Engaging Decision Makers:

A review of climate services and communication from the University of Reading (UoR), by its Hub for Applied Weather and Climate Research (HAWC).

The present document serves two purposes. Primarily, it demonstrates the range and expertise regarding engagement with decision makers on weather and climate information available from UoR and its associated practitioners. Secondly, through mapping said range and expertise across UoR and its associated practitioners, we aim to identify a consensus on what should be UoR future research priorities for improving the use of weather and climate information in decision making. To achieve these aims the present document reports on the outputs of an 'Engaging Decision Makers internal workshop' that took place at UoR on the 15th of November, 2023, while also reviewing contemporary relevant literature originating from UoR. Many authors of the reviewed literature were also participants or presenters in the internal workshop. Note that publications without at least one UoR coauthor are underlined.

For both the workshop and the literature reviewed here, there are three central interconnecting themes: 'Storylines' (i.e., exploration of plausible past and/or future events), 'Serious Games' (i.e., games designed to teach) and 'Co-Production' (i.e., production through collaboration), the latter of which could arguably be further categorised into co-production of a climate service or co-production of knowledge (a.k.a., participatory research). What each of these themes specifically refer to in the context of engagement with decision makers on weather and climate information will be defined in detail in their corresponding sections. Almost all the literature discussed here was selected from the Central Archive at the University of Reading (CentAUR), via an advanced search of all items uploaded and tagged to be related to the Department of Meteorology (henceforth 'UoR Met'). Three searches were run, i.e. one for each of the central interconnecting themes, using only the 'full text' search function. Every item on the generated lists of literature was individually inspected to ensure the usage of the tagged search term was contextually relevant, and was removed from the list if it was not (e.g., 'game' can refer to multiple concepts, models and places, none of which are relevant here). Furthermore, there are numerous research outputs from UoR Met that have domestic and international policy implications. Subsequently, inclusion of some kind of recommendation for decision maker engagement is a common occurrence in contemporary research articles, which reflects a shared sentiment among many UoR Met scientists, that being a need to further relationships with social scientists and weather application sector practitioners, as well as an explicit willingness to do so. As such, it should be noted that this literature review is not comprehensive (neither in terms of the breadth of recommendation for engagement, nor actual reported engagement), and is mostly limited to items published between January 2018 and April 2024.

Each section of this paper includes essentially the same elements: the interconnecting theme is defined,then attributes related to the effectiveness of the theme in engaging decision makers are discussed. We report on how this theme was covered during the November 2023 internal workshop and highlight pertinent ideas. Next, the identified literature from UoR Met scientists and associates that either contributes to knowledge/discussion of the interconnecting theme, or utilises a theme for a practical research output, are explored and showcased. We also discuss the seven REF2021 impact case studies submitted by UoR Met (all of which can be found via www.reading.ac.uk/research/impact/REF-2021/earth-systems-environmental-sciences) and discuss their relevance to these interconnecting themes.

Serious Games

Serious games (also referred to as 'participatory games') simply refer to games that have been developed with the primary goal of promoting cognitive, normative and relational learning among players, with entertainment generally being a secondary aim (Chew *et al*, 2013; Baird *et al*, 2014). When utilised specifically for climate change adaptation learning, these games provide a medium for experts and non-experts to engage with diverse and complex datasets, and observe the myriad complementary and confounding interactions between inter-related variables without any of the technical knowledge required to identify and quantify said datasets and variables (Reckien and Eisenack, 2013). Moreover, the potential pedagogical scale and depth of these games can be as wide or narrow as is thematically appropriate, or as resources allow. For example, the use of virtual reality games for scientists involved in public engagement are an increasingly common means of disseminating their work across large, typically less-engaged audiences, such as Flack *et al* (2019) who aimed to raise public awareness of their end-to-end flood forecasting system and bolster public flood literacy by demonstrating the 'Flash Flood!' applications (Skinner, 2018) at numerous national-level science festivals in the UK. By contrast, the games may use minimal resources but be hyper-specialised to the targeted audience. For example, Arnal *et al* (2016) describe a game inspired by the Red Cross/Crescent Climate Centres 'Paying for Predictions', which places participants in the role of prospective flood protection company executives, competing for a top job, from which they report successful facilitation of reflexive and autonomous learning following the games use at conferences and international workshops. Whatever form a serious game may take, the ideal outcome of these types of engagement is realisation and/or acceleration of some kind of climate change action (Flood *et al*, 2018).

Serious games broadly related to climate change are not a particularly new concept, with their utilisation seeing a rapid uptake prior to the 2009 United Nations Framework Convention on Climate Change meeting (Reckien and Eisenack, 2013), yet climate change adaptation games specifically were previously underrepresented. More recently, in their systematic review of climate adaptation games, Flood *et al* (2018) explore the emergent themes of 43 research outputs associated with said games. The topics that explored games considered ranged from food security to disaster response, logistics and development, and were set from international to regional scales. Moreover, the authors identified eight attributes as intrinsic to a functional climate adaption game: the game must capture adaptation complexity; it should challenge existing beliefs; the game and its purpose should be effectively communicated; it should provide space for reflexive learning, collaboration and dialogue; facilitate negotiation and conflict resolution; enable autonomous learning; and encourage utilisation of harnessing local knowledge.

One noteworthy example of a serious game by UoR Met scientists and associates that demonstrates these attributes is described by Stephens *et al* (2019). The authors use an 'ice-cream seller' game to communicate the uncertainty in rainfall and temperature forecasts to 8220 participants. Essentially, the game involved rounds of participants having to decide where and when to sell based on temperature and rainfall forecasts, as well as stating their certainty for these decisions. Critically, some participants were provided with probability percentages of forecasts whereas others only had weather symbols. The result of participants with probability percentages scoring higher than those with only symbols, demonstrates that most people provided with additional information on uncertainty are able to make use of it. In this instance, as well as effectively communicating aspects of forecasting considered by some to be too complex for the general public, this serious game also provides evidence in the debate for probabilistic versus deterministic forecasts.

The majority of reported serious game use by UoR Met scientists has been to communicate concepts of 'event attribution science'. This refers to the study and quantification of impact of drivers such as anthropogenic climate change on individual extreme events (Stott *et al*, 2013). This topic can be controversial given its association with reparations (Mechler *et al*, 2019). Nonetheless, literacy of event attribution science in adaptation policy makers is desirable, because findings from probabilistic event attribution (Allen, 2003) can help inform on the likelihood of future event frequency (Otto *et al*, 2015). In their chapter on the relevance of event attribution science to loss and damage policy, James *et al* (2019) draw from their experiences playing the CAULDRON game (Climate Attribution Under Loss and Damage: Risking, Observing, Negotiating, Suarez *et al*, 2015; Parker *et al*, 2016) at workshops and conferences to explore nuanced approaches to application and study of event attribution, and subsequently are able to provide further guidance on use and communication of attribution science. Young *et al* (2019) also utilised the CAULDRON game when considering the potential utility of event attribution for flood management in urban Senegal. Their paper reports that the majority of participants were not previously aware of probabilistic event attribution, yet were subsequently able to identify how it may be useful for Senegal's national adaptation policy, as well as highlight where event attribution may not be appropriate, suggesting the occurrence of cognitive and normative learning. CAULDRON specifically, is a pertinent example of a climate adaptation serious game that meets all eight of Flood *et al*'s (2018) desired criteria, and has been repeatedly utilised by UoR Met scientists and associates (e.g., Parker *et al*, 2016).

Despite their demonstrated utility, the mention of serious game usage for climate change adaptation in much published literature is relegated to a broad recommendation of their usage (e.g., Arnal *et al*, 2019; Dasgupta *et al*, 2023), instead of reporting on any specific game outcome. Likewise, of the themes discussed in this document, serious games was the only theme to not have its own explicit representation during the HAWC internal workshop (excluding usage of a short game at the end of the workshop to gauge participant opinion). This underrepresentation of contemporary climate adaptation serious game literature from UoR Met may give the appearance of little utilisation of serious games, yet individual testimony from UoR Met associates (both from the workshop discussion and individual discussion) suggests the contrary, albeit without comprehensive reporting on their usage. The reason for this lack of reporting is unclear, but may be attributed in part to lack of incentive (i.e., interest from meteorology journals and/or specific waged positions), or even to out-dated views of decision maker engagement as a 'soft science' (a common theme when discussing culture change in the internal workshop). Either way, this is problematic because improvement in design and delivery of climate science and adaptation serious games is impeded by the relative absence of iterative feedback loops of learning, monitoring and impact evaluation (De Suarez *et* al, 2012; Flood *et al*, 2018). A cultural change for simplification and facilitation of pathways for UoR Met serious game practitioners to disseminate the outcomes of their games may be required for building comprehensive knowledge bases. Alternatively, instead of championing any kind of systemic change for serious game reporting, simply encouraging and providing incentives for serious game reporting and literature generation through inter-departmental collaboration with social scientists may prove beneficial.

