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Towards an IPCC Atlas for comprehensive climate change risk assessments

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Climate risk assessments are crucial in quantifying and communicating risks in a clear and concise manner. In light of the rapidly proceeding climatic changes, there is a growing need for a more comprehensive integration and a more effective overview of available and relevant data that go into these assessments, particularly on the temporal and spatial dynamics of risk. In this paper, we describe the advantages, challenges and opportunities for increasing the accessibility of temporal and spatial data needed to support climate risk assessments through the development of an Intergovernmental Panel on Climate Change (IPCC) Atlas, integrated across IPCC Working Groups. We propose that using a climate risk framework to organise this Atlas will result in a more practical resource for understanding and informing risk assessments undertaken by the IPCC, and also make methodologies and results more accessible to a wider audience.

The accelerating pace of climate change is increasing the demand for tools that help people understand and access data to better inform decision-making processes, particularly on the temporal and spatial dynamics of risk[1–4]. Being made aware of increasing risks associated with climate change should be a key motivation for decision-makers and each individual member of society to take appropriate action to counter risk increments and minimise any impacts and associated losses and damages caused by climate change. Target audiences for such climate risk assessments include virtually everybody from all elements of society. Climate risk assessments especially concern the communities and regions most vulnerable to the adverse impacts of climate change and the national and international authorities that can help alleviate risks.

Climate risk assessments, such as those undertaken by the Intergovernmental Panel on Climate Change (IPCC) (Risk is defined in the IPCC Sixth Assessment Report (AR6) as "The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change"[5].), are crucial in quantifying and communicating risks in a clear and concise manner that facilitates public debate, policy making and the urgent implementation of solutions in the realms of climate change mitigation and adaptation. In the last few years, standardised methods are resulting in more robust and comparable assessments[2,6,7]. In addition, the dynamic nature of risk has been better reflected through advancements in its conceptualization with a recognition that increasing risks can arise both from potential impacts due to climate change and from human adaptation and mitigation responses to climate change (In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with, or negative side-effects on, other societal objectives, such as the Sustainable Development Goals (SDGs). Risks can arise for example from uncertainty in the implementation, effectiveness or outcomes of climate policy, climate-related investments, technology development or adoption, and system transitions[5].)[1,2]. For instance, risk can increase through negative side-effects, lack of understanding of risk leading to maladaptation, or through interactions with other drivers of risk increasing vulnerability and/or exposure[8].

At the same time, the accessibility of temporal and spatial data needed to support climate risk assessments has increased significantly with the emergence of climate information services for many regions and sectors in recent years[9]. These services offer non-expert users the ability to navigate through user-friendly platforms and access data in pre-processed, usable, and accessible formats, which is a significant improvement over the original raw data formats that require programming skills. Climate information services typically consist of interactive web portals that provide visual information for a specific geographic location, such as a country, region, geography, or the entire world. Many of these portals often offer the ability to zoom in on specific areas and are commonly referred to as "Atlases."

The IPCC made significant progress in advancing integrated and cross working-group risk assessments during its AR6 cycle (2016–2023)[1]. In addition, more accurate and accessible climate- and risk-related data was provided through the Atlases of Working Groups (WG) I and II. WGII (*Impacts, Adaptation and Vulnerability*) for the first time delivered a Global to Regional Atlas as an Annex in the main Assessment Report in pdf and print formats[10]. Despite the limitation of not having dedicated resources, this annex serves as a visual communication tool to support the report's key findings. It pulls together topical information from sections of the report and provides a comparative overview across regions. The WGII Global to Regional Atlas also brings together diverse datasets from different

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disciplines to provide information related to decision-making. Relevant disciplinary information includes the physical sciences of climate phenomena affecting life on earth, life sciences such as biodiversity, agriculture and fisheries, health including planetary health, i.e. the health of humans, species and ecosystems, the vulnerability of ecosystems and human societies, and social sciences addressing aspects of sustainability and development. By doing so, it enhanced coordination among WGII chapters and across the three IPCC Working Groups with respect to regionalisations, metrics, scenarios, and temporal scales.

