Mitig Adapt Strateg Glob Change (2024) 29:10
https://doi.org/10.1007/s11027-023-10103-3

# Climatic risks to adaptive capacity

**Olivia Serdeczny[1,2] · Marina Andrijevic[3] · Claire Fyson[1] · Tabea Lissner[1,4] · Inga Menke[1] · Carl-Friedrich Schleussner[1,2] · Emily Theokritoff[1,2] · Adelle Thomas[1,5]**

Received: 30 March 2023 / Accepted: 22 December 2023 / Published online: 19 January 2024


**Abstract**
Does climate change influence if societies will be better or worse equipped to reduce climatic risks in the future? A society's adaptive capacity determines whether the potential of adaptation to reduce risks will be realized. Assumptions about the level of adaptive capacity are inherently made when the potential for adaptation to reduce risks in the future and resultant levels of risk are estimated. In this review, we look at the literature on human impacts of climate change through the lens of adaptive capacity. Building on evidence of impacts on financial resources as presented in the Working Group 2 (WG2) report of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), we here present the methodology behind this review and complement it with an analysis of climatic risks to human resources. Based on our review, we argue that climate change itself adds to adaptation constraints and limits. We show that for more realistic assessments of sectoral climate risks, assumed levels of future adaptive capacity should — and can — be usefully constrained in assessments that rely on expert judgment, and propose avenues for doing so.

**Keywords** Adaptive capacity · Adaptation feasibility · Residual risks · Expert-based judgment

## 1 Introduction

"Without adaptation" is a recurrent qualifier when climate impact projections are reported, for example in the Sixth Assessment Report (AR6) of Working Group 2 (WG2) of the Intergovernmental Panel on Climate Change (IPCC). This implies that impacts "with

✉ Olivia Serdeczny
Olivia.serdeczny@climateanalytics.org

1 Climate Analytics gGmbH, Ritterstraße 3, 10969 Berlin, Germany

2 Humboldt-Universität zu Berlin, Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys) & Geography Department, Berlin, Germany

3 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

4 The New Institute, Hamburg, Germany

5 University of the Bahamas, Nassau, 4912, The Bahamas

adaptation" are expected to be lower. So far so good. But what exactly do we know about the feasibility of adaptation in the future? Most quantitative modelling studies of climate impacts assume optimal levels of adaptation (Andrijevic 2021; Füssel 2010; Holman et al. 2019; van Maanen et al. 2023). Such optimistic assumptions deserve scrutiny. In particular for developing countries, the recent record-breaking intensity and frequency of observed climate extremes (Otto and Raju 2023) in tandem with effects of the COVID-pandemic have severely stressed national budgets and governments' overall capacities (Thomas and Theokritoff 2021). In light of more such effects unfolding as temperatures climb, a scenario of adaptive capacity collapsing, leading to adverse social tipping points beyond which human wellbeing spirals downward cannot be excluded.

The concept of adaptive capacity is understood as "the potential or capability of a system to adapt to (to alter to better suit) climatic stimuli or their effects or impacts" (Smit and Pilifosova 2001). A society's adaptive capacity determines whether hypothetical adaptation potential can be realized, and risks consequently reduced. Adaptive capacity, which describes the conditions that are necessary to implement adaptation, is distinct from adaptation effectiveness which describes whether an implemented adaptation option can reduce risks (Owen 2020; Yohe and Tol 2002). To date, there is limited evidence of adaptation effectiveness in practice (Berrang-Ford et al. 2021). Adaptation effectiveness has been shown to decrease as a function of rising temperatures and associated impacts, even assuming high adaptive capacity (Lissner et al. n.d.).

Our understanding of what constitutes adaptive capacity has gained considerable nuance. In the IPCC's Third Assessment Report, various "determinants" of adaptive capacity were identified, including the availability of economic resources, technology, information and skills, infrastructure, institutions, and equity (Smit and Pilifosova 2001). Building on additional individual cases (e.g. Adger et al. 2007), insights from disaster management (IPCC 2012), and resilience frameworks (Nelson et al. 2007), the list of determinants expanded, mostly to include social values and psychological factors such as risk attitudes (Mortreux and Barnett 2017). The IPCC's Fifth Assessment Report (AR5) expands the framework to assess constraints and limits to adaptation, which capture key impediments to adaptation and adaptive capacity (Klein et al. 2014). While constraints are defined as factors that make it harder to implement adaptation, limits are considered to be the points at which actors' objectives or systems needs can no longer be secured from intolerable risks through adaptation. Limits can be further broken down into soft and hard ones. Hard limits occur when no adaptation options are foreseeable in the future to avoid intolerable risks, whereas for soft ones, adaptation options could become available in the future (Klein et al. 2014). Simply put, the more constraints and limits a country or a community faces, the lower the level of its adaptive capacity. This is particularly pertinent for Small Islands States and Central and South America, who most often report on adaptation constraints and limits (Thomas et al. 2021). The IPCC's AR6 stresses that both hard and soft limits to adaptation have been reached and that the latter can be overcome by addressing a range of primarily financial, governance, institutional, and policy constraints (IPCC 2022a). In addition, it also states that if interacting adaptation constraints are not addressed, they can lead to increasing limits (O'Neill et al. 2022), further hampering adaptive capacity.

As much of the knowledge on adaptive capacity relies on case studies, our understanding of determinants and adaptation constraints and limits at present is relatively comprehensive. However, little has been written about the future development of adaptive capacity. The basic