Climatic Change (2023) 176:134
https://doi.org/10.1007/s10584-023-03607-z

Implementing climate literacy in schools — what to teach our teachers?

Anna-Kathryn Leve[1] · **Hanno Michel**[1] · **Ute Harms**[1]

Received: 16 November 2022 / Accepted: 7 September 2023 / Published online: 26 September 2023

Abstract
Climate literacy (CL) comprises knowledge, skills, and attitudes that enable individuals to counteract the global threat of anthropogenic climate change. Teachers' knowledge and pedagogy are main predictors of students' learning outcomes, but teachers are insufficiently prepared in the interdisciplinary field of CL. In a multilevel interrogation of experts in the fields of climate science, education research, and school, we derived 13 delineated themes describing necessary knowledge concerning the scientific background of climate change as well as pedagogy and teaching strategies. These themes indicate that teachers need a broad basis of understanding the climate system, climate science, causes of, impacts of, and dealing with climate change as well as the ability to convey this interdisciplinary content into teaching, by making the topic personally relevant and strengthening students' role as change agents. The findings underline the need to promote interdisciplinary ways of teaching towards CL and provide a baseline for the development of future teacher preparation.

Keywords Climate literacy · Teacher education · Climate change · Teaching strategies

1 Introduction

With each passing year, there is growing scientific evidence regarding anthropogenic climate change and its impacts (IPCC 2021). Despite rising awareness throughout society (Leiserowitz et al. 2015; European Commission 2021), a perceived uncertainty about the topic remains and the assumption that scientific findings about climate change are controversial and doubtful is prevailing (Niepold et al. 2007; Uherek and Schüpbach 2008; Leiserowitz et al. 2015). In order to address the challenges of climate change by means of individual and collective action, sophisticated education plays a pivotal role by promoting scientific findings without paralyzing students and thus enabling subsequent action (Milér and Sládek 2011; Ledley et al. 2017; Crandon et al. 2022).

✉ Anna-Kathryn Leve
leve@leibniz-ipn.de

1 IPN – Leibniz Institute for Science and Mathematics Education, Olshausenstraße 62, 24118 Kiel, Germany

To achieve this, the concept of scientific literacy has been put forward, which covers the understanding of natural systems and their functioning as well as an understanding of the nature of science (DeBoer 2000) and which, besides knowledge, includes skills such as the assessment of information and decision-making (Dupigny-Giroux 2008). For climate change, a context-specific notion of scientific literacy — climate literacy (CL) — was defined (Niepold et al. 2007; Azevedo and Marques 2017) which this study is based on because it relates to a theoretically well-founded framework in education research. Although further, broader definitions do exist, the OECD has adopted the same conceptualization (OECD 2022). As such, CL comprises (1) content knowledge of climate and climate change, (2) skills needed to assess, interpret and communicate (scientific) information, and (3) attitudes that result in climate-friendly behavior (Azevedo and Marques 2017). Hence, education plays a significant role in promoting CL (Lee et al. 2015; Simpson et al. 2021), and students are a highly relevant target group to sensitize for the challenges of climate change, for they are still developing their worldviews (Stevenson et al. 2014). Studies show that students lack knowledge and hold misconceptions about climate change (Shepardson et al. 2009) and have difficulties regarding knowledge on action or willingness to act (Tolppanen et al. 2022).

Thus, teachers play a pivotal role in connecting students to the matter of climate, climate change, and thus CL (Dupigny-Giroux 2010). Therefore, teachers need to translate complex concepts and specialized terminology — which are likely to form obstacles to understanding the issues correctly (Dupigny-Giroux 2010) — into the context of school subject matter. Furthermore, in order to implement CL in a way that leverages the necessary changes in society, the focus may not only be on scientific and technological aspects but also on societal and ethical dimensions (USGCRP 2009; Azevedo and Marques 2017; Shwom et al. 2017).