Storylines

In the context of climate change, adaptation and mitigation, 'storylines' (a.k.a, 'physical climate storyline', or PCS) refers to 'physically self-consistent unfolding of past events, or of plausible future events or pathways' (Shepherd *et al*, 2018). It is a relatively new approach to representing uncertainty in climate change, suggested and utilised by UoR Met scientists and practitioners, wherein consideration of probability of a realised climate is deemphasised and more importance is given to exploring a range of plausible outcomes (i.e., qualitative understanding > quantitative precision). In practice this can mean, for example, forgoing a probabilistic climate forecast based on projections from multi-model averages, and instead considering multiple imagined futures based on projections from individual models. This conditional approach can be considered similar in nature to practices of 'stress testing' utilised in disaster risk management, when concerning event-based storylines (Sillmann *et al*, 2021). This approach is not confined solely to consideration of plausible futures, as consideration of past realised and plausible events can still be useful. In their seminal paper 'Storylines: an alternative approach to representing uncertainty in physical aspects of climate change', Shepherd *et al* (2018) use a 2011 flooding event in the valleys of the Swiss Alps to demonstrate this, noting that a change in seasonality of this flood associated with climate change (autumn to winter) could have had numerous differences in the consequences for the hydrological system and subsequent flood management. While this paper may not have been the first instance of some kind of 'narrative' or 'scenario' approach to climate change adaptation (e.g., Alcamo, 2008; Fløttum and Gjerstad, 2017), it arguably was the inciting publication for the contemporary ubiquity of the storyline approach. Critically, adopting the storyline approach can be substantially more helpful for regional and international decision makers because it affords them the opportunity to iteratively examine management options for specific vulnerabilities, or based on subjective expectations and value judgements (Kunimitsu *et al*, 2023), which may be especially helpful for decision makers in regions subject to multiple phenomena (Lloyd and Shepherd, 2023). In fact, the most recent Intergovernmental Panel for Climate Change (IPCC) report from Working Group 1 (Masson-Delmotte *et al*, 2021) dedicates multiple sections to this approach, highlighting its utility in exploring low-likelihood but high-impact events, as well a means of delivering climate information that is integrated with socio-economic information, to name a few (see Baldissera *et al*, 2023 for a wider review on the use of PCS).

UoR Met scientists and practitioners have since made numerous contributions to both the development and the communication of PCS. These contributions can be categorised into four types, the first of which uses storylines as a vehicle for scaling global-scale meteorology to regional levels. Examples of these include Mindlin *et al* (2020), who developed storylines for the Southern Hemisphere midlatitude circulation changes based on possible future warming response in the tropical upper troposphere and the stratospheric polar vortex; Mindlin *et al*'s (2021) continuation of this work to incorporate storylines of ozone depletion or recovery; and Dong and Sutton (2021) who use a storyline approach to explore drivers of decadal changes in summer atmospheric circulation over the North Atlantic and Europe. The other three contribution types, discussed in more detail here, include: the works that expand, develop or promote the climate storyline concept, practically and epistemically, contributions/integration of storylines to IPCC documentation, and arguably most pertinently, the use of storylines for exploration of specific climate vulnerabilities.

Regarding the promotion and development of the climate storyline approach, several modern UoR Met research outputs demonstrate the possible expanded complexity of this comparatively straightforward concept, and how the appended complexity bolsters the storyline approach's capacity to explore and discuss climate. Zappa (2019) reviews numerous cases wherein regional precipitation and windiness is highly subject to alterations in mid-latitude atmospheric circulation, a forcing of which is highly uncertain and may unfold differently depending on the interplay of different climate drivers, such as surface warming patterns, sea ice loss and stratospheric changes. Given the uncertainty, in this case Zappa notes that "it is useful [for communicating projections] to discuss regional climate change conditionally on alternative plausible storylines of atmospheric circulation change". Furthermore, the relative disregard of probability calculations and contemplation of uncertainty does not exclude usage of inferential statistics in this approach, which can instead be applied to the causal networks present in climate storylines (Shepherd, 2019). Kretschmer *et al* (2021) and Shepherd (2021) both discuss this. In the former paper the authors argue for and give examples of adopting a causal inference-based framework in the statistical analysis of teleconnections in order to quantify causal pathways of teleconnections to regional anomalies. In the latter perspective piece, Shepherd discusses the usage of frequentist statistics in climate science, and notes the difficulty in expressing uncertainty with said methods, of which may be better represented conditionally. These traits of the climate storyline approach also make them suitable candidates for the integration of predictive Artificial Intelligence (AI), as highlighted by Caviedes-Voullième and Shepherd (2023) who argued that the risk-causality and contextualisation of plausible risks from storylines, provide a framework to adapt and prepare for extreme hydrological events. The integration of AI for climate storylines was a central point of discussion during the UoR Met internal workshop, and is of immediate research interest to many of the participants, both for climate experiments and decision maker communication.

In recognition of its communicative ability, UoR Met researchers and practitioners have also made contributions to the simplification of the storyline approach. After all, effective decision maker engagement requires a shared understanding of the pertinent policy point. This is recognised in two commentaries from UoR Met associates: 'Meaningful Climate Science' (Shepherd and Lloyd, 2021) and 'Small is beautiful: climate-change science as if people mattered' (Rodrigues and Shepherd, 2022). Both commentaries highlight the propensity of climate science to "detach knowledge from meaning", and the gap between its production and usage. In the former commentary, a suggested driver of this gap is the idea that most people (users/decision makers) find numerical information to be abstruse, and therefore not readily usable. The latter commentary, which discusses the role of climate change in local decision making, explores how this complexity can compromise 'bottom-up' approaches to adaptation. Both conclude with the need of a level of communicable simplicity afforded by the storyline approach, with the former commentary recommending it to be part of the 'pidgin language' available to climate scientists to bring meaning to climate knowledge. For users more familiar with projections and Global Circulation Models (GCMs), Trancoso *et al* (2024) present a different option for exploring storylines of precipitation and drying: essentially foregoing multi-model averages and instead focuses detecting anomalous results and agreement between GCMs, wherein individual GCMs are themselves considered independent storylines. For both researchers and decision makers, van den Hurk *et al* (2023) suggest informal guidelines for the development of climate event storylines that incorporate socioeconomic factors, and provide specific real-world examples of each step.

Through iterating on the storyline approach, UoR Met researchers and associates have not only refined and improved its communicative effectiveness, but have been able to translate and adapt it across many overlapping disciplines. In their discussion on ecological crises resulting from extreme weather events, Lloyd and Shepherd (2020) highlight the advantages for conservation scientists performing climate-attribution studies, of adopting a storyline approach instead of a 'risk-based' approach, given the similarity of causal networks for climate storylines to the longstanding 'press and pulse' framework frequently used for describing ecological disturbances (see Bender *et al*, 1984). The same authors also demonstrate the potential value of the storyline approach for climate-related litigation: in their article commenting on the usage of a storyline approach as evidence in the controversial court case *Juliana v. United States*, Lloyd and Shepherd (2021) argue that the storyline approach was and is "well aligned with the concept of evidence that is appropriate in the legal context of tort law" in the US. For future utility in climate law evidence, they suggest the complementary development of storylines and probabilistic approaches to attribution studies, given the local scale of the former and reliable quantification of the latter. For other disciplines, in their chapter in 'Storying Multipolar Climes of the Himalayas, Andes and Arctic' (Yü and Wouters, 2023), Shepherd and Truong (2023) essentially demonstrate how the climate storyline approach can be integrated into ethnography, through integrating lived experiences of otherwise unheard voices.

Following these contributions to the climate storyline approach as a whole, UoR Met researchers and associates have subsequently provided significant contributions to arguably the most important modern climate change decision maker documents: the IPCC Sixth Assessment Report (AR6), primarily 'The Physical Science Basis' (Working Group 1, WG1; Masson-Delmotte *et al*, 2021). Before the WG1 contribution released in August 2021, Sutton (2018) highlighted that the focus on 'likely ranges' for future climate in the previous Assessment Report (AR5) did not meet the needs of policy makers contending with risk assessment. Subsequently, chapter 4 of the AR6 adopts Sutton's storyline approach to high-risk, low-likelihood scenarios (Physically Plausible High Impact Scenarios or PPHIS). Within the AR6 WG1 document itself, the storyline approach is central throughout, described as "a complementary approach to ensemble projections for generating more accessible climate information and promoting a more comprehensive treatment of risk". Accordingly, UoR Met researchers were involved in some capacity with the authorship of chapters 10, 11 and 12, as well the technical and policymaker summaries (Arias *et al*, 2021 and Allan *et al*, 2023, respectively). Doblas-Reyes *et al* (2021; chapter 10) describe the use of storylines for scaling of global climate information to regional information. Seneviratne *et al* (2021; chapter 11) explain the relevance of climate storylines to extreme event attribution. Ranasinghe *et al* (2021; chapter 12) encourage the use of storylines to consider multiple climate impact drivers affecting a given sector. Furthermore, not included in the AR6 but recommended as part of the High Impact-Low Likelihood toolkit for risk-assessment in the Seventh Assessment Cycle, Wood *et al* (2023) recommends the integration of climate storylines and specifically recommend the co-development and identification of "tipping points" or "thresholds" in the physical climate system.

