. https://doi.org/10.1080/10911359.2018.1527739

Bray JR (2001) *Hardship in Australia: an analysis of financial stress indicators in the 1998–99 Australian Bureau of Statistics Household Expenditure Survey*. Occasional Paper no. 4. Canberra: Department of Family and Community Services

Butterworth P, Olesen SC, Leach LS (2012) The role of hardship in the association between socioeconomic position and depression. Australian New Z J Psychiatry 46(4):364–373. https://doi.org/10.1177/0004867411433215

Chancel L (2022) Global carbon inequality over 1990–2019. Nat Sustain 1–8. https://doi.org/10.1038/s41893-022-00955-z

Chen FF (2007) Sensitivity of goodness of fit indexes to lack of measurement invariance. Struct Equation Modeling: Multidisciplinary J 14(3):464–504. https://doi.org/10.1080/10705510701301834

Cianconi P, Betrò S, Janiri L (2020) The impact of climate change on mental health: a systematic descriptive review. Front Psychiatry 11:74. https://doi.org/10.3389/fpsyt.2020.00074

Clayton S (2020) Climate anxiety: psychological responses to climate change. J Anxiety Disord 74:102263. https://doi.org/10.1016/j.janxdis.2020.102263

Clayton S, Karazsia BT (2020) Development and validation of a measure of climate change anxiety. J Environ Psychol 69:101434. https://doi.org/10.1016/j.jenvp.2020.101434

Coffey Y, Bhullar N, Durkin J, Islam MS, Usher K (2021) Understanding eco-anxiety: a systematic scoping review of current literature and identified knowledge gaps. J Clim Change Health 3:100047. https://doi.org/10.1016/j.joclim.2021.100047

Field A (2018) Discovering statistics using IMB SPSS statistics, 5th edn. Sage

Frankham C, Richardson T, Maguire N (2020) Psychological factors associated with financial hardship and mental health: a systematic review. Clin Psychol Rev 77:101832. https://doi.org/10.1016/j.cpr.2020.101832

Gago T, Sargisson RJ, Milfont TL (2023) A meta-analysis on the relationship between climate anxiety and wellbeing. J Environ Psychol 94:102230 https://doi.org/10.1016/j.jenvp.2024.102230

Gibson K, Haslam N, Kaplan I (2019) Distressing encounters in the context of climate change: idioms of distress, determinants, and responses to distress in Tuvalu. Transcult Psychiatry 56(4):667–696. https://doi.org/10.1177/1363461519847705

Gibson KE, Barnett J, Haslam N, Kaplan I (2020) The mental health impacts of climate change: findings from a Pacific Island Atoll nation. J Anxiety Disord 73:102237. https://doi.org/10.1016/j.janxdis.2020.102237

Gunasiri H, Wang Y, Watkins E-M, Capetola T, Henderson-Wilson C, Patrick R (2022) Hope, coping and eco-anxiety: young people's mental health in a climate-impacted Australia. Int J Environ Res Public Health 19(9):5528. https://doi.org/10.3390/ijerph19095528

Heeren A, Mouguiama-Daouda C, Contreras A (2022) On climate anxiety and the threat it may pose to daily life functioning and adaptation: a study among European and African french-speaking participants. Clim Change 173(1):15. https://doi.org/10.1007/s10584-022-03402-2

Hickman C (2020) We need to (find a way to) talk about… eco-anxiety. J Social Work Pract 34(4):411–424. https://doi.org/10.1080/02650533.2020.1844166

Hickman C, Marks E, Pihkala P, Clayton S, Lewandowski RE, Mayall EE, van Susteren L (2021) Climate anxiety in children and young people and their beliefs about government responses to climate change: a global survey. Lancet Planet Health 5(12):e863–e873. https://doi.org/10.1016/S2542-5196(21)00278-3

Hogg TL, Stanley SK, O'Brien LV, Wilson MS, Watsford CR (2021) The Hogg Eco-anxiety Scale: Development and validation of a multidimensional scale. Glob Environ Change 71:102391. https://doi.org/10.1016/j.gloenvcha.2021.102391

