Towards User-Centred Climate Services: the Role of Human-Computer Interaction

Jacob M. Rigby
Department of Computer Science
University of Bristol
Bristol, UK
j.rigby@bristol.ac.uk

Chris Preist
Department of Computer Science
University of Bristol
Bristol, UK
chris.preist@bristol.ac.uk

ABSTRACT

Climate services are systems that provide climate and climate-related information to inform decision making around the world. Despite these systems featuring diverse interactions between technologies and a variety of user groups, and frequent calls in the literature for more a more user-centred focus, HCI researchers do not appear to have engaged much with this active research area. In this paper, we demonstrate this lack of interaction via a systematic literature search and offer possible explanations for this. We also map out opportunities for how HCI researchers can use their highly relevant skillsets to contribute to this research and aid climate change adaptation, notably around the user-facing elements of climate services. Finally, we offer some reasons why HCI researchers might want to engage, such as furthering existing HCI research avenues, and creating new ones through collaborations with researchers in disciplines such as climate science, development, and policy.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Climate change, climate adaptation, decision making, development.

ACM Reference Format:
Jacob M. Rigby and Chris Preist. 2023. Towards User-Centred Climate Services: the Role of Human-Computer Interaction. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3544548.3580663

1 INTRODUCTION

Even if humanity manages to strongly reduce and mitigate its greenhouse gas emissions to reach net zero, scenarios prepared by the Intergovernmental Panel for Climate Change show that an increase in temperature of at least 1.5 degrees above pre-industrial levels is near inevitable [75, 113]. Already, the effects of climate change are becoming more strongly felt around the world, and adapting to a warmer and more variable climate by taking measures to protect societies and ecosystems is necessary. Central to these efforts are *climate services* — the systems that provide climate, weather, and other related information to various stakeholders around to world to inform decision making processes [51], allowing for planning and preparation for upcoming conditions. Climate services also provide early warning systems for extreme events [124], such as heat waves, drought, and flooding, which are already commonplace in many parts of the world. This allows for effective preparation and timely action, from government resource provisioning through to preparedness measures for individuals. Outside of extreme events, climate services are also relied upon by countless communities around the world for their livelihoods, as weather patterns they are habituated to are no longer a reliable guide to the present or the future. For example, smallholder farmers may use rainfall information for the coming season to inform crop selection and planting times, or how much fertiliser to apply [4]. Though research efforts are commonly focused on aiding adaptation in developing regions that are currently being most affected, climate services also operate in developed regions [16, 116] (e.g. Europe [19, 27, 89], North America [31], and Australia [28, 54]). Furthermore, the increasing effects of climate change worldwide mean that many more people will have cause to interact with these services and rely on them in the future. Throughout the world, climate services can help guide long-term development [60] and address broader societal challenges in the context of the Sustainable Development Goals [57], such as improving food security and increasing household incomes, democratising information to reduce inequalities, and guiding policy on climate action.

Climate services exist as a combination of local, national, regional, and international services [68] that are provided through the collaboration of a wide range of stakeholders. Typically, climate scientists provide data from observation networks and models, which then goes through various value-adding steps, stakeholders, and users, which forms a value chain [4, 119]. Services are often interacted with through tools, products, websites, or bulletins, and the value chain also necessitates various technical, institutional, and social infrastructures for effective service delivery [115]. Despite the range of users involved and the critical nature of these systems, prior research has repeatedly identified a lack of user interaction as a shortcoming of current climate services development and implementation [16, 18, 72, 92, 118, 121], which leads to services that do not meet user needs and therefore go unused.

The HCI discipline has previously engaged with climate change and adaptation in areas such as sustainable HCI [33, 104], smart cities [6, 48], and sustainable food systems [24, 25]. However, HCI's

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04.
https://doi.org/10.1145/3544548.3580663

engagement with climate services research specifically appears limited. Despite this, HCI researchers would be well-placed to address the need for user-centred process in designing and implementing climate services — for instance by cultivating a deeper understanding of users, their tasks, and the tools they use, allowing for the development of systems that better support decision making. Furthermore, new interfaces and paradigms for delivering climate information could be developed. In this paper, we explore possible reasons for this apparent lack of crossover, and identify effective ways in which HCI researchers can contribute to this increasingly crucial field.

2 RELATED WORK

2.1 Climate services

Climate services — sometimes referred to as *climate information services, climate and weather services*, and *weather and climate services* — is an active area of research research spanning climate science, policy, development, and more. Terminology surrounding climate services can vary between sources [116], and a number of definitions for climate services have been proposed [16, 121]. For this paper, we use the widely used definition provided by via the World Meteorological Organisation's (WMO) *Global Framework for Climate Services* (GFCS): *"the provision of climate information in such a way as to assist decision-making"* [51]. This provides a broad, simple framing which can be further developed with additional details where necessary [52]. Furthermore, most other definitions also reference the provision of information to inform decision making [16, 121]. The types of information provided also vary — contrary to their name, climate services often do not *only* provide information about the climate in the sense of long-term projections of climatic conditions. Some services may incorporate shorter-term weather outlooks and related information, such as hydrological variables. Indeed, for many users the terms "climate" and "weather" are largely interchangeable [110]. However, these outputs are loosely referred to as *climate information.*

In practice, there is no one-size-fits-all model to describe a climate service. They consist of a variety of institutions, technical and non-technical systems, stakeholders, and users, and these will vary based on location and context [121]. However, services will typically be managed by an international or national meteorology service [73] who cascade information to different users and stakeholders further down the value chain (though this may be better characterised as a "value web", as information flow is not necessarily linear [52]). They will often operate a website which provides an entry-level user interface to the service, which maybe be supplemented with apps and a social media presence [53, 109], and other tools and bulletins may also form part of the service [115]. Users and stakeholders may also interact with climate services in non-technical ways, for example through climate outlook forums used to produce and disseminate regional forecasts to intermediate users [29], participatory scenario planning meetings that engage stakeholders at more local levels and plan for potential eventualities [42], and other events and activities [53]. It also is worth noting that in some areas, end users may not access these services directly. Instead, they may receive forecasts and climate information from a service indirectly, such as through members of their community or governmental and non-governmental organisations [96].

Many stakeholders are involved in the the value chain of production, delivery, and use of climate services, including a range of co-ordinating bodies, service providers, and service users (who may also be providers) [115]. Given the wide-ranging applications and complexity of providing climate services, the WMO established the GFCS to guide and support their development [51]. The GFCS highlights the importance of interaction between the providers and users of climate services to tailor services to different users, though prior research has repeatedly highlighted that this is often lacking. This lack of interaction means that service providers and scientists often do not fully understand user needs [92], leading to a so-called "usability gap" where there is a mismatch between information provided and what is actually required by users [65]. There has also historically been a tendency to develop "supply-driven" services based on what climate scientists are able to provide, rather than "demand-driven" services based on user needs [68]. This is sometimes based on the erroneous assumption that simply providing information will translate to effective action, known at the "deficit model", where inaction is seen as being caused by a deficit of knowledge which should be filled [119].

In an attempt to address these shortcomings co-production processes have been advocated for, whereby climate services and information are developed in conjunction with users in the hope that uptake will be maximised [8, 66, 117]. This is opposed to the top-down provision of climate services that has traditionally prevailed, whereby scientists produce and provide services and information that may not meet the real-world needs of users. Co-production methods share similarities with established HCI approaches, such as co-design and participatory design, and more generally involving users in the development of information and services [94]. However, despite co-production being seen as a potential remedy to some of the failings of climate services, in practice this is still uncommon and the processes are not well-defined [119].

2.2 HCI and climate adaptation

Research in HCI engaged with climate change has largely been via the field of sustainable HCI, which has focused primarily on mitigation of its impacts, and more widely on engaging citizens in activism. For a systematic review of this work, see [45]. There has been relatively little work focused on adaptation, but one exception to this is the use of games to engage people in thinking about adaptation. Serious games [55, 78] have been used to engage high-school students with the challenges of climate adaptation. More widely, many virtual world games have climate change incorporated in them, as detailed in a survey by Fernández Galeote et al. [39]. They identify that while a number of games do feature adaptation, it is significantly lower than those which feature mitigation. These games tend to be ones where the player represents an authority (as opposed to citizen), and the authors identify the need to explore such citizen-focused perspectives on adaptation in games as a means to raise awareness.

2.3 ICT and HCI for development

Developing regions are a common focus in climate services literature [116]. HCI research intersects this application area via ICT for Development (ICTD) and and HCI for Development (HCID) which, given the focus on development, have tended to focus on "ground-level" end-user beneficiaries such as smallholder farmers children, or patients [32]. ICTD and HCID have often taken an interventionist approach, such as deploying a new technology with a specific user group (e.g. women, farmers), in a specific location in the developing world (e.g. India, parts of Africa and South America), or for a particular application (e.g. health, agriculture) [23, 70].

As these users have obvious use cases and immediate needs, such focus is understandable in ICTD and HCID research. However, this only represents one part of the climate services value chain. In addition to end users, the are also various intermediate- and high-level users such as local and national decision makers from governments and NGOs, as well as climate service providers who supply data and information at the top of the value chain [94]. Furthermore, we stress that climate services are not only for the developing world. However, our literature search shows that HCI interventions that interact and deliver climate services appear to be limited.