Most pertinently, the contemporary UoR Met literature that uses storyline approaches for informing on a specific climate vulnerability are varied in subject and spatial scope, indicative of both the versatility of the approach, and the aptitude of UoR Met practitioners to apply and communicate it across a diverse range of policy points. For Africa, Young *et al* (2020 and 2021) utilise the storyline approach for food security. In a policy brief on the Sweet Potato Catalyst Project for Uganda, Young *et al* (2020) describe their use of causal networks to investigate drivers of sweet potato yields in Uganda under different climate change scenarios. Their choice of adopted approach allows for flexibility and iteration on the causal networks as new information becomes available, be it from improved data availability and model development, or from further insights of drivers from Ugandan sweet potato experts. As such, achievement of the long-term desired outputs of this project applicable to policy planning and infrastructure investment, will be facilitated by the stakeholders (e.g., Climate Action Network – Uganda, and the Koronivia Joint Work on Agriculture). Later, using data and reports from the Namibia Vulnerability Assessment Committee, Young *et al* (2021) develop a network characterising influences on household food security in Namibia's Caprivi region, then use it to understand the drivers of a low consumption year affected by flooding (2013 to 2014), and subsequently generate counterfactual storylines for this event. The authors note that they "know the policy options described [in their counterfactuals] are plausible because they are based on decisions that have been recommended or implemented in the past by those working in the specific context". For Europe, Bevacqua *et al* (2020) use novel diagnostics to inform on future wintertime cyclone clusters, and demonstrate middling growth in accumulated precipitation extremes across Europe, with the extent of decreased wintertime storminess varying from north to south dependant on the future storyline of atmospheric circulation change. Working with the European Climate Energy Mixes, Bloomfield *et al* (2021) estimate the impact of climate change on future European power systems with a storyline approach, noting that the future small mean energy responses projected by a traditional multi-model mean approach would not actually be representative of individual climate model trajectories, and the subsequent potential future energy system uncertainty. For the Americas, as part of the US Department of Energy HyperFACETS project, Letson *et al* (2021) present a method for identifying and characterising severe windstorms, and through the application of a storyline approach to past realised events are able to identify and generate damage indices for the top 10 windstorms during 1979–2018 over the northeastern states. For the UK, Chan *et al* (2022 and 2024) use storyline approaches to explore hydrological droughts occurring during 2010-2012 and 2022, respectively. In both cases the storylines are generated for the benefit of British water companies who are required to consider water supply reliability under plausible worst-case droughts, under the UK Water Act 2014. By contrast, Bulgin *et al* (2023) and Hawkins *et al* (2023) use storyline approaches to explore a previous UK flood and storm event, respectively. By extrapolating from storylines of dynamic sea-level rises by the end of the century, the former paper presents a counterfactual scenario of a 2013 flood on the east coast of England occurring instead in a 2100 climate, and estimate that an extra 1414 km^2 of land would have been affected by the flooding. In the latter paper, the authors simulate the 1903 'Storm Ulysses' under modern warmer climates, and by doing so present a storyline of greater wind speed, rainfall and more overall damage if the same storm occurred today. For wider application, in terms of both policy and geographical extent, Arnell *et al* (2019) presents change in hazard and resource base under different rates of climate change, and provides quantitative and qualitative assessments of consequences of policy under climate change scenarios. For extreme or problem precipitation events, Zappa *et al* (2021) suggest a method of identifying areas suitable for unlikely but plausible variable storylines of extreme precipitation, while Bevacqua *et al* (2021) apply a storyline approach to consider the spatial extent of historical extreme precipitation events, using new multi-thousand-year climate model simulations to show how wintertime total precipitation extreme extents could increase over the Northern Hemisphere extratropics under different warming scenarios.

Given its relative novelty, the storyline approach was not well represented in UoR Met's REF2021 impact case studies. However, given the originality, significance and applicability beyond academia of the related works described here, we confidently assume that the storyline approach will be better represented in the REF2029 case studies. Ironically, the inherent breadth of practical applications of the storyline approach complicate the identification of specific desirable future research directions, however feedback from the HAWC internal workshop on decision maker engagement may help inform this. The sentiment expressed by Caviedes-Voullième and Shepherd (2023), that storylines could bridge physically-based explanations and AI generated predictions, was shared in principal, amongst the workshop participants, who also expressed desire to see AI integrated into model interpretation, instead of being only utilised at the modelling stage. However, as also pointed out by workshop participants, the potential benefits of AI integration to decision maker engagement and virtual communication are not immediately available to all decision makers. This means potential beneficiaries of the developing approach may be 'left behind' if unable to utilise or access the associated technologies (e.g., unreliable internet in developing countries). What was more straightforward was the sentiment for better collaboration between UoR Met scientists and social scientists. Indeed, as a key strength of the storyline approach is its effectiveness at communicating climate information, social scientists may provide fresh perspectives on how to further improve the approach’s efficacy.

Co-production

The lag between production of climate adaptation science and the implementation of science-informed adaptation measures (e.g., Runhaar *et al*, 2018) may be expedited by nurturing trust of the stakeholders in the scientific process and/or through tailoring the generated information to maximise its relevance and usability for the user (see Lemos *et al*, 2012). Co-production, referred to here as a “two-way collaborative process of product construction” (based on Vincent *et al*, 2018, who also provide multiple definitions based on conceptual features of co-production), essentially aims to do both of these by having the ‘users’ (i.e., climate service users) integrated into the production process in partnership with the ‘producers’ (i.e., climate scientists). This is not necessarily a linear process, in fact it should ideally be “an [iterative] cycle characterised by continuous monitoring, knowledge exchange and learning that enables reflexive review and refinement of both the process and product” (Vincent *et al*, 2018). But in either case the desired outcome is the same: generation of useful and usable climate information of which the ‘user’ feels a sense of shared ownership (Dilling and Lemos, 2011). Similarly, co-production of knowledge (i.e., ‘participatory research’), which here refers to the active involvement of a diverse range of stakeholders in the creation and utilisation of climate adaptation science (based on Few *et al*, 2007), aims to facilitate trust building towards scientists and the scientific method, by having the research process be guided by multiple perspectives and tailored to the specific needs of those perspectives (Cvitanovic *et al*, 2019). By Meadow *et* al’s (2015) typology on co-production, participatory research may arguably be under the umbrella of collegial and collaborative modes of stakeholder engagement, but in practice, tends to exist somewhere along a spectrum of stakeholder involvement between informal consultants to full partners (Reed *et al*, 2017). By placing potential decision makers at the academic forefront, participatory research allows participants to circumvent some of the barriers to access and dissemination of the generated knowledge (e.g., research publication and paywalls, Cvitanovic *et al*, 2015), it facilitates input of multiple epistemological perspectives (Blythe *et al*, 2017), and it has been shown to effectively foster cognitive and behavioural change (Gupta, 2016). There are, however, risks associated with participatory research approaches to all involved actors. Cvitanovic *et al* (2019) provide a non-exhaustive list of risks to the involved climate adaptation scientists and stakeholders, and their respective institutions, as well as to the funders of the participatory research and to the scientific process itself. Ironically, the pervading theme across their identified risks is in regards to perceptions of legitimacy, both within and across respective sectors (e.g., ‘contaminated’ participants or unobjective researchers), paradoxically meaning that institutions that engage in participatory research to build trust with users often do so at risk to their reputations. These risks remain relevant to co-production of climate services, and in both of these avenues of decision maker engagement UoR Met have repeatedly demonstrated the epistemological, ethical and practical benefits of taking these risks.

Across climate science, contributions to literature pertaining co-production of climate adaptation include but are not limited to publications describing the need for co-production, commentaries identifying challenges associated with co-production and reports on workshops to guide co-production. Each of these formats have fed in to the most recent IPCC Assessment Report (Masson-Delmotte *et al*, 2021 and Arias *et al*, 2021), where chapters 10 and 12 of the Working Group 1 contribution (Doblas-Reyes *et al*, 2021 and Ranasinghe *et al*, 2021, respectively) discuss the importance of co-production to distilling regional climate data in to regional user-oriented information, and to facilitating the spread and diversification of climate services. However, the apparent majority of literature associated with climate adaptation co-production are papers that both report on a specific co-developed product and/or knowledge, while reflecting on the co-production and engagement process. These formats of contribution to climate service/knowledge co-production are also among the research outputs of UoR Met, including contributions to the aforementioned IPCC AR6 WG1 chapters.

