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Beyond climate anxiety: Development and validation of the inventory of climate emotions (ICE): A measure of multiple emotions experienced in relation to climate change

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ABSTRACT

There is a growing research interest in the affective aspects of climate change and their links with pro-climate engagement. Yet, psychometrically valid instruments assessing the wide panorama of emotional responses to climate change are limited. Here, we report on the development and validation of the Inventory of Climate Emotions (ICE), a self-report measure of multiple emotions experienced in relation to climate change. Based on qualitative exploration, literature review, along with expert and target population content validation, we operationally defined a spectrum of emotional responses to climate change which guided the formulation of a large initial item pool. High psychometric quality of the ICE was secured in two quantitative studies conducted in samples from the general population in Poland. In Study 1, based on exploratory factor analysis, we indicate that a broad range of emotional responses to climate change can be viably captured by 8 underlying factors: anger, contempt, enthusiasm, powerlessness, guilt, isolation, anxiety, and sorrow. This structure was corroborated in Study 2 with confirmatory factor analysis on an independent sample. Across studies, we provide evidence for the reliability and validity of the ICE in terms of internal consistency of the subscales and convergent, discriminant and concurrent validity. We also show the functionality of the ICE in the context of pro-climate behaviour. The ICE provides an integrative approach to emotional responses to climate change and it can be used to further the understanding of the complex role of emotions in climate change engagement.

1. Introduction

Every region of the world is already visibly affected by anthropogenic climate change, and the effects of changing climate by the end of the 21st century will be catastrophic for life on Earth unless rapid transformation limiting greenhouse gas emissions is implemented globally (IPCC, 2022). On these grounds, people report experiencing various, often strong emotions in relation to climate change including anxiety, grief, anger, frustration, sadness, fear, powerlessness, hopelessness, guilt, despair, isolation, but also hopefulness and empowerment (Fischer et al., 2012; Moser, 2013; Willox *et al.*, 2013; Kleres and Wettergren, 2017; Clayton, 2018; Wang et al., 2018; Kemkes and Akerman, 2019; Verlie, 2019; Gibson et al., 2020; Loureiro and Alló, 2020; Martiskainen et al., 2020; Duggan, Haddaway and Badullovich, 2021; Hiser and Lynch, 2021; Iniguez-Gallardo, Lenti Boero and Tzanopoulos, 2021; Ágoston et al., 2022; Zaremba et al; Marczak et al., 2023), as well as boredom, irritation, and contempt about the topic (Wang et al., 2018; Hemsley et al., 2021).

Recently, considerable research focus has been placed on quantitatively studying psychological conditions coined climate or eco-anxiety (e.g., Clayton and Karazsia, 2020; Pihkala, 2020; Hogg et al., 2021; Sangervo, Jylhä and Pihkala, 2022). It is important to note that these

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terms do not exclusively describe potentially mentally disturbing reactions (Pihkala, 2020). Rather, they capture a broader range of emotions and thoughts associated with climate change. Our research aims to contribute to the understanding of this complexity by exploring the wider spectrum of emotional responses to climate change, including those intertwined with individuals' engagement with the issue. Although participatory research approaches have been employed to capture the emotional attributes of concern about climate change (e.g., Hickman et al. 2021), psychometrically sound measurement instruments assessing a variety of emotions that people experience in relation to this issue are limited. This paper reports on the development and psychometric validation of the Inventory of Climate Emotions (ICE), a self-report tool to assess multiple emotional responses to climate change.

The ICE has primarily been designed for research purposes, with a strong emphasis on establishing robust psychometric properties to ensure valid statistical inference. By capturing a diverse range of climate-related emotions, we aimed to complement other metrics that predominantly capture cognitive aspects such as perceptions and experiences. In line with the observation that emotions to a large extent steer the way people operate in the world (Dukes et al. 2021; Berlant 2011; Ahmed 2013; Massumi 2015), such multidimensional understanding of emotional responses, in conjunction with other established factors, can enable the development of more advanced models of the psychology of climate change which can in turn inform the design of interventions and policies that effectively address the psychological dimensions of climate change.

1.1. Measurement of emotional responses to climate change

Although several typologies of environmentally-relevant emotions have been proposed (Landmann, 2020), studies investigating a wider array of emotional responses to climate change, beyond anxiety, relied mostly on arbitrary lists of emotion words, which differed between studies (see Supplementary File 1 for an extensive list of examples). With some exceptions (e.g., Hickman et al. 2021), no specific conceptual or psychometric reasons for including a particular set of emotion words have been articulated. It is difficult, however, to determine a priori which emotion words are the most relevant for the phenomenology of the emotional experience of climate change.

Another complication with using lists of emotion-words is that single items are more vulnerable than multiple-item scales to random measurement errors and unknown biases in meaning and interpretation (Bergkvist and Rossiter, 2007; Furr, 2011). Moreover, there is a risk that single words might not accurately capture individual emotional experience because the interpretation of a single emotion-word both by the respondent and by the researcher may be ambiguous. For example, an individual might indicate that they are "angry" about climate change, but if no further context is provided, it is difficult to say what exactly makes them angry as it could be the lack of decisive action to mitigate climate change, but also something completely opposite such as, e.g., feeling forced to give up on conveniences such as frequent aeroplane travels. These two types of anger are likely to have different implications for climate change perception and action. Such issues can negatively affect the reliability and validity, effect sizes and statistical significance of models which include such potentially unreliable measures (Furr, 2011).

1.2. The Inventory of climate emotions

To construct our measure, *climate emotions* were defined as affective phenomena that accompany specific climate-change related perceptions. This operational definition resonates with the more general one proposed by Pihkala (2022) who defined climate change emotions as affective events which are experienced in the context of climate change regardless of other factors that may influence people's emotions at a given moment, such as, e.g., temperament.

We decided to assess the phenomenological contents of emotional experience, i.e., the way people represent their affective states through language. Such understanding of emotion is in line with the conceptual act theory of emotions (Barrett, 2014). According to this theory, strongly supported by current research (Barrett, 2012; Quigley and Barrett, 2014; Clark-Polner, Johnson and Barrett, 2017; Siegel et al., 2018; Lebois et al., 2020; Hoemann et al., 2021), language plays a constitutive role in emotional processes, as emotions are not merely detected from a set of physiological "fingerprints" but they are constructed by the human mind using conceptual knowledge about emotion (Lindquist et al., 2016). Thus, the most direct way to assess emotion is through language-based self-report measures (Barrett, 2016).

To avoid ambiguity in interpretation of the items, we also specified the context of experiencing various emotions (i.e. particular perceptions of climate change associated with specific emotions). This way, aligned with the conceptual act theory of emotion, climate emotions can be understood as a composite construct built upon the recognition of the interplay between emotions and cognitions. This approach, while valuable for the purposes of our study, may not fully encompass the entire spectrum of emotional responses or capture the intricacies of individual experiences. The multifaceted nature of human emotions and the diverse ways in which individuals interpret and react to climate change pose challenges in creating all-encompassing definitions. Thus, in defining climate emotions, we took into account the practicality and feasibility of measuring them consistently and meaningfully across different individuals and contexts. By linking emotions to specific perceptions related to climate change, our aim was to capture the interaction between cognition and emotion while providing a framework that could be reliably applied to a broader range of participants in a psychometrically valid way.

To ensure the psychometric quality of our tool, we aimed to create a multi-item subscale for each climate change emotion. We deliberately kept the contexts narrow to establish robust one-dimensional subscales with strong internal consistency (Furr 2011).

The development of the initial item pool followed a systematic process advised in the psychometrics literature (Furr 2011; DeVellis and Thorpe, 2021). Firstly, we identified twelve commonly reported climate emotions related to climate change based on our in-depth qualitative research in Norway and Poland (the studies, mapping the variety of emotional responses to climate change along with their contextual triggers and implications, are described in detail in Marczak et al. (2023) and Zaremba et al. (2022)). To reduce the possibility of misrepresenting reality based on inductive inference from our exploratory studies only, this step was complemented with a review of the literature listed in the introduction, as well as online fora and blogs (see Supplementary File 1 for the list of online sources). Subsequently, operational definitions were formulated for each climate emotion to provide clear guidance for item development. Lastly, we formulated a set of 236 items aimed to represent the experience of each of these *climate emotions*. Table 1 presents these constructs along with the operational definitions.

Six experts were asked to evaluate, both quantitatively and qualitatively, the relevance and quality of the initial item pool, along with the representativeness of the assumed subscales for the phenomenology of the emotional experience of climate change (see Supplementary File 2 for details). Based on their ratings and comments, we selected the 14 best items in each category for further empirical testing. We used these 168 items in cognitive interviews with 8 people representing various demographic backgrounds (see Supplementary File 2 for details) to ensure that respondents understand the items as intended and that they are able to respond in a way that reflects their experience (Beatty and Willis, 2007). Both the expert and target population were of Polish origin and evaluated the items presented to them in the Polish language, as the scale development and the subsequent validation studies were conducted in Poland. Based on the cognitive interviews, we introduced final modifications to the wording of the items and the instructions. The

Table 1
Climate emotions and their operational definitions.

Emotion	Definition
Climate sorrow	Feeling sad, sorry, and experiencing grief due to the perception that climate change is irretrievably changing the world and causing great losses to life on Earth.
Climate anger	Feeling angry, furious, irritated, and frustrated around the perception that people in power have not been doing enough to mitigate climate change or that they have been intentionally harming the climate.
Climate irritation	Feeling irritated and annoyed around the perception of ignorance and short-sightedness of the society when it comes to showing concern and addressing climate change.
Climate apprehension	Feeling apprehension, fear and anxiety due to the perceptions that climate change is a serious hindrance and threat to human life.
Climate powerlessness	Feeling powerless and confused around the perception that one has little individual agency to fight climate change.
Climate guilt	Feeling remorse, guilty, and upset around the perception that one's behaviour negatively affects the climate. It applies both to activities that can be seen as "harmful to the environment" and to non-performance of activities that one feels should be performed to reduce one's impact on the climate. It may also refer to past behaviour that makes an individual feel guilty at present.
Climate hopelessness	Feeling hopeless, pessimistic, insecure, and overwhelmed around the perception that the most catastrophic effects of climate change are inevitable.
Climate isolation	Feeling lonely, and isolated around the perception that other people are not engaged in the topic of climate change as much as oneself.
Climate hopefulness	Feeling hopeful, trusting, and experiencing peace of mind around the perception of witnessing the implementation of pro-climate solutions and the belief in the potential for effective climate change mitigation.
Climate empowerment	Feeling positive emotions - joy, a sense of strength and meaning, inspiration and energy around witnessing or participating in collective climate action.
Climate discontent	Feeling angry, frustrated, and discontented around the perception that climate change is an exaggerated problem that should not be in the centre of people's attention.
Climate indifference	Feeling indifferent and bored around the perception that climate change is not an important topic - nor is it worth special engagement in fighting it, or in denying its importance.

initial item pool is included in Supplementary File 3.