Hogg TL, Stanley SK, O'Brien LV (2023) Synthesising psychometric evidence for the Climate Anxiety Scale and Hogg Eco-Anxiety Scale. J Environ Psychol 88:102003. https://doi.org/10.1016/j.jenvp.2023.102003

Hogg TL, Stanley SK, O'Brien LV, Watsford CR, Walker I (2024) Clarifying the nature of the association between eco-anxiety, wellbeing and pro-environmental behaviour. J Environ Psychol 95:102249 https://doi.org/10.1016/j.jenvp.2024.102249

Hornsey MJ, Fielding KS (2016) A cautionary note about messages of hope: focusing on progress in reducing carbon emissions weakens mitigation motivation. Glob Environ Change 39:26–34. https://doi.org/10.1016/j.gloenvcha.2016.04.003

Howard L (2022) When global problems come home: Engagement with climate change within the intersecting affective spaces of parenting and activism. Emot Space Soc 44:100894. https://doi.org/10.1016/j.emospa.2022.100894

Hu LT, Bentler PM (1999) Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. Struct Equation Modeling: Multidisciplinary J 6(1):1–55. https://www.tandfonline.com/doi/abs/10.1080/10705519909540118

Intergovernmental Panel on Climate Change [IPCC] (2023) *AR6 synthesis report: Climate change 2023* IPCC. https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf

Larionow P, Sołtys M, Izdebski P, Mudło-Głagolska K, Golonka J, Demski M, Rosińska M (2022) Climate change anxiety Assessment: the Psychometric properties of the Polish Version of the climate anxiety scale. Front Psychol 13. https://doi.org/10.3389/fpsyg.2022.870392

Leiserowitz A, Maibach E, Rosenthal S, Kotcher J, Carman J, Verner M, Lee S, Ballew M, Uppalapati S, Campbell E, Myers T, Goldberg M, Marlon J (2023) Climate Change in the American mind: beliefs & attitudes, December 2022. Yale University and George Mason University, New Haven, CT: Yale Program on Climate Change Communication

Lutz PK, Passmore HA, Howell AJ, Zelenski JM, Yang Y, Richardson M (2023) The Continuum of Eco-anxiety responses: a preliminary investigation of its Nomological Network. Collabra: Psychol 9(1). https://doi.org/10.1525/collabra.67838

Marquart-Pyatt ST (2012) Contextual influences on environmental concerns cross-nationally: a multilevel investigation. Soc Sci Res 41(5):1085–1099. https://doi.org/10.1016/j.ssresearch.2012.04.003

Milfont TL, Fischer R (2010) Testing measurement invariance across groups: applications in cross-cultural research. Int J Psychol Res 3(1):111–130. https://revistas.usb.edu.co/index.php/IJPR/article/view/857/607

Ogunbode CA, Doran R, Hanss D, Ojala M, Salmela-Aro K, van den Broek KL, Bhullar N, Aquino SD, Marot T, Schermer JA (2022) Climate anxiety, wellbeing and pro-environmental action: correlates of negative emotional responses to climate change in 32 countries. J Environ Psychol 84:101887. https://doi.org/10.1016/j.jenvp.2022.101887

Ojala M (2012) How do children cope with global climate change? Coping strategies, engagement, and well-being. J Environ Psychol 32(3):225–233. https://doi.org/10.1016/j.jenvp.2012.02.004

Ojala M (2013) Coping with climate change among adolescents: implications for subjective well-being and environmental engagement. Sustainability 5(5):2191–2209. https://doi.org/10.3390/su5052191

Ojala M, Cunsolo A, Ogunbode CA, Middleton J (2021) Anxiety, worry, and grief in a time of environmental and climate crisis: a narrative review. Annu Rev Environ Resour 46:35–58. https://doi.org/10.1146/annurev-environ-012220-022716

Orr A, Krishnan S (2022) *Pacific leaders will declare a 'climate emergency'. This is what it looks like across the region*. SBS News. https://www.sbs.com.au/news/article/pacific-leaders-will-declare-a-climate-emergency-this-is-what-it-looks-like-across-the-region/5gsvgem4h