Regarding the need for co-production, Rodrigues and Shepherd (2022) perspective piece on applying bottom-up economics to climate science note how the top-down broad policies, while necessary for the global action required for global mitigation, effectively overlooks regional needs. For managing regional vulnerabilities (i.e., climate adaptation) and navigating the complexity of local situations, local coordinated action and the development of 'intermediate technologies' (i.e., co-developed climate services) is needed (Rodrigues and Shepherd, 2022). For the UK specifically, in their discussion on community engagement by flooding authorities, Mehring *et al* (2018) compare and contrast how flood communities experience engagement with flood risk management through questionnaires and thematic analyses, and ultimately conclude that "adopting a one-size-fits-all approach to engagement fails to recognise that communities are heterogenous and that good engagement requires gaining an understanding of the social dimensions of a community". The need for co-production is also apparent when observing adaptation management that is predominantly top-down. A lack of clarity and transparency regarding citizen and institutional responsibilities for flood risk governance in Germany likely underpins a lot of detrimental inaction, of which would likely be avoided through co-development and refinement of social contracts (Ommer *et al*, 2024). Likewise, Emerton *et al* (2020) critique the process of the UoR-Met-co-developed emergency bulletin creation for humanitarian decision makers during Cyclones Idai and Kenneth (which impacted Mozambique in 2019). While the reported feedback from humanitarian actors and involved governments was generally very positive, as bulletins were considered essential for providing situation overviews and supported preparatory measures; 'information overload' for decision makers on the ground was a concern throughout, which would benefit from further filtering defined through user-specified needs. Moreover, from a purely academic perspective, there are numerous knowledge gaps wherein a co-production approach represents the most effective and practical methodological option available to scientists. For example, in their review of the gaps in current remote sensing land data assimilation research and application (fed by satellite earth observation data), Kumar *et al* (2022) note that "there is a need for co-producing land observation datasets in coordination with the land data assimilation community so that a consistent characterization of spatiotemporal errors of observations can be established", highlighting the need for active two-way communication between ground-truthers/data producers and data modellers. Black *et al* (2024) come to a similar conclusion in their assessment of projected drought change across African elephant ranges for the biodiversity conservation sector. Following ubiquitous worsened projections of drought across Sub-Saharan Africa, the authors subsequently recommend further research into drought impacts on African elephants by conservationists and closer collaboration with meteorologists to co-produce relevant, usable seasonal metrics.

The need for co-production of climate services and knowledge is a motivation for many workshops and conferences, given that multidisciplinary approaches are required to generate multifaceted information, needed to support multi-sectoral systems that may be under-resourced or data-deficient. Rother *et al* (2023) report on one such workshop pertaining to health and climate change adaptive capacities (Adaptations Futures 2018 Conference in Cape Town). There they demonstrated a method of promoting dialog between climate scientists, health scientists, governmental officials and non-governmental organisations, that they called 'Q-storming'. Essentially, this method is an inverse of brainstorming wherein the aim is to identify what the 'best' questions to ask about a policy issue are. Subsequently, across each theme discussed in their sessions, bottom-up approaches and well-defined pathways for information exchange were represented in example solutions for all themes. Bloomfield *et al* (2021) report on an online workshop hosted by UoR that aimed to identify and address challenges associated with modelling climate risk in energy systems. While the workshop participants were predominantly academics, a key outcome of the discussions were that regional and national utilities, transmission system operators, energy traders, and policy-makers should be more involved in the climate risk modelling chains. Dasgupta *et al* (2023) summarise and provide an early-career perspective on an online hydrological modelling and forecasting workshop hosted in part by UoR Met, wherein presentations and speakers showcased diverse incorporation and application of local knowledge in to the 'Climate Service Value Chain', and predict that "in the next decade, the portion of research that is directly related to [co-produced global to local hydrological forecasting] will increase". Critically, the workshops themselves can be an important part of the co-production process (arguably including the workshops hosted by HAWC). Matthews *et al* (2023) summarise the outcomes of a workshop that aimed to determine usage, identify limitations and determine future priorities for the post-processed flood forecast products of the European Flood Awareness System. From feedback they were able to generate a list of potential future developments based on themes of local relevance of product, availability of user-focused auxiliary information and ease of access to products. Perhaps most importantly, the workshop in this instance (which was part of an annual conference for developers and users of the European Flood Awareness System) is framed as "part of a larger iterative co-production process", representing a medium for continuous knowledge exchange.

Some of the most significant benefits of co-production can also be the source of the most difficult challenges. For example, several UoR Met outputs demonstrate that challenges to co-production are not always practical in nature, but sometimes epistemological. Cornforth *et al* (2019) describe the creation and key elements of their 'Forecaster's Handbook' for West Africa, which aimed to make the methods and tools used and developed in the African Monsoon Multidisciplinary Analysis (Redelsperger *et al*, 2006) available to the operational prediction community in West Africa. The authors note how development of the handbook was often impeded by difficulty reaching the consensus required to provide summaries of mutual understandings, stating that "at times, both [researchers and forecasters] displayed conservatism and were unwilling to abandon their accepted ideas and untested methods". This kind of challenge can extend to mismatches in scientific capacity and intellectual ownership, as highlighted in a commentary piece by Lamptey *et al* (2024). They outline challenges to the sustainability of African weather information and suggest incentives to address each. Among these challenges includes Africa's reliance on externally imposed solutions due to the lack of scientific capability and resources available to the African research community. This also underpins contrasts in understanding, for example of differences between tropical-weather systems and mid-latitude weather systems, that can undermine the practical and perceived efficacy of any co-produced product. Consequently, they suggest better investment into core sciences training and for long-term career support for African scientists.

The motivation of UoR Met scientists and associates to provide these kinds of commentaries on the need, processes and challenges to co-production, has been inspired by their numerous multi-sectoral contributions to co-produced climate services in developed and developing nations. For example, Goodess *et al* (2019) describes and reflects on the development of a set of products for the energy sector by the European Climatic Energy Mixes. Primarily, they discuss the creation of the "C3S ECEM Demonstrator", an interface for visualisation and exploration of climate and energy datasets across historical, seasonal and projected future timescales (of which UoR scientists were considered the team experts for software development and its subsequent demonstration via event case studies). A noteworthy aspect of the project is how clarity in definitions and guidance of co-production can influence the efficacy of a product. For example, from their described timeline of the software production and stakeholder engagement, developmental priority was initially focussed on data visualisation, then reprioritized to data access following feedback from users with technical expertise, then changed back towards data visualisation when contending a wider range of potential users (see Figure 2 in Goodess *et al*, 2019). Consequently, in their self-critique the authors scrutinise the ambitiousness and ambiguity of their initial co-production plans, but through an iterative co-production process they ultimately generate a refined pre-operational product for a clearly defined target audience.

Of these experiential outputs associated with co-produced climate adaptation products and knowledge, without a doubt, the most represented contemporary contributions from UoR Met scientists and associates are those related to the Global Challenges Research Fund, African SWIFT programme (GCRF African SWIFT, henceforth SWIFT). The project aims to make the same quality of operational weather forecasting services enjoyed in European and North American countries (specifically nowcasting, synoptic and seasonal-to-subseasonal predictions), available to Africa, wherein uptake and quality of climate services have been undermined by insufficient funding from international donors, relative lack of regional weather monitoring infrastructure, absence of feedback towards forecasts from external commercial forecasters and poor performance of global numerical weather predictions over tropical Africa specifically (Vogel *et* al, 2018; Hirons *et* al, 2021; Parker *et al*, 2022). These objectives would be achieved in part through capacity building activities including workshops for early career researchers, international summer schools, secondments and research exchanges, and training of operational forecasters to a globally consistent standard (Parker *et al*, 2022). However, the main defining feature of the SWIFT project is the hosting of "operational forecasting testbeds" in Senegal, Nigeria, Kenya and Ghana, in which UoR scientists would hold key positions of responsibility. In this context, 'testbeds' refer to forums wherein interaction between stakeholders (e.g., forecasters, academics and climate information users) generate co-produced forecast products that are continually used, iterated and evaluated in real time to improve their practical application for decision making. These have previously been used to support weather forecasting internationally but the SWIFT project represents their first use in Africa (Parker *et al*, 2022). Hirons *et al* (2021) describe the testbed that contends with the provision of bespoke subseasonal products (i.e., 2-4-week forecasts with significant potential benefit to resilience to weather-related extremes). This testbed used real-time forecast data from the operational configuration of the European Centre for Medium-Range Weather Forecasts (ECMWF) model which produces bi-weekly forecasts from 51 ensemble members, and daily forecasts for 1 to 46 days in advance. They subsequently provide two case studies of co-produced products under this testbed: a bulletin of extreme precipitation events, based on probabilities of anomalous weekly-accumulated precipitation in ensemble members, and a set of weekly rainfall forecasts for Nairobi that visualise forecasted, hindcasted, observed data and uncertainty. Drawing from these case studies and their experiences at that stage of SWIFT, Hirons *et al* (2021) highlight three lessons to further guide SWIFT: recognition that in-depth co-production is resource-intensive, recognition that responsibility for addressing communication challenges lies with all involved parties, and that systems to evaluate any co-produced product must also be co-developed with decision makers. One of the participants of the seasonal-to-subseasonal (S2S) testbeds were the Nigerian Meteorological Agency, who previously were only able deliver short-term weather and climate information to weather sensitive sectors, but through involvement with SWIFT, co-produced a range of S2S climate forecast products that were operationally issued to Nigerian stakeholders. Performance evaluations of products via media coverage, eye-witness reports and comparisons against Nigerian Meteorological Agency observations suggested that products captured about 80% of severe weather events over the country (Lawal *et al*, 2021). These co-produced products from the Nigerian Meteorological Agency have been thought to support agricultural planning for more than 10,500 farmers since 2020, leading to improved food security across the nation (Hirons *et al*, 2021). However, in terms of sheer number of beneficiaries of the SWIFT testbeds, the most significant co-produced SWIFT output is certainly the improved Meningitis Early Warning system for the 26 countries in the African meningitis belt (approximately 300 million people). For context, meningitis epidemics in Sub-Saharan Africa have previously been linked with humidity, dust and rainfall (see Molesworth *et al*, 2003). Dione *et al* (2022) describes how the SWIFT partner, the African Centre of Meteorological Applications for Development (ACMAD), co-developed weekly meningitis bulletins with the regional African branch of the World Health Organisation, with the former generating early warning data from the S2S forecasts, while the latter provides feedback on both the assessment of meningitis climate risk factors and the coordinated responses of the affected countries. Crucially, the subsequent co-produced vigilance maps add two weeks' lead time to guide pre-outbreak decision makers in health sectors, which may prove crucial to the World Health Organisation's mission to defeat meningitis in Africa by 2030. Following the successes of SWIFT, Visman *et al* (2022) advocates for, and suggests pathways towards, co-production becoming institutionalised as a method for weather and climate service creation. Notably, the key suggestions in their white paper (i.e., formalisation of user-engagement in co-production and incentivisation for researchers) align with key feedback from the UoR Met internal workshop.