A parallel and notable achievement during the AR6 was the creation of the WGI (*The Physical Science Basis*) Interactive Atlas[11]; an online climate information service that provides temporal and spatial climate data. This tool was developed with the help and resources of external partnerships and dedicated chapter teams. The WGI Atlas interface was made public with the publication of the WGI assessment report in 2021 and it allows external users to explore and download data and findings in greater detail at spatial and temporal scales most relevant to their interests. During the development of the AR6 reports, early access to the interactive atlas for IPCC authors allowed WGII and WGIII (*Mitigation of Climate Change*) authors to generate results on climate hazards for their assessments. Early access also enabled author teams to coordinate efforts across Working Groups. For WGII, the WGI Interactive Atlas was a key source of climate hazard information for risk assessments. However, the diversity of information and approaches included in WGII assessments prevented the comprehensive development of quantified links from WGII to the climate information provided by WGI. We envision this to be a potential next step in the maturation of spatial and temporal approaches to risk.

Building on the experience with Atlases in AR6, our suggestion for the Seventh Assessment Report cycle (AR7) is to create a user-friendly tool that complements climate risk assessments bringing together data across all three IPCC Working Groups, from information on climate to that on impacts and responses. This tool should provide a structured and differentiated look at risk and its determinant factors considering temporal and spatial dynamics, and using data-driven models that go beyond just empirical relationships. It should also build on the mechanism-based quantified understanding of the links between climate and its impacts. We describe below the advantages of using a climate risk framework for Atlas structuring, and the challenges and opportunities for an integrated cross-Working Group IPCC atlas.

Climate risk framing as an Atlas structure

An integrated cross-Working Group IPCC Atlas should bring together lines of evidence from across the three Working Groups on the changing climate system, impacts, and risks as well as risk reduction by effective adaptation and mitigation responses, using the IPCC risk framework as a guiding principle. As a first step towards this goal, the AR6 WGII Global to Regional Atlas aimed to provide structured and differentiated information on risk and its components to help understand and communicate climate policy issues. However, it is important to note that the collection of data for the WGII atlas was not intended to be comprehensive due to resource and data limitations at the time. Examples where a complete set of differentiated spatial data was available at global level can be seen in the drought and flooding risk maps in the AR6 WGII Atlas (Fig. 1). Likewise, the IPCC AR6 Synthesis Report[12] provides an illustrative example of combined content featuring data on changes in climatic extremes (hazards) from WGI together with observed impacts from WGII (i.e. realized risks) and national population vulnerability with greenhouse emissions per capita from WGIII (see www.ipcc.ch/report/ar6/syr/figures/figure-2-3). It thereby provides a more comprehensive narrative. However, the depiction is divided into WG subpanels rather than integrated. The diversification of primary data sources into an IPCC Atlas could enhance the opportunities of more complete and integrated sets featured in AR7 and beyond.

During the AR6, the WGII updated the risk framework to include a fourth determinant that considers responses to climate change as a key avenue to reduce risk as well as a source of risk itself[13]. Responses include a range of adaptation and mitigation options including Carbon Dioxide Removal and solar radiation modification approaches. For example, the deployment of land-based mitigation measures such as bioenergy crops, solar parks (farms) or afforestation at scale can displace other land uses and increase risks related to increased greenhouse gas emissions, land degradation, water availability and food insecurity depending on the locality and context. The discourse around solar radiation modification and its potential to introduce a wide range of new, unevenly distributed and poorly understood risks underscores the importance of integrating responses into climate change risk assessments. The inclusion of response information in risk assessments (Fig. 1) will advance as the understanding of the interconnections among drivers of risk and the broader consequences of responses to climate change emerge but at present remains as a data gap.