Yet, the inclusion of political, social, and economic aspects in CL education seems to be of difficulty for secondary science teachers (Herman et al. 2017). One possibility to overcome this challenge is an interdisciplinary approach to CL education which was appreciated by secondary teachers according to Johnson et al. (2008) and primary and secondary teachers according to Howard-Jones et al. (2021). Nevertheless, Wise (2010) reports that CL education was included in earth-science curricula in her sample whilst teachers in other subjects include the topic in informal ways, and Howard-Jones et al. (2021) also see a focus in science and geography. Thus, although willing to teach interdisciplinary climate change, pre-service teachers would need more knowledge throughout different subjects (Demant-Poort and Berger 2021), and they would need to be in agreement about (1) what content and (2) where in the curriculum of (3) which subject (e.g., chemistry) to teach (Feierabend et al. 2011). Apart from the interdisciplinary challenge, teachers' attitudes and further barriers towards teaching climate change have been investigated. Competente (2019) reports low awareness towards climate change in pre-service teachers due to missing content knowledge and teaching strategies, whereas Liu et al. (2015) and Jeong et al. (2021) could improve pre-service teachers' climate change awareness by their interventions. In fact, missing content knowledge and teaching strategies along with a perceived scientific controversy in the topic regarding climate change were often mentioned as barriers that make teachers feel underprepared for CL education according to several studies (e.g., Johnson et al. 2008; Sullivan et al. 2014; Berger et al. 2015; Boon 2016). In line with teachers' perceptions of their own knowledge, research has been conducted, testing teachers' general knowledge in the field of CL education. Several studies found that teachers have incomplete content knowledge (e.g., of the greenhouse effect) and hold misconceptions (e.g., about presumptive relations between climate change and ozone depletion or pollution) (Papadimitriou 2004; Ratinen 2013; Nyarko and Petcovic 2021; Eze et al. 2022). However, McNeal et al. (2014) report that they investigated an informed group of secondary teachers who showed a good knowledge basis but still had some uncertainties about causes and impacts of climate change, which is partially in line with Anyanwu et al. (2015) who report that a group of high school geography teachers they tested understood the causes and processes of climate change better than impacts and solutions and still held misconceptions. Regarding the resources that (pre-service) teachers gained their knowledge from, several investigations revealed that the internet and (social) media play a significant role, indicating that learning from professional development programs is of minor significance (Wise 2010; Berger et al. 2015; Boon 2016; Competente 2019). Still, research on such professional development courses for CL education (e.g., including climate change adaptation, the greenhouse effect, climate change as a socioscientific issue, and pedagogy) reveals that those courses do help to improve teachers' knowledge (Ekborg and Areskoug 2012; Berger et al. 2015; Favier et al. 2021).

The studies outlined above were conducted mainly in Europe and the USA, although Ghana, Nigeria, South Africa, Australia, the Philippines, and Puerto Rico are also represented, and with (pre-service) teachers from either primary or secondary or both levels who cover many subjects with a strong emphasis on science. Given the fact that teachers from such diverse backgrounds feel poorly prepared, hold misconceptions, and gain their knowledge from internet sources according to the challenges outlined above, the question arises, what exactly teachers need to know to be firmly prepared. It has been acknowledged in the lessons learned from the professional development program by Johnson et al. (2008) and in the literature review by Hestness et al. (2014) that there are manifold requirements towards such programs. Yet, it remains still fragmented and vague and not empirically compiled what specific knowledge aspects teachers need for CL education and in which way these are specific to certain subjects and students' age levels. This includes knowledge of the content and scientific background of the topic of climate change (e.g., the climate system; the greenhouse effect), which means a level of knowledge that goes well beyond the level being taught at school, but that is still not the same knowledge as that of research scientists (Baumert et al. 2013). This is particularly important but challenging with respect to the constantly developing field of climate science as continuously analyzed and documented by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2021) and, at the same time, puts constraints on teachers that could prevent them from participating in climate-related professional development programs (Ennes et al. 2021). Additionally, teachers need to know how to teach the relevant content knowledge to students (e.g., knowledge about students' conceptions; instructional strategies) (Shulman 1987; Baumert et al. 2013; Großschedl et al. 2015). These two areas of teachers' professional knowledge are of significant relevance for students' learning outcomes (Mahler et al. 2017) which is why they are in focus of this study.

We aim to compile and empirically support those aspects of scientific background knowledge that teachers need to foster students' CL and how those aspects are allocated in different disciplines. Furthermore, we aim to compile and empirically support those aspects of knowledge that teachers need to foster CL with an emphasis on (mis-)conceptions and teaching strategies. First of all, we do so without referring to specific subjects or age levels of students. Our compilation of knowledge aspects should help to provide a basis for the support and equipment of teachers that could be adapted to their individual needs of knowledge according to subject and their students' age levels. For this, we used a panel composed of experts from the fields of climate science, education research, and educational practice applying a Delphi method. We interrogated the expert panel in three subsequent rounds asking them to bring up ideas for relevant knowledge aspects and to rate and modify their collective suggestions. We aim to identify those knowledge aspects that we could find consensus for among the expert panel regarding their relevance for CL teaching.

2 Methods

The research questions in this study were addressed using the Delphi method, an iterative interrogation of experts in the field of study in premising rounds (Linstone and Turoff 1975). The Delphi technique is a group communication process that aims to find consensus or opinion stability when empirical findings are missing. Due to anonymous interaction of the panelists, group consensus is allowed to form without single group members becoming dominant (Osborne et al. 2003). The Delphi technique often starts with an open, qualitative round providing the basis for the subsequent rounds that become more quantitative and include rating techniques (Powell 2003).

