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INTRODUCTION

Editorial Introduction to the Topical Collection: *Accrual of Climate Change Risk in Six Vulnerable Countries*

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Climate change risk assessment is a major topic of current research, with an increasing number of publications appearing annually that project changes in indicators of climate risk to particular sectors of the economy or elements of the natural world, at a wide range of scales ranging from global to local. The increase in risk-related research is also aligned with the need created by the Paris Agreement (PA) (UNFCCC 2015), which aims to constrain global temperature rise to 'well below 2 °C' and to 'pursue efforts' to limit this warming to 1.5 °C above pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) highlighted the need for more research aligned to the PA and the related risks in its Special Report on the 1.5 °C of global warming (IPCC 2018).

However, typically, each study utilises its own selected climate change and socioeconomic scenarios to describe the future. It may apply its own selected method of downscaling socioeconomic and/or climate change scenarios to the appropriate scale for the assessment in question, and may, or may not, encapsulate the implications of uncertainties in regional climate projection. Finally, risks are usually projected using a single model that is deemed most appropriate for the risk in question, and such models may be either process-based or empirical. Owing to the diversity of approaches, the research community organised model inter-comparison projects (MIPS) in order to assess global-scale indicators of various climate-related risks in a consistent manner. These include AgMIP (Rosenzweig et al. 2013), WaterMIP (Haddeland et al. 2014), and ISIMIP (Frieler et al. 2017), which conduct regular organised harmonised assessments of future risk which have standard procedures for exploration of uncertainties associated with climate projections. However, at the national scale, countries tend to conduct their own independent risk assessments (e.g.,

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US Fourth National Assessment USGCRP, (2018); UK CCRA2 - Committee on Climate Change (2016), using widely different sets of scenarios and modelling approaches, making replication or comparison between risks in different countries difficult.

This Topical Collection addresses this research gap in assessing climate change risks in a consistent fashion across countries, yet at the national (not global) scale. It publishes the outputs of a new research programme designed to fill knowledge gaps related to the consistent and harmonised projection of the future risks associated with global warming levels from 1.5 to 4 °C in six illustrative nations. The risks assessed are the additional risks due to anthropogenic climate change corresponding to these elevated levels of global warming in comparison with a baseline of levels of risk in 1961–1990 when levels of global warming were approximately 0.3 °C above pre-industrial levels.

The research underpinning the Collection received its primary funding from the UK Government, Department for Business, Energy and Industrial Strategy, as part of the 1.5–4 °C warming project under contract number UKSBS CR18083-S2. The research programme was led and coordinated by Prof. Rachel Warren at the Tyndall Centre headquarters at the University of East Anglia, to which many of the lead authors of the published papers are also affiliated. The Guest Editors are affiliated with the Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon.

The knowledge gaps that the Topical Collection covers relate to three key elements: (a) assessing risks consistently for a range of policy-relevant levels of global warming, (b) doing so consistently across a range of six illustrative developing countries across three continents, (c) assessing the economic and societal implications for these countries. The Collection focuses on changes in exposure to climate hazards such as drought, water stress, fluvial and coastal flooding, and also quantifies projected changes in crop yields and effects of climate change on biodiversity. It also assesses regional economic implications and risks to natural capital. Risk results from the exposure of a vulnerable system to a change in climate hazard such as flooding or drough. In this Topical Collection, as in much of the literature pertaining to climate change risk assessment, changes in exposure to climate risk are quantified and used as an indicator of changing risk, since a detailed analysis of vulnerability of specific human and natural systems, or the potential for them to adapt to risk, is limited by the availability of information, data and the scope of the research.

Relevant levels of global warming The Paris Climate Agreement relies on mitigation policies at the national level (or below) to achieve its targets—requesting countries to report their contributions in the form of Nationally Determined Contributions (NDCs) (UNFCCC 2022). Currently, such pledges are sufficient only to limit warming of between 2.5 °C above pre-industrial levels (full range, 2–3 °C, Climate Action Tracker (2023)). This means that there is still a range of possible temperature outcomes for 2100, ranging from about 3–4 °C in the absence of climate policy all the way to possibly 1.5–2 °C in the case of full implementation of the Paris Climate Agreement. Hence, the research reported here explores global warming of between 1.5 and 4 °C above pre-industrial levels.