3 EXPLORING THE CROSSOVER OF CLIMATE SERVICES AND HCI

There have been frequent calls for climate services development to incorporate more user interaction and user-centred methods, including HCI methods specifically more recently [94, 112]. However, there appears to be little research that links these two fields. To investigate the extent of interaction between climate services and HCI, we performed a systematic literature search using some commonly-used literature databases, namely IEEE Xplore, ACM Digital Library, SCOPUS, and Web of Science. Initially, we searched for direct mentions of climate services and HCI. As we found that HCI also denotes the "holiday climate index" used in tourism research, we ensured terms relating to this were not included in our results. Search fields included were as broad as possible within the limitations of the selected search engines; we typically searched article titles, abstracts, and associated metadata (e.g. keywords), as well as the full article text if the option was available (not including references). The following syntax was used, which was modified accordingly to the requirements of particular search engines:

> ("climate service*" AND ("HCI" OR "human computer interaction")) NOT ("touris*" OR "holiday climate index")

As this initial search only generated a single relevant result across the databases, we decided to take a broader approach. To capture variations in terminology, we included "climate services", "climate information services", "climate and weather services", and "climate information" in our search, resulting in the following query:

> (("climate service*" OR "climate information service*" OR "climate and weather service*" OR "climate information") AND ("HCI" OR "human computer interaction")) NOT ("touris*" OR "holiday climate index")

Across the four databases, this search yielded 21 results. To ensure greater coverage, we performed additional targeted searches of specific journals and conference proceedings. In case some HCI papers did not contain the terms "HCI" or "human-computer interaction", we searched the ACM Digital Library using the following query, and constrained the results to HCI-centric venues:

> "climate service*" OR "climate information service*" OR "climate and weather service*" OR "climate information"

This returned five results, one each from CHI, DIS, OzCHI, ACI, and ICTD proceedings. Finally, we also searched some common publication venues for climate services research in case there were papers that did not feature the terms "climate services", "climate information services", or "climate information". We searched five journals using the following query:

> ("HCI" OR "human computer interaction") NOT ("touris*" OR "holiday climate index")

Firstly, the journal *Climate Services*[1] yielded a single result. We repeated this process for the journal *Climatic Change*[2], which produced two results, *Weather, Climate, and Society*[3], which produced five results, and *Wiley Interdisciplinary Reviews (WIREs) Climate Change*[4] , which produced no results, and *Nature Climate Change* [5], which produced two results. This gave a total of 31 results across all searches. Accounting for duplicates, there were 23 unique results (see Table 1 for an overview).

We then filtered the results for relevance according to some inclusion criteria. Firstly, we were interested only in results that explore climate services and/or climate information to inform decision making, in line the widely-accepted definitions of climate services [16, 51]. Secondly, climate services and/or climate information should form a significant focus of the research, and each publication should also contain a relevant HCI component. Based on these criteria, 24 papers were omitted:

- Twelve papers mentioned "climate information" only once in passing, and outside of the context of research into climate services as a means to inform decision making (e.g. voice assistants relaying the local weather forecast, local weather conditions being displayed on a smart home dashboard, or room temperature being conveyed through the shape of an artefact)
- One paper used rainfall data only as a test dataset for their haptics system and did not elaborate any further
- One paper coincidentally contained matching text from two clauses linked by a comma ("...climate, information...")
- Two papers did not contain a significant HCI component: a paper concerned with data formats for climate services which was partially categorised as an HCI paper, and a paper focused on the design of wireless sensors
- Five papers contained only a single of mention of HCI in the references section
- Three papers contained mentions of "HCI" that was not human-computer interaction (e.g. "heat centre index")

[1]https://www.sciencedirect.com/journal/climate-services, accessed 16th August 2022
[2]https://www.springer.com/journal/10584, accessed 16th August 2022
[3]https://journals.ametsoc.org/view/journals/wcas/wcas-overview.xml, accessed 16th August 2022
[4]https://wires.onlinelibrary.wiley.com/journal/17577799, accessed 16th August 2022
[5]https://www.nature.com/nclimate/, accessed 16th August 2022

Table 1: Literature search results. ***Animal-Computer Interaction — we include this with HCI for the purposes of this search.**

Source type	Source	Initial results	Relevant results
Literature databases	ACM Digital Library	9	2
	IEEEXplore	10	0
	SCOPUS	2	0
	Web of Science	0	0
HCI venues	CHI	1	1
	DIS	1	1
	OzCHI	1	0
	ICTD	1	0
	ACI*	1	0
Targeted climate services venues	Climate Services	1	1
	Climatic Change	2	2
	Weather, Climate, and Society	5	0
	Wiley Interdisciplinary Reviews: Climate Change	0	0
	Nature Climate Change	2	0
	Subtotal (inc. duplicates)	36	7
	Total distinct publications	30	6

After removing irrelevant results, six publications were remaining (see Table 2 for an overview). There were only two results from HCI-specific venues indexed by the ACM digital library: Myllynpää et al. [76] details the design of a smartphone app to deliver weather and climate information to farmers in Namibia, and Soden et al. [105] details an "artathon" event to develop new ways of communicating climate information to empower people and involve them in decision making. The remaining four publications were from climate services and climate science-related journals. Terrado et al. [112] discusses how climate services can learn from the disciplines of HCI, UX, graphic design, and psychology to develop better visualisations. They specifically advocate for user-centred processes. Wong-Parodi et al. [126] discuss the usability evaluation of a decision support tool that delivers risk information about rising sea levels in the USA, and specifically cite HCI research as a guide for their method. Eggeling et al. [37] also details using HCI methods to assess usability of the "ClimApp" tool, which combines local forecasts and and the users context to deliver personalised information about the user's thermal stress level. Dow et al. [34] details a survey study that investigated user needs in terms of different mapping conventions used in decision support tools.

We do not claim this search to be entirely exhaustive, as we may have missed some relevant research that did not contain our search terms, or may have been indexed in places we did not search (e.g. there is a significant body of climate services grey literature). However, for the purposes of scoping, it does serve to demonstrate that crossover between HCI and climate services research appears to be minimal, and notably so in high-impact HCI publication venues. Furthermore, it seems that most of the research from this search is quite narrow in terms of scope — two of the publications [37, 76] detail specific technology implementations of a climate service interface, two papers [34, 112] are concerned with guiding design of visualisation, two detail usability evaluations [37, 126] (note that one paper overlaps these categories). The final paper [105], is arguably the most unconventional paper, and which uses methods not traditionally seen in climate services literature. However, these publications seem disconnected from the broader context of climate services, and there is little engagement with the growing body of research into the theory and practice of climate services as its own research field. Prior research notes that climate services exist in an ecosystem of different interacting services, related processes, institutions, and stakeholders, and that a broader HCI-centric focus that engages with these different elements would be beneficial [94].

3.1 Extending the scope of the literature search

Following the small number of results from our above searches, we decided to extend the scope of our literature search to capture research that is related to HCI, but may not have appeared under our previous queries. Specifically, we looked for publications that included reference to user-centred methods in the context of climate services, with the intention of highlighting some example areas of where this type of research is happening and could be further developed by HCI specialists. We again searched IEEE Xplore, ACM Digital Library, SCOPUS, and Web of Science, using the following query:

> ("climate service*" OR "climate information service*" OR "climate information") AND ("user centred" OR "user centered")

As user experience design is a common application of HCI and user-centred methods, we also searched for papers that reference "user experience" using the following query:

> ("climate service*" OR "climate information service*" OR "climate information") AND ("user experience" OR UX)

These searches returned 30 results (11 and 19 respectively) across the databases. After accounting for duplicates, there were 17 results (see Table 3 for an overview). These were then subjected to the

Table 2: Filtered literature search results. **Journal of the American Water Resources Association*

Publication	Venue	Matched term(s)
Myllynpää et al. [76]	CHI 2020 Late breaking Work	Climate services, climate information
Soden et al. [105]	DIS 2020 proceedings	Climate information
Dow et al. [34]	JAWRA*	Human-computer interaction (indexed keyword)
Eggeling et al. [37]	Climate Services	Human-computer interaction, HCI
Terrado et al. [112]	Climatic Change	Human-computer interaction
Wong-Parodi et al. [126]	Climatic Change	Human-computer interaction

Table 3: Extended literature search results.

Source	Initial results	Relevant results
ACM Digital Library	6	2
IEEEXplore	0	0
SCOPUS	14	14
Web of Science	10	10
Subtotal (inc. duplicates)	30	26
Total distinct publications	17	14

following inclusion criteria: 1. Publications must have a climate services focus, and 2. Publications must explicitly use, advocate for, or critically examine (e.g. through evaluation) user-centred methods. After filtering for these criteria, six publications were omitted

- Four mentioned "climate information" only in passing, and did not have a significant climate services focus
- One paper coincidentally contained matching text from two clauses linked by a comma ("...climate, information...")
- One paper used the term "user experience" to mean the level of experience a user had, rather than the UX context

This left 11 publications remaining. Of these, eight used user-centred methods as part of their research, six advocated for the use of user-centred methods, and four critically examined new or existing user-centred methods (note that categories are not mutually exclusive). See Table 4 for a complete overview of the results.

In terms of subject matter, we were able to categorise the papers under three broad headings. Three papers were concerned with the design of decision support tools and visualisations (Calvo et al. [21], Hewitson et al. [49], Terrado et al. [112][6]). Three papers detailed the development of a new service or system (Gbangou et al. [43], Sotelo et al. [106], Wilson et al. [125]). Five papers were concerned with the theory and practice of climate services to better engage with and understand users (Bouroncle et al. [15], Harvey et al. [47], Nost [80], Rigby et al. [94], Steuri et al. [108]), e.g. by critically evaluating the effectiveness of a particular method, or empirical studies applying a method. From these additional literature searches, we find that there is some HCI-relevant research that is directly applicable to climate services published outside of the typical HCI sphere. While this appears to be limited in quantity, it does suggest areas for contribution and collaboration with HCI.

[6]Note that Terrado et al. [112] also appeared in our main literature search; we also discuss it here in the context of user-centred methods.