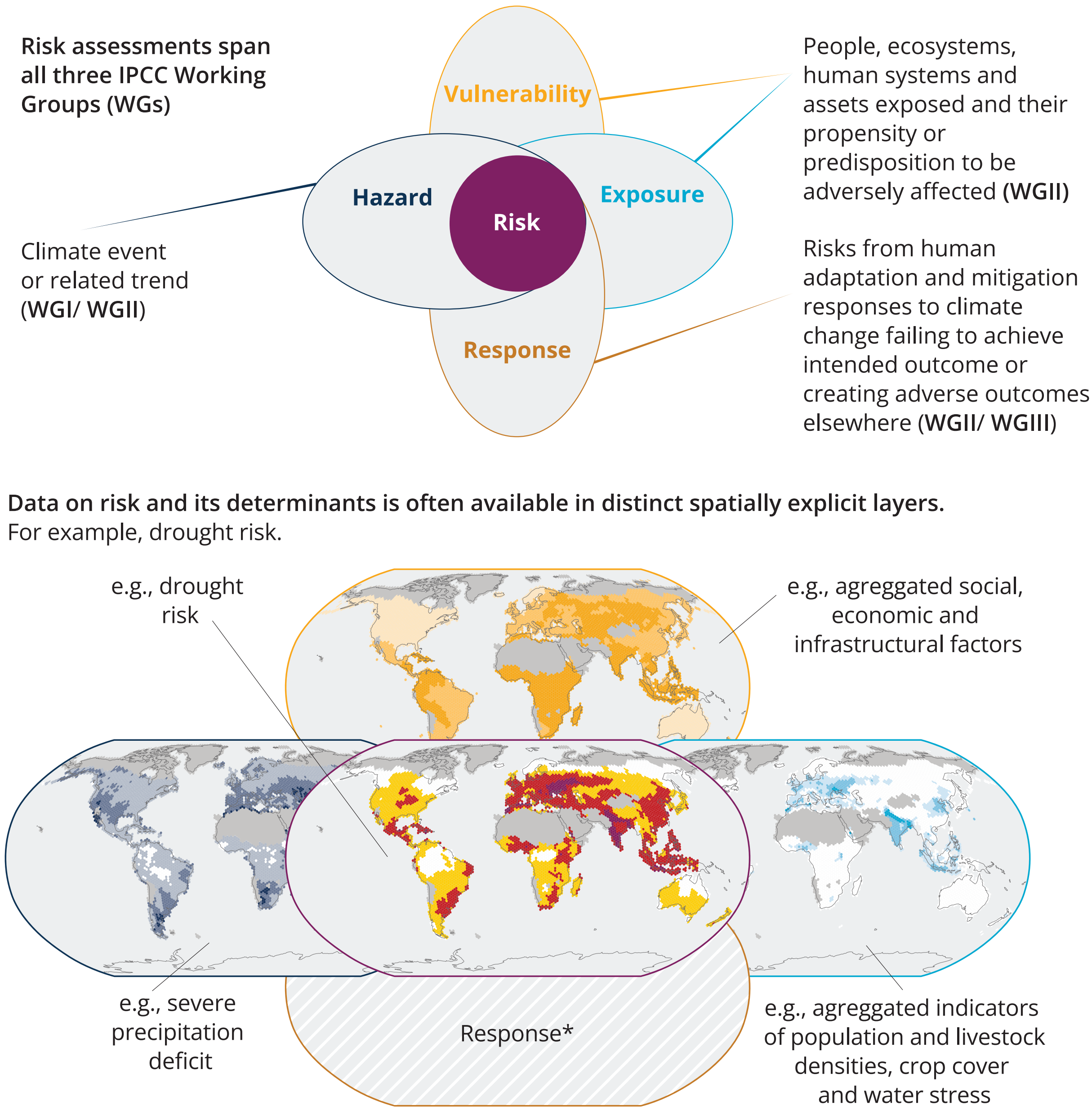
The way forward

The AR6 version of the WGI Interactive Atlas achieved a comprehensive depiction of climate hazard information from a range of different datasets, including the three most recent coordinated global and regional climate projection experiments: CMIP5, CORDEX and CMIP6[11]. With this precedent, and with the expected alignment of the upcoming CMIP7 experiments with the IPCC AR7 cycle, the potential exists for a successful update for WGI. However, a key advance would be an integrated, interactive cross-Working Group IPCC Atlas to support AR7 risk assessments and provide key information for policies addressing climate change. A base step for achieving this is for WGII and WGIII to explore partnerships with providers of relevant data including and beyond those available from the scientific literature. For example, the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; see www.isimip.org/) could become a primary source for data derived from global climate impact models on key WGII-relevant sectors such as health, water, forests, agriculture, and fisheries. Another example applied to Ocean data is Bio-ORACLE (see bio-oracle.org). Bio-ORACLE offers observed and projected physical, chemical, biological and topographic data layers for surface and benthic marine realms up to global scales[14]. The WGII AR6 sourced data ad hoc from both these projects, however, a more structured interaction such as for WGI with CMIP and CORDEX would increase alignment. Publicly available Atlases that have successfully incorporated diverse data sources to support a climate risk framework structure are already available at regional scales and could inform IPCC AR7 risk assessments. For example, the Atlas of Climate Risks for Chile (ARClim, see arclim.mma.gob.cl) is an online platform built by the Center for Climate and Resilience Research (CR2) and the Center for Global Change (CCG-Universidad Católica de Chile), and is presented as a collection of maps organised in sectors (e.g., agriculture, human health, tourism, electric power, biodiversity). The sectoral data are differentiated into risks and their components, namely hazards, exposures and vulnerabilities of each corresponding system with maps at national and subnational levels. The Agricultural Model Intercomparison and Improvement Project (AgMIP) Impacts Explorer (see agmipimpactsexplorer.wenr.wur.nl/ and agmip.org/impacts-explorer-2/) is another example and provides global maps of crop yield changes under specific climatic conditions, with a regional focus on Africa and South Asia. Similarly, the Agriculture Adaptation Atlas (see adaptationatlas.cgiar.org) built by the Consortium of International Agricultural Research Centers (CGIAR) also focuses on the African continent. Here, users can evaluate different climate hazards (e.g. heat, drought, flooding), exposure of different types of crops, livestock and population (rural and urban), their vulnerability (e.g. health facility access, wealth) and associated risks in different parts of Africa and then estimate the potential impacts and identify response options.