2.1 The expert panel

For our research interest, we involved climate researchers, educational researchers, teacher educators, and teachers, who were considered as all relevant participant groups in the field of climate education bringing together expertise from the scientific background and from education expertise and practice. Experts were recruited following two expert level criteria: (1) government research or educational institutions and consortia were chosen that put an emphasis on the field of research on climate, climate change, or climate education/sustainability education (e.g., working groups, research consortia, formal education institutions). (2) People were chosen who hold a high position or a responsible role. Invited experts were offered the possibility to recommend colleagues from their institution as further experts to us. Regarding the subject backgrounds of our expert panel, about half of the experts had a science-only background, and about half had a background in science and further subjects or other than science (e.g., social studies, interdisciplinary subjects). The study was administered to an expert panel from the German-speaking area of Austria, Switzerland, and Germany. In all three countries, teacher education for the most part takes place at higher education institutions or universities with different amounts of mandatory practical training at schools. A large panel of experts was aimed at, thus up to 175 experts were invited with a feedback quota of about 30%. The resulting number of participants was considered as sufficient, particularly since most answers were quite detailed which was preferred over numerous shallow answers. Furthermore, the subsequent rounds offered the opportunity for additional participants to contribute to our interim results as outlined below. Experts were invited via e-mail, and all Delphi rounds were conducted using online questionnaires in German. The study and research questions are framed by the international research around CL. Yet, the study was implemented in German only to avoid limitations to experts who might be less familiar with English. The Delphi study was conducted in three subsequent rounds from February until October 2021.

The experts' answers towards CL-related knowledge aspects from the interrogation rounds (1 to 3) were analyzed between the rounds and fed back to the expert panel. By these feedback loops, the experts could modify their collective answers and rate and rerate what knowledge aspects are being considered as relevant for teachers by the whole expert panel. We followed a procedure similar to but not precisely the same as described by Osborne et al. (2003). In our study, the knowledge aspects were represented as themes including a heading and a description text. Themes evolved throughout the subsequent interrogation-rounds of the study (cf. Fig. 1) by achieving consensus among the expert panel about which themes are being considered as relevant knowledge for teachers. The three Delphi rounds are described in detail in the following section.

2.2 Delphi round 1 and qualitative content analysis

The first round aimed at gathering ideas, suggestions, and experience from the expert panel. In order to meet the research interests, questions were prompted that asked for (1) basic knowledge about climate and climate change including human interference, (2) pre- and misconceptions, and (3) exemplary teaching strategies. Additionally, experts were asked to rate their subjective competence in these three sections on a 4-point Likert scale from "not competent" to "very competent." In total, 129 experts were invited to round 1, 44 of whom participated. All four groups were reasonably equally represented (climate researchers (11), education researchers (11), teacher educators (12), teachers (9), not specified (1)).

The experts' answers from Delphi round 1 were analyzed using a deductive-inductive approach of qualitative content analysis (Mayring 2014; Kuckartz 2019) using the content analysis software MAXQDA (VERBI Software, 2021). Primary coding was conducted by the first author of this article. The development of the coding scheme and primary coding was done within the answer-section to each question; thus, codes were assigned to smaller thematically related text segments within each answer-section. For the intercoding of 20% of the material, each answer-section was treated as one coding unit. A good inter-coder-reliability was achieved (Kappa = 0.75). The resulting 20 themes

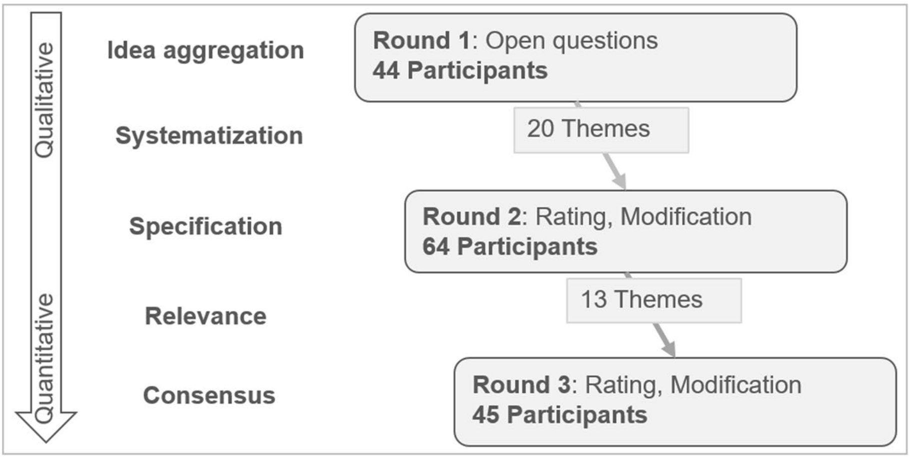

Fig. 1 Schematic diagram of the Delphi method process. The first round of interrogation had qualitative character, and the subsequent interrogation rounds became more quantitative, including rating techniques

cover content- and teaching-related knowledge. In preparation of the second Delphi round, descriptions reflecting all 20 themes were written based upon the expert answers.