Unlike the other topics relevant to decision maker engagement discussed here, co-production was well represented across the submitted impact case studies for REF2021 (and will presumably be well represented in the REF2029 submission, especially in relation to SWIFT). Indeed, of the seven case studies, the only two submissions with arguably no form of co-production explicitly included were the "Communicating climate change through spirals and stripes visualisations and engaging a diverse global audience of millions" and "Research supporting the use of climate emission metrics in policymaking" case studies. The former case study refers to the generation of simple, unambiguous infographics able to effectively communicate the reality of post-industrial climate change across an inclusive and global audience. Even in this case, the project's subsequent creation of the 'ShowYourStripes' website, which allows users to produce similar regionally relevant infographics, could arguably be seen as a sort of open-ended contribution to co-production of climate education tools. The latter case study refers to both the contribution towards computation of necessary inputs for metrics of non-carbon dioxide greenhouse gas emissions (i.e., "Radiative Efficiency"), and the development of alternative metrics for the same purpose. While no co-production is evident, this project's importance to decision maker engagement, and showcasing of UoR Met's status as world-leading in this regard through its utilisation in multiple IPCC reports and multiple international treaties, is undeniable.

The five remaining impact case study submissions represent co-production of climate knowledge and services across humanitarian, urban planning, aviation, agriculture, energy and insurance sectors. In the case study: "Improved turbulence forecasts for the aviation sector", UoR Met scientists co-produced an improved clear-air turbulence forecasting algorithm with collaborators associated with the US National Weather Service, motivated by the financial costs, safety concerns and exacerbated environmental impact of atmospheric turbulence on air travel. Their co-developed "Lighthill–Ford algorithm" is now in operational usage in the US National Weather Service, and is widely used by private US forecasters, with the associated aviation weather forecasts being freely available via a federal government website. For the energy and insurance sectors, UoR Met scientists co-produced a new operational method to assess wave and wind risk with BP, for their North Sea and Caspian oil and gas platforms, based on climate model simulations and storm-tracking tools to assess wind and wave risk from extreme storms developed by UoR Met, as part of the "Improved assessment of extreme storm risk for the oil and gas and insurance sectors" case study. For urban planning, as part of the impact case study "Novel model improves Met Office urban weather forecasting and informs strategic planning for urban heatwaves and climate projections", co-produced research with the UK Met Office pertaining to heat exchange between buildings and atmosphere, has led to the development of the Met Office Reading Urban Surface Exchange Scheme (MORUSES), a model for the heat fluxes within 'street canyons', but with more flexibility for different building types than its contemporaries. This co-produced scheme was a necessary step towards the UK Met Office's aim of high-resolution urban climate forecasts by the end of the decade.

The two impact case study submissions representing co-production with agricultural and humanitarian sectors involved forecasting and monitoring of droughts and floods. Specifically, the "Drought monitoring and early warning for African food security using remote sensing of rainfall by the TAMSAT project" case study, which refers to a UoR Met developed satellite-based rainfall estimation and drought forecasting system for tropical agriculture with low ground rainfall data availability (Tropical Applications of Meteorology using SATellite data), has actively facilitated co-production of climate services with their users through several means. The TAMSAT software and datasets are open source and designed to be usable on low-specification hardware, and UoR Met scientists have facilitated workshops and delivered training courses throughout Africa. Subsequently, users in Africa have been able to develop their own TAMSAT-based climate services without being limited by technical prerequisites (e.g., Zambia's Weather-Index Insurance scheme). Moreover, as part of this project UoR Met scientists have offered internships and research supervision to many African nationals, many of whom would go on to hold senior positions in African national hydro-meteorological services. While the former impact case study has supported agriculture and humanitarian sectors through improved drought awareness, the impact case study "Strengthening the quality and use of flood forecasts to maximise effectiveness of humanitarian aid" has done so through improved flood awareness. Working with and based on the decision-making processes of the Red Cross Red Crescent movement (RCRC), UoR Met scientists developed new flood risk metrics ('Floodiness') to better inform forecast-based action and flood preparedness. Subsequently, the RCRC have moved incitement of their flood preparedness activities from being based on regional seasonal rainfall forecasts, to being based on incidence of flooding across river networks. Furthermore, working with the European Commission and the ECMWF, and acting as a mediary between developers and the humanitarian sector, UoR Met researchers made significant contributions to the development of the tool used to drive the floodiness calculations: the Global Flood Awareness System (GloFAS). Both of these case studies represent co-produced work by UoR Met that has benefited the lives and livelihoods of hundreds of thousands of people around the world and the Global South.

Co-production and participatory research themes were also well represented in the HAWC internal workshop. The speaker associated with the co-production of climate services summarised some of the work related to SWIFT, while the speaker associated with participatory research demonstrated the suite of opportunities through which UoR Met may contribute to 'decision focussed research', through interdisciplinary research between the leading applied environmental science departments hosted by UoR. A desire for better facilitation of further co-production was a shared sentiment among workshop participant responses. For example, almost every suggestion for improved financial and bureaucratic support for potential overseas PhD students (i.e., participatory research on an individual scale) was universally agreed upon, whereas the decision to impose the same costs to remote PhD students as in-person students, was universally condemned. Indeed, when participants recounted their experience of virtual decision maker engagement and online workshops during Covid-19 lockdowns, a common complaint was that while in some cases the nurturing of pre-pandemic relationships became simpler, the initial building of trust with new potential partners was significantly more difficult. Furthermore, participants commented on the proliferation of vocal non-authoritative voices (e.g., popular disinformation spreading social media accounts) which may obfuscate communication between genuine parties, and can make risk-mitigating strategies associated with participant selection more difficult. Comments regarding AI as a means of identifying co-production collaborators are also relevant here, as a potential tool to aid participant selection (e.g., using algorithms using stakeholder analysis techniques described in Reed, 2008). At the time of writing UoR Met is updating its Current Research Information System, which should expedite careful consideration of participants via the provision of a list of trusted potential partners, but may not influence any departmental culture change. Perhaps the most relevant workshop comment in the context of the risks associated with participatory research, is the expressed desire to see better incentivisation for researchers to use co-production approaches (professional and financial), which is also mirrored in Cvitanovic *et al* (2019) suggestions for re-imagined professional development and institutional support.

A final noteworthy commentary from participants of the workshop was the desire for 'co-production best practices guidelines'. This sentiment is echoed in Vincent *et al* (2018) who notes that the numerous initiatives attempting to co-produce climate services in developing countries are "largely not drawing on the long history and lessons learned from co-production in other fields". However, the material basis of a set co-production guidelines, by and for UoR Met, arguably already exists in the form of the aforementioned reflective co-production literature. A prudent subsequent action following this report and participant suggestions, may be synthesis of the advice provided by the reflective research, iterative consultation with UoR social scientists, then distillation into user-specific guidelines, in a process itself similar to co-production of knowledge.