Passmore H-A, Lutz PK, Howell AJ (2022) Eco-anxiety: a cascade of fundamental existential anxieties. J Constructivist Psychol 1–16. https://doi.org/10.1080/10720537.2022.2068706

Pihkala P (2020) Anxiety and the ecological crisis: an analysis of eco-anxiety and climate anxiety. Sustainability 12(19):1–20. https://doi.org/10.3390/su12197836

Putnick DL, Bornstein MH (2016) Measurement invariance conventions and reporting: the state of the art and future directions for psychological research. Dev Rev 41:71–90. https://doi.org/10.1016/j.dr.2016.06.004

Rosseel Y (2012) Lavaan: an R package for structural equation modeling. J Stat Softw 48:1–36. https://doi.org/10.18637/jss.v048.i02

Sangervo J, Jylhä KM, Pihkala P (2022) Climate anxiety: Conceptual considerations, and connections with climate hope and action. Glob Environ Change 76:102569. https://doi.org/10.1016/j.gloenvcha.2022.102569

Spitzer RL, Kroenke K, Williams JB, Löwe B (2006) A brief measure for assessing generalized anxiety disorder: the GAD-7. Arch Intern Med 166(10):1092-1097. https://doi.org/10.1001/archinte.166.10.1092

Stanley SK, Hogg TL, Leviston Z, Walker I (2021) 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. https://doi.org/10.1016/j.joclim.2021.100003

Tam KP, Chan HW, Clayton S (2023) Climate change anxiety in China, India, Japan, and the United States. J Environ Psychol 87:101991. https://doi.org/10.1016/j.jenvp.2023.101991

Topper M, Emmelkamp PM, Watkins E, Ehring T (2014) Development and assessment of brief versions of the Penn state worry questionnaire and the ruminative response scale. Br J Clin Psychol 53(4):402–421. https://doi.org/10.1111/bjc.12052

Uchendu JO (2022) Eco-anxiety and its divergent power holds: a youth climate activist's perspective. South Afr J Psychol 52(4):545–547. https://doi.org/10.1177/00812463221130586

Van Houtan KS, Tanaka KR, Gagné TO, Becker SL (2021) The geographic disparity of historical greenhouse emissions and projected climate change. Sci Adv 7(29):eabe4342. https://doi.org/10.1126/sciadv.abe4342

van Valkengoed AM, Steg L, de Jonge P (2023) Climate anxiety: a research agenda inspired by emotion research. Emot Rev 15(4):258–262. https://doi.org/10.1177/17540739231193752

Van Zomeren M, Spears R, Leach CW (2010) Experimental evidence for a dual pathway model analysis of coping with the climate crisis. J Environ Psychol 30(4):339–346. https://doi.org/10.1016/j.jenvp.2010.02.006

Van Zomeren M, Saguy T, Schellhaas FM (2013) Believing in making a difference to collective efforts: participative efficacy beliefs as a unique predictor of collective action. Group Processes Intergroup Relations 16(5):618–634. https://doi.org/10.1177/1368430212467476

Verlie B (2022) Learning to live with climate change: from anxiety to transformation. Taylor & Francis

Weckroth M, Ala-Mantila S (2022) Socioeconomic geography of climate change views in Europe. Glob Environ Change 72:102453. https://doi.org/10.1016/j.gloenvcha.2021.102453

Whitmarsh L, Player L, Jiongco A, James M, Williams M, Marks E, Kennedy-Williams P (2022) Climate anxiety: what predicts it and how is it related to climate action? J Environ Psychol 83:101866. https://doi.org/10.1016/j.jenvp.2022.101866

World Health Organization [WHO] (2014) *Social determinant of mental health* WHO. https://apps.who.int/iris/bitstream/handle/10665/112828/9789241506809_eng.pdf

Wullenkord MC, Tröger J, Hamann KR, Loy LS, Reese G (2021) 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(3–4):20. https://doi.org/10.1007/s10584-021-03234-6