4 POSSIBLE REASONS FOR LACK OF CROSSOVER

Given the lack of consideration for different user groups in the climate services ecosystem that has been noted by prior research, and the mismatch between the information provided and user needs which prevents effective use, there seems an obvious case for user-centred research methods in this area. Though some relevant research is being conducted in this area, it seems that the wider HCI community has engaged very little with this field, as shown by our literature search above. This raises the question of why this is the case. Based on our literature search, related literature, and our experience working in this area, we suggest that there are a number of reasons for this which we detail in turn.

4.1 HCI researchers are not aware of this research area

An obvious reason for a lack of attention from HCI researchers is that they are simply not aware of this research area. As evidenced by our literature search, few HCI publications seem to engage with climate services. This potentially leads to a self-perpetuating cycle where it is not visible or discoverable in typical HCI publication venues, and therefore is not further engaged with. The inverse also appears to be true — the field of climate services in general may be unaware of HCI as a discipline and HCI researchers' specific skillset. Anecdotally, we authors reflect on our own experiences as HCI researchers working on interdisciplinary climate services projects for over two years — colleagues have often never heard of HCI as a field, and are unaware of key principles that are of direct relevance, such as user-centred design.

4.2 This research can be logistically challenging

There can be significant logistical difficulties in conducting this work. There are many barriers in place in conducting effective research in this area, many of which are shared with ICTD and HCID [127]. A major one is location — researchers may be required to perform situated studies, either for methodological reasons or because remote data collection is not feasible. Given that developing countries are often the focus of climate services research, travel to these locations can be prohibitively expensive, difficult to arrange if the researcher is not familiar with the local context, or even unsafe for reasons such as political instability or risk of danger to

Table 4: Filtered results of extended literature search.

Publication	Venue	User-centred methods		
		Uses	*Advocates*	*Examines*
Gbangou et al. [43]	Atmosphere	✓		
Calvo et al. [21]	Bulletin of the American Meteorological Society	✓		
Steuri et al. [108]	Bulletin of the American Meteorological Society		✓	✓
Rigby et al. [94]	Climate and Development	✓	✓	
Bouroncle et al. [15]	Climate Services	✓	✓	✓
Wilson et al. [125]	Climate Services	✓		
Terrado et al. [112]	Climatic Change		✓	✓
Nost [80]	Climatic Change	✓	✓	
Sotelo et al. [106]	Computers and Electronics in Agriculture	✓		
Harvey et al. [47]	Frontiers in Climate	✓		✓
Hewitson et al. [49]	Wiley Interdisciplinary Reviews: Climate Change		✓	

researchers (research institutions would also probably not permit this research in such cases).

Another difficulty is access to user groups. For example, if a rural farming community has been identified as a user group of interest, how does one contact them to perform research? Even in cases where users are professional office workers, there still may be no obvious way to get access to these groups if they are outside of researchers' typical networks. We acknowledge that access to users is not a new challenge in HCI or research in general [128], especially when working with under-represented user groups, but it can nonetheless present a significant barrier to research.

4.3 This research requires new collaborations

As climate services exist as interconnected data, technologies, and institutional infrastructures, it is likely that many of these elements will fall outside of HCI researchers' typical skillset. Indeed, sustainable HCI researchers have suggested that technology can only form part of a response to climate change and other sustainability challenges [17]. Though HCI is often interdisciplinary [11, 46], the types of collaboration necessary to contribute meaningfully to climate services work appear to be outside of typical HCI networks. Furthermore, our literature search shows that they appear to be uncommon.

Many existing climate services are the result of international collaborations incorporating experts in climate science, social science, policy research, international development, and more, e.g. research projects such as the WISER[7], CONFER[8], and DOWN2EARTH[9] projects. Thus, this level of collaboration is often necessary to perform relevant and impactful research — something that has been recognised in climate services literature [50]. In addition to bringing different expertise and experience, collaboration can address practical difficulties in performing research locations that may be difficult to reach, or with user groups that are difficult to access. Local collaborators can design culturally-appropriate studies, perform data collection, and facilitate access to different user groups. Also, collaborators embedded in institutions may have preexisting working relationships with other stakeholders and experts.

Despite the obvious benefits of collaboration, competing priorities can introduce difficulties. Furthermore, these relationships can be difficult to arrange or even discover in the first place, as it seems that HCI and climate services are not already in regular communication through preexisting collaborations or other research avenues. The pervasiveness of HCI could also be problematic when it comes to fostering collaborations, as HCI's interdisciplinary nature could mean that HCI thinking and skills are present in researchers from other fields. If so, HCI researchers may be deemed unnecessary as their duties can be covered by others.

An additional challenge for projects which include partners in the Global South, is that most large national academic funding schemes do not have straightforward ways to include such partners. An exception to this, the UK Global Challenges Research Fund[10], has recently been closed following the reduction of UK aid spending.

4.4 This research requires a long-tailed approach

Previous research in climate services has repeatedly highlighted the numerous sustainability challenges of climate services that should be considered from the outset [19, 36, 117], as services and interventions that are not actively supported and maintained fall out of use, which calls into question their value. Such a long-tailed approach can be at odds with HCI research, which often focuses on new and immature technologies on a superficial level. Some even argue that HCI actively supports and encourage unsustainable practices, both in terms of technology and research life cycles [104]. Therefore, it is possible that climate services research could appear unappealing to HCI researchers in comparison with other "low-hanging fruit" research that focuses and new or currently-popular technology. For example, different periods in recent years have seen a proliferation of HCI research into Pokémon Go (e.g. [9, 26, 85]), pandemic-induced remote working and teleconferencing (e.g. [22, 77]), and Covid-19 more generally (e.g [20, 90]) that captured the zeitgeist (note that we do not wish to diminish the worthiness

[7]https://www.metoffice.gov.uk/about-us/what/working-with-other-organisations/international/projects/wiser, accessed 8th September 2022
[8]https://confer-h2020.eu/, accessed 8th September 2022
[9]http://down2earthproject.org/, accessed 8th September 2022
[10]https://www.ukri.org/what-we-offer/international-funding/global-challenges-research-fund/, accessed 8th September 2022

or rigour of such work). This may also be affected by funding and publication cycles which can favour more immediate and self-contained research, which has also been identified in other areas of HCI research [104].

Despite this, there are large bodies of HCI research intersecting with other disciplines which may require a similar long-term view. One example is HCI and healthcare, where studies can have stringent ethical, design, and evaluation requirements [14] to ensure interventions do not compromise patient safety [12], which can add significant time overheads. For comparison, a search of the ACM Digital Library using the query "HCI AND Health" returns 17,318 results, versus the nine results from our literature search above. Another example is ICTD and HCID research, which face some of the challenges we detail above. A search for "HCI AND ICTD" on the ACM Digital Library returns 567 results. Thus, it seems that research on longer timescales is not insurmountable for HCI researchers — this suggests it may only be a contributing factor to the lack of crossover of HCI and climate services, or that the timescales are much greater.

5 AREAS WHERE HCI CAN CONTRIBUTE TO CLIMATE SERVICES RESEARCH

Climate services is an active research area that is constantly moving forward. However, advances have more consistently resulted in better data, rather than better services that lead to better decisions from users [41]. The numerous barriers facing this research area have been extensively documented. In particular, we draw attention to the "people side" of climate services — interactions between the various stakeholders, users, infrastructures, and technical systems within climate services. This has repeatedly been identified as an area for improvement and sits firmly within the remit of HCI as a discipline. Our literature search in Section 3 highlighted the small amount of climate services research that is both directly relevant to HCI and tangential to it, which revealed some areas ripe for contribution from HCI researchers. Therefore, in this section we present some possible ways in which HCI can make valuable contributions to furthering climate services research and implementation.

5.1 Understanding users and context, and ensuring needs are met

As already discussed, a wide variety of user groups interact with climate services, each with specific needs and capabilities. Previous research has shown that climate services and the information they provide should be demand-driven and tailored to user needs, but in reality there is little interaction between providers and users meaning that needs are poorly understood [115], and there is a significant "usability gap" between what is needed and what is provided [65]. Our literature search uncovered papers focused on the implementation and discussion of methods and theories relevant to HCI to improve user engagement, to enable researchers better understand users and their needs and develop better services. This demonstrates an appetite to develop this kind of work within the climate services field, though the small number suggests room for additional research. Typically, to fully understand user needs, we must understand users in the context of use — this sits firmly within HCI territory and the skillset of HCI researchers. There exist a variety of methods to achieve this [13], such as interviews, focus groups, various flavours of workshop, contextual inquiry, and observation. Thus, studies enhancing our understanding of different user groups using both qualitative and quantitative methods present opportunities for HCI researchers.

Once user needs are established and a system or service has been designed around these, how to do we ensure that these needs are adequately met? Another frequent criticism of climate services is lacking or non-existent assessment and evaluation following implementation [111, 115]. Again, HCI researchers are well positioned to address this need via the range of established HCI and UX evaluation methods that have been developed over recent decades [69], including various types of usability testing [7], heuristic evaluation [79], and cognitive walkthroughs [91]. Furthermore, HCI brings with it an ever-expanding body of theories, models, and frameworks to help guide design and evaluation and situate research within the broader body of research, both within HCI and in fields that it intersects [95]. Evaluation forms a central part of the user-centred design process (and HCI itself). By conducting robust evaluation, we can ensure the validity of research and that interventions fulfil user needs. Therefore, this should be integrated into the development of climate services to ensure they are truly user-centred and demand-driven [68].

5.2 Development of decision support tools

One of the ways that users interact with climate services is through decision support tools. These are entry points for users that are frequently implemented as geospatial systems or dashboards to visualise climate data and information [53], but can take other forms such as mobile apps for end users. They can be conceptualised as boundary objects between the scientific information and decision makers [107, 123] to enable actionable science [88].