1.3. Overview of the studies

In Study 1, we explored the factor structure and the internal consistency of the extracted subscales using the initial item pool aimed to capture the variety of emotional responses to climate change. In Study 2, we aimed at replicating the factor structure, fine-tuning the measurement model, and assessing evidence for the validity and reliability of the ICE. To this end, we used the climate emotions items extracted in Study 1, along with measures of the following constructs: climate change concern, emotional reactivity, climate change perceptions, environmental attitudes, climate action efficacy, climate- and eco-anxiety, individual climate change mitigation behaviour, pro-climate policy support, and social desirability. In both studies we also collected socio-demographic information. The sample sizes were determined a priori to ensure the minimum sample size for factor analysis ($n = 300$, Tabachnick, Fidell and Ullman, 2007). In both studies, we worked with an internet-based consumer panel, ePanel.pl owned by ARC Rynek i Opinia (https://arc.com.pl/en), one of the largest research panels in Poland. The steps of the development of the ICE are presented in Fig. 1.

The research protocols of studies presented in this paper were approved by the SWPS University of Social Sciences and Humanities Research Ethics Committee (approval no. 2021–52-12). All measures for which no validated Polish translations were available were translated using the translation/back-translation procedure. To control data quality, in each study, three attention check questions were presented among the ICE items. Participants were asked to mark the required response on a five point Likert-scale (e.g., "To convince us that you are reading this, please, just mark the option "Strongly disagree"). All the data analyses were conducted using the R Statistical Software (R Core Team, 2019). All datasets, data cleaning and data analysis scripts are available on https://osf.io/78d6u/. In addition, the extended reports from the analyses are available in Supplementary Files 4–6.

1.3.1. Study 1

The aim of Study 1 was to determine the appropriate number of common factors and to uncover which of the 168 items are the most reasonable indicators of the latent dimensions of the emotional experience of climate change.

2. Method study 1

2.1. Participants and procedure

Participants in this study were 875 Polish residents. The majority of them were quota sampled from the general population according to their diverse level of concern about climate change. Since it was difficult to capture a sufficient number of individuals with a very high level of climate change concern, we supplemented the general population sample by recruiting additional participants through snowball sampling from pro-climate activist groups ($n = 14$). This deliberate inclusion aimed to provide a more balanced representation of individuals with potentially strong emotional engagement in climate change issues (Marczak et al. 2023; Wang et al. 2018).

To ensure data quality we defined the following criteria: (1) the participants had to respond correctly to all three attention check questions (181 participants were excluded), and (2) their responses regarding gender, age, and level of concern about climate change had to be consistent with their responses to the same questions in the screening survey (16, 16, and 82 participants were excluded due to these criteria, respectively). Some participants were excluded based on more than one reason. None of the climate activists were excluded from the study. Overall, 632 responses (74 %) were retained for further analysis.

The socio-demographic characteristics of the study sample are presented in Table 2. For the quota sampling, the study was advertised by the panel data provider, and those willing to participate and meeting the screening criteria were provided with a link to the online procedure programmed using the LimeSurvey (Limesurvey GmbH, 2012) on a dedicated secure server. The participants first read the description of the aims of the study and provided their informed consent. They were also informed that the survey included control questions verifying their attention. Next, they evaluated the climate change emotions items presented in a randomised order in 14 blocks each containing 12 items representing each of the assumed emotions. In the final part of the procedure, participants provided their demographic data.

2.2. Materials

Climate Change Emotions. Participants evaluated 168 items about their emotional experience of climate change. They responded on a 5-point Likert-scale from "strongly disagree" to "strongly agree".

Socio-demographic information. Participants indicated their gender, year of birth, place of residence, educational attainment, and level of concern about climate change.

2.3. Results study 1

To examine the latent structure of the proposed indicators of emotional responses to climate change and assess their factor loadings, thereby providing insights into the underlying constructs and their interrelationships in a data-driven way, we employed exploratory factor analysis (EFA) (Brown, 2015). EFA helps in identifying and eliminating

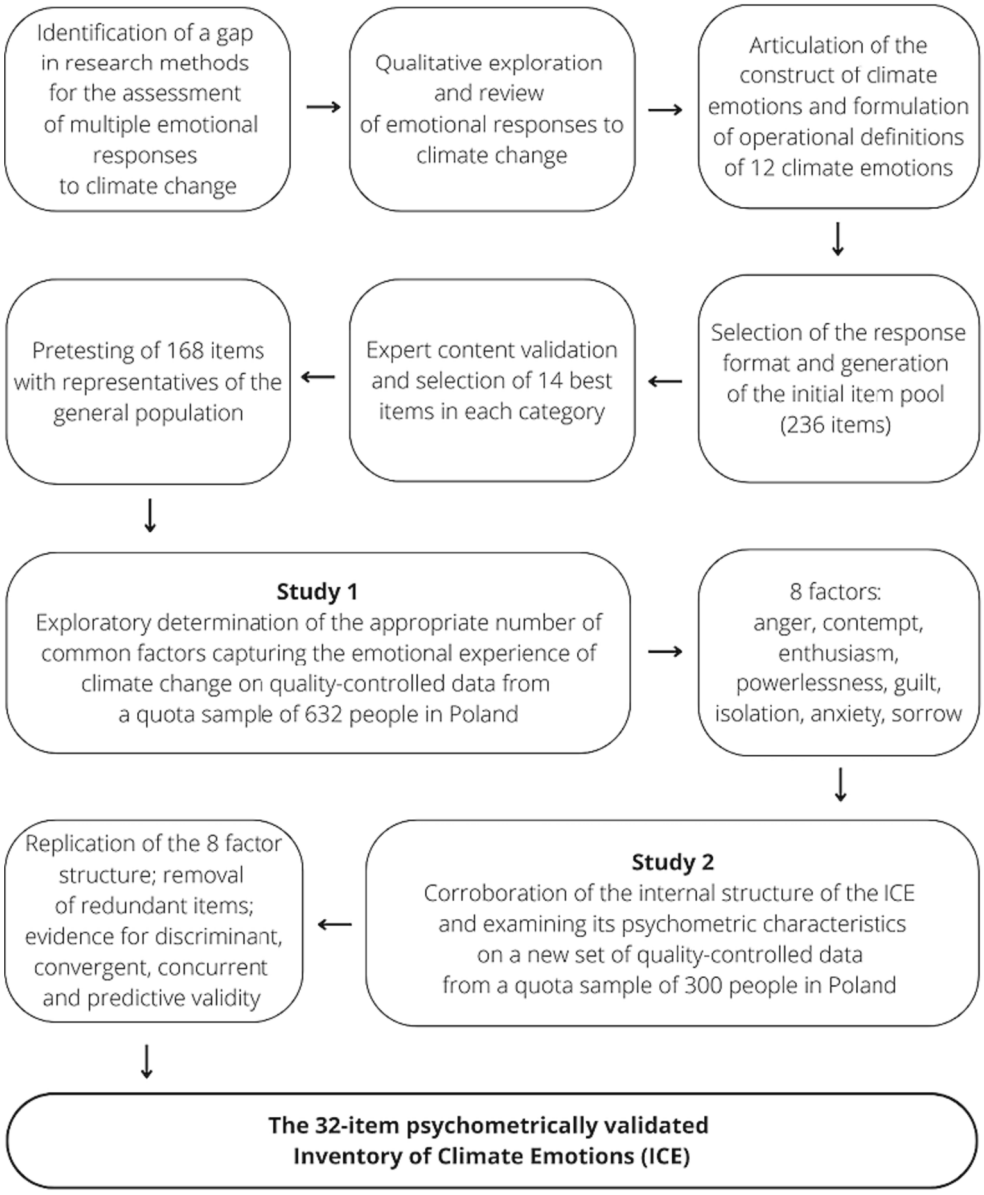

Fig. 1. Flowchart presenting the steps of the development and validation of the ICE.

redundant or poorly performing items from the questionnaire, which is an important step in constructing a concise and psychometrically robust measurement instrument. In addition, using EFA, researchers can assess the extent to which the items align with the hypothesised theoretical constructs, providing initial evidence of construct validity (Hinkin, 1998).

The results of the Kaiser-Meyer-Olkin test of sampling adequacy (0.99), and the significant Bartlett's test of sphericity ($\chi 2$ (14028) = 25464.23, p <.001) indicated that EFA was suitable for the collected data (Brown, 2015). Based on parallel analysis of eigenvalues (Horn, 1965), we retained 7 factors for which eigenvalue from the actual data was greater than eigenvalues of the corresponding 10,000 random datasets.

Next, we conducted EFA using the principal axis factoring method with PROMAX rotation to identify factor loadings for each item. Oblique rotation was used, because of the assumption that experiences of various climate change related emotions are correlated. To include the most relevant indicators, an item was retained if its corresponding factor loading was > 0.5, and its primary factor loading was ≥ 0.3 higher than its loadings for the remaining factors. In the next step, guided by the desired length and coherence of the subscales, we eliminated similarly phrased and complex items. Indicators of climate apprehension and climate hopelessness consistently formed one factor. It was also the case for climate hopefulness and climate empowerment, as well as climate discontent and climate indifference. To designate these three "double emotions'' factors, i.e., factors consisting of two of the assumed emotions, we selected four items from each of the two assumed emotions which loaded on these factors. The final subscales at this stage of questionnaire development comprised 8 items per factor.

The factor of climate sorrow was not identified in the 7-factor model. Nevertheless, we decided to include it based on theoretical grounds (see Study 1 discussion for details). Climate sorrow was identified in the 11-factor solution and we included 4 best items representing this factor. The internal consistency of the final subscales was $\geq$ Cronbach's $\alpha = 0.81$. The summary of the results of the EFA along with Cronbach's α values for each subscale are presented in Table 3. Supplementary Files 4 and 5

Table 2
Socio-demographic characteristics of samples in Studies 1 and 2.

	Study 1 ($n = 632$)	Study 2 ($n = 300$)
% Women	52.69	59.33
Mean age (SD)	39.28 (16.33)	40.30 (14.63)
% 18–23 ("gen z")	22	14
% 24–35 ("millennial")	29	32
% 36–55 ("gen x")	28	33
% 56–74 ("baby boomer")	21	21
% Urban population	80	80
Education		
% Primary education	8	4
% Secondary education or vocational training	58	47
% University/College degree and higher	33	49
Perceived SES (collected only for S2)		
% "Living comfortably on present income"		10
% "Coping on present income"		71
% "Finding it difficult on present income"		19
% "Finding it very difficult on present income"		0
Climate change concern		
% "Not at all concerned"	1	6
% "Not very concerned"	9	6
% "Somewhat concerned"	40	39
% "Very concerned"	37	42
% "Extremely concerned"	12	7

Note. Due to rounding the numbers to integers, some data reported in percentage does not sum up to 100 % but to 99 %

contain results not outlined here, including an exploration of the relationships between the preliminary climate emotions and socio-demographic information.

2.4. Discussion study 1

Based on the results of Study 1, we proposed 8 subscales to assess climate change emotions with 60 items in total. EFA indicated a 7 factor structure of the investigated aspects of emotional responses to climate change. The indicators of four assumed climate emotions – climate anger, climate powerlessness, climate guilt and climate isolation – consistently loaded on four corresponding factors. Six of the assumed climate change emotions formed, what we called, "double emotions", i.e., factors consisting of two of the theoretically assumed emotions, which we named: climate contempt, climate enthusiasm and climate anxiety, respectively.