2.3 Delphi round 2, qualitative, and quantitative analysis

In the second Delphi round, the expert panel was asked to rate the 20 themes according to their relevance for the education of teachers to foster CL on a seven-point Likert scale from 1 (not relevant) to 7 (very relevant). Experts were asked to justify their rating, to make suggestions for changes, and to state whether they would merge, split, or add any themes. For the second (and third) round, the pool of experts who were invited was enlarged to 175 following the same expert criteria as indicated above. In total, 64 experts participated in round 2 (climate researchers (18), education researchers (14), teacher educators (15), teachers (16), not specified (1)). Twenty-six of the participating experts were the same as in round 1, 38 were new participants.

The answers were analyzed quantitatively and qualitatively. Means, standard deviations, and frequency distributions of the experts' ratings were calculated. Experts' feedback on overlaps between themes was analyzed by frequency. Themes were merged when at least two experts saw overlaps and further comments indicated missing distinction from other themes. No indications for splits were expressed by the experts. Experts' reasons for their ratings and on possible changes were analyzed for suggested additions, reductions or corrections, comments towards the structure, focus, and complexity of themes as well as interrelations with other themes and target group specificity. The descriptions of themes were revised accordingly. Thirteen themes remained covering content- and teaching-related knowledge.

2.4 Delphi round 3 and statistical analysis

The third Delphi round asked the expert panel to rerate the revised themes under consideration of the panels' ratings from round 2 and to comment on them. To this end, the frequency distributions of Likert scale ratings and the means for all former themes were presented. Eventually, they were asked if they would merge or split any themes. In total, 45 experts participated in round 3 (climate researchers (11), education researchers (13), teacher educators (10), teachers (11)). Fifteen of the participants were the same as in round 1 and 2, 30 were the same as in round 1 or 2, and there were no new participants.

The experts' answers from Delphi round 3 were analyzed analogous to round 2. According to this feedback, the themes were revised by further additions and adjustments of wording. No indications for merging or splitting any themes were expressed.

As to compare the central tendency of ratings between expert groups for the final themes in round 3, a Kruskal–Wallis test (non-parametric for ordinal scaled data) was conducted ($p < 0.05$), and a Dunn-Bonferroni post hoc test was used to identify the particular expert groups between which significant differences occurred (adj. $p < 0.05$).

Statistical analyses were done using the statistic computing language and environment R (R Core Team 2020), including the following packages: dplyr (Wickham et al. 2021), mosaic (Pruim et al. 2017), ggplot2 (Wickham 2016), and FSA (Ogle et al. 2021).

3 Results

Themes that are considered as relevant knowledge for teachers have been identified by achieving consensus among the expert panel throughout the subsequent interrogation-rounds of the study. Hence, consensus as a measure in this study indicates which knowledge aspects originally brought up during round 1 were subsequently highly rated among the expert panel and how they evolved during the subsequent rounds. Defining consensus by means of a predefined majority within the expert panel is common, even though the critical share to build a majority varies among different authors (Osborne et al. 2003; von der Gracht 2012; Deeken et al. 2020). Following the more conservative two-thirds rule, consensus for rating themes as important (≥ 4 on the Likert scale) was reached for 17 out of 20 themes in round 2 and for all remaining 13 themes in round 3.

Since the study was conducted in German, all of the results presented here have been translated thoroughly into English. Yet, slight inaccuracies resulting from the translation cannot be absolutely excluded. The titles of themes that originally emerged from round 1, their ratings, and their evolvement between round 2 and 3 are displayed in Table 1. Ratings of themes from round 3 are displayed by expert groups in Table 2. The final themes (headings and description texts) as resulting from the study are provided in the supplementary material in English, translated from the original German results (Online Resource 1).