Pearman and Cravens [88] interviewed tool creators in the USA, and their results again suggested that for these tools to be successful, frequent engagement with users and an understanding of their needs and context is essential. However, they also highlighted a reliance on informal feedback rather than formal evaluations, which could be unreliable and difficult to act on. Note that the interviewees worked for relatively well-funded USA government organisations who appear to have dedicated tool creators — outside of this setting, many decision support tools are created as a way of giving others access to their data by researchers themselves, who likely do not have specific expertise in creating effective or usable software [87]. This conforms to the "supply-driven" model of climate service provision where services are based around what scientists can provide, rather than a demand-driven one based around stakeholder needs [87].

Our literature review showed that there is some HCI-relevant research in this area, but again it was limited. This therefore leave room for significant contributions from HCI researchers, who are extremely well equipped to realise the demand-driven development of decision support tools. A wealth of established user-centred HCI and UX methods can be implemented throughout the entire development pipeline, from inception through to implementation and evaluation. Furthermore, recognising that these tools often exist within a broader decision making framework and organisational structure [87], situated studies and contextual methods can be used to understand the context of user – again, this is well established in HCI.

5.3 Data visualisation and mapping

Many decision support tools incorporate Geographical Information Systems (GIS) and mapping elements to visualise geospatial data, and climate bulletins and forecasts often incorporate a visual element to convey their message. Data visualisation is an active area of HCI research, e.g. in evaluating visualisation methods [100, 120], and visualisations for new and emerging interfaces such as mobile devices [63], and virtual and mixed reality [64]. Prior HCI research has also focused on the visualisation of geospatial data and GIS specifically, e.g. examining the cognitive aspects of interpreting and interacting with GIS [81], evaluating new and existing visualisation techniques [61, 101], and new interaction methods for geospatial data such as multi-touch [102] systems and multi surface environments [103].

Though HCI research has included the visualisation of climate change data [40], our literature search suggests that this has not been widely incorporated into climate services research. This therefore leaves opportunities for HCI research contributions, for both data visualisation in general and for mapping elements of climate services. Such a gap has also been identified by the cartography research community, who have recognised the need for HCI and user-centred methods to move from the concept of a map *reader* to a map *user* [98].

5.4 Understanding decision making and the nature of climate service "work"

Climate services are designed to assist decision making at various levels. Researchers would therefore benefit from developing a detailed understanding of the psychology and cognitive processes that underpin decision making in various contexts, so that they can identify how to support this with technology. HCI has a strong record of cognitive psychology-oriented research that implements established cognitive models of decision making in the development of computer systems [10, 83], and the different contexts and users in the climate services value chain present further opportunities in this area. Furthermore, this could also aid the future development of AI decision making tools.

Though rural end-users in developing countries are often a focus of climate services research, there are significant numbers of professionals who are "intermediate users" at different points in the value chain who are less well studied [94]. For example, these may be educated office workers working for local governments or NGOs. HCI research has previously sought to understand different aspects of technology-assisted knowledge work, such as crowdworking [97], multitasking and interruptions in the workplace [58, 71], remote work [22], and healthcare [12]. Climate service users, the tasks they perform, and the decisions they make present relatively untapped research opportunities in this area. Furthermore, as climate services are partly formed from institutional and stakeholder networks who frequently collaborate, there are many opportunities for impactful research in the area of Computer-Supported Co-operative Work (CSCW).

5.5 Integrating scientific and indigenous knowledge

Prior research has shown that climate information and its source needs to be trusted by users to maximise chances of uptake, and ultimately effective action. In some regions of the world, indigenous knowledge forms a crucial part of the climate information ecosystem, especially for end-user communities — for example, traditional weather forecasting by assessing the appearance of clouds or plants, or reading the intestines of animals, are common in parts of Africa [93]. Those who convey this knowledge are trusted and respected within their communities, and individuals may then then choose to use this information to inform their agricultural decisions. Thus, the juxtaposition of traditional knowledge systems and new technologies and how they might be integrated present interesting challenges for HCI researchers. Though this is certainly not a new observation and has been given attention by ICTD researchers previously [1], there is room for expanding our understanding in this area and implementing this in the wider context of climate services. Some ICTD work has criticised the subordination of indigenous knowledge in relation to scientific knowledge, often as a result of Golbal North-located researchers importing Western agendas and ideals [59]

5.6 New paradigms for climate services delivery

Adaptation, particularly in the Global South, is primarily a community rather than an individual activity. The "personal app" paradigm, where tailored information is delivered to an individual through a digital service, prioritises individual autonomy [2, 122] and often may not be appropriate when delivering climate services to communities in developing regions. This is for two reasons. Firstly, many members of a community may not have access to a digital device, and so would be excluded. Secondly, decisions in response to such information (such as where nomadic pastoralists might choose to move to) are often collective, though interventions are often aimed at individuals. As such, a climate service delivered over a mobile device can be considered a boundary object [3] to stimulate discussion and provide a resource for collective decision making within a community. How can a service, and interaction with it, be designed with this in mind? Can a service be designed to harmonise with existing decision making and information sharing practices within the community? Can the service be designed to encourage the sharing and involving of more marginalised members of the community (particularly women)? Such questions are best answered through participatory design approaches, involving the community and stakeholders in the process [117].

A related question is an understanding of the potential impact of any such service on the power structures within a community. Digital technology is often most used by younger members, while the power resides traditionally with the elders. For example, research into Chinese farmers found that young people were more likely to use technology to access information, whereas older often did not use or even own technology [82]. In what ways might the delivery of a service reinforce traditional power structures, or disrupt them? What is appropriate, and how can any potential problems be mitigated? Technology offers both the opportunity to amplify existing inequalities and power structures [114], but also to challenge them by democratising information. Care must be taken in any participatory process to understand these power structures — and hence involvement of social science academics and professionals who are closely linked to the culture and community being engaged with is important in any such research.

5.7 General technology-lead innovation for climate services

HCI's focus on new technologies has previously been a source of criticism, especially around unsustainable product life cycles, pursuing unlikely future scenarios, and general short-termist research practices [104]. However, the discipline's imagination and forward-thinking ethos can also be a great strength in pursuing new directions for existing and future technologies. Prior work has noted a lack of innovation in climate services research and the need to embrace new technologies [57], which could in part-be provided by HCI researchers (an example of such imaginative thinking in the "artathon" uncovered by our literature search [105]). Speculative design and design fiction approaches allow us to imagine and critique potential futures [38, 67], and emerging interfaces such as touch, haptics, gestures, and speech could offer new ways for users to interact with climate services, and can help overcome language and literacy barriers to use. However, this must be conducted in a way that is primarily driven by user and community needs rather than technology. This may be at odds with funding sources and publication cycles in HCI and related fields that can favour the application of technologies based on their novelty [86].

6 DISCUSSION

In this paper we have demonstrated the lack of interaction between HCI and climate services research through a systematic literature search. Our main search revealed only six directly relevant publications — two from HCI venues and four from climate services and climate science venues. Furthermore, only one paper matched the term "climate services" directly; the remaining five contained the related term "climate information". To remedy this, we have set out concrete ways in which HCI research can contribute to climate services research. These are numerous and diverse, and highlight how multifaceted the HCI discipline can be, and the wide spectrum of skills HCI researchers can offer. Predominantly, the central theme is in understanding users and their needs, and ensuring that these needs are met. For a number of years, climate services research has repeatedly highlighted the need for user involvement in knowledge production and service development [16, 18, 72, 92, 118, 121] (e.g. through co-production methods), and a shift from supply-driven services based around what scientists can provide to demand-driven ones based around user requirements [68]. Despite this, user centred approaches are still uncommon, and advances centre on improving underlying data rather actionable decision making [41]. Given that these are central themes of HCI, we suggest that HCI researchers can take their traditional role of "representing the user" [56] in this context. Moreover, we would also encourage researchers to situate themselves at the centre of climate services projects and advocate loudly for user-centred approaches throughout all areas. Not only would this fulfil recommendations from the literature to ensure climate services that are fit for purpose and ultimately well-used, it also makes financial sense to avoid developing the wrong service for users. While some areas of climate service development require particular specialisms (e.g. climate scientists developing models or monitoring an observation network), the HCI skillset can be cross-cutting in this regard. If successful in this endeavour, HCI researchers can make impactful contributions to climate change adaptation.

Though there is a salient need for the skills that HCI researchers can offer, how can this be put into practice? Our literature search demonstrated that there is very little interaction between HCI and climate services research, so it seems that climate services researchers(including climate scientists) and those who understand how to design genuinely useful services are not really talking to each other. This is demonstrated by the single HCI paper we found in our search that mentions climate services ([76]), which specifically states that the authors are not partnered with a local climate or weather services, preferring to focus on the technology first. We therefore believe that we should start with communication and collaboration with other researchers from academia, governmental agencies, non-governmental organisations, and the private sector, who currently drive climate services development. Given the need for end-to-end consideration of user needs and user-centred processes, HCI researchers would ideally embed themselves in projects for their entire duration. To some extent, this is a structural problem reinforced by existing disciplinary boundaries and funding sources. As such, we advocate that research funding organisations run "sandpits" bringing together HCI researchers with communities currently researching climate services, to discuss challenges and identify how HCI can contribute. We also advocate that funding is made available to involve HCI researchers in the evaluation of existing climate services.

As the Global South is often the focus of climate services research, development, and implementation, there is naturally crossover with HCID (and ICTD) in this setting. However, it is clear that this is not the only area of application for this research, and that there are opportunities for researchers who do not currently work in the development space. The increasing need for these services mean that there are opportunities to explore climate services in other settings that HCI researchers are familiar with, and perhaps more accessible. Furthermore, though we do advocate for user-centred process and HCI involvement throughout project life cycles, there are incremental gains to be made on shorter timescales in the areas we describe earlier, perhaps without the need for significant buy-in in terms of time and expertise.