Indicators of one of the assumed emotions - climate irritation, referring to negative feelings around the perception of societal passivity in response to climate change, did not load consistently on any factor and they were not included in the final inventory. Similarly, the items representing climate sorrow did not form a separate subscale in the 7-factor solution. However, as climate change related sadness has been reported as the very core dimension of the emotional experience of climate change (e.g. Cunsolo and Ellis, 2018; Pihkala, 2020, 2022; Ojala et al., 2021; Marczak et al., 2023), we decided to include the indicators of climate sorrow for further evaluation. One speculation for why climate sorrow did not emerge as a separate factor in the EFA could be attributed to the specific wording or formulation of the range of items representing this emotion category. It is possible that, despite drawing from our analysis of lived experiences and literature on the topic, the initial selection of items for climate sorrow may not have fully captured the nuanced aspects associated with it.

All scales demonstrated high Cronbach's α values providing evidence for their ability to measure each climate change emotion consistently. However, Cronbach's α values above 0.9 may suggest that some items are redundant and indicate that the scale length should be shortened (Streiner, 2003). In Study 2, we addressed this issue and continued the ICE development and validation.

2.5. Study 2

The aim of Study 2 was to test the replicability of the internal structure of the ICE on a new set of data and to provide more evidence for the reliability and validity of the instrument. To evaluate and inform the modifications in the structure of the ICE, we used Confirmatory Factor Analysis (CFA).

To examine evidence for discriminant validity, we analysed whether patterns of responses across groups for which differences may be expected – men and women, as well as people declaring various degrees of climate change concern – differ in the assumed directions. Based on previous research and theoretical considerations, we hypothesised that women would exhibit significantly higher scores than men on all climate emotions, except for climate contempt. This expectation was driven by several factors. First, women have been shown to exhibit higher levels of climate change concern compared to men (Knight, 2019). Second, research suggests that women tend to express emotions more openly and intensively than men (Kring and Gordon, 1998; Wester et al., 2002). The hypothesis regarding climate contempt was driven by the conceptual similarity between climate contempt and climate denial, as the climate contempt subscale was specifically designed to capture the emotional aspects of attitudes associated with a negative stance towards the gravity of climate issues. In this context, male gender is a consistent predictor of climate denial (Wullenkord, 2022), thus we expected to observe this effect also on the emotional level.

Regarding climate change concern, we expected that individuals with higher levels of concern would exhibit significantly higher scores on what we refer to as "pro-climate emotions." These emotions, including climate anger, climate enthusiasm, climate sorrow, climate anxiety, climate guilt, and climate isolation, have been linked to pro-climate engagement in various studies (Schneider, Zaval and Markowitz, 2021; Stanley et al., 2021; Wullenkord et al., 2021; Shipley and van Riper, 2022; Marczak et al., 2023). In line with the arguments presented above, we also expected the high concern group to score lower on climate contempt. We did not have directional hypotheses regarding climate powerlessness as it can be related to "climate nihilistic" attitudes representing a sense of acceptance that the current state of climate-relevant events cannot be changed (Pölzler, 2015) and "soft climate denialism", i.e., behaving as though the existence or severity of global warming are not fully real (Hoexter, 2016), but also to feeling paralysed in one's concern and awareness about the complexity of addressing climate change (Marczak et al., 2023).

To assess concurrent and predictive validity of the ICE, we investigated the patterns of subscales' correlations with a set of theoretically related constructs. First, to validate that the ICE subscales assess affective phenomena, we assumed that they would show significant positive correlations with emotional reactivity, i.e., the tendency to experience frequent and intense emotional arousal (Becerra and Campitelli, 2013).

Second, since people's climate emotions are interconnected with the ways they perceive climate change (Clayton and Karazsia, 2020; van Valkengoed, Steg and Perlaviciute, 2021; Marczak et al., 2023), we hypothesised that the more a person perceives that climate change is real, human-made, and that it will have negative consequences not distant in time and space, as well as the more they perceived that they have had personal experience of climate change, the more they would declare experiencing pro-climate emotions. Concurrently, given the above characteristics, the less they would declare experiencing climate contempt. We did not expect to observe meaningful associations for climate powerlessness because of its assumed relation with the above-mentioned "soft climate denial" (Hoexter, 2016).

Third, we expected environmental attitudes, i.e., people's evaluations of the natural environment with some degree of favour or disfavour (Milfont and Duckitt, 2010), to be meaningfully interrelated with distinct climate change emotions, because of the valence component of attitudes. Specifically, we expected that people who enjoy nature more, who endorse the view of the fragility of the natural environment and the

Table 3
Summary of EFA of climate emotions indicators along with items representing each factor and estimates of their internal consistency.

Factor name	Item ID	Item wording	Factor Loading	Eigen-values	Variance explained	Internal consistency
Climate anger	ANG14	I feel angry that the political and economic system that we live in harms the climate.	0.94	74.75	67 %	α = 0.95
	ANG13	I am outraged that politicians allowed climate change to come this far.	0.98			
	ANG10	I feel outraged at corporations that harm the climate.	0.94			
	ANG5	I am angry with our leaders for not taking climate change seriously.	0.96			
	ANG6	I am angry at political leaders who ignore scientific knowledge about climate change.	0.91			
	ANG8	It annoys me that, when faced with climate change, people in power place money above the interests of humanity and the environment.	0.86			
	ANG3	I feel anger when I think of politicians who delay efforts to mitigate climate change.	1.00			
	ANG1	I am angry that governments have done so little to deal with climate change.	0.93			
Climate contempt	IND7	I am tired of the topic of climate change.	0.75	10.40	46 %	α = 0.92
	DIS5	It annoys me to watch people succumb to climate hysteria.	0.76			
	DIS13	It makes me angry that sacrifices are expected of me to fight climate change.	0.84			
	DIS10	I feel outraged that so much time and energy is being spent fighting climate change.	0.76			
	IND6	I am not particularly moved by the topic of climate change.	0.63			
	DIS7	I am annoyed by the constant publicity around climate change.	0.87			
	IND2	I am bored of hearing about climate change.	0.71			
	IND13	I am surprised that people experience strong emotions in connection with climate change.	0.74			
Climate enthusiasm	EMP12	The increasing public engagement with climate change gives me hope.	0.60	7.28	42 %	α = 0.91
	EMP9	Knowing that there are people who care about climate change gives me a sense of empowerment.	0.52			
	HOPF9	I believe that there are emerging solutions that will allow us to stop climate change.	0.83			
	HOPF8	Concrete actions for the climate allow me to be optimistic about the future.	0.85			
	HOPF10	I am hopeful about the future when I see the pace of positive changes for climate protection.	0.85			
	EMP14	Knowing that more and more people are becoming aware of the dangers of climate change gives me hope.	0.57			
	HOPF13	I strongly believe that we will be able to tackle climate change.	0.93			
	EMP7	Social mobilisation in the fight against climate change makes me feel that together we can achieve this goal.	0.57			
Climate powerlessness	POWL11	I feel confused about what I can do to reduce climate change.	0.55	4.10	23 %	α = 0.81
	POWL5	When I think about what I can do to mitigate climate change, I feel very small.	0.53			
	POWL7	I am overwhelmed by how many aspects of life would need to be changed to limit climate change.	0.52			
	POWL4	I feel there isn't much I can do to limit climate change.	0.61			
	POWL8	I feel powerless in the face of the complexity of the climate change problem.	0.50			
	POWL12	It is difficult for me to understand what I can do to help fight climate change effectively.	0.59			
	POWL2	As an individual, I feel powerless with little agency over what happens with the climate.	0.55			
	POWL13	I feel helpless when I think of how difficult it is to live in a climate-friendly way.	0.51			
Climate guilt	GUI11	I have a guilty conscience about not doing enough to mitigate climate change.	0.84	3.35	49 %	α = 0.93
	GUI6	It upsets me that I have a big negative impact on the climate.	0.72			
	GUI2	I feel remorse when I do something that contributes to climate change.	0.58			
	GUI8	I feel guilty that my lifestyle contributes to climate change.	0.78			
	GUI9	I feel remorse for doing too little to mitigate climate change.	0.78			
	GUI4	I have a sense of guilt for doing things that contribute to climate change.	0.66			
	GUI12	I am angry at myself for not doing enough to limit my negative impact on the climate.	0.83			
	GUI14	I blame myself for not doing more to help with the fight against climate change.	0.78			
Climate isolation	ISO4	I feel like one of the few people who actually understand what climate change entails.	0.73	2.42	41 %	α = 0.92
	ISO13	I feel lonely when others don't understand my concerns about climate change.	0.66			
	ISO5	I feel lonely because most of the people around me don't care about climate change as much as I do.	0.84			
	ISO8	I feel lonely because it's difficult to talk about my climate change concerns with other people.	0.77			
	ISO3	I feel as if I were the only person around who cares about climate change.	0.84			
	ISO12	I feel alienated because society considers concern for climate change as something strange.	0.79			
	ISO2	I feel alone in my concern for climate change.	0.79			

(*continued on next page*)

Table 3 (*continued*)

Factor name	Item ID	Item wording	Factor Loading	Eigen-values	Variance explained	Internal consistency
	ISO9	Sometimes I feel lonely because people live as if climate change isn't happening.	0.59			
Climate anxiety	APP10	I fear the impact of climate change on peoples' lives.	0.62	1.10	64 %	α = 0.94
	HOPL7	Climate change makes me feel like I have been diagnosed with a terminal illness.	0.70			
	HOPL1	Being aware of climate change takes away the joy in my life.	0.72			
	APP2	I am anxious when I think about the negative effects of climate change.	0.56			
	APP7	Thinking about climate change makes me fear for the future of our children.	0.59			
	HOPL5	I am overwhelmed by the awareness of the approaching climate disaster.	0.71			
	HOPL11	Everything seems uncertain because of climate change.	0.69			
	APP14	I fear how climate change will affect me and my loved ones.	0.68			
Climate sorrow*	SOR13	The thought of so many species going extinct under the pressure of climate change fills me with sorrow.	0.78			α = 0.91
	SOR6	The thought that the world I know is disappearing forever because of climate change makes me sad.	0.58			
	SOR4	I feel sorry about the possibilities we are losing forever because of climate change.	0.55			
	SOR14	I am sad that so many living creatures suffer because of climate change.	0.57			

Note. *The 8th factor, climate sorrow, was added to the 7-factor solution on theoretical grounds. The items in this factor were selected based on the 11 factor EFA solution available in the Supplementary File 5. Because it is a different factor model than for the rest of the factors, we do not report the eigenvalues and the proportion of explained variance for climate sorrow. In this table, for readability, we report the absolute values of factor loadings. The raw table of loadings is available in the Supplementary Files 4 and 5.

threat humans pose to it, and who express ecocentric concern, i.e., a sense of emotional loss over environmental damage, would declare experiencing higher levels of pro-climate emotions. Concurrently, the less they were expected to experience climate contempt. We assumed that the stronger people support interventionist pro-environmental policies, the more angry they would be at the inaction of people in power, and the less they would experience climate contempt. We expected that confidence in science and technology would correlate positively with climate enthusiasm. Finally, the stronger people endorsed the view that nature exists primarily for human use (human utilisation of nature) and that economic growth and development should have priority over environmental protection (human dominance over nature), the higher their score would be on climate contempt, and the lower their scores on pro-climate-emotions, especially climate anger and sorrow, and, for human dominance over nature, also climate guilt.