3.1 Variance of group ratings

Significant differences in ratings between expert groups ($p < 0.05$) were revealed by a Kruskal–Wallis test for four out of 13 themes: *Components and functioning of the climate system* ($\chi^2 = 15.25$, $df = 3$, $p = 0.002$); *Impacts of anthropogenic climate change* ($\chi^2 = 8.19$, $df = 3$, $p = 0.04$); *Pre- and misconceptions* ($\chi^2 = 8.52$, $df = 3$, $p = 0.04$); *Self-reference: living environments and options to act* ($\chi^2 = 11.95$, $df = 3$, $p = 0.008$). A Dunn-Bonferroni post hoc test revealed that for *Components and functioning of the climate system* the differences were between the group of climate scientists and teachers (adj. $p = 0.01$) as well as between climate scientists and teacher educators (adj. $p = 0.008$). Furthermore, it revealed that for *Self-reference: living environments and options to act* differences were between climate researchers and education researchers (adj. $p = 0.02$) as well as between climate researchers and teachers (adj. $p = 0.03$). Significant differences between groups for *Impacts of anthropogenic climate change* and *Pre- and misconceptions* were not verified by the post hoc test (adj. $p > 0.05$). Thus, regarding the respective measures of central tendency, climate scientists rated one content-related theme (*Components and functioning of the climate system*) as significantly more relevant than teachers and teacher educators did, whereas education researchers and teachers rated one teaching-related theme (*Self-reference: living environments and options to act*) as significantly more relevant than climate researchers did.

In round 3, only two themes show mean ratings < 6 across all groups: *Pre- and misconceptions* and *Formation of opinion and argumentation*. These two, as well as *Self-reference: living environments and options to act*, show high standard deviations > 1. Teaching-related themes were overall rated with less relevance (mean < 6, except for one theme) by climate researchers and show a higher variance (standard deviation > 1 for all but one

Table 1 Themes that emerged from the Delphi rounds after the analysis of round 1 and their ratings (rating scale 1 (not important) to 7 (very important)) in round 2 and round 3 (themes ranged left are according to their final wording, indented themes were merged or changed in wording between round 2 and round 3)

Theme titles	Round 2 Mean	Round 2 Mode	Round 2 SD	Round 3 Mean	Round 3 Mode	Round 3 SD
Knowledge of scientific background and content						
Climate history and natural climate fluctuation	5.84	6	1.25	6.20	6	0.63
Components and functioning of the climate system				6.53	7	0.69
formerly: Components and functioning of the climate system	5.80	7	1.34			
and Climate as a system	5.55	6	1.39			
Climate science and dealing with information				6.33	7	0.8
formerly: Climate science, information, and media	5.98	7	1.29			
and: Denial of climate change, skepticism against climate science	5.56	7	1.62			
and: Genesis and status of scientific knowledge	5.00	7	1.66			
Relation to other societal/global problems	5.54	6	1.34	6.02	6	0.94
Causes of anthropogenic climate change	6.27	7	1.13	6.69	7	0.63
Impacts of anthropogenic climate change	6.15	7	1.24	6.53	7	0.84
Dealing with climate change				6.58	7	0.62
formerly: Mitigation- and adaptation strategies	5.92	7	1.35			
and: Societal changes and processes	5.83	7	1.20			
Interdisciplinary structure of climate education and curricular integration				6.28	7	0.98
formerly: Interdisciplinary content and fields of specific subjects	5.77	7	1.59			
and: Thematic structure of climate education and curricular integration	5.73	7	1.70			
Knowledge about how to foster CL in teaching						
Pre- and misconceptions				5.82	6	1.04
formerly: Misjudgments	5.59	7	1.52			
and: False or simplified concepts	5.25	7	1.70			
and: Visualization and further development of students' conceptions	5.39	6	1.57			
Dealing with willingness and capacity to act (*formerly wording*: Perceived obstacles to willingness to act)	5.52	7	1.48	6.16	7	0.88
Formation of opinion and argumentation integrated into climate education (*formerly wording*: Formation of opinion and argumentation)	5.63	7	1.51	5.76	7	1.21
Self-reference: living environments and options to act	5.85	7	1.59	6.19	7	1.26
Teaching: strategies and illustration	6.12	7	0.98	6.31	7	0.9

Table 2 Means and standard deviations by expert groups for all themes of round 3 (rating scale 1 (not important) to 7 (very important))