A challenge for an IPCC Atlas is to capture the complexities that arise from compound, cascading and transboundary interactions of the drivers of risk determinants which can give rise to new and unexpected risks and constrain adaptation options. For example, national border policies can influence international migration flows and the exposure and vulnerability of people to climate change impacts. Restrictive cross-border policies can trap populations in higher-risk areas[15]. Biodiversity losses can cascade to

a. The Risk Framework can be an effective way to present a comprehensive IPCC Atlas.
Risk is determined by interactions among hazard, vulnerability, exposure and responses to risk.

b. Data on risk and its determinants is often available in distinct spatially explicit layers.
For example, drought risk.



* Although limited availability of data hindered the inclusion of the response determinant in the risk framework for the IPCC sixth assessment, it remains an opportunity for the next assessment cycle.

Fig. 1 | The risk framework as a conceptual basis of an IPCC atlas. a The risk framework combines information on climatic factors, vulnerability and exposure and responses to climate change from the three IPCC working groups. **b** The example illustrates which factors shape drought risk and how they are considered in the risk assessment. Risks are also shaped by responses to climate change and their interactions. Drought risk maps from Caretta, M.A. et al. Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, 10.1017/9781009325844.006 (Cambridge University Press, 2022).

impacts and losses in food and water security, health and wellbeing, livelihoods and cultural and linguistic diversity[5]. While an IPCC Atlas ultimately wants to provide quantifiable determinants of risk, risk assessment includes evaluations of vulnerability and may therefore need to capture the more abstract determinants of vulnerability and resilience e.g. Indigenous knowledge systems, cultural heritage, spiritual values, social bonds, intangible ecosystem services. This requires developing robust, sometimes indirect indicators where possible.

Data challenges and opportunities for an integrated cross-Working Group IPCC Atlas

The integration of datasets across different Working Groups poses a significant challenge due to the heterogeneous nature of the formats in which these datasets are available. Each Working Group relies on specific types of data, often collected and structured differently, making it difficult to seamlessly integrate and analyse them collectively.

For example, spatial data on observed climate hazards is commonly derived from remote sensing technologies, such as satellite imagery. This type of data is usually presented in a gridded format, meaning the information is organised into a matrix of cells, each representing a specific geographic area. Gridded data is highly detailed, allowing for precise mapping and analysis at a granular level, often 1 to 30 m/pixel. However, this fine level of detail contrasts with the broader geographic scopes typically used in risk and impact data related to social and natural systems, such as the vulnerability of populations to climate change or the resilience of ecosystems. These are typically gathered and reported at non-gridded national or subnational levels. These datasets are generally less detailed and more aggregated compared to gridded climate data. The discrepancy in the level of detail makes it difficult to integrate this risk and impact data with gridded climate data, hindering efforts to analyse them collectively.