References:

- Alcamo, J., 2008. Chapter six the SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. *Developments in integrated environmental assessment*, *2*, pp.123-150.
- Allan, R.P., Arias, P.A., Berger, S., Canadell, J.G., Cassou, C., Chen, D., Cherchi, A., Connors, S.L., Coppola, E., Cruz, F.A. and Diongue-Niang, A., 2023. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3-32). Cambridge University Press.
- Allen, M., 2003. Liability for climate change. *Nature*, *421*(6926), pp.891-892.
- Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.K., Rogelj, J. and Rojas, M., 2021. Technical summary.
- Arnal, L., Anspoks, L., Manson, S., Neumann, J., Norton, T., Stephens, E., Wolfenden, L. and Cloke, H.L., 2019. Are we talking just a bit of water out of bank? Or is it Armageddon? Front line perspectives on transitioning to probabilistic fluvial flood forecasts in England. *Geoscience Communication Discussions*, *2019*, pp.1-34.
- Arnal, L., Ramos, M.H., Coughlan de Perez, E., Cloke, H.L., Stephens, E., Wetterhall, F., van Andel, S.J. and Pappenberger, F., 2016. Willingness-to-pay for a probabilistic flood forecast: A risk-based decision-making game. *Hydrology and Earth System Sciences*, *20*(8), pp.3109-3128.
- Arnell, N.W., Lowe, J.A., Bernie, D., Nicholls, R.J., Brown, S., Challinor, A.J. and Osborn, T.J., 2019. The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios. *Environmental Research Letters*, *14*(8), p.084046.
- Baird, J., Plummer, R., Haug, C. and Huitema, D., 2014. Learning effects of interactive decision-making processes for climate change adaptation. *Global Environmental Change*, *27*, pp.51-63.
- Baldissera Pacchetti, M., Coulter, L., Dessai, S., Shepherd, T.G., Sillmann, J. and Van Den Hurk, B., 2023. Varieties of approaches to constructing physical climate storylines: A review. *Wiley Interdisciplinary Reviews: Climate Change*, p.e869.
- Bender, E.A., Case, T.J. and Gilpin, M.E., 1984. Perturbation experiments in community ecology: theory and practice. *Ecology*, *65*(1), pp.1-13.
- Bevacqua, E., Shepherd, T.G., Watson, P.A., Sparrow, S., Wallom, D. and Mitchell, D., 2021. Larger spatial footprint of wintertime total precipitation extremes in a warmer climate. *Geophysical Research Letters*, *48*(8), p.e2020GL091990.
- Bevacqua, E., Zappa, G. and Shepherd, T.G., 2020. Shorter cyclone clusters modulate changes in European wintertime precipitation extremes. *Environmental Research Letters*, *15*(12), p.124005.
- Black, E., Boult, V., Hirons, L. and Woolnough, S., 2024. The potential value of seasonal drought forecasts in the context of climate change: A case study of the African elephant conservation sector. *Meteorological Applications*, *31*(2), p.e2190.
- Bloomfield, H.C., Brayshaw, D.J., Troccoli, A., Goodess, C.M., De Felice, M., Dubus, L., Bett, P.E. and Saint-Drenan, Y.M., 2021. Quantifying the sensitivity of european power systems to energy scenarios and climate change projections. *Renewable Energy*, *164*, pp.1062-1075.
- Bloomfield, H.C., Gonzalez, P.L.M., Lundquist, J.K., Stoop, L.P., Browell, J., Dargaville, R., De Felice, M., Gruber, K., Hilbers, A., Kies, A. and Panteli, M., 2021. The importance of weather and climate to energy systems: a workshop on next generation challenges in energy–climate modeling. *Bulletin of the American Meteorological Society*, *102*(1), pp.E159-E167.
- Blythe, J., Nash, K., Yates, J. and Cumming, G., 2017. Feedbacks as a bridging concept for advancing transdisciplinary sustainability research. *Current Opinion in Environmental Sustainability*, *26*, pp.114-119.

- Bulgin, C.E., Mecking, J.V., Harvey, B.J., Jevrejeva, S., McCarroll, N.F., Merchant, C.J. and Sinha, B., 2023. Dynamic sea-level changes and potential implications for storm surges in the UK: a storylines perspective. *Environmental Research Letters*, *18*(4), p.044033.
- Caviedes-Voullième, D. and Shepherd, T.G., 2023. Climate storylines as a way of bridging the gap between information and decision-making in hydrological risk. *PLOS Climate*, *2*(8), p.e0000270.
- Chan, W.C., Arnell, N.W., Darch, G., Facer-Childs, K., Shepherd, T.G. and Tanguy, M., 2024. Added value of seasonal hindcasts to create UK hydrological drought storylines. *Natural Hazards and Earth System Sciences*, *24*(3), pp.1065-1078.
- Chan, W.C., Shepherd, T.G., Facer-Childs, K., Darch, G. and Arnell, N.W., 2022. Storylines of UK drought based on the 2010–2012 event. *Hydrology and Earth System Sciences*, *26*(7), pp.1755-1777.
- Chew, C., Lloyd, G.J. and Knudsen, E., 2013. An interactive capacity building experience–an approach with serious games. *Serious Games and Social Connect Conference, Singapore*.
- Cornforth, R., Parker, D.J., Diop-Kane, M., Fink, A.H., Lafore, J.P., Laing, A., Afiesimama, E., Caughey, J., Diongue-Niang, A., Kassimou, A. and Lamb, P., 2019. The First Forecasters' Handbook for West Africa. *Bulletin of the American Meteorological Society*, *100*(11), pp.2343-2351.
- Cvitanovic, C., Hobday, A.J., van Kerkhoff, L. and Marshall, N.A., 2015. Overcoming barriers to knowledge exchange for adaptive resource management; the perspectives of Australian marine scientists. *Marine policy*, *52*, pp.38-44.
- Cvitanovic, C., Howden, M., Colvin, R.M., Norström, A., Meadow, A.M. and Addison, P.F.E., 2019. Maximising the benefits of participatory climate adaptation research by understanding and managing the associated challenges and risks. *Environmental Science & Policy*, *94*, pp.20-31.
- Dasgupta, A., Arnal, L., Emerton, R., Harrigan, S., Matthews, G., Muhammad, A., O'Regan, K., Pérez-Ciria, T., Valdez, E., van Osnabrugge, B. and Werner, M., 2023. Connecting hydrological modelling and forecasting from global to local scales: Perspectives from an international joint virtual workshop. *Journal of Flood Risk Management*, p.e12880.
- Dasgupta, A., Arnal, L., Emerton, R., Harrigan, S., Matthews, G., Muhammad, A., O'Regan, K., Pérez-Ciria, T., Valdez, E., van Osnabrugge, B. and Werner, M., 2023. Connecting hydrological modelling and forecasting from global to local scales: Perspectives from an international joint virtual workshop. *Journal of Flood Risk Management*, p.e12880.
- de Suarez, J.M., Suarez, P., Bachofen, C., Fortugno, N., Goentzel, J., Gonçalves, P., Grist, N., Macklin, C., Pfeifer, K., Schweizer, S. and van Aalst, M., 2012. Games for a new climate: Experiencing the complexity of future risks. *Pardee Center Task Force Report*, pp.9-67.
- Dilling, L. and Lemos, M.C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global environmental change*, *21*(2), pp.680-689.
- Dione, C., Talib, J., Bwaka, A.M., Kamga, A.F., Fouda, A.A.B., Hirons, L., Latt, A., Thompson, E., Lingani, C., Indasi, V.S. and Adefisan, E.A., 2022. Improved sub-seasonal forecasts to support preparedness action for meningitis outbreak in Africa. *Climate Services*, *28*, p.100326.
- Doblas-Reyes, F.J., Sorensson, A.A., Almazroui, M., Dosio, A., Gutowski, W.J., Haarsma, R., Hamdi, R., Hewitson, B., Kwon, W.T., Lamptey, B.L. and Maraun, D., 2021. Linking global to regional climate change.
- Dong, B. and Sutton, R.T., 2021. Recent trends in summer atmospheric circulation in the North Atlantic/European region: is there a role for anthropogenic aerosols?. *Journal of Climate*, *34*(16), pp.6777-6795.
- Emerton, R., Cloke, H., Ficchi, A., Hawker, L., de Wit, S., Speight, L., Prudhomme, C., Rundell, P., West, R., Neal, J. and Cuna, J., 2020. Emergency flood bulletins for Cyclones Idai and Kenneth: A critical evaluation of the use of global flood forecasts for international

humanitarian preparedness and response. *International Journal of Disaster Risk Reduction*, *50*, p.101811.