6.1 Reasons for HCI researchers to pursue work in this area

In the previous sections, we identified possible reasons for a lack of engagement between HCI and climate services, and areas where HCI could make valuable contributions. However, aside from *what* HCI researchers can contribute, there are also a number of reasons *why* they might wish to — we discuss some of these below. Climate services research can offer enticing opportunities for HCI researchers, which can enable them to develop existing research themes and develop new ones.

Responding to climate change. some research areas of HCI are working to respond to climate change, most notably the field of sustainable HCI. However, despite the best intentions, impact of this research outside of HCI has been low [104], and it can often appear quite introspective with frequent meta-discussions about previous and future directions (e.g. [45, 62, 104]). Climate services research offers another avenue to further these goals, as well as a more direct route to real-world impact. Climate services research also provides opportunities to affect system-level change, rather than purely persuading individuals to change their behaviour (an approach that has often pervaded sustainable HCI in the past [17]). Furthermore, research with individual users and their communities seeks to empower people to make informed and effective decisions, rather than correcting a perceived detrimental behaviour.

Research with marginalised and underrepresented groups. Though we highlight that there are a variety of users within the climate services ecosystem, there is a large current and potential user base of marginalised communities who rely on particular weather and climate conditions for their livelihoods, or who may be especially affected by extreme events or adverse conditions [4]. For example, farmers around the world rely on rainfall for their crops, and the poorest are worst affected when the rain does not come at the right times or in the right quantities — they are also less able to recover from subsequent unfavourable seasons, as they may not have the money or resources needed to fall back on. As well as leading to food insecurity and reduced income [99], it can also cause secondary effects such as inter-group conflict [74]. Other examples are some pastoralist communities in Africa, where traditional governance systems exclude women from formal decision making [44] and may not have the means to access important climate information that could improve their lives.

Foresight of upcoming conditions can help communities prepare, for example in selecting suitable crop varieties, enhancing water collection systems, or locating water sources. However, to do this climate services need to provide the correct information in an accessible way, and that information needs to be actionable — a number of issues factor into this, such education, literacy skills, culture, and application area. Though the ICTD and HCID communities have been conducting research with the goal of aiding marginalised people for a number of years [32], a specific focus on interfaces for climate services that are integrated with the rest of the climate services value chain presents additional opportunities. HCI researchers can contribute to the design and implementation of systems to deliver actionable information based on the needs of particular user groups and communities, and in turn, action as a result of this can enable people to plan and react more effectively. As such, this could present a natural area of expansion for HCID researchers specifically who have a record of community-based research [5], but also HCI researchers more broadly. This aligns with the "CHI4Good" philosophy of recent years, though care must be taken to ensure social good is truly the objective of such research rather than merely providing an interesting research context [86] or outlet for new technology [5].

Interdisciplinary research and collaboration. Earlier in this document, we noted that climate services researches tends to necessitate collaboration, and this this can be a barrier to entry. However, it can also offer another opportunity for HCI to extend into another research space. Many climate services are themselves interdisciplinary and previous research has encouraged transdiciplinarity [30, 84, 119]. HCI sits at the intersection of a number of other disciplines and is often seen as interdisciplinary by nature [11, 46] – thus, managing collaborations and interdisciplinary research is not unfamiliar territory for HCI researchers.

Situating HCI at the forefront of an increasingly critical field. HCI has continually developed as a discipline [35], and has typically been at the cutting edge of developments in many areas of technology. However, HCI researchers do not currently seem to have a seat at the climate services table. As climate change and a warmer planet becomes an every day reality for more and more people around the world, these systems are set to be used and relied upon by many more people. The year 2022 has seen unprecedented high temperatures and droughts[11], even in places that that have not previously been affected, such as Weastern Europe[12]. As such, individuals who may have previously only interacted with climate services for trivial purposes, e.g. to predict summer holiday weather or decide if they need to wear a raincoat, may soon be using these services to make decisions about domestic water conservation, or how and when to take measures to reduce the internal temperature of their home. Thus, this greater number of users and interactions for increasingly critical purposes creates a need for interfaces that are fit for purpose and well designed, using sound principles, methods, and theories that HCI can provide.

7 CONCLUSION

This paper highlights the apparent lack of crossover between climate services research and HCI, despite HCI researchers having especially useful skillsets applicable to many aspects of climate services. We suggest possible reasons for this lack of interaction, such as lack of awareness between disciplines and barriers to conducting this research. We also offer a number of suggestions for concrete ways in which HCI researchers can contribute by applying wide-ranging HCI skillsets and research methods, and discuss reasons why they may wish to do so. However, we also acknowledge that climate services research is largely dependant on collaborations which HCI researchers have typically not been involved in, and establishing such relationships presents challenges. By engaging with climate services research we hope that HCI as a discipline can make important contributions to climate change adaptation.

ACKNOWLEDGMENTS

This research was supported by Horizon Europe Framework Programme grant 69550.

REFERENCES

[1] Jose Abdelnour-Nocera, Torkil Clemmensen, and Masaaki Kurosu. 2013. Reframing HCI through local and indigenous perspectives. *International Journal of Human-Computer Interaction* 29, 4 (2013), 201–204.
[2] Gregory D. Abowd. 2016. Beyond Weiser: From Ubiquitous to Collective Computing. *Computer* 49, 1 (2016), 17–23. https://doi.org/10.1109/MC.2016.22
[3] Sanne F Akkerman and Arthur Bakker. 2011. Boundary crossing and boundary objects. *Review of educational research* 81, 2 (2011), 132–169.
[4] Glen Anderson, Haleh Kootval Md Kootval, Daniel Werner Kull, Janet Clements, Stratus Consulting, Gerald Fleming, Met Éireann, Thomas Frei, Jeffrey K Lazo,

[11] https://www.theguardian.com/world/2022/aug/20/drought-in-horn-of-africa-places-22m-people-at-risk-of-starvation-says-un, accessed 8th September 2022
[12] https://www.bbc.com/news/world-europe-62648912, accessed 8th September 2022

David Letson, et al. 2015. *Valuing weather and climate: Economic assessment of meteorological and hydrological services.* Technical Report. The World Bank. https://library.wmo.int/doc_num.php?explnum_id=3314

[5] Yaw Anokwa, Thomas N Smyth, Divya Ramachandran, Jahanzeb Sherwani, Yael Schwartzman, Rowena Luk, Melissa Ho, Neema Moraveji, and Brian DeRenzi. 2009. Stories from the field: Reflections on HCI4D experiences. *Information Technologies & International Development* 5, 4 (2009), pp–101.

[6] Mara Balestrini, Yvonne Rogers, Carolyn Hassan, Javi Creus, Martha King, and Paul Marshall. 2017. A City in Common: A Framework to Orchestrate Large-Scale Citizen Engagement around Urban Issues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 2282–2294. https://doi.org/10.1145/3025453.3025915

[7] JM Christian Bastien. 2010. Usability testing: a review of some methodological and technical aspects of the method. *International journal of medical informatics* 79, 4 (2010), e18–e23.

[8] Paul Beier, Lara J Hansen, Lynn Helbrecht, and David Behar. 2017. A how-to guide for coproduction of actionable science. *Conservation Letters* 10, 3 (2017), 288–296.

[9] Arpita Bhattacharya, Travis W. Windleharth, Rio Anthony Ishii, Ivy M. Acevedo, Cecilia R. Aragon, Julie A. Kientz, Jason C. Yip, and Jin Ha Lee. 2019. Group Interactions in Location-Based Gaming: A Case Study of Raiding in Pokémon GO. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300817

[10] Pradipta Biswas and Peter Robinson. 2010. A brief survey on user modelling in HCI. In *Proc. of the International Conference on Intelligent Human Computer Interaction (IHCI)*, Vol. 2010.

[11] Alan F. Blackwell. 2015. HCI as an Inter-Discipline. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 503–516. https://doi.org/10.1145/2702613.2732505

[12] Ann Blandford. 2019. HCI for health and wellbeing: Challenges and opportunities. *International journal of human-computer studies* 131 (2019), 41–51.

[13] Ann Blandford, Dominic Furniss, and Stephann Makri. 2016. Qualitative HCI research: Going behind the scenes. *Synthesis lectures on human-centered informatics* 9, 1 (2016), 1–115.

[14] Ann Blandford, Jo Gibbs, Nikki Newhouse, Olga Perski, Aneesha Singh, and Elizabeth Murray. 2018. Seven lessons for interdisciplinary research on interactive digital health interventions. *Digital health* 4 (2018), 2055207618770325.

[15] Claudia Bouroncle, Anna Müller, Diana Giraldo, David Rios, Pablo Imbach, Estuardo Girón, Fernando Portillo, Alejandra Boni, Jacob Van Etten, and Julian Ramirez-Villegas. 2019. A systematic approach to assess climate information products applied to agriculture and food security in Guatemala and Colombia. *Climate Services* 16 (2019), 100137.

[16] Guy P. Brasseur and Laura Gallardo. 2016. Climate services: Lessons learned and future prospects. *Earth's Future* 4, 3 (3 2016), 79–89. https://doi.org/10.1002/2015EF000338

[17] Christina Bremer, Bran Knowles, and Adrian Friday. 2022. Have We Taken On Too Much?: A Critical Review of the Sustainable HCI Landscape. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 41, 11 pages. https://doi.org/10.1145/3491102.3517609

[18] Mark S Brooks. 2013. Accelerating innovation in climate services: The 3 E's for climate service providers. *Bulletin of the American Meteorological Society* 94, 6 (2013), 807–819.

[19] Marta Bruno Soares and Carlo Buontempo. 2019. Challenges to the sustainability of climate services in Europe. *Wiley Interdisciplinary Reviews: Climate Change* 10, 4 (2019), e587.