Fourth, we assumed that beliefs about self- and collective climate action efficacy, i.e., the perception that one is capable of achieving desired climate-relevant outcomes by acting alone, and the belief that desired climate-relevant results can be achieved by acting as a group (Jugert et al., 2016) would have meaningful associations with climate emotions. Specifically, we expected that climate action self-efficacy would correlate negatively with climate powerlessness, as we intended powerlessness to capture the emotional aspect of a sense of lack of ability, influence, or power over addressing climate change. We also hypothesised that climate action self-efficacy would correlate positively with climate enthusiasm (Feldman and Hart, 2016; Schneider, Zaval and Markowitz, 2021), but also with climate guilt, as guilt can be related to the individualisation of responsibility for climate change (Marczak et al., 2023). When it comes to climate action collective efficacy, we expected it to correlate positively predominantly with climate enthusiasm (Schneider, Zaval and Markowitz, 2021; Marczak et al., 2023).

Fifth, we expected climate change emotions to be meaningfully associated with the affective dimension of eco-anxiety as measured by the Hogg Eco-Anxiety Scale (HEAS, Hogg et al., 2021). We expected significant positive correlations between the affective symptoms subscale of HEAS and climate anxiety, sorrow, isolation, guilt, and powerlessness, because we assumed that these emotions constitute the affective component of eco-anxiety (Pihkala, 2020; Ojala et al., 2021; Marczak et al., 2023). We also expected these components to correlate negatively with climate contempt, due to its conceptual links with climate denial, and the established negative empirical links between different forms of climate denial and climate anxiety (Wullenkord et al., 2021). In addition, we expected a positive correlation between climate guilt and the "anxiety about personal impact" dimension of the HEAS (Hogg et al., 2021), as they both capture the negative emotional experience of feeling personally responsible for addressing climate change.

To provide evidence for the predictive validity of the ICE subscales, we expected that they would have meaningful associations with measures of climate change mitigation, both in terms of individual mitigation behaviours, and support for mitigation policies. Based on the existing literature (e.g., Wang et al., 2018; Schneider, Zaval and Markowitz, 2021; Stanley et al., 2021; Wullenkord et al., 2021; Shipley and van Riper, 2022), we expected that the experience of pro-climate emotions such as climate anger, enthusiasm, anxiety, sorrow, and guilt would be related to stronger engagement in climate change mitigation. Concurrently, we assumed that climate contempt would be negatively related to climate change mitigation. We hypothesised that climate powerlessness would have little relationship with climate-relevant behaviour and policy support due to its assumed links with climate nihilistic attitudes (Pölzler, 2015; Hoexter, 2016). Likewise, we expected weak correlations between climate change mitigation and climate isolation because, as much as this feeling may be related to higher climate change concern, it may have disempowering effects, impeding behavioural engagement (Rokach, 2004). In addition, referring to our previous assumption that climate anxiety, sorrow, isolation, guilt, and powerlessness constitute the affective component of a potentially more clinically significant response to the environmental crisis, we expected that they would correlate also with the cognitive-emotional impairment dimension of the Climate Anxiety Scale (Clayton and Karazsia 2020).

Lastly, the way people report on their environmentally-relevant characteristics, might be subject to respondents' tendency to answer in a way that makes them look good (Vesely and Klöckner, 2020). Therefore, we inspected the correlations between the ICE scales and social desirability. An overview of the hypothesised correlations is presented in Fig. 2.

3. Method study 2

3.1. Participants and procedure

Participants in this study were 319 residents of Poland, quota sampled from the general population according to their level of concern about climate change. Prior to data collection, the distribution of climate

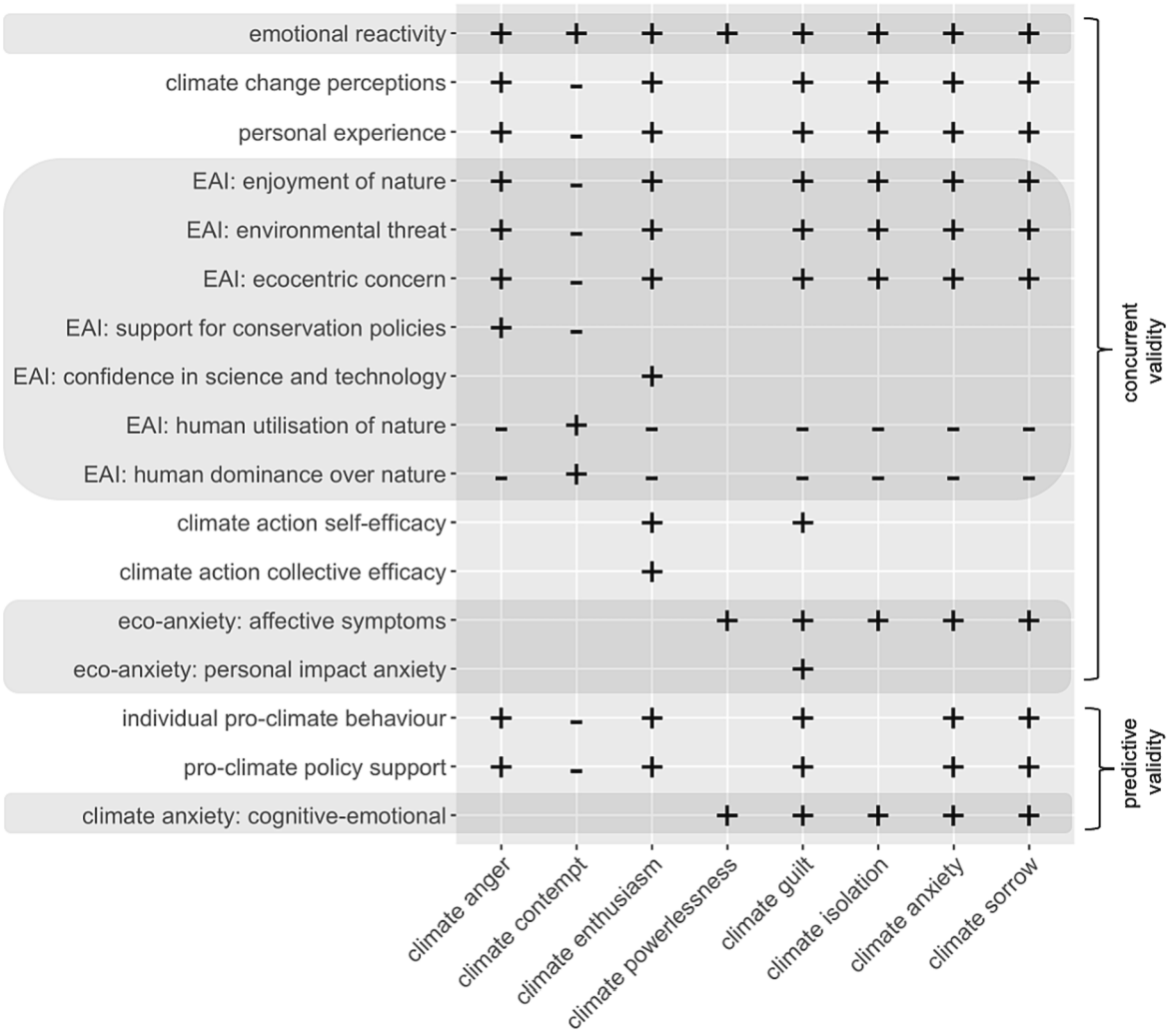

Fig. 2. Hypothesised associations between climate emotions and theoretically relevant constructs.

change concern within the Polish population was estimated by the contracted panel-data provider using an omnibus screening conducted on a panel-based sample representative of the Polish population. This screening involved a 5-point Likert scale ranging from 'not at all concerned' to 'extremely concerned.' The results indicated that approximately one-third of respondents chose answers 1–3, another one-third chose answer 4, and the remaining one-third chose answer 5. Consequently, our study aimed to achieve a similar distribution by recruiting participants representing each level of climate change concern.

To ensure data quality we defined the following criteria: (1) the participants had to respond correctly to all 3 attention check questions (13 participants excluded), and (2) their responses regarding gender (3 participants excluded) and age (3 participants excluded) had to be consistent with their responses to the same questions in the screening survey. Some participants were excluded based on more than one reason. Overall, 300 responses (94 %) were retained for further analysis. The characteristics of the study sample are presented in Table 2.

The study was advertised by the panel data provider, and those willing to participate and meeting the screening criteria were invited to participate in an online data collection group session, which was supervised over a video-conferencing platform to improve data quality. Conducting a supervised online data collection group session can offer several advantages compared to having participants answer an online questionnaire privately: it makes it possible to control the data collection process more effectively through ensuring a more standardised environment, it can increase participants' engagement and motivation, and hence reduce dropout rates (Dillman et al., 2014). On average 9 people participated in each session (min = 1, max = 16). The participants completed the study procedure using an online platform developed for the purpose of our research project. The platform was implemented using open-source tools (Common Lisp, Elm, PostgreSQL and git) to increase the flexibility of setting the research tasks while eschewing browser-based configuration instruments.

The participants first read the description of the aims of the study and provided their informed consent. They were also informed that the procedure included control questions verifying their attention. Next, they evaluated 60 climate change emotions items presented in a random order. Then, they completed the scales included to validate the ICE, also in a random order, where item-order was also randomised. In the last step, they filled in their demographics.

3.2. Materials

Climate Change Emotions. Participants evaluated sixty items about the emotional experience of climate change selected in Study 1. They marked their responses on a 5-point Likert-scale from "strongly disagree" (1) to "strongly agree" (5). The higher the score, the more the person identified with experiencing a given climate emotion. The internal consistencies of all the scales are available in Tables 5, 7 and 8.

Emotional Reactivity. To gauge participants' tendency to experience frequent and intense emotional arousal of positive and negative valence, we employed the 18-item short form of the Perth Emotional

Table 4
Parameter estimates from CFA of the final measurement model and psychometric characteristics of the ICE subscales.