Theme	Mean ± SD expert groups				
	Education researchers	Climate researchers	Teachers	Teacher educators	Mean ± SD
Knowledge of scientific background and content					
Climate history and natural climate fluctuation	6.23 ± 0.73	6.36 ± 0.67	6.09 ± 0.7	6.10 ± 0.32	6.20 ± 0.63
Components and functioning of the climate system	6.77 ± 0.44	7.00* ± 0	6.18* ± 0.75	6.10 ± 0.88	6.53 ± 0.69
Climate science and dealing with information	6.46 ± 0.78	6.36 ± 0.5	6.09 ± 1.04	6.40 ± 0.84	6.33 ± 0.8
Relation to other societal and global problems	6.31 ± 0.95	5.64 ± 1.21	6.00 ± 0.63	6.10 ± 0.88	6.02 ± 0.94
Causes of anthropogenic climate change	6.69 ± 0.63	6.73 ± 0.47	6.82 ± 0.4	6.50 ± 0.97	6.69 ± 0.63
Impacts of anthropogenic climate change	6.62 ± 0.87	6.00 ± 1	6.73 ± 0.65	6.80 ± 0.63	6.53(*) ± 0.84
Dealing with climate change	6.62 ± 0.65	6.73 ± 0.47	6.55 ± 0.69	6.40 ± 0.7	6.58 ± 0.62
Knowledge about how to foster CL in teaching					
Interdisciplinary structure of climate education and curricular integration	6.25 ± 1.06	6.00 ± 1.26	6.64 ± 0.67	6.22 ± 0.83	6.28 ± 0.98
Pre- and misconceptions	6.31 ± 0.95	5.40 ± 1.07	5.36 ± 0.92	6.10 ± 0.99	5.82(*) ± 1.04
Dealing with willingness and capacity to act	6.23 ± 0.60	5.55 ± 1.13	6.64 ± 0.5	6.20 ± 0.92	6.16 ± 0.88
Formation of opinion and argumentation integrated into climate education	6.00 ± 1.53	5.73 ± 0.79	5.82 ± 0.98	5.40 ± 1.43	5.76 ± 1.21
Self-reference: living environments and options to act	6.46* ± 1.13	5.18* ± 1.72	6.60 ± 0.7	6.56 ± 0.53	6.19 ± 1.26
Teaching: strategies and illustration	6.08 ± 1.04	5.91 ± 1.04	6.55 ± 0.69	6.80 ± 0.42	6.31 ± 0.9

*Significant differences of ratings were found for the respective theme between the indicated expert groups according to the Dunn-Bonferroni post hoc test

(*)Significant differences of ratings were indicated for the respective theme by Kruskal–Wallis test, but not verified by Dunn-Bonferroni post hoc test theme). Moreover, all teaching-related themes except for *Pre- and misconceptions* and *Dealing with willingness and capacity to act* show high standard deviations of > 1 within the group of education researchers. Thus, teaching-related themes are rated more controversially than content-related themes especially with respect to different expert groups.

4 Coverage of the final themes and overall discussion

The study aimed at answering the question what knowledge teachers need to support students in the development of CL with regard to knowledge of scientific background and content related to climate change as well as knowledge of how to convey this into teaching. As results of our Delphi method, 13 overarching themes evolved (see Table 1). Experts might have spent less time suggesting ways to merge or split themes in the third round than they had before, but increasing relevance levels in the ratings of the themes indicate that throughout the iterative process of the Delphi rounds, the themes have become increasingly precise, distinct, and phrased in ways that allowed experts to agree to the themes with larger consensus and with increasing relevance levels. The significant differences between group ratings revealed by the Kruskal–Wallis test indicate that climate researchers seem to rate content-related themes higher and teaching-related themes lower than the other expert groups do. This pattern can also be observed as a tendency in descriptive (non-significant) differences in mean ratings but not very pronounced. Hence, there could have been a growing understanding of teaching-related issues by climate researchers or of content related issues by educators that attributed to higher ratings and increased consensus.

The seven content-related themes comprise climate history, the climate system, climate science, causes of, impacts of, and ways to deal with climate change as well as relationships of climate change to other global challenges. The six teaching-related themes cover students' conceptions, broad approaches towards climate change in the classroom such as argumentation, action, and personal relevance, specific methods, and they stress the interdisciplinary character of the topic. The themes with the highest mean ratings (> 6.5) are related to the *climate system*, *causes* of, *impacts* of, and ways to *deal with climate change*. These aspects are reflected in the *Climate Literacy: Essential Principles* (CLEP), a detailed elaboration of aspects of CL published by the US Global Change Research Program (USGCRP) — although structured differently. Also reflected in the CLEP is the theme *Climate history and natural climate fluctuation*. The focus in the CLEP is strongly on physical and biological aspects of climate and climate change (USGCRP 2009), whereas the present study also considers social and economic aspects as they need to be integrated in a system-wide approach (Shepardson et al. 2011b) and thus addresses the need for teachers to include political, social, and economic aspects of climate change (Herman et al. 2017). Furthermore, since the study was meant to consider the specific knowledge of teachers and, thus, knowledge especially relevant for teaching, this framing needs to be considered as well.