Global context To set the global context, Warren et al. (2021) quantify global and regional aggregate damages from global warming of 1.5 to 4 °C above pre-industrial levels using a well-established integrated assessment model, PAGE09. It also provides a detailed account of the design and origin of the harmonised global climate change and socioeconomic scenarios used to analyse climate change risks in the six countries throughout the Collection. Global population is assumed to remain constant or to grow (from 8 billion today) to 9.2 billion by

2100. The vulnerability of human and natural systems is assumed to remain constant. Adaptation to climate change is not included in these risk assessments, rather the risk assessments might inform decisions about how much invest in adaptation in the various countries.

Warren et al. (2021) estimate that global aggregate damages in 2100 of 0.29% (0.09–0.6%) of GDP emerge if global warming is limited to about 1.5 °C (0.09–0.60%) compared with 0.40% for 2 °C (0.12–0.91%). These are, respectively, 92% and 89% lower than mean losses of 3.67% of GDP (0.64–10.77%) associated with global warming of 4 °C. This leads to a mean social cost of CO2 emitted in 2020 of ~ $150 for 4 °C warming compared to $30 at ~ 1.5 °C warming. The benefits of limiting warming to 1.5 °C rather than 2 °C might be underestimated since PAGE09 is not recalibrated to reflect the recent understanding of the full range of risks at 1.5 °C warming.

The economic literature relating to climate change damages focuses largely on global scale simulations. Yet, decision-makers are often interested in implications for their own countries, to inform national policy and action. New research methods are enabling the simulation of economic impacts at the country level. Here, both global and country-specific damage assessments are provided. Therefore, a detailed, bottom-up approach is employed later in the Collection (Wang et al. 2021; Yin et al. 2021) to estimate country-specific direct and indirect damages from specific climate change-related risks.

Country-specific focus The focus is on developing countries, since they tend to be more vulnerable to climate change than others. The country-cases span the continents of Asia, Africa and South America, presenting examples of both large and small countries, and spanning a range of levels of socioeconomic development. The selected countries are China, India, Brazil, Ethiopia, Ghana and Egypt. With the exception of China and Brazil, most climate change impacts literature published to date focuses on global or continental scale risk projections, rather than on implications for individual countries. Published risk assessments focused on single countries are generally independent of studies of other countries, making comparisons difficult owing to methodological inconsistencies. The research presented in this Topical Collection has the advantage of projecting climate change risks consistently in the six individual countries. This consistency means that not only is the same set of models and input data used but also the spatial scale at which each individual risk metric is estimated is identical across the countries. For example, risks to biodiversity and natural capital are projected at 1 × 1 km scale and resampled to 300 m scale using maps of current land use. Similarly, drought exposure, although simulated more coarsely, is also resampled to 300 m. Fluvial flood risk information, however, is most useful at the catchment scale, so those risk metrics are simulated for major country catchments.

The nine publications in the Collection (Table 1) together provide a harmonised assessment for the six countries of projected changes in exposure of humans and land to climate-related hazards, the projected effects of climate change on biodiversity, and the economic and societal implications of climate risks.

1 Projected changes in exposure to climate-related hazards and their economic implications

Brown et al. (2021) explore coastal flood risks in the five countries with a coastline, also quantifying the economic costs of flooding and protection in the countries due to sea level rise using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling

Table 1 Content of the Topical Collection 'Accrual of Climate Change Risk in Six Vulnerable Countries'