Factor name, its internal consistency and AVE	Item ID	Item wording	*B*	*SE*	*z*-value	β
Climate anger α = 0.88 ρ = 0.88 AVE = 0.65	ANG14	I feel angry that the political and economic system that we live in harms the climate.	1.00			0.82
	ANG13	I am outraged that politicians allowed climate change to come this far.	1.00	0.05	19.35	0.84
	ANG10	I feel outraged at corporations that harm the climate.	0.83	0.07	12.60	0.69
	ANG3	I feel anger when I think of politicians who delay efforts to mitigate climate change.	1.05	0.06	17.38	0.85
Climate contempt α = 0.86 ρ = 0.87 AVE = 0.62	DIS5	It annoys me to watch people succumb to climate hysteria.	1.00			0.82
	DIS7	I am annoyed by the constant publicity around climate change.	1.01	0.05	18.90	0.84
	IND2	I am bored of hearing about climate change.	0.98	0.05	18.34	0.85
	IND13	I am surprised that people experience strong emotions in connection with climate change.	0.70	0.06	11.83	0.63
Climate enthusiasm α = 0.77 ρ = 0.77 AVE = 0.45	EMP12	The increasing public engagement with climate change gives me hope.	1.00			0.72
	HOPF9	I believe that there are emerging solutions that will allow us to stop climate change.	1.02	0.116	8.85	0.66
	HOPF8	Concrete actions for the climate allow me to be optimistic about the future.	0.88	0.102	8.62	0.60
	EMP7	Social mobilisation in the fight against climate change makes me feel that together we can achieve this goal.	1.06	0.11	9.37	0.71
Climate powerlessness α = 0.64	POWL11	I feel confused about what I can do to reduce climate change.	1.00			0.59
ρ = 0.64 AVE = 0.31	POWL7	I am overwhelmed by how many aspects of life would need to be changed to limit climate change.	0.82	0.15	5.38	0.44
	POWL2	As an individual, I feel powerless with little agency over what happens with the climate.	1.11	0.14	8.19	0.64
	POWL13	I feel helpless when I think of how difficult it is to live in a climate-friendly way.	0.92	0.13	7.31	0.56
Climate guilt α = 0.86 ρ = 0.86 AVE = 0.61	GUI11	I have a guilty conscience about not doing enough to mitigate climate change.	1.00			0.85
	GUI6	It upsets me that I have a big negative impact on the climate.	0.74	0.06	13.09	0.67
	GUI8	I feel guilty that my lifestyle contributes to climate change.	0.82	0.06	14.09	0.73
	GUI12	I am angry at myself for not doing enough to limit my negative impact on the climate.	0.97	0.05	17.96	0.84
Climate isolation α = 0.82 ρ = 0.82 AVE = 0.54	ISO4	I feel like one of the few people who actually understand what climate change entails.	1.00			0.70
	ISO5	I feel lonely because most of the people around me don't care about climate change as much as I do.	1.06	0.102	10.32	0.74
	ISO8	I feel lonely because it's difficult to talk about my climate change concerns with other people.	0.99	0.10	10.23	0.72
	ISO12	I feel alienated because society considers concern for climate change as something strange.	1.07	0.10	11.13	0.77
Climate anxiety α = 0.86 ρ = 0.86 AVE = 0.61	APP7	Thinking about climate change makes me fear for the future of our children.	1.00			0.79
	HOPL5	I am overwhelmed by	1.14	0.08	14.90	0.82

(*continued on next page*)

Table 4 (*continued*)

Factor name, its internal consistency and AVE	Item ID	Item wording	*B*	*SE*	*z*-value	β
		the awareness of the approaching climate disaster.				
	HOPL11	Everything seems uncertain because of climate change.	0.77	0.07	11.79	0.68
	APP14	I fear how climate change will affect me and my loved ones.	1.07	0.06	16.77	0.83
Climate sorrow α = 0.85 ρ = 0.85 AVE = 0.60	SOR13	The thought of so many species going extinct under the pressure of climate change fills me with sorrow.	1.00			0.76
	SOR6	The thought that the world I know is disappearing forever because of climate change makes me sad.	1.11	0.12	8.93	0.74
	SOR4	I feel sorry about the possibilities we are losing forever because of climate change.	1.18	0.10	11.90	0.77
	SOR14	I am sad that so many living creatures suffer because of climate change.	1.14	0.11	10.85	0.83

Note. The factor loading of the first indicator of each latent variable is fixed to 1. The *p*-values corresponding to the *z*-statistic were all < 0.001.

Reactivity Scale (Preece, Becerra and Campitelli, 2019). Participants marked their responses on a 5-point Likert scale from "very unlike me" to "very like me". The higher the score, the more emotionally reactive the person. The example items from this measure are: "I tend to get upset very easily" or "When I am joyful, I tend to feel it very deeply."

Climate Change Perceptions. We used the 5-item version of the Climate Change Perceptions Scale comprising people's perception of the reality and anthropogenic causes of climate change, as well as the perceived valence, spatial distance and temporal distance of consequences of climate change (van Valkengoed, Steg and Perlaviciute, 2021). Responses were marked on a 7-point Likert-scale from "strongly disagree" to "strongly agree". In the item indicating the perceived reality of climate change ("I believe that climate change is real"), the option "I do not believe climate change exists" was also available in line with the original formulation of the scale. Another example item from this scale is: "Climate change will bring about serious negative consequences." The higher the score, the more the person believed that climate change is a real and human-made problem that will bring about negative consequences not far in time and space.

Personal Experience of Climate Change was assessed based on three items adapted from Clayton and Karazsia (2020). The responses were indicated on a 5-point Likert scale from "never" to "almost always". The higher the score, the more the person perceived that they have personally experienced climate change. The example items from this measure include: "I have been directly affected by climate change" and "I know someone who has been directly affected by climate change".

Environmental Attitudes. We assessed relevant dimensions of environmental attitudes based on the scales selected from the brief version of the Environmental Attitudes Inventory (Milfont and Duckitt, 2010). We used the following two-item scales: "Enjoyment of nature" (e.g., " I really like going on trips into the countryside, for example to forests or fields"), "Fragility of the natural environment" (e.g., "Humans are severely abusing the environment"), "Ecocentric concern" (e.g., "It makes me sad to see forests cleared for agriculture"), "Interventionist policy support" (e.g., "Governments should control the rate at which raw materials are used to ensure that they last as long as possible"), "Confidence in science and technology" (e.g., "Modern science will solve our environmental problems"), "Human dominance over nature" (e.g., "Human beings were created or evolved to dominate the rest of nature"), and "Human utilisation of nature" (e.g., "Protecting peoples' jobs is more important than protecting the environment"). The participants responded on a 7-point Likert-scale from "strongly disagree" to "strongly agree". The higher the score, the more the person exhibited a given attitude.

Perceived climate action efficacy. To evaluate participants' subjective beliefs regarding their capacity to make a positive impact on individual and collective actions to mitigate climate change we used a two-dimensional measure adapted from Chu & Yang (2020) that comprises two items about self-efficacy and two items capturing collective efficacy. Participants indicated their responses on a 5-point Likert scale from "strongly disagree" to "strongly agree". The higher the score, the more climate action efficacy the person perceived to have. The measure consists of items such as, e.g., "I believe my actions can have a beneficial influence on climate change" (self-efficacy) and "If we act collectively, we will be able to minimise the consequences of climate change" (collective efficacy).

Eco-Anxiety. We assessed two dimensions of anxiety relating to widely understood environmental crises: affective symptoms (four items), and anxiety about one's negative impact on the planet (three items) using two subscales from the Hogg Eco-Anxiety Scale (HEAS, Hogg et al., 2021). Participants marked their responses to the question "Over the last 2 weeks, how often have you been bothered by the following problems, when thinking about climate change and other global environmental conditions (e.g., global warming, ecological degradation, resource depletion, species extinction, ozone hole, pollution of the oceans, deforestation)?" on a 4-point Likert scale from "not at all" to "nearly every day". The higher the score, the higher the degree of the selected symptoms of eco-anxiety. The example items in the HEAS are: "Feeling afraid" or "Feeling anxious about the impact of your personal behaviours on the earth."

Individual mitigation behaviour. We assessed individual behaviour relevant for climate change mitigation using ten items adapted from van Valkengoed and colleagues (2021). Participants indicated the frequency of performing various behaviours on a 7-point Likert scale from "never" (1) to "always" (7). The higher the score, the more frequently the person reported to engage in individual mitigation behaviour. Some of the items in this measure are: "I ride a bicycle or take public transportation rather than take the car" and "I wait until I have a full load before doing laundry".

Mitigation policy support. Participants' support for climate policies aimed at mitigating climate change was gauged using five items developed by van Valkengoed and colleagues (2021). Participants marked their responses on a 7-point Likert-scale from "strongly oppose" to "strongly support". The higher the score, the more the participant supported climate change mitigation policies. The measure consists of items such as, e.g., "Using public money to subsidise renewable energy such as wind and solar power" and "Setting national targets to reduce carbon emissions."

Climate Anxiety. We assessed the cognitive-emotional impairment associated with climate change anxiety using eight items from the measure of climate change anxiety proposed by Clayton and Karazsia (2020). Participants rated how often the scale's statements were true of

them on a 5-point Likert scale from "never" to "almost always". The higher the score, the more cognitive-emotional impairment. The questionnaire includes items like, e.g., "Thinking about climate change makes it difficult for me to concentrate" or "I find myself crying because of climate change."

Social Desirability. We used ten balanced items measuring impression management selected by Milfont and Duckitt (2010) from the Balanced Inventory of Desirable Responding scale (Paulhus, 1991). The responses were marked on a 7-point Likert scale from "not true" to "very true". In the process of data analysis, the results were recoded into a binary format in line with Paulhus' (1991) recommendations. The higher the score, the higher the person's tendency to present themselves in a good light. The measure comprises items, such as, e.g., "I never cover up my mistakes" and "I sometimes tell lies if I have to."

Demographic information. Participants indicated their gender, year of birth, educational attainment, area of residence, and perceived socio-economic status. They also reported their level of concern about climate change, answering the question: "How concerned are you about climate change?" on a scale from 1 ("Not at all concerned") to 5 ("Extremely concerned").

4. Results study 2

4.1. Confirmatory factor analysis of the ICE

To validate the proposed structure of climate emotions established in Study 1, we utilised Confirmatory Factor Analysis (CFA). By testing a theory-driven framework, CFA evaluates the degree of fit between the hypothesised model and the collected data (Brown, 2015). This method offers a systematic approach to assessing construct validity and allows researchers to adjust the tested measurement model to enhance its fit.

First, we evaluated data distribution based on Mardia's test for multivariate skewness and kurtosis and the Shapiro-Wilk test for univariate normal distribution. Data departed considerably from multi- and univariate normal distribution, therefore, we conducted CFA with maximum likelihood estimation with robust standard errors and Satorra-Bentler scaled test statistic.

The fit of the initial measurement model, specified based on the results of Study 1, left room for improvement (*scaled* $\chi 2(1682) = 2660.36$, $p < .001$, *SRMR* = 0.09, *scaled RMSEA* = 0.044 [90 % *CI* = 0.041, 0.047], *scaled TLI* = 0.88, *scaled CFI* = 0.88). To identify localised areas of strain, we inspected the standardised residual covariance matrix and performed a stepwise deletion of items with consistently high standardised residuals, keeping an equal number of items in each subscale, and equal number of items representing each emotion in the "double emotion" factors. After the re-specification, the model with 4 items per factor and 8 factors demonstrated excellent fit (*scaled* $\chi 2(436) = 527.97$, $p = .002$, *SRMR* = 0.05, *scaled RMSEA* = 0.027 [90 % *CI* = 0.018, 0.033], *scaled TLI* = 0.97, *scaled CFI* = 0.98). All factor loadings were above the customary threshold of 0.4 (Brown, 2015).