- Few, R., Brown, K. and Tompkins, E.L., 2007. Public participation and climate change adaptation: avoiding the illusion of inclusion. *Climate policy*, *7*(1), pp.46-59.
- Flack, D.L., Skinner, C.J., Hawkness-Smith, L., O'Donnell, G., Thompson, R.J., Waller, J.A., Chen, A.S., Moloney, J., Largeron, C., Xia, X. and Blenkinsop, S., 2019. Recommendations for improving integration in national end-to-end flood forecasting systems: An overview of the FFIR (Flooding From Intense Rainfall) programme. *Water*, *11*(4), p.725.
- Fletcher, J.K., Diop, C.A., Adefisan, E., Ahiataku, M.A., Ansah, S.O., Birch, C.E., Burns, H.L., Clarke, S.J., Gacheru, J., James, T.D. and Tuikong, C.N., 2023. Tropical Africa's first testbed for high-impact weather forecasting and nowcasting. *Bulletin of the American Meteorological Society*, *104*(8), pp.E1409-E1425.
- Flood, S., Cradock-Henry, N.A., Blackett, P. and Edwards, P., 2018. Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. *Environmental Research Letters*, *13*(6), p.063005.
- Fløttum, K. and Gjerstad, Ø., 2017. Narratives in climate change discourse. *Wiley Interdisciplinary Reviews: Climate Change*, *8*(1), p.e429.
- Goodess, C.M., Troccoli, A., Acton, C., Añel, J.A., Bett, P.E., Brayshaw, D.J., De Felice, M., Dorling, S.R., Dubus, L., Penny, L. and Percy, B., 2019. Advancing climate services for the European renewable energy sector through capacity building and user engagement. *Climate services*, *16*, p.100139.
- Gudoshava, M., Wanzala, M., Thompson, E., Mwesigwa, J., Endris, H.S., Segele, Z., Hirons, L., Kipkogei, O., Mumbua, C., Njoka, W. and Baraibar, M., 2022. Application of real time S2S forecasts over Eastern Africa in the co-production of climate services. *Climate Services*, *27*, p.100319.
- Gupta, J., 2016. Climate change governance: history, future, and triple-loop learning?. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(2), pp.192-210.
- Hawkins, E., Compo, G.P. and Sardeshmukh, P.D., 2023. ESD Ideas: Translating historical extreme weather events into a warmer world. *Earth System Dynamics*, *14*(5), pp.1081-1084.
- Hirons, L., Thompson, E., Dione, C., Indasi, V.S., Kilavi, M., Nkiaka, E., Talib, J., Visman, E., Adefisan, E.A., de Andrade, F. and Ashong, J., 2021. Using co-production to improve the appropriate use of sub-seasonal forecasts in Africa. *Climate Services*, *23*, p.100246.
- Hirons, L., Wainwright, C.M., Nying'uro, P., Quaye, D., Ashong, J., Kiptum, C., Opoku, N.K., Thompson, E.M. and Lamptey, B., 2023. Experiences of co-producing sub-seasonal forecast products for agricultural application in Kenya and Ghana. *Weather*, *78*(5), pp.148-153.
- Hirons, L., Woolnough, S., Dione, C., Thompson, E., de Andrade, F., Talib, J., Konte, O., Diedhiou, T., Quaye, D., Opoku, N. and Lawal, K., 2021. GCRF African SWIFT White Paper Policy Brief. Exploiting Sub-seasonal Forecast Predictability in Africa: a key to sustainable development.
- James, R.A., Jones, R.G., Boyd, E., Young, H.R., Otto, F.E., Huggel, C. and Fuglestvedt, J.S., 2019. Attribution: how is it relevant for loss and damage policy and practice?. *Loss and damage from climate change: Concepts, methods and policy options*, pp.113-154.
- Kretschmer, M., Adams, S.V., Arribas, A., Prudden, R., Robinson, N., Saggioro, E. and Shepherd, T.G., 2021. Quantifying causal pathways of teleconnections. *Bulletin of the American Meteorological Society*, pp.1-34.
- Kumar, S., Kolassa, J., Reichle, R., Crow, W., de Lannoy, G., de Rosnay, P., MacBean, N., Girotto, M., Fox, A., Quaife, T. and Draper, C., 2022. An agenda for land data assimilation priorities: Realizing the promise of terrestrial water, energy, and vegetation observations from space. *Journal of Advances in Modeling Earth Systems*, *14*(11), p.e2022MS003259.

- Kunimitsu, T., Pacchetti, M.B., Ciullo, A., Sillmann, J., Shepherd, T.G., Taner, M.Ü. and van den Hurk, B., 2023. Representing storylines with causal networks to support decision making: Framework and example. *Climate Risk Management*, *40*, p.100496.
- Lamptey, B., SAHABI ABED, S., Gudoshava, M., Mutemi, J., Bopape, M.J., Adefisan, E.A., Igri, M.P., Seidou Sanda, I., Ndiaye, O., Parker, D.J. and Dougill, A.J., 2024. Challenges and ways forward for sustainable weather and climate services in Africa. *nature communications*, *15*(1), pp.1-4.
- Lawal, K.A., Olaniyan, E., Ishiyaku, I., Hirons, L.C., Thompson, E., Talib, J., Boult, V.L., Ogungbenro, S.B., Gbode, I.E., Ajayi, V.O. and Okogbue, E.C., 2021. Progress and challenges of demand-led co-produced sub-seasonal-to-seasonal (S2S) climate forecasts in Nigeria. *Frontiers in Climate*, *3*, p.712502.
- Lemos, M.C., Kirchhoff, C.J. and Ramprasad, V., 2012. Narrowing the climate information usability gap. *Nature climate change*, *2*(11), pp.789-794.
- Letson, F.W., Barthelmie, R.J., Hodges, K.I. and Pryor, S.C., 2021. Intense windstorms in the northeastern United States. *Natural Hazards and Earth System Sciences*, *21*(7), pp.2001-2020.
- Lloyd, E.A. and Shepherd, T.G., 2020. Environmental catastrophes, climate change, and attribution. *Annals of the New York Academy of Sciences*, *1469*(1), pp.105-124.
- Lloyd, E.A. and Shepherd, T.G., 2021. Climate change attribution and legal contexts: evidence and the role of storylines. *Climatic Change*, *167*(3), p.28.
- Lloyd, E.A. and Shepherd, T.G., 2023. Foundations of attribution in climate-change science. *Environmental Research: Climate*, *2*(3), p.035014.
- Martínez-Alvarado, O. and Sánchez, C., 2020. Examining model error in potential temperature and potential vorticity weather forecasts at different lead times. *Quarterly Journal of the Royal Meteorological Society*, *146*(728), pp.1264-1280.
- Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I. and Huang, M., 2021. Climate change 2021: the physical science basis. *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, *2*(1), p.2391.
- Matthews, G., Cloke, H.L., Dance, S.L., Hansford, E., Mazzetti, C. and Prudhomme, C., 2023. Co-design and co-production of flood forecast products: Summary of a hybrid workshop. *Bulletin of the American Meteorological Society*, *104*(5), pp.E1058-E1066.
- Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G. and Wall, T., 2015. Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society*, *7*(2), pp.179-191.
- Mechler, R., Calliari, E., Bouwer, L.M., Schinko, T., Surminski, S., Linnerooth-Bayer, J., Aerts, J., Botzen, W., Boyd, E., Deckard, N.D. and Fuglestvedt, J.S., 2019. Science for loss and damage. Findings and propositions. *Loss and damage from climate change: Concepts, methods and policy options*, pp.3-37.
- Mehring, P., Geoghegan, H., Cloke, H.L. and Clark, J.M., 2018. What is going wrong with community engagement? How flood communities and flood authorities construct engagement and partnership working. *Environmental science & policy*, *89*, pp.109-115.
- Mehring, P., Geoghegan, H., Cloke, H.L. and Clark, J.M., 2023. The F word: The experiential construction of flooding in England. *Emotion, Space and Society*, *48*, p.100966.
- Mindlin, J., Shepherd, T.G., Vera, C. and Osman, M., 2021. Combined effects of global warming and ozone depletion/recovery on Southern Hemisphere atmospheric circulation and regional precipitation. *Geophysical Research Letters*, *48*(12), p.e2021GL092568.
- Mindlin, J., Shepherd, T.G., Vera, C.S., Osman, M., Zappa, G., Lee, R.W. and Hodges, K.I., 2020. Storyline description of Southern Hemisphere midlatitude circulation and precipitation response to greenhouse gas forcing. *Climate Dynamics*, *54*, pp.4399-4421.