Hestness et al. (2014) take this into account in their literature review and stress the need for teachers to handle complex knowledge of climate change although coming from different disciplinary backgrounds. Hence, aspects of the climate system as reflected in the theme *Components and functioning of the climate system* are reported as basic knowledge that needs to be recognized in its complexity and in a correct way by teachers, especially those who teach science (Wise 2010; Ekborg and Areskoug 2012; Hestness et al. 2014;

Hannah and Rhubart 2020; Howard-Jones et al. 2021). Further involved with the social side of climate education is the theme *Dealing with climate change* that reflects different levels of action to mitigate climate change and to adapt to its impacts. Experts commented on both individual and societal measures, and while some stated that individual action will not solve the problem, others stressed the necessity to include options that students can take themselves. The teaching-related themes of *Dealing with willingness and capacity to act* and *Self-reference: living environments and options to act* pertain to the same levels of individual and structural action. These findings open up opportunities for teachers to include CL education beyond science and earth science subjects, but also stress the need to prepare teachers with a profound scientific knowledge basis. However, teachers need to be enabled to guide students towards action competence and agency (Crandon et al. 2022) of which appropriate career choices could be part of, and instruction should include occasions for the reflection and discussion of values and worldviews (Libarkin et al. 2018).

In this sense, approaches including the local allocation of climate change and personal significance in order to enhance relevance of the topic (Johnson et al. 2008; Kirk et al. 2014) — such as experiencing climate change-related weather events can raise awareness (Lee et al. 2015; Hoffmann et al. 2022) — are reflected in these themes. Students seem to have difficulties connecting climate change (solutions) and their own lives (Shepardson et al. 2011b), but decreasing psychological distance leads to higher concern towards climate change (Busch and Ayala Chávez 2022). Overall, this might eventually lead to the evocation of counteracting climate change. The experts discussed measures of individual action for counteracting eco anxiety and enabling students to draw positive solutions for the problem, in line with Johnson et al. (2008). The right way to deal with climate change in society is not defined yet. Some students themselves think education to be important, while others value instant school striking higher (Lee et al. 2022), and also teachers do seem to be unsure about the adequate path (Liu et al. 2015) which imposes unease on the question how to handle the societal debate about the topic (Uherek and Schüpbach 2008). However, our themes outline suggestions of how to approach these issues in classes. Climate change being perceived as a controversial topic in the media and by teachers requires preparation and strategies to handle the topic in class (Hestness et al. 2014). Therefore, the integration of *Opinion formation and argumentation* has been implemented in this study giving teachers opportunities to handle the perceived controversy. People are confronted with information about climate and climate change in everyday news media, where imbalanced impressions of the scientific consensus about anthropogenic climate change might be promoted and the perceived controversy of the topic is cultivated by a lack of understanding of the nature of climate science (Niepold et al. 2007). This is reflected in the theme of *Climate science and dealing with information* where the need for awareness of the evolving status of knowledge is addressed as well as the handling of information sources and uncertainties. Teachers seem to have difficulties with the scientific process as such and with handling controversies about perceived uncertainties in classes (Johnson et al. 2008; Liu et al. 2015). Related to other research (Johnson et al. 2008; Hestness et al. 2014), experts stressed the necessity for teachers to know about the scientific process themselves, the ability to scrutinize information, and sources in order to counteract positions of climate change denial due to perceived absence of scientific consensus providing a profound basis for the development of teachers' professional development.

Regarding the interdisciplinary nature of climate education, experts have emphasized the need for connecting different school subjects with the topic — which would provide different perspectives — in the theme *Interdisciplinary structure of climate education and curricular integration*. Some, however, opined that science should be the central discipline of focus. For the time being, the practice of allocating climate education in science curricula rather than in social disciplines prevails, although the latter has gained relevance in education research recently (Dupigny-Giroux 2010; Shwom et al. 2017). Comments from the expert panel underlined the need for such interdisciplinary education but pointed at constraints of overscheduled separated disciplinary curricula, missing opportunities for interdisciplinary exchange, and limited amount of time. While some suggested assigning specific knowledge aspects to single subjects, others advocated for dissolving the current separation of subjects in general. Especially experts (including teachers) coming from non-scientific disciplines were calling for approaches towards the topic that were not only focused on the physical and natural basics. In general, teachers seem to be open to include the topic in their classes, independent from their disciplines (Johnson et al. 2008) but seem to have problems with the missing explicit coverage within disciplinary curricula and standards (Sullivan et al. 2014), and they miss preparation (Demant-Poort and Berger 2021). Thus, climate education is rather being included subordinate to classical (e.g., chemistry) topics or postponed to upper secondary classes (Feierabend et al. 2011). The study results, however, could lead to new integrated approaches of curricula, inter-subject collaborations, and team teaching.