In the next step, we examined construct validity in the CFA framework, fulfilling the criteria that convergent validity is established when the average variance extracted (AVE) by the latent variables is greater than 0.5, and discriminant validity is established when the average correlation between a latent variable and its indicators is higher than the squared correlation between the latent variables (Fornell and Larcker, 1981). The AVE values were above 0.5, except climate enthusiasm and climate powerlessness which had AVE of 0.45 and 0.31, respectively. Except climate powerlessness, all factors met the criteria for discriminant validity (see Supplementary File 6). To evaluate the internal consistency, Cronbach α and Raykov's ρ reliability coefficients were calculated for each subscale. The coefficients indicated good or very good internal consistency for all subscales except climate powerlessness which presented acceptable internal consistency. Table 5 presents the final results of CFA with 8 factors and 4 items per factor, as well as the values relevant for convergent and discriminant validity, and the internal consistency of each subscale. Fig. 3 depicts the variability and shape of the distribution for each climate emotion. Table 6 presents basic descriptive statistics and correlations between climate emotions. Detailed descriptives of the final climate emotions along with other variables used in the study are presented in Supplementary File 6.

4.2. Discriminant validity

To inspect the discriminant validity, we examined whether the scores on the ICE subscales differ across men and women, as well as groups declaring different levels of climate change concern. With regards to climate change concern, we used the median split to divide it into two groups: low ($n = 153$) and high ($n = 147$) concern, respectively.

Because the data departed from normality, to inspect differences between the above groups, we conducted a nonparametric permutational multivariate analysis of variance (PERMANOVA) based on Bray-Curtis dissimilarities using the 'vegan' package in R (Oksanen et al., 2022). The results showed that there were significant differences in climate change emotions between men and women (*Sum Sq* = 0.21, Pseudo-*F* (1) = 315.75, $R^2 = 0.05$, *p* from 999 permutations = 0.001, *p* from the test for homogeneity of multivariate dispersions based on 999 permutations = 0.002). To examine whether the two groups differed in expected directions on specific subscales, we performed post-hoc Monte Carlo Fisher-Pitman tests (Berry, Mielke and Mielke, 2002) using the 'coin' R package (Zeileis et al., 2008). To control the false discovery rate, we adjusted the obtained significance levels with Benjamini-Hochberg correction (Benjamini and Hochberg, 1995). The distribution of scores on different subscales using combined violin and whisker-and-box plots along with significance levels is presented in Fig. 4.

We conducted similar steps for two groups declaring different levels of concern for climate change. Overall, climate emotions of the low and high concern groups differed significantly (*Sum Sq* = 0.92, Pseudo-*F* (1) = 83.89, $R^2 = 0.22$, *p* from 999 permutations = 0.001, *p* from the test for homogeneity of multivariate dispersions based on 999 permutations = 0.001). Monte Carlo Fisher-Pitman tests with Benjamini-Hochberg correction showed that the differences were significant for all emotions except climate powerlessness. The distribution, direction of effects, and significance levels are visualised in Fig. 4. In sum, the results provided evidence for good discriminant validity of the ICE, however, for the subscales of climate powerlessness and climate isolation, the expected differences were only bordering statistical significance levels.

4.3. Concurrent and predictive validity

Basic descriptive statistics, internal consistencies of the theoretically relevant scales, and Spearman's rank correlations between mean scores on each ICE subscale and theoretically related variables are shown in Tables 6-8. Internal consistencies for each scale were above the customary cut-off point of 0.6 with the exception of two scales from the brief version of the Environmental Attitudes inventory - the "Ecocentric concern" scale and the "Interventionist policy support" scale (values from the Spearman-Brown formula for two-item measures = 0.28 and 0.59, respectively). Considering the existing body of literature and the contextual significance of these scales, we deemed it appropriate to include them in our study. More detailed elaboration on the inclusion of these two scales is presented in Supplementary File 6.

The results of the correlational analyses demonstrate that certain climate emotions were strongly interrelated with one another. This was the case especially for climate anger, climate anxiety, and climate sorrow, which showed strong positive associations. We observed moderate significant associations between climate guilt, isolation and anxiety. Climate contempt was significantly negatively correlated with all other climate emotions, except climate powerlessness. Climate enthusiasm was moderately positively correlated with climate anger, anxiety and sorrow, and to some extent with guilt.

Regarding concurrent validity, all but one of the ICE subscales were

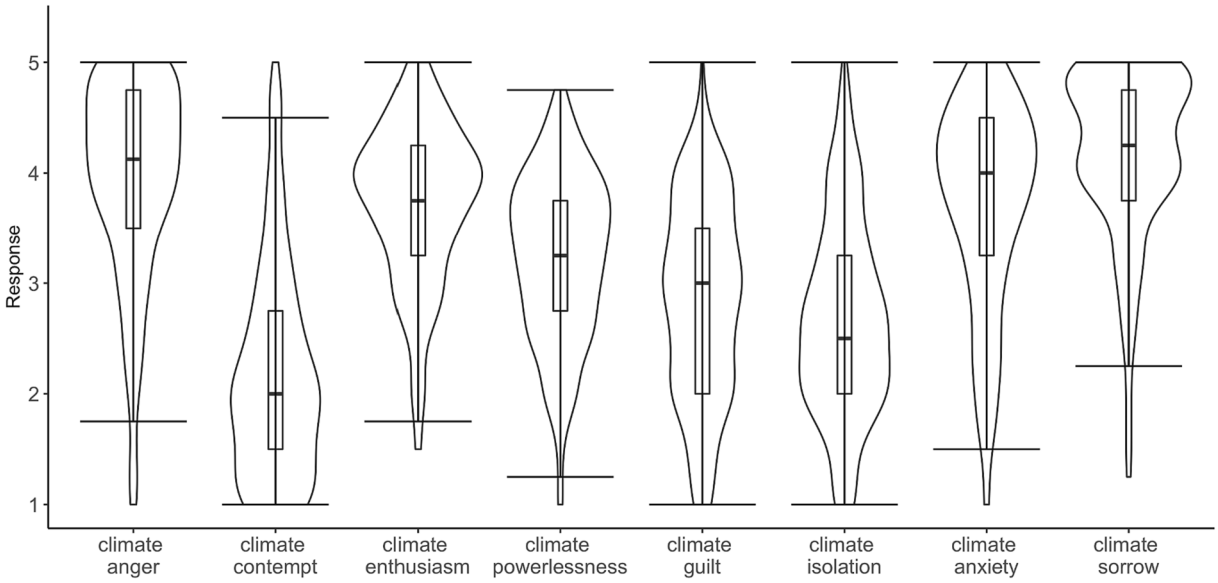

Fig. 3. *The variability and shape of the distribution for each climate emotion* Note. The boxplots indicate the median and quartiles with whiskers reaching up to 1.5 times the interquartile range. The violin plots illustrate kernel probability density.

Table 5
Spearman r_s correlation coefficients between climate emotions.

	CAng	CCon	CEnt	CPow	CGui	CIso	CAnx	CSor	*M* (*SD*)
Climate Anger									3.95 (0.91)
Climate Contempt	-0.57***								2.17 (0.95)
Climate Enthusiasm	0.34***	-0.27***							3.73 (0.72)
Climate Powerlessness	0.25***	-0.01	-0.02						3.23 (0.75)
Climate Guilt	0.43***	-0.29***	0.25***	0.45***					2.85 (0.90)
Climate Isolation	0.31***	-0.12*	0.11	0.37***	0.51***				2.67 (0.88)
Climate Anxiety	0.65***	-0.55***	0.37***	0.33***	0.55***	0.43***			3.70 (0.93)
Climate Sorrow	0.73***	-0.63***	0.36***	0.25***	0.45***	0.24***	0.68***		4.17 (0.78)

Note. *p <.05; **p <.01; ***p <.001.

Table 6
Spearman r_s correlation coefficients between climate change emotions and variables included to test concurrent validity, along with mean (*M*) and standard deviation (*SD*) values for all the scales, and the internal consistency (*IC*) values.

	CAng	CCon	CEnt	CPow	CGui	CIso	CAnx	CSor	*M* (*SD*)	*IC*[1]
Emotional reactivity	**0.30***	-0.23***	**0.15***	**0.33***	**0.26***	**0.21***	**0.33***	**0.30***	3.50 (0.48)	0.88
Climate change perceptions	**0.58***	**-0.62***	**0.22***	**0.1**	**0.27***	**0.20***	**0.54***	**0.60***	5.47 (1.03)	0.72
Personal experience of climate change	**0.50***	**-0.37***	**0.32***	0.13*	**0.39***	**0.37***	**0.60***	**0.46***	2.50 (0.90)	0.79
Enjoyment of nature (EAI)	**0.25***	**-0.26***	**0.25***	-0.02	0.01	-0.01	**0.21***	**0.34***	6.32 (0.90)	0.65
Fragility of the natural environment (EAI)	**0.48***	**-0.54***	**0.20***	0.02	0.11	-0.05	**0.32***	**0.45***	5.84 (1.14)	0.69
Ecocentric concern (EAI)	**0.43***	**-0.44***	**0.21***	0.13*	**0.12***	**0.17****	**0.34***	**0.49***	5.94 (1.15)	0.28
Interventionist policy support (EAI)	**0.31***	**-0.32***	0.12*	-0.02	0.07	-0.09	0.11	0.27***	5.12 (1.28)	0.59
Confidence in science & technology (EAI)	0.11	-0.13*	**0.28***	-0.11	-0.03	-0.05	0.05	0.06	4.33 (1.30)	0.78
Human dominance over nature (EAI)	**-0.22***	**0.34***	0	0.05	-0.09	-0.02	**-0.15****	**-0.22***	3.47 (1.68)	0.80
Human utilisation of nature (EAI)	**-0.38***	**0.43***	**-0.16****	0.01	**-0.20***	**-0.13***	**-0.31***	**-0.34***	3.70 (1.21)	0.68
Climate action efficacy: self	0.37***	-0.38***	**0.55***	**-0.12***	**0.18****	0.11	0.39***	0.43***	3.81 (0.95)	0.86
Climate action efficacy: collective	0.39***	-0.40***	**0.62***	-0.01	0.20***	0.03	0.38***	0.43***	4.31 (0.87)	0.85
Affective symptoms (HEAS)	0.27***	**-0.21***	0.13*	**0.30***	**0.38***	**0.42***	**0.44***	**0.25***	1.66 (0.66)	0.87
Personal impact anxiety (HEAS)	0.41***	-0.30***	0.34***	0.33***	**0.54***	0.42***	0.56***	0.44***	1.72 (0.61)	0.82

Note. *p <.05; **p <.01; ***p <.001. Correlations conforming to the hypotheses are marked in bold.
[1]Internal consistency of the scales. For the scales consisting of 2 items, Spearman-Brown formula was used to estimate the internal consistency (Eisinga, Grotenhuis and Pelzer, 2013). For scales consisting of more than 2 items, Cronbach's alpha coefficient was computed.

significantly positively correlated with emotional reactivity lending support to the hypothesised affective nature of the construct of climate emotions. The only exception was climate contempt, which showed moderate negative association with emotional reactivity. Climate change emotions correlated in the expected directions with climate change perceptions. Our hypotheses regarding correlations with various environmental attitudes were met with the exception of climate isolation and guilt, which either did not show the hypothesised associations with the measures of enjoyment of nature, environmental fragility, and ecocentric concern or only weakly correlated with them. Similarly, these two variables did not show the expected negative correlations with the attitudes regarding the positive evaluation of human dominance over nature. Expectations regarding correlations with climate action efficacy were also met. All the expected correlations with

Table 7
Spearman r_s correlation coefficients between climate change emotions and variables included to test predictive validity and social desirability, along with mean (*M*) and standard deviation (*SD*) values for all the scales, and the internal consistency (*IC*) values quantified by Cronbach's alpha coefficient.