[20] Carrie J Cai, Michelle Carney, Nida Zada, and Michael Terry. 2021. Breakdowns and Breakthroughs: Observing Musicians' Responses to the COVID-19 Pandemic. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 571, 13 pages. https://doi.org/10.1145/3411764.3445192

[21] Luz Calvo, Isadora Christel, Marta Terrado, Fernando Cucchietti, and Mario Pérez-Montoro. 2022. Users' Cognitive Load: A Key Aspect to Successfully Communicate Visual Climate Information. *Bulletin of the American Meteorological Society* 103, 1 (2022), E1–E16.

[22] Hancheng Cao, Chia-Jung Lee, Shamsi Iqbal, Mary Czerwinski, Priscilla N Y Wong, Sean Rintel, Brent Hecht, Jaime Teevan, and Longqi Yang. 2021. Large Scale Analysis of Multitasking Behavior During Remote Meetings. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 448, 13 pages. https://doi.org/10.1145/3411764.3445243

[23] Christopher Chepken, Raymond Mugwanya, Edwin Blake, and Gary Marsden. 2012. ICTD Interventions: Trends over the Last Decade. In *Proceedings of the Fifth International Conference on Information and Communication Technologies and Development* (Atlanta, Georgia, USA) *(ICTD '12)*. Association for Computing Machinery, New York, NY, USA, 241–248. https://doi.org/10.1145/2160673.2160704

[24] Jaz Hee-jeong Choi and Eli Blevis. 2010. HCI & Sustainable Food Culture: A Design Framework for Engagement. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (Reykjavik, Iceland) *(NordiCHI '10)*. Association for Computing Machinery, New York, NY, USA, 112–117. https://doi.org/10.1145/1868914.1868931

[25] Adrian K Clear, Kirstie O'neill, Adrian Friday, and Mike Hazas. 2016. Bearing an Open "Pandora's Box" HCI for Reconciling Everyday Food and Sustainability. *ACM Transactions on Computer-Human Interaction (TOCHI)* 23, 5 (2016), 1–25.

[26] Ashley Colley, Jacob Thebault-Spieker, Allen Yilun Lin, Donald Degraen, Benjamin Fischman, Jonna Häkkilä, Kate Kuehl, Valentina Nisi, Nuno Jardim Nunes, Nina Wenig, Dirk Wenig, Brent Hecht, and Johannes Schöning. 2017. The Geography of Pokémon GO: Beneficial and Problematic Effects on Places and Movement. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1179–1192. https://doi.org/10.1145/3025453.3025495

[27] European Commission, Directorate-General for Research, Innovation, D Jacob, T Runge, R Street, M Parry, and J Scott. 2015. *A European research and innovation roadmap for climate services.* Publications Office. https://doi.org/10.2777/702151

[28] R Cunningham. 2020. Mapping Climate Services Capabilities in Australia. (2020).

[29] Meaghan Daly and Suraje Dessai. 2018. Examining the Goals of the Regional Climate Outlook Forums: What Role for User Engagement? *Weather, Climate, and Society* 10, 4 (10 2018), 693–708. https://doi.org/10.1175/WCAS-D-18-0015.1

[30] Elizabeth Daniels, Sukaina Bharwani, Åsa Gerger Swartling, Gregor Vulturius, and Karen Brandon. 2020. Refocusing the climate services lens: introducing a framework for co-designing "transdisciplinary knowledge integration processes" to build climate resilience. *Climate Services* 19 (2020), 100181.

[31] Arthur T Degaetano, Timothy J Brown, Steven D Hilberg, Kelly Redmond, Kevin Robbins, Peter Robinson, Martha Shulski, and Marjorie McGuirk. 2010. Toward regional climate services: The role of NOAA's Regional Climate Centers. *Bulletin of the American Meteorological Society* 91, 12 (2010), 1633–1644.

[32] Nicola Dell and Neha Kumar. 2016. The Ins and Outs of HCI for Development. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 2220–2232. https://doi.org/10.1145/2858036.2858081

[33] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the Landscape of Sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. https://doi.org/10.1145/1753326.1753625

[34] Kirstin Dow, Richard L Murphy, and Gregory J Carbone. 2009. Consideration of user needs and spatial accuracy in drought mapping 1. *JAWRA Journal of the American Water Resources Association* 45, 1 (2009), 187–197.

[35] Emanuel Felipe Duarte and M. Cecília C. Baranauskas. 2016. Revisiting the Three HCI Waves: A Preliminary Discussion on Philosophy of Science and Research Paradigms. In *Proceedings of the 15th Brazilian Symposium on Human Factors in Computing Systems* (São Paulo, Brazil) *(IHC '16)*. Association for Computing Machinery, New York, NY, USA, Article 38, 4 pages. https://doi.org/10.1145/3033701.3033740

[36] Mairi Dupar, Lena Weingärtner, and Sarah Opitz-Stapleton. 2021. *Investing for sustainable climate services: insights from African experience.* Technical Report. ODI Report.

[37] Jakob Eggeling, Christofer Rydenfält, Boris Kingma, Jørn Toftum, and Chuansi Gao. 2022. The usability of ClimApp: A personalized thermal stress warning tool. *Climate Services* 27 (2022), 100310.

[38] Chris Elsden, David Chatting, Abigail C. Durrant, Andrew Garbett, Bettina Nissen, John Vines, and David S. Kirk. 2017. On Speculative Enactments. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5386–5399. https://doi.org/10.1145/3025453.3025503

[39] Daniel Fernández Galeote, Nikoletta-Zampeta Legaki, and Juho Hamari. 2022. Avatar Identities and Climate Change Action in Video Games: Analysis of Mitigation and Adaptation Practices. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 561, 18 pages. https://doi.org/10.1145/3491102.3517438

[40] Marta Ferreira, Miguel Coelho, Valentina Nisi, and Nuno Jardim Nunes. 2021. Climate Change Communication in HCI: A Visual Analysis of the Past Decade. In *Creativity and Cognition* (Virtual Event, Italy) *(C&C '21)*. Association for Computing Machinery, New York, NY, USA, Article 5, 16 pages. https://doi.org/10.1145/3450741.3466774

[41] Kieran Findlater, Sophie Webber, Milind Kandlikar, and Simon Donner. 2021. Climate services promise better decisions but mainly focus on better data. *Nature*