As central aspects of teachers' knowledge, we asked particularly for common pre- and misconceptions. Experts named well-known examples of *Pre- and misconceptions* that can be found throughout the literature (McCaffrey and Buhr 2008; Shepardson et al. 2011a; McCuin et al. 2014) and that may be triggered by school books (Shepardson et al. 2011b). Accordingly, they mentioned simplified concepts, biased proportions of variables or the relocation of the problem elsewhere, and the overgeneralization of environmental problems such as pollution (Papadimitriou 2004; Lambert et al. 2012) which even merits an own theme, *Relation to other societal or global problems*, in the present study. Since misconceptions among teachers do occur (Papadimitriou 2004; Hestness et al. 2014; Anyanwu et al. 2015; Ratinen 2013), this is a highly relevant part of teacher professionalization regarding climate education, and our results pinpoint the relevant concepts that teachers need to overcome. The promotion of the scientific background knowledge is a basis to prevent teachers from holding misconceptions (Sullivan et al. 2014), which the present study contributes to providing profound description of knowledge aspects that can be transferred into the professional development of teachers.

Eventually, for teachers to be enabled to take CL into their teaching, they need to be equipped with skills, tools, and techniques for managing the topic in classrooms (Holthuis et al. 2014). The theme *Teaching: strategies and illustration* brings together particular methods and classroom activities that focus on illustration, practice-orientation, personal involvement, and changing perspectives. Thus, inquiry-based science education, hands-on work with data, role plays, and the application to personal livelihoods and environments are reflected as they are found throughout the literature (Johnson et al. 2008; Dupigny-Giroux 2010; Hestness et al. 2014; Kirk et al. 2014; Sullivan et al. 2014) but are compiled and supported by experts' consensus in our results.

Throughout several themes, experts pointed to the need for teachers to be able to adapt the aspects of CL reflected in the themes to different target groups, especially regarding the age of students. So far, teachers must do this by experience and may be hindered by curricula for schools and for teacher education that allocate complex issues to upper secondary classes and leave out adequate preparation for primary or lower secondary educators (Uherek and Schüpbach 2008). Here, more work needs to be done in the elaboration of new concepts regarding curricula, school development, and teachers' collaboration which the present study's results could be a valuable starting point for.

5 Conclusion

Using a Delphi method with an expert panel, we identified specific aspects of what teachers need to know with regard to the scientific background and content related to climate change in order to convey this into teaching. We could derive 13 clearly delineated themes, seven of which contain content knowledge that goes some way beyond the strong focus of scientific aspects and additionally takes social sciences into account. Furthermore, six themes outline how to support students with their role in society beyond the limitation of single disciplines. The 13 themes provide — to our knowledge — the first compilation of the basic knowledge aspects for teachers aiming at teaching for CL that moreover has been validated by experts in the field in a multilevel process. However, the question remains to what extent teachers from different subject backgrounds and for different school levels or age groups need the whole range of this knowledge compilation or in which ways it could and should be adapted to individual focus groups depending on their respective scientific preparation. Furthermore, as our experts came from three different countries that bring together different backgrounds in teacher training and teachers' professional development (PD), this is something that needs to be taken into account as well. Yet, the results of our Delphi study prepare the ground for adaptations on different levels of the educational system to integrate CL into education: They can serve as (a) guideline for school curriculum development and (b) a starting point for developing respective teacher preparation and professional development courses in order to enable teachers to address CL in classrooms from a broad multidisciplinary basis. One relevant outcome is that CL should be approached as transcending science and geoscience classes in trans- and interdisciplinary ways. This, in our opinion, is a challenge that needs to be overcome by transforming traditional school curricula on the basis of respective research. In order to develop teacher preparation, future research should also focus on how teacher PD is organized in different countries looking for best practice models. Longitudinal studies that investigate teachers' PD with respect to CL as well as the learning outcomes of their students could help to understand the impacts of teacher education on students' CL.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-023-03607-z.

Acknowledgements We thank all experts who took part in either one or several of the interrogation rounds. We would like to thank Carola Garrecht and our student assistants for assistance with data analysis and interpretation.

Author contribution The study was designed by Kathryn Leve. Ute Harms and Hanno Michel contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Kathryn Leve. The study was supervised by Ute Harms. The first draft of the manuscript was written by Kathryn Leve. Ute Harms and Hanno Michel revised previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. This work was funded by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt DBU).

Data availability The datasets generated during the current study are not publicly available due to participants in this study consenting to their data being stored securely at IPN. They did not consent to their data being shared publicly.

Declarations

Ethical approval Ethical approval for this study was granted by the IPN Ethics commission in January 2021. The authors declare that they have adhered to all ethical regulations.

Competing interests The authors declare no competing interests.

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