	CAng	CCon	CEnt	CPow	CGui	CIso	CAnx	CSor	*M* (*SD*)	*IC*
Individual mitigation behaviour	**0.21*****	**-0.27*****	**0.31*****	**-0.07**	**-0.02**	**0.01**	**0.24*****	**0.24*****	5.38 (0.62)	0.61
Mitigation policy support	**0.58*****	**-0.52*****	**0.35*****	**0.03**	**0.27*****	**0.12***	**0.45*****	**0.53*****	5.41 (1.05)	0.80
Cognitive-emotional impairment (CAS)	0.36***	**-0.23*****	0.27***	**0.21*****	**0.47*****	**0.50*****	**0.54*****	**0.33*****	1.67 (0.67)	0.90
Social desirability	**0.08**	**-0.07**	**0.25*****	**-0.24*****	**-0.10**	**-0.03**	**0.10**	**0.12***	3.93 (0.68)	0.71

Note. *p <.05; **p <.01; ***p <.001. Correlations conforming to the hypotheses are marked in bold.

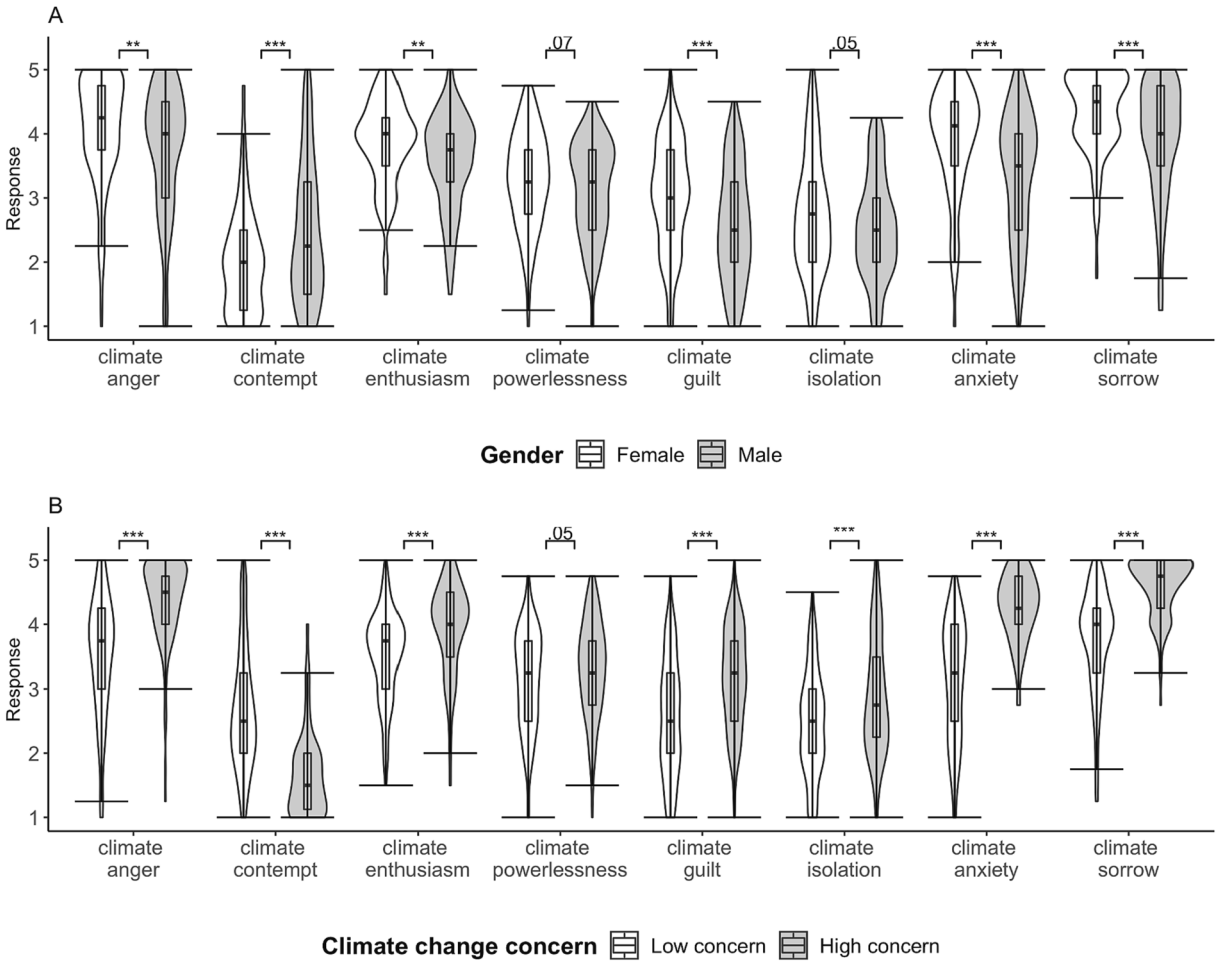

Fig. 4. *Comparisons of scores on eight climate change emotions subscales between genders (A) and groups declaring different levels of climate change concern (B). Note.* The boxplots indicate the median and quartiles with whiskers reaching up to 1.5 times the interquartile range. The violin plots illustrate kernel probability density. Notation of significance levels: *p <.05; **p <.01; ***p <.001.

the relevant dimensions of eco-anxiety found confirmation in our results.

The results of correlational analysis between each climate change emotion and individual mitigation behaviour and mitigation policy support confirmed the hypotheses about the predictive validity of the ICE with an exception of climate guilt, which did not show the expected positive correlation with individual mitigation behaviour but, as assumed, it did correlate positively with mitigation policy support. Nevertheless, the more people experienced climate anger, climate enthusiasm, climate anxiety and climate sorrow, the more they declared engaging in individual mitigation behaviour and the more they supported climate mitigation policies. At the same time, the more climate contempt, the smaller the engagement in climate change mitigation. As expected, climate powerlessness did not show any significant correlations in this regard. Climate isolation was weakly positively interrelated with mitigation policy support. However, as we did not have any directional hypotheses regarding this emotion, and given multiple correlations performed in this analysis, this finding should be treated with caution. Concurrently, all the hypothesised links between climate emotions and the cognitive-emotional impairment associated with climate anxiety were confirmed. Our results provide initial evidence for the functional validity of the majority of the ICE subscales in the context of climate-relevant behaviour.

Lastly, the ICE was largely free from social desirability. However, indicating a higher degree of climate enthusiasm was moderately related to a tendency to present oneself in a favourable light, while climate sorrow showed a weak positive correlation in this regard. Simultaneously, declaring a higher degree of climate powerlessness was associated with a decreased tendency toward socially desirable responding. Supplementary Material 6 contains results not outlined here in a clear

and concise format, including a complete overview of the correlations between all the variables included in this study.

4.4. Discussion study 2

In Study 2, we demonstrated initial evidence that the ICE can be considered a valid and reliable measure of multiple emotions experienced in relation to climate change. In sum, we confirmed the 8-factor structure of the ICE on a new set of data and we shortened the subscales to include 4 items for each factor to conform to a high quality measurement model. Most subscales demonstrated excellent internal consistency, as well as good convergent and discriminant validity as assessed in the CFA framework. The subscales, in most cases, varied as expected between the groups which were assumed to differ, providing evidence for the discriminant validity of the ICE. The patterns of correlations of the ICE subscales with the theoretically and functionally related constructs predominantly closely mimicked the hypothesised patterns of correlations lending support for the concurrent validity of the ICE and the predictive validity of specific subscales of the ICE in relation to climate-relevant behaviour. Lastly, the ICE proved to be largely free from social desirability.

Interestingly, in the analysis of concurrent evidence for validity of the ICE, climate contempt not only did not show the expected positive correlation with emotional reactivity, but it significantly negatively correlated with the tendency to experience frequent and intense emotional arousal. This subscale is built up by two subcomponents - "climate discontent" and "climate indifference". While the former is likely to be positively related to emotional arousal which lies at the heart of the construct of emotional reactivity, the latter might drive this relationship in the opposite direction. Speaking in terms of core affect (Barrett and Russell, 2014), climate contempt therefore might reflect an affective construct characterised by negative valence and low arousal hence the negative correlation with the arousal-driven emotional reactivity. These results also point to the similarity of climate contempt and climate denial as climate denial might serve as a defence mechanism against the discomfort of confronting difficult emotions (Wullenkord, 2022).

Concerning predictive validity, selected scales showed small to moderate correlations with individual mitigation behaviour, yet they demonstrated moderate to strong correlations with policy support, suggesting that climate emotions might be particularly important for more politically-oriented behavioural variables related to climate change mitigation. However, as the findings are based on cross-sectional, self-report data, caution is needed in drawing strong conclusions about causality.

At the same time, convergent validity based on the customary value of AVE could not be established for climate enthusiasm and climate powerlessness. AVE reflects the proportion of variance in the indicators that can be attributed to the construct itself, rather than measurement error or other factors (Brown, 2015). Low AVE suggests that the observed indicators do not adequately reflect the underlying construct. However, before jumping to conclusions, it is important to interpret the low AVE value in the context of other validity evidence. In this sense, the climate enthusiasm subscale could be defended by rather strong support in other metrics (e.g., factor loadings, discriminant and concurrent validity). In addition, its AVE value is only slightly below the cut-off point and may be an artefact of the particular study sample.

Regarding climate powerlessness, besides low AVE, this subscale did not meet the strict criteria for discriminant validity in the CFA framework, and although acceptable, its internal consistency was low, as were the factor loadings. These observations cast doubt on the validity of this subscale. When looking for interpretation of this finding, it is important to note that the psychological construction approach highlights the multidimensional nature of emotions, suggesting that many emotional experiences involve a complex interplay of various affective dimensions. In this light, a sense of powerlessness likely overlaps with other negative emotions within the broader emotional context of climate-related concerns, and it might be hard to discern from them. This raises questions about the specific contribution of the climate powerlessness subscale in capturing a unique category of emotional experience of climate change.

Despite these limitations, the fit indices and evidence for discriminant concurrent and predictive validity of the ICE were overall very good lending support to validity of the ICE in assessing multiple emotional responses to climate change. Nonetheless, more research is needed to evaluate the psychometric quality of the subscales, especially for the subscales of climate powerlessness and climate enthusiasm.

4.5. General discussion

We addressed the gap in literature concerning the valid assessment of the wide panorama of people's emotional responses to climate change by developing and validating a multi-scale self-report instrument that captures various affective phenomena that accompany specific climate-change related perceptions. In our research, we laid the foundations for understanding the nature of multiple climate change emotions, suggesting the definitions of the studied constructs and investigating their relationships with relevant variables. In addition, the analyses presented here were based on the original, strictly quality-controlled data from the general population in Poland. To our knowledge, this is the first quantitative study on the emotional responses to climate change in this country.