Paper	Topic	Citation
Editorial		
1	Drought	Price, J., et al. 2022 Quantification of drought risks between 1.5 °C and 4 °C of global warming in six countries. *Climatic Change* 174, article no. 12
2	Fluvial flooding	He, Y., et al. 2022 Quantification of impacts between 1.5 °C and 4 °C of global warming on flooding risks in six countries. *Climatic Change* 170, article no. 15
3	Economic implications of fluvial flooding	Yin, Z., et al. 2021 Assessing the economic impacts of future fluvial flooding in six countries under climate change and socio-economic development *Climatic Change* 166, article no. 38
4	Economic implications of impacts on crop yields	Wang, D, et al. 2021 Economic impacts of climate-induced crop yield changes: Evidence from agri-food industries in six countries. *Climatic Change* 166, article no. 30
5	Economic implications of coastal flooding	Brown, S., et al. 2021 Global cost of protecting against sea level rise at 1.5 to 4 °C. *Climatic Change* 167, article no. 4
6	Biodiversity	Price, J. et al. 2024a. Biodiversity losses associated with global warming of 1.5 to 4 °C above pre-industrial levels in six countries. *Climatic Change*, article no. 66
7	Natural capital risk registers	Price, J. et al. 2024b. Assessing the potential risks of climate change on the natural capital of six countries resulting from global warming of 1.5 to 4 °C above pre-industrial levels. Climatic Change , article no. 50
8	Global economic implications	Warren, R., et al. 2021. Global and regional aggregate damages associated with global warming of 1.5 to 4 °C above pre-industrial levels. *Climatic Change*, 168, article no. 24
9	Synthesis	Warren, R. et al. 2024. Risks associated with global warming of 1.5 to 4 °C above pre-industrial levels in human and natural systems in six countries. *Climatic Change*, article no. 46

framework. Sea flood damage costs are found to be strongly determined by development choices, whereas sea dike investment costs are dependent on the magnitude of sea level rise. Annual sea flood damage costs without additional adaptation are projected to rapidly increase with approximately 0.2 m of sea level rise, leaving limited time to plan and adapt. Although sea levels will continue to rise after global mean temperatures are stabilised, stringent mitigation will slow the rate of sea level rise. This will help provide a greater time for human and natural systems to adapt (and hence, a greater potential for them to do so). China is likely to experience the greatest impacts of sea level rise due to densely populated cities located in low-lying areas with relatively low standards of protection. Economic damages associated with sea level rise are projected to increase, but more slowly if warming were limited to 1.5 °C. Actual benefits on the ground will also depend on national and local contexts and the extent of future investment in adaptation.

Price et al. (2022) explore the probability and length of severe drought in the six countries looking at different land cover classes and associated human exposure. With 3 °C warming, more than 50% of the agricultural area in each country is projected to be exposed to severe droughts of longer than one year in a 30-year period. Over 80% of the population in Brazil, China, Egypt, Ethiopia and Ghana (and ~ 50% of the population of India) are projected to be exposed to a severe drought lasting one year or longer in a 30-year period.

He et al. (2022) project climate change-induced changes in fluvial flood risks focusing on the major river basins of the six countries using the HBV hydrological model and the CaMa-Flood hydrodynamic model to simulate river discharge and flood inundation. The return periods of very large floods (1 in 100-year floods in the late twentieth century (Q100-20C)) are projected to decrease with warming, i.e., they become more frequent. At 1.5 °C warming, 47%, 66%, 27%, 65%, 62% and 92% of the major basin areas in Brazil, China, Egypt, Ethiopia, Ghana and India, respectively, experience a decrease in the return period of Q100-20C, rising to 54%, 81%, 28%, 82%, 86% and 96% with 4 °C warming. This leads to greatly increased human exposure to flood risks, particularly with 4 °C warming. Yin et al. (2021) link these projections of increased flood risk with depth-damage functions in each country, and hence to an input–output model allowing an exploration of the consequent flood-related direct and indirect economic damages. In absolute terms, the economic losses due to climate-change-related increases in flooding are largest in China and India, but in percentage terms they are largest in Egypt. If socioeconomic conditions change is also accounted for, the indirect losses increase even further.