- Molesworth, A.M., Cuevas, L.E., Connor, S.J., Morse, A.P. and Thomson, M.C., 2003. Environmental risk and meningitis epidemics in Africa. *Emerging infectious diseases*, *9*(10), p.1287.
- Ommer, J., Blackburn, S., Kalas, M., Neumann, J. and Cloke, H.L., 2024. Risk social contracts: exploring responsibilities through the lens of citizens affected by flooding in Germany in 2021. *Progress in Disaster Science*, p.100315.
- Otto, F.E., Boyd, E., Jones, R.G., Cornforth, R.J., James, R., Parker, H.R. and Allen, M.R., 2015. Attribution of extreme weather events in Africa: a preliminary exploration of the science and policy implications. *Climatic Change*, *132*, pp.531-543.
- Parker, D.J., Blyth, A.M., Woolnough, S.J., Dougill, A.J., Bain, C.L., de Coning, E., Diop-Kane, M., Kamga Foamouhoue, A., Lamptey, B., Ndiaye, O. and Ruti, P., 2022. The African SWIFT project: growing science capability to bring about a revolution in weather prediction. *Bulletin of the American Meteorological Society*, *103*(2), pp.E349-E369.
- Parker, H.R., Cornforth, R.J., Suarez, P., Allen, M.R., Boyd, E., James, R., Jones, R.G., Otto, F.E. and Walton, P., 2016. Using a game to engage stakeholders in extreme event attribution science. *International Journal of Disaster Risk Science*, *7*, pp.353-365.
- Pascal, I.M., Jores, T.K., Talib, J., Appolinaire, V.D., Hirons, L., Christian, N., Romeo-Ledoux, D.T., Michael, T.F., Marceline, M., Roméo, S.T. and Dione, C., 2023. Strengthening weather forecast and dissemination capabilities in Central Africa: Case assessment of intense flooding in January 2020. *Climate Services*, *32*, p.100411.
- Plumpton, H. and Cornforth, R., 2020. BRAVE: building understanding of climate variability into planning of groundwater supplies from low storage aquifers in Africa.
- Ranasinghe, R., 2022. Climate science: a summary for actuaries-What the IPCC climate change report 2021 means for the actuarial profession.
- Ranasinghe, R., Ruane, A.C., Vautard, R., Arnell, N., Coppola, E., Cruz, F.A., Dessai, S., Saiful Islam, A.K.M., Rahimi, M., Carrascal, D.R. and Sillmann, J., 2021. Climate change information for regional impact and for risk assessment.
- Reckien, D. and Eisenack, K., 2013. Climate change gaming on board and screen: A review. *Simulation & Gaming*, *44*(2-3), pp.253-271.
- Redelsperger, J.L., Thorncroft, C.D., Diedhiou, A., Lebel, T., Parker, D.J. and Polcher, J., 2006. African Monsoon Multidisciplinary Analysis: An international research project and field campaign. *Bulletin of the American Meteorological Society*, *87*(12), pp.1739-1746.
- Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. *Biological conservation*, *141*(10), pp.2417-2431.
- Reed, M.S., Vella, S., Challies, E., De Vente, J., Frewer, L., Hohenwallner-Ries, D., Huber, T., Neumann, R.K., Oughton, E.A., Sidoli del Ceno, J. and Van Delden, H., 2018. A theory of participation: what makes stakeholder and public engagement in environmental management work?. *Restoration ecology*, *26*, pp.S7-S17.
- Rodrigues, R.R. and Shepherd, T.G., 2022. Small is beautiful: climate-change science as if people mattered. *PNAS nexus*, *1*(1), p.pgac009.
- Rother, H.A., Dove, C.M., Cornforth, R., Petty, C., Euripidou, R., Irlam, J., Gikungu, D., Chivese, T., Kutane, W., Jourou, A. and van Bavel, B., 2023. ‘Q-Storming’to identify challenges and opportunities for integrating health and climate adaptation measures in Africa. *The Journal of Climate Change and Health*, p.100254.
- Ruane, A.C., Vautard, R., Ranasinghe, R., Sillmann, J., Coppola, E., Arnell, N., Cruz, F.A., Dessai, S., Iles, C.E., Islam, A.S. and Jones, R.G., 2022. The climatic impact-driver framework for assessment of risk-relevant climate information. *Earth's Future*, *10*(11), p.e2022EF002803.
- Runhaar, H., Wilk, B., Persson, Å., Uittenbroek, C. and Wamsler, C., 2018. Mainstreaming climate adaptation: taking stock about “what works” from empirical research worldwide. *Regional environmental change*, *18*, pp.1201-1210.

- Savelli, E., Rusca, M., Cloke, H., Flügel, T.J., Karriem, A. and Di Baldassarre, G., 2022. All dried up: The materiality of drought in Ladismith, South Africa. *Environment and Planning E: Nature and Space*, p.25148486221126617.
- Schäfler, A., Craig, G., Wernli, H., Arbogast, P., Doyle, J.D., McTaggart-Cowan, R., Methven, J., Rivière, G., Ament, F., Boettcher, M. and Bramberger, M., 2018. The North Atlantic waveguide and downstream impact experiment. *Bulletin of the American Meteorological Society*, *99*(8), pp.1607-1637.
- Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A.D., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S. and Otto, F., 2021. Weather and climate extreme events in a changing climate.
- Shepherd, T.G. and Lloyd, E.A., 2021. Meaningful climate science. *Climatic Change*, *169*(1), p.17.
- Shepherd, T.G. and Truong, H.C., 2023. Storylining Climes. In *Storying Multipolar Climes of the Himalaya, Andes and Arctic*. Taylor & Francis.
- Shepherd, T.G., 2019. Storyline approach to the construction of regional climate change information. *Proceedings of the Royal Society A*, *475*(2225), p.20190013.
- Shepherd, T.G., 2021. Bringing physical reasoning into statistical practice in climate-change science. *Climatic Change*, *169*(1-2), p.2.
- Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Fowler, H.J., James, R., Maraun, D., Martius, O. and Senior, C.A., 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic change*, *151*, pp.555-571.
- Sillmann, J., Shepherd, T.G., Van Den Hurk, B., Hazeleger, W., Martius, O., Slingo, J. and Zscheischler, J., 2021. Event-based storylines to address climate risk. *Earth's Future*, *9*(2), p.e2020EF001783.
- Skinner, C., 2018. Riding the (flood) wave: The Flash Flood! desktop application. *Teaching Geography*, *43*(1), pp.28-31.
- Stephens, E.M., Spiegelhalter, D.J., Mylne, K. and Harrison, M., 2019. The Met Office Weather Game: investigating how different methods for presenting probabilistic weather forecasts influence decision-making. *Geoscience Communication*, *2*(2), pp.101-116.
- Stott, P.A., Allen, M., Christidis, N., Dole, R.M., Hoerling, M., Huntingford, C., Pall, P., Perlwitz, J. and Stone, D., 2013. Attribution of weather and climate-related events. *Climate science for serving society: research, modeling and prediction priorities*, pp.307-337.
- Suarez, P., Otto, F.E., Kalra, N., Bachofen, C., Gordon, E. and Mudenda, W., Loss and damage in a changing climate.
- Sutton, R.T., 2018. ESD Ideas: a simple proposal to improve the contribution of IPCC WGI to the assessment and communication of climate change risks. *Earth System Dynamics*, *9*(4), pp.1155-1158.
- Trancoso, R., Syktus, J., Allan, R.P., Croke, J., Hoegh-Guldberg, O. and Chadwick, R., 2024. Significantly wetter or drier future conditions for one to two thirds of the world's population. *Nature Communications*, *15*(1), p.483.
- van den Hurk, B.J., Pacchetti, M.B., Boere, E., Ciullo, A., Coulter, L., Dessai, S., Ercin, E., Goulart, H.M., Hamed, R., Hochrainer-Stigler, S. and Koks, E., 2023. Climate impact storylines for assessing socio-economic responses to remote events. *Climate Risk Management*, *40*, p.100500.
- Vincent, K., Daly, M., Scannell, C. and Leathes, B., 2018. What can climate services learn from theory and practice of co-production?. *Climate Services*, *12*, pp.48-58.
- Visman, E., Hirons, L., Todd, M., Mwangi, E., Dione, C., Gudoshava, M., Otieno, G., Ahiataku, M., Quaye, D., Lawal, K. and Talib, J., 2022. Institutionalising co-production of weather and climate services: Learning from the African SWIFT and ForPAc projects.

- Vogel, P., Knippertz, P., Fink, A.H., Schlueter, A. and Gneiting, T., 2018. Skill of global raw and postprocessed ensemble predictions of rainfall over northern tropical Africa. *Weather and Forecasting*, *33*(2), pp.369-388.
- Wood, R.A., Crucifix, M., Lenton, T.M., Mach, K.J., Moore, C., New, M., Sharpe, S., Stocker, T.F. and Sutton, R.T., 2023. A climate science toolkit for high impact-low likelihood climate risks. *Earth's future*, *11*(4), p.e2022EF003369.
- Young, H.R., Cornforth, R.J., Gaye, A.T. and Boyd, E., 2019. Event Attribution science in adaptation decision-making: the context of extreme rainfall in urban Senegal. *Climate and development*, *11*(9), pp.812-824.
- Young, H.R., Cornforth, R.J., Todman, L.C., Miret Barrio, J.A., Shepherd, T.G., Petty, C., O'Sullivan, D., Wagstaff, C., Mason, O. and Talwisa, M., 2020. Assessing the impact of climate change on sweet potato in Uganda.
- Young, H.R., Shepherd, T.G., Acidri, J., Cornforth, R.J., Petty, C., Seaman, J. and Todman, L.C., 2021. Storylines for decision-making: climate and food security in Namibia. *Climate and Development*, *13*(6), pp.515-528.
- Yü, D.S. and Wouters, J.J. eds., 2023. *Storying Multipolar Climes of the Himalaya, Andes and Arctic: Anthropocenic Climate and Shapeshifting Watery Lifeworlds*. Taylor & Francis.
- Zappa, G., 2019. Regional climate impacts of future changes in the mid–latitude atmospheric circulation: a storyline view. *Current Climate Change Reports*, *5*, pp.358-371.
- Zappa, G., Bevacqua, E. and Shepherd, T.G., 2021. Communicating potentially large but non-robust changes in multi-model projections of future climate. *International Journal of Climatology*, *41*(6), pp.3657-3669.