The EFA in Study 1 indicated that important aspects of emotional responses to climate change can be viably captured by 7 underlying factors which are fully interpretable in the light of our theoretical assumptions and operational definitions: climate anger, contempt, enthusiasm, powerlessness, guilt, isolation and anxiety. In addition, because sadness has been reported as one of the very core dimensions of the emotional experience of climate change (Cunsolo and Ellis, 2018; Pihkala, 2020, 2022; Ojala et al., 2021; Marczak et al., 2023), to avoid misrepresenting reality based on data from one study only, we decided to include indicators of climate sorrow for further evaluation, even though they did not form a separate subscale in the 7-factor EFA solution.

The 8-factor structure of the ICE was corroborated in CFA on an independent sample in Study 2. In the analysis, the number of items was reduced to 32 to guarantee good fit of the measurement model and to improve the internal consistency of the ICE subscales as very high Cronbach alpha values in Study 1 indicated that the subscales should be shortened. We also demonstrated that the ICE can be used to discriminate between groups assumed to differ on the variables of interest - men and women, as well as groups declaring different levels of climate change concern. However, as much as climate isolation and powerlessness differed in the hypothesised directions, the differences for these climate emotions only approached the predetermined significance thresholds.

We also found evidence for the validity of the ICE based on investigating its associations with measures of theoretically related constructs. To this end, based on the existing literature, we formulated an extensive set of directional hypotheses about the relationships between the ICE subscales and measures of emotional reactivity, climate change perceptions, various environmental attitudes, climate action efficacy, and affective dimensions of climate- and eco-anxiety.

In most cases, our hypotheses were confirmed indicating that the ICE assesses affective constructs that are related to people's perceptions of climate change, their capability to address it, and, more generally, to people's evaluations of the natural environment and the place of humans in it. The exceptions were climate guilt and isolation for which empirical associations with certain environmental attitudes were weaker than expected or were not observed at all. When forming the hypotheses, we coined these emotions, along with climate anger, enthusiasm, anxiety, and sorrow, "pro-climate emotions" because in our exploratory research (Zaremba et al., 2022; Marczak et al., 2023), and in

the existing literature (e.g., Schneider, Zaval and Markowitz, 2021; Stanley et al., 2021; Wullenkord et al., 2021; Shipley and van Riper, 2022), they were associated with pro-climate engagement. The results of correlational analyses in Study 2 suggest, however, that the links between pro-environmental attitudes and climate guilt and isolation might be more ambiguous.

The final 4-item subscales showed very good internal consistency, except the climate powerlessness subscale for which we found minimally acceptable internal consistency values. Overall, from the psychometric perspective, the climate powerlessness subscale performed consistently worse than other subscales. Its factor loadings, although acceptable, were lower than for other subscales. In addition, its convergent and discriminant validity, as analysed in the factor analytic framework, did not reach satisfactory levels. Furthermore, this subscale did not perform strictly as expected in the discriminatory and concurrent analysis, which might be related to its unsatisfactory reliability and validity. As much as the content of this subscale was informed by careful qualitative and quantitative analyses, our evidence suggests that it may lack sufficient psychometric quality that would justify retaining it as part of the ICE. More research is needed, however, to conclusively evaluate the validity of the climate powerlessness subscale.

Our research provided initial evidence for the utility of the ICE for research on climate-relevant behaviour. Specifically, climate enthusiasm, anxiety, sorrow, and anger showed moderate positive associations with individual mitigation behaviour. Climate anger, sorrow and anxiety were strongly positively related with support for climate mitigation policies, whereas climate enthusiasm and guilt correlated with it moderately. In line with our hypotheses, we found strong negative correlation of climate contempt with policy support, and moderate negative correlation with individual mitigation behaviour. Climate isolation and powerlessness were not meaningfully related to climate-relevant behaviour. These results provide preliminary quantitative verification of our assumption about what we coined "pro-climate emotions", and they suggest that this category should include predominantly climate anger, enthusiasm, anxiety and sorrow, leaving out the more ambiguous guilt and isolation.

Quantitative research on the natural (not experimentally induced) emotional responses to climate change focused so far mostly on anxiety, often measured in reference to symptoms of ill mental health rather than the core affective response (feeling anxious, apprehensive or scared about climate change) (Clayton and Karazsia, 2020; Wullenkord et al., 2021). Studies in Germany, Philippines and Italy showed that such climate anxiety can be positively related to pro-environmental behavioural intentions and policy support (Innocenti et al., 2021; Wullenkord et al., 2021; Simon, Pakingan and Aruta, 2022). Our work extends this perspective, as the ICE makes it possible to assess a wide range of climate emotions simultaneously.

Unlike other, available measures (e.g., the Climate Anxiety Scale; Clayton and Karazsia, 2020), the ICE allows for disentangling the emotional experience of anxiety from other emotions such as sorrow, anger, guilt and isolation. As suggested in the literature (e.g., Landmann, 2020), it is important to consider various climate emotions separately because they can be associated with different action tendencies. For example, in a cross-sectional study in Australia, using an ad hoc measure of climate emotions, Stanley and colleagues (2021) showed that anxiety, sadness and anger differently predicted climate action and mental health and wellbeing. The ICE allows for moving toward such more nuanced models of climate change emotions, a need for which was signalled in the literature (Albrecht, 2019; Berry et al., 2018; Chapman et al., 2017; Prescott et al., 2018; Landmann, 2020).

4.6. Limitations and future directions

Due to the breadth of our instrument, it was difficult to convincingly cover the concurrent and predictive validation of all its dimensions in two studies presented here. In this vein, acknowledging that establishing questionnaire's validity is an ongoing process rather than a single "all or none" demonstration (Furr, 2011), more conclusive evidence is needed to decide whether the climate powerlessness subscale should be retained in the ICE. Considering evidence provided here, before more research is available, we recommend caution in the use of this subscale.

Despite our efforts, we acknowledge that the dimensions included in the ICE might not capture the full phenomenology of the emotional experience of climate change. One reason for that might be that emotions are culturally embedded phenomena (Mesquita et al., 2007). Here, it is important to note that the ICE was developed in the cultural context of Poland that has its unique socio-cultural factors and policy landscape that influence people's attitudes, beliefs, and emotional responses regarding climate change. Poland is heavily reliant on fossil fuels (Statistics Poland, 2021). In addition, this Eastern European country is characterised by reluctance to climate protection at the political level and hence a lack of adequate policy instruments in place to address climate change effectively (Brauers and Oei, 2020). Despite these political reservations, recent research indicates that public support for climate policy in the Polish society is comparable to that in European countries with more ambitious and progressive climate agendas (Bohdanowicz, 2021). Given this background, the final formulation of certain climate emotions subscales, such as, e.g., anger or anxiety, may reflect the specific circumstances in Poland, including its reliance on fossil fuels and lack of political will regarding climate change mitigation and adaptation. To enhance the generalisability of our findings and the utility of the ICE in other cultural contexts, further research assessing the cross-cultural equivalence of the instrument is needed.

Another point to consider is that the progressing climate change might bring about new forms of emotional experience. Therefore, the ICE is constructed in a way that makes it possible to add new dimensions, as well as to use the subscales proposed here selectively. Here, it is important to acknowledge that the complexity of human emotions and the varied perspectives through which individuals interpret and respond to climate change pose significant challenges in measuring emotional responses to climate change. Thus, the scientific study of climate emotions requires a careful equilibrium between capturing the subtleties of individual experiences and developing robust measures that can be applied to broader populations. While the ICE does not capture every facet of the emotional experience, we believe it offers a meaningful approach for further exploration and understanding in this important field of research.

Moreover, the ICE has inherent limitations associated with the use of self-report measures in psychology, including potential biases and reliance on individuals' self-perception and introspection (Furr 2011). In that sense, it focuses on individuals' consciously articulated emotions, potentially overlooking other emotional factors that operate outside conscious awareness. Future studies could incorporate alternative methods, such as physiological measures, to complement self-report data and provide a more comprehensive understanding of climate-related emotional responses.

Prospective research utilising the ICE can contribute to the ongoing development of the scale by exploring the temporal dynamics of climate emotions, examining their associations with mental health and well-being, and advancing more nuanced and context-specific theories of climate change emotions. It is crucial to acknowledge that the ICE is a work-in-progress, and further refinement and validation are imperative. This includes, as mentioned above, conducting cross-cultural research to ensure its applicability across diverse populations, as well as moving beyond cross-sectional design and investigating, e.g., the temporal stability of the measurement. Continuous research and collaborative efforts are vital to ensure the scale's robustness, relevance, and utility in informing global environmental change research and policy. In addition, as addressing climate change is an extremely pressing issue, we hope that the ICE can also be used in the applied settings, for example to improve climate change communications by, for example, matching messages to receivers' emotional needs (Chapman, Lickel and

Markowitz, 2017).

5. Conclusion

We showed that eight important aspects of emotional responses to climate change can be assessed in a valid and reliable manner using the ICE (the complete final questionnaire is available in Supplementary File 7). We believe that the ICE is a useful tool to further theory development and that it can be used in research endeavours aiming at advancing the understanding of the complex role of emotions in climate change engagement and psycho-social impacts of climate change. We encourage researchers to further investigate the utility of the ICE in these contexts.

CRediT authorship contribution statement

Michalina Marczak: Conceptualization (lead), Methodology (lead), Writing – original draft (lead), Formal analysis (lead study 2; supporting study 1), Visualisation (lead), Software (supporting study 1, lead study 2), Validation (equal), Writing – review & editing (lead), Funding acquisition (equal), Investigation (supporting), Project administration (supporting). **Małgorzata Wierzba:** Data curation (lead), Investigation (lead), Formal analysis (equal study 1), Software (equal study 1), Validation (equal), Writing – review & editing (supporting), Conceptualization (supporting), Methodology (supporting), Project administration (supporting), Resources (supporting). **Dominika Zaremba:** Formal analysis (equal study 1), Software (equal study 1), Validation (equal study 1), Writing – review & editing (supporting), Conceptualization (supporting), Methodology (supporting), Writing – original draft (supporting), Investigation (supporting). **Maria Kulesza:** Conceptualization (supporting), Methodology (supporting). **Jan Szczypiński:** Formal analysis (equal study 1), Software (equal study 1), Validation (equal study 1), Writing – review & editing (supporting). **Bartosz Kossowski:** Resources (lead), Data curation (supporting). **Magdalena Budziszewska:** Writing – review & editing (supporting), Methodology (supporting). **Jarosław M. Michałowski:** Writing – review & editing (supporting), Conceptualization (supporting), Methodology (supporting). **Christian A. Klöckner:** Supervision (equal), Writing – review & editing (supporting), Conceptualization (supporting), Methodology (supporting), Funding acquisition (supporting). **Artur Marchewka:** Project administration (lead), Supervision (equal), Writing – review & editing (supporting), Funding acquisition (equal), Conceptualization (supporting), Methodology (supporting).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

https://osf.io/78d6u/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102764.

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Further reading

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