2 Projected risks to agriculture, biodiversity and natural capital

Wang et al. (2021) explore the risks to crop yields and the associated economic implications within each nation. All countries except China are negatively impacted at all levels of warming due to declining crop yields, with increasing consumer prices of domestic and imported rice and wheat. GDP and welfare decline as a result, with more severe reductions associated with the higher warming levels, particularly in India and Ethiopia. For China, rice yield increases for lower levels of warming and decreases again for higher levels of warming.

Price et al. (2024a) explore the risks to plants and vertebrates, quantifying how the climatically determined geographic ranges of species change with climate, and locating the refugia where over 75% of the species currently present can still remain after the climate has changed. It finds that climate refugia for plants are largely preserved at 1.5 °C warming in Ghana, China and Ethiopia, but refugia shrink in areal extent by a factor of 2, 3, 3, 4 and 10 in Ghana, China, India, Ethiopia and Brazil, respectively, if warming reaches 3 °C. The study finds that an expansion of the protected area networks in these six countries will be necessary in order to meet the Convention on Biological Diversity (CBD) targets in a manner that is resilient to climate change. In particular, only small percentages of Brazil, India and China are both climate refugia for biodiversity and lie within protected areas, arguing for an expansion of the protected area networks in these countries in order to make biodiversity conservation resilient to climate change.

Price et al. (2024b) develop a new natural capital risk register consistently for each country. This new framework encapsulates wider societal implications not captured in the economic analyses, including, in particular, the loss of biodiversity and ecosystem services. It compares the effects of projected climate change only, with the combined effects of climate change population change, under an assumption of current land use across a range of 17 ecosystem services. The potential impacts of climate change (alone) on natural capital at 1.5 °C is greatest in Brazil and least in Ghana. However, when population and land-use change is included, high natural capital risk begin to accrue already by 1.5 °C global warming in all countries, with India and Egypt showing the greatest area at high risk. By 2 °C, Ethiopia and Ghana both show increasing areas at high risk, even though they are at low risk owing to climate alone. Adaptation potential exists, especially at 1.5 to 2 °C to reduce risk through reducing demand and restoring habitat. At lower levels of warming targeted restoration of low-quality agricultural habitats would increase the bank of natural capital for use by people and provide support for remaining agricultural lands. By 3 °C, the adaptation potential from restoration is substantially less: < 1% in Brazil, India and Egypt; 7–8% in China and Ethiopia; and still 26% in Ghana. This indicates that adaptation options for biodiversity, and thus, natural capital, rapidly decrease with increasing temperatures.

The overarching picture for the accrual of climate risk across the six countries is synthesised in Warren et al. (2024). It compares risks in 2100 if warming has reached 3 °C, broadly corresponding to current global greenhouse gas emission reduction policies, including countries' National Determined Contributions, rather than the Paris Agreement goal of limiting warming to 'well below' 2 °C and 'pursuing efforts' to limit to 1.5 °C. Global population is assumed either constant at year 2000 levels or to increase to 9.2 billion by 2100. In either case, greater warming is projected to lead, in all six countries, to greater exposure of land and people to drought and fluvial flood hazards, greater declines in biodiversity and greater reductions in the yield of maize and wheat. Limiting global warming to 1.5 °C, compared with ~ 3 °C, is projected to deliver large benefits for all six countries, including reduced economic damages due to fluvial flooding. The greatest projected benefits are the avoidance of a large increase in exposure of agricultural land to severe drought, which is 61%, 43%, 18% and 21% lower in Ethiopia, China, Ghana and India at 1.5 °C than at 3 °C, whilst avoided increases in human exposure to severe drought are 20–80% lower at 1.5 °C than 3 °C across the six countries.

The results presented in this Topical Collection confirm the need for the implementation of climate policies aligned to the Paris Agreement limits if widespread and escalating climate change risk is to be avoided. They provide additional confirmation of the rapid escalation of climate change risks with global warming found in IPCC (2022), which identifies how the risk of severe impacts increases with every additional increment of global warming. Although the Collection focuses on the risks to six countries only, it is clear from IPCC (2022) that other nations are projected to experience similar issues. Hence, greater emphasis needs to be placed on both climate change mitigation and climate change adaptation to avoid large increases in risks to both human and natural systems.

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