Climate Change 11, 9 (2021), 731–737.
[42] Rebecca Freeth and Scott Drimie. 2016. Participatory scenario planning: from scenario 'stakeholders' to scenario 'owners'. *Environment: Science and Policy for Sustainable Development* 58, 4 (2016), 32–43.
[43] Talardia Gbangou, Rebecca Sarku, Erik Van Slobbe, Fulco Ludwig, Gordana Kranjac-Berisavljevic, and Spyridon Paparrizos. 2020. Coproducing weather forecast information with and for smallholder farmers in Ghana: Evaluation and design principles. *Atmosphere* 11, 9 (2020), 902.
[44] Joakim Gundel and Ahmed A Omar Dharbaxo. 2006. The predicament of the 'Oday'. *The role of traditional structures in security, rights, law and development in Somalia. Final Report. Danish Refugee Council & Novib-Oxfam, Nairobi* (2006).
[45] Lon Åke Erni Johannes Hansson, Teresa Cerratto Pargman, and Daniel Sapiens Pargman. 2021. A Decade of Sustainable HCI: Connecting SHCI to the Sustainable Development Goals. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 300, 19 pages. https://doi.org/10.1145/3411764.3445069
[46] H Rex Hartson. 1998. Human–computer interaction: Interdisciplinary roots and trends. *Journal of systems and software* 43, 2 (1998), 103–118.
[47] Blane Harvey, Ying-Syuan Huang, Julio Araujo, Katharine Vincent, Jean-Pierre Roux, Estelle Rouhaud, and Emma Visman. 2021. Mobilizing climate information for decision-making in Africa: contrasting user-centered and knowledge-centered approaches. *Frontiers in Climate* 2 (2021), 589282.
[48] Sara Heitlinger, Nick Bryan-Kinns, and Rob Comber. 2019. The Right to the Sustainable Smart City. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300517
[49] Bruce Hewitson, Katinka Waagsaether, Jan Wohland, Kate Kloppers, and Teizeen Kara. 2017. Climate information websites: an evolving landscape. *Wiley Interdisciplinary Reviews: Climate Change* 8, 5 (2017), e470.
[50] CD Hewitt, Erica Allis, Simon J Mason, Meredith Muth, Roger Pulwarty, J Shumake-Guillemot, Anna Bucher, Manola Brunet, AM Fischer, AM Hama, et al. 2020. Making society climate resilient: International progress under the Global Framework for Climate Services. *Bulletin of the American Meteorological Society* 101, 2 (2020), E237–E252.
[51] Chris Hewitt, Simon Mason, and David Walland. 2012. The global framework for climate services. *Nature Climate Change* 2, 12 (2012), 831–832.
[52] Chris D Hewitt and Roger Stone. 2021. Climate services for managing societal risks and opportunities. *Climate Services* 23 (2021), 100240.
[53] Chris D Hewitt, Roger C Stone, and Andrew B Tait. 2017. Improving the use of climate information in decision-making. *Nature Climate Change* 7, 9 (2017), 614–616.
[54] Debra Hudson, Oscar Alves, Harry H Hendon, Eun-Pa Lim, Guoqiang Liu, Jing-Jia Luo, Craig MacLachlan, Andrew G Marshall, Li Shi, Guomin Wang, et al. 2017. ACCESS-S1 The new Bureau of Meteorology multi-week to seasonal prediction system. *Journal of Southern Hemisphere Earth Systems Science* 67, 3 (2017), 132–159.
[55] Stephan Hügel and Anna R Davies. 2022. Playing for Keeps: Designing Serious Games for Climate Adaptation Planning Education With Young People. *Urban Planning* 7, 2 (2022), 306–320.
[56] Netta Iivari. 2006. Understanding the Work of an HCI Practitioner. In *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles* (Oslo, Norway) *(NordiCHI '06)*. Association for Computing Machinery, New York, NY, USA, 185–194. https://doi.org/10.1145/1182475.1182495
[57] Katharine L Jacobs and Roger Brian Street. 2020. The next generation of climate services. *Climate Services* 20 (2020), 100199.
[58] Christian P Janssen, Sandy JJ Gould, Simon YW Li, Duncan P Brumby, and Anna L Cox. 2015. Integrating knowledge of multitasking and interruptions across different perspectives and research methods. , 5 pages.
[59] Andrea Jimenez, Pamela Abbott, and Salihu Dasuki. 2022. In-betweenness in ICT4D research: critically examining the role of the researcher. *European Journal of Information Systems* 31, 1 (2022), 25–39.
[60] Lindsey Jones, Andrew Dougill, Richard G Jones, Anna Steynor, Paul Watkiss, Cheikh Kane, Bettina Koelle, Wilfran Moufouma-Okia, Jon Padgham, Nicola Ranger, et al. 2015. Ensuring climate information guides long-term development. *Nature Climate Change* 5, 9 (2015), 812–814.
[61] Nikhil Kalghatgi, Aaron Burgman, Erika Darling, Chris Newbern, Kristine Recktenwald, Shawn Chin, and Howard Kong. 2006. Geospatial Intelligence Analysis via Semantic Lensing. In *CHI '06 Extended Abstracts on Human Factors in Computing Systems* (Montréal, Québec, Canada) *(CHI EA '06)*. Association for Computing Machinery, New York, NY, USA, 935–940. https://doi.org/10.1145/1125451.1125632
[62] Bran Knowles, Lynne Blair, Paul Coulton, and Mark Lochrie. 2014. Rethinking Plan A for Sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 3593–3596. https://doi.org/10.1145/2556288.2557311
[63] Bongshin Lee, Matthew Brehmer, Petra Isenberg, Eun Kyoung Choe, Ricardo Langner, and Raimund Dachselt. 2018. Data Visualization on Mobile Devices. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3170427.3170631
[64] Benjamin Lee, Maxime Cordeil, Arnaud Prouzeau, Bernhard Jenny, and Tim Dwyer. 2022. A Design Space For Data Visualisation Transformations Between 2D And 3D In Mixed-Reality Environments. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 25, 14 pages. https://doi.org/10.1145/3491102.3501859
[65] Maria Carmen Lemos, Christine J. Kirchhoff, and Vijay Ramprasad. 2012. Narrowing the climate information usability gap. , 789–794 pages. https://doi.org/10.1038/nclimate1614
[66] Maria Carmen Lemos and Barbara J Morehouse. 2005. The co-production of science and policy in integrated climate assessments. *Global environmental change* 15, 1 (2005), 57–68.
[67] Joseph Lindley and Paul Coulton. 2015. Back to the Future: 10 Years of Design Fiction. In *Proceedings of the 2015 British HCI Conference* (Lincoln, Lincolnshire, United Kingdom) *(British HCI '15)*. Association for Computing Machinery, New York, NY, USA, 210–211. https://doi.org/10.1145/2783446.2783592
[68] Tiago Capela Lourenço, Rob Swart, Hasse Goosen, and Roger Street. 2016. The rise of demand-driven climate services. *Nature Climate Change* 6, 1 (2016), 13–14.
[69] Craig M. MacDonald and Michael E. Atwood. 2013. Changing Perspectives on Evaluation in HCI: Past, Present, and Future. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (Paris, France) *(CHI EA '13)*. Association for Computing Machinery, New York, NY, USA, 1969–1978. https://doi.org/10.1145/2468356.2468714
[70] Megh Marathe, Priyank Chandra, Vaishnav Kameswaran, Tsuyoshi Kano, and Syed Ishtiaque Ahmed. 2016. In Search of Missing Pieces: A Re-Examination of Trends in ICTD Research. In *Proceedings of the Eighth International Conference on Information and Communication Technologies and Development* (Ann Arbor, MI, USA) *(ICTD '16)*. Association for Computing Machinery, New York, NY, USA, Article 60, 4 pages. https://doi.org/10.1145/2909609.2909644
[71] Gloria Mark, Daniela Gudith, and Ulrich Klocke. 2008. The Cost of Interrupted Work: More Speed and Stress. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 107–110. https://doi.org/10.1145/1357054.1357072
[72] Elizabeth C McNie. 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental science & policy* 10, 1 (2007), 17–38.
[73] Silvia Medri, Eva Banos de Guisasola, and Silvio Gualdi. 2012. Overview of the main international climate services. *CMCC Research Paper* 134 (2012).
[74] Patrick Meier, Doug Bond, and Joe Bond. 2007. Environmental influences on pastoral conflict in the Horn of Africa. *Political Geography* 26, 6 (8 2007), 716–735. https://doi.org/10.1016/j.polgeo.2007.06.001
[75] Richard J Millar, Jan S Fuglestvedt, Pierre Friedlingstein, Joeri Rogelj, Michael J Grubb, H Damon Matthews, Ragnhild B Skeie, Piers M Forster, David J Frame, and Myles R Allen. 2017. Emission budgets and pathways consistent with limiting warming to 1.5 C. *Nature Geoscience* 10, 10 (2017), 741–747.
[76] Ville Myllynpää, Jani Haakana, Julius Virtanen, and Erkki Sutinen. 2020. Holistic Model for Designing a Climate Service Application on the KaiOS Platform. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3334480.3383084
[77] Timothy Neate, Vasiliki Kladouchou, Stephanie Wilson, and Shehzmani Shams. 2022. "Just Not Together": The Experience of Videoconferencing for People with Aphasia during the Covid-19 Pandemic. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 606, 16 pages. https://doi.org/10.1145/3491102.3502017
[78] Tina-Simone Neset, Lotta Andersson, Ola Uhrqvist, and Carlo Navarra. 2020. Serious gaming for climate adaptation—assessing the potential and challenges of a digital serious game for urban climate adaptation. *Sustainability* 12, 5 (2020), 1789.
[79] Jakob Nielsen and Rolf Molich. 1990. Heuristic Evaluation of User Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Seattle, Washington, USA) *(CHI '90)*. Association for Computing Machinery, New York, NY, USA, 249–256. https://doi.org/10.1145/97243.97281
[80] Eric Nost. 2019. Climate services for whom? The political economics of contextualizing climate data in Louisiana's coastal Master Plan. *Climatic Change* 157, 1 (2019), 27–42.
[81] Timothy L Nyerges, David M Mark, Robert Laurini, and Max J Egenhofer. 2012. *Cognitive aspects of human-computer interaction for geographic information systems*. Vol. 83. Springer Science & Business Media.

[82] Elisa Oreglia. 2013. When technology doesn't fit: Information sharing practices among farmers in rural China. In *ACM International Conference Proceeding Series*. ACM Press, New York, New York, USA, 165–176. https://doi.org/10.1145/2516604.2516610

[83] Antti Oulasvirta. 2019. It's time to rediscover HCI models. *interactions* 26, 4 (2019), 52–56.

[84] Gigi Owen, Daniel B Ferguson, and Ben McMahan. 2019. Contextualizing climate science: applying social learning systems theory to knowledge production, climate services, and use-inspired research. *Climatic Change* 157, 1 (2019), 151–170.

[85] Janne Paavilainen, Hannu Korhonen, Kati Alha, Jaakko Stenros, Elina Koskinen, and Frans Mayra. 2017. The Pokémon GO Experience: A Location-Based Augmented Reality Mobile Game Goes Mainstream. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 2493–2498. https://doi.org/10.1145/3025453.3025871

[86] Joyojeet Pal. 2017. CHI4Good or Good4CHI. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 709–721. https://doi.org/10.1145/3027063.3052766

[87] Jean P Palutikof, Roger B Street, and Edward P Gardiner. 2019. Decision support platforms for climate change adaptation: an overview and introduction. *Climatic Change* 153, 4 (2019), 459–476.

[88] Olivia Pearman and Amanda E Cravens. 2022. Institutional barriers to actionable science: Perspectives from decision support tool creators. *Environmental Science & Policy* 128 (2022), 317–325.

[89] A Perrels, Th Frei, F Espejo, L Jamin, and A Thomalla. 2013. Socio-economic benefits of weather and climate services in Europe. *Advances in Science and Research* 10, 1 (2013), 65–70.

[90] Kathleen H Pine, Myeong Lee, Samantha A. Whitman, Yunan Chen, and Kathryn Henne. 2021. Making Sense of Risk Information amidst Uncertainty: Individuals' Perceived Risks Associated with the COVID-19 Pandemic. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 653, 15 pages. https://doi.org/10.1145/3411764.3445051

[91] Peter G Polson, Clayton Lewis, John Rieman, and Cathleen Wharton. 1992. Cognitive walkthroughs: a method for theory-based evaluation of user interfaces. *International Journal of man-machine studies* 36, 5 (1992), 741–773.

[92] James J Porter and Suraje Dessai. 2017. Mini-me: Why do climate scientists' misunderstand users and their needs? *Environmental science & policy* 77 (2017), 9–14.

[93] Maren Radeny, Ayal Desalegn, Drake Mubiru, Florence Kyazze, Henry Mahoo, John Recha, Philip Kimeli, and Dawit Solomon. 2019. Indigenous knowledge for seasonal weather and climate forecasting across East Africa. *Climatic Change* 156, 4 (2019), 509–526.

[94] Jacob M Rigby, Michaelina Almaz Yohannis, Chris Preist, Michael Bliss Singer, Timothy M Waema, Agnes N Wausi, and Katerina Michaelides. 2022. Climate services for the Greater Horn of Africa: interviews exploring practitioner perspectives from Kenya and beyond. *Climate and Development* (2022), 1–13.