To overcome these integration challenges and enhance the potential for cross-Working Group data analysis, it is crucial to undertake a timely and thorough review of potential data sources and providers, including those mentioned in the previous section, for example. This review would aim to identify additional datasets that could bridge the gaps between different data formats and spatial resolutions, facilitating a more coherent and unified approach to data integration.

Another significant challenge arises from inequities in research funding and programmes among countries and regions[16,17]. These disparities often result in uneven data availability, with some regions and sectors being underrepresented in the global dataset. This lack of comprehensive regional and sectoral data further complicates the integration process. Datasets collected at a country level can pose an additional political challenge for the IPCC assessments. However, understanding of differential vulnerability often comes from economic, institutional and social data collected at national, sub-national and smaller scales. For example, the AR6 WGII assessment combined the INFORM Risk Index[18] and the World Risk Index[19] based on national level indicators, to produce a global map of vulnerability (refer to fig. 7.2 in ref. 20). This map was deleted from the WGII Summary for Policymakers draft as "Many countries found the figure problematic for its nationally averaging approach and what they considered a misleading representation of their country's vulnerability"[21]. Ultimately, such maps are intended to provide contextual understanding and initiate evidence-driven action. The resulting map provides context to the global problem and as such, it formed part of the narrative for WGII Technical Summary[5] and Chapter 7[20]. This case highlights that providing clear information on the selection, limitations, and advantages of the data is important for decision-making and for a useful atlas.

While the IPCC AR6 made advances in the use of common climate dimensions across WGs for scenarios, global warming levels, time periods, and levels of other variables for consistency and comparability of data[22], this is not always the case in the scientific and technical literature on which assessments are based. For example, there is a lag between the publication of climatic data sets, e.g., CMIP, and their use and publication in impacts and adaptation research[23]. The use of different models and/or climate dimensions including different variables makes the integration and coherent visualisation of data much more difficult. Focus on an integrated Atlas early in the cycle, e.g. starting with the Special Report on Cities due in 2027, could provide stimulus to the relevant research communities as well as setting the parameters for cross Working Group integration of risk assessments.

Conclusions

Considering the progress achieved in AR6, the diversity of data sources available and the benchmark of risk-structured atlases, an integrated, interactive cross-Working Group IPCC Atlas could be developed to provide a more comprehensive and complete picture of climate-related risks and its determinant factors in AR7. In any case, such endeavour would be better served with a proper allocation of resources, and author team as was the case with WGI in AR6. Such an IPCC Atlas may not be comprehensive from the start due to challenges attributed to the integration of diverse datasets and those arising from data gaps across regional and sectors, but it could grow over time. In addition, it will present a quantified understanding of risk noting that intangible dimensions of risk will be challenging to portray.

Although the primary target audience of IPCC reports are policymakers and their advisors at all levels of government[24], the IPCC is often criticised for the inaccessibility of its reports to a non-expert audience. An integrated Atlas focusing on risks and their determinant factors would provide information in a more understandable way and facilitate the communication of complex cause-and-effect chains. However, such an Atlas relies on the provision of data and their coherent interpretation while, at present, global inequalities in climate change-related research funding and focus exist - particularly for regions most vulnerable to climate change. Addressing these challenges will require not only technical solutions for data integration but also a concerted effort by funders and governments to promote equitable research funding and data collection initiatives across all regions and sectors.

Incorporating risks within the IPCC risk assessment framework that arise from potentially misled adaptation and mitigation responses will provide insight on potential tradeoffs as climate policies are increasingly implemented across sectors and regions. As a corollary, with the AR7 underway, opportunities exist to establish the foundations of an IPCC AR7 Atlas, and its first elements through the Special Report on Cities being developed under the joint scientific leadership of all three Working Groups. The publication of an integrated cross-Working Group IPCC atlas structured on a climate risk framework will result in a more accessible and useful product for communication of IPCC findings to a growing set of users, including practitioners, business people, the research community, civil society and the media.

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