[95] Yvonne Rogers. 2012. HCI theory: classical, modern, and contemporary. *Synthesis lectures on human-centered informatics* 5, 2 (2012), 1–129.

[96] Carla Roncoli, Christine Jost, Paul Kirshen, Moussa Sanon, Keith T Ingram, Mark Woodin, Léopold Somé, Frédéric Ouattara, Bienvenue J Sanfo, Ciriaque Sia, et al. 2009. From accessing to assessing forecasts: an end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). *Climatic Change* 92, 3 (2009), 433–460.

[97] Joel Ross, Lilly Irani, M. Six Silberman, Andrew Zaldivar, and Bill Tomlinson. 2010. Who Are the Crowdworkers? Shifting Demographics in Mechanical Turk. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 2863–2872. https://doi.org/10.1145/1753846.1753873

[98] Robert E Roth, Arzu Çöltekin, Luciene Delazari, Homero Fonseca Filho, Amy Griffin, Andreas Hall, Jari Korpi, Ismini Lokka, André Mendonça, Kristien Ooms, et al. 2017. User studies in cartography: opportunities for empirical research on interactive maps and visualizations. *International Journal of Cartography* 3, sup1 (2017), 61–89.

[99] M. C. Rufino, P. K. Thornton, S. K. Ng'ang'a, I. Mutie, P. G. Jones, M. T. van Wijk, and M. Herrero. 2013. Transitions in agro-pastoralist systems of East Africa: Impacts on food security and poverty. *Agriculture, Ecosystems and Environment* 179 (10 2013), 215–230. https://doi.org/10.1016/j.agee.2013.08.019

[100] Bahador Saket, Alex Endert, and John Stasko. 2016. Beyond Usability and Performance: A Review of User Experience-Focused Evaluations in Visualization. In *Proceedings of the Sixth Workshop on Beyond Time and Errors on Novel Evaluation Methods for Visualization* (Baltimore, MD, USA) *(BELIV '16)*. Association for Computing Machinery, New York, NY, USA, 133–142. https://doi.org/10.1145/2993901.2993903

[101] Kadek Ananta Satriadi, Barrett Ens, Tobias Czauderna, Maxime Cordeil, and Bernhard Jenny. 2021. Quantitative Data Visualisation on Virtual Globes. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 460, 14 pages. https://doi.org/10.1145/3411764.3445152

[102] Johannes Schöning, Florian Daiber, Antonio Krüger, and Michael Rohs. 2009. Using Hands and Feet to Navigate and Manipulate Spatial Data. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 4663–4668. https://doi.org/10.1145/1520340.1520717

[103] Zahra Shakeri Hossein Abad, Craig Anslow, and Frank Maurer. 2014. Multi Surface Interactions with Geospatial Data: A Systematic Review. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces* (Dresden, Germany) *(ITS '14)*. Association for Computing Machinery, New York, NY, USA, 69–78. https://doi.org/10.1145/2669485.2669505

[104] M Six Silberman, Lisa Nathan, Bran Knowles, Roy Bendor, Adrian Clear, Maria Håkansson, Tawanna Dillahunt, and Jennifer Mankoff. 2014. Next steps for sustainable HCI. *interactions* 21, 5 (2014), 66–69.

[105] Robert Soden, Perrine Hamel, David Lallemant, and James Pierce. 2020. The Disaster and Climate Change Artathon: Staging Art/Science Collaborations in Crisis Informatics. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1273–1286. https://doi.org/10.1145/3357236.3395461

[106] Steven Sotelo, Edward Guevara, Lizeth Llanos-Herrera, Diego Agudelo, Alejandra Esquivel, Jeferson Rodriguez, Leonardo Ordoñez, Jeison Mesa, Luis Armando Muñoz Borja, Fanny Howland, Sebastian Amariles, Alexander Rojas, Jhon Jairo Valencia, Cristian Camilo Segura, Freddy Grajales, Francisco Hernández, Fabián Cote, Enrique Saavedra, Franklyn Ruiz, Julieta Serna, Daniel Jimenez, Jeimar Tapasco, Steven D. Prager, Pete Epanchin, and Julian Ramirez-Villegas. 2020. Pronosticos AClimateColombia: A system for the provision of information for climate risk reduction in Colombia. *Computers and Electronics in Agriculture* 174 (2020), 105486. https://doi.org/10.1016/j.compag.2020.105486

[107] Peter Stegmaier, Robin Hamaker-Taylor, and Elisa Jiménez Alonso. 2020. Reflexive climate service infrastructure relations. *Climate Services* 17 (2020), 100151.

[108] Bettina Steuri, Elisabeth Viktor, Juliane El Zohbi, and Daniela Jacob. 2022. Fashionable Climate Services: The Hats and Styles of User Engagement. *Bulletin of the American Meteorological Society* 103, 10 (2022), E2341–E2353.

[109] RJ Swart, K de Bruin, S Dhenain, G Dubois, Annemarie Groot, and E von der Forst. 2017. Developing climate information portals with users: Promises and pitfalls. *Climate services* 6 (2017), 12–22.

[110] Arame Tall. 2013. What do we mean by Climate Services? *Special Bulletin of the World Meteorological Organization* (6 2013). https://cgspace.cgiar.org/handle/10568/100273

[111] Arame Tall, Jeanne Y. Coulibaly, and Moustapha Diop. 2018. Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. , 12 pages. https://doi.org/10.1016/j.cliser.2018.06.001

[112] Marta Terrado, Luz Calvo, and Isadora Christel. 2022. Towards more effective visualisations in climate services: good practices and recommendations. *Climatic Change* 172, 1 (2022), 1–26.

[113] Jeff Tollefson. 2018. IPCC says limiting global warming to 1.5 [degrees] C will require drastic action. *Nature* 562, 7726 (2018), 172–174.

[114] Kentaro Toyama. 2011. Technology as amplifier in international development. In *Proceedings of the 2011 {iConference} ({iConference} '11)*. Association for Computing Machinery, Seattle, Washington, USA, 75–82. https://doi.org/10.1145/1940761.1940772

[115] Catherine Vaughan and Suraje Dessai. 2014. Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change* 5, 5 (9 2014), 587–603. https://doi.org/10.1002/wcc.290

[116] Catherine Vaughan, Suraje Dessai, and Chris Hewitt. 2018. Surveying climate services: What can we learn from a bird's-eye view? *Weather, Climate, and Society* 10, 2 (4 2018), 373–395. https://doi.org/10.1175/WCAS-D-17-0030.1

[117] Katharine Vincent, Meaghan Daly, Claire Scannell, and Bill Leathes. 2018. What can climate services learn from theory and practice of co-production? *Climate Services* 12 (2018), 48–58.

[118] Katharine Vincent, Andrew J Dougill, Jami L Dixon, Lindsay C Stringer, and Tracy Cull. 2017. Identifying climate services needs for national planning: insights from Malawi. *Climate Policy* 17, 2 (2017), 189–202.

[119] Coleen Vogel, Anna Steynor, and Albert Manyuchi. 2019. Climate services in Africa: Re-imagining an inclusive, robust and sustainable service. , 100107 pages. https://doi.org/10.1016/j.cliser.2019.100107

[120] Zezhong Wang, Lovisa Sundin, Dave Murray-Rust, and Benjamin Bach. 2020. Cheat Sheets for Data Visualization Techniques. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376271

[121] Juergen Weichselgartner and Berit Arheimer. 2019. Evolving climate services into knowledge–action systems. *Weather, climate, and society* 11, 2 (2019), 385–399.

[122] Barry Wellman, Anabel Quan-Haase, Jeffrey Boase, Wenhong Chen, Keith Hampton, Isabel Díaz, and Kakuko Miyata. 2003. The social affordances of the Internet for networked individualism. *Journal of computer-mediated communication* 8, 3 (2003), JCMC834. https://doi.org/10.1111/j.1083-6101.2003.tb00216.x

[123] Dave D White, Amber Wutich, Kelli L Larson, Patricia Gober, Timothy Lant, and Clea Senneville. 2010. Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. *Science and Public Policy* 37, 3 (2010), 219–232.

[124] Robert L Wilby, Jessica Troni, Yvan Biot, Lennard Tedd, Bruce C Hewitson, Doug M Smith, and Rowan T Sutton. 2009. A review of climate risk information for adaptation and development planning. *International Journal of Climatology: A Journal of the Royal Meteorological Society* 29, 9 (2009), 1193–1215.

[125] Louise Wilson, Ulrike Bende-Michl, Wendy Sharples, Elisabeth Vogel, Justin Peter, Sri Srikanthan, Zaved Khan, Vjekoslav Matic, Alison Oke, Margot Turner, et al. 2022. A national hydrological projections service for Australia. *Climate Services* 28 (2022), 100331.

[126] Gabrielle Wong-Parodi, Baruch Fischhoff, and Ben Strauss. 2014. A method to evaluate the usability of interactive climate change impact decision aids. *Climatic change* 126, 3 (2014), 485–493.

[127] Kaitlin D Wowak, Idris Adjerid, Corey M Angst, and Juan Carlos Guzman. 2016. A tutorial on empirical ICT4D research in developing countries: processes, challenges, and lessons. *Communications of the Association for Information Systems* 38, 1 (2016), 21.

[128] Xuecong Xu, Xiang Yan, and Tawanna R. Dillahunt. 2019. Reaching Hard-To-Reach Populations: An Analysis of Survey Recruitment Methods. In *Conference Companion Publication of the 2019 on Computer Supported Cooperative Work and Social Computing* (Austin, TX, USA) *(CSCW '19)*. Association for Computing Machinery, New York, NY, USA, 428–432. https://doi.org/10.1145/3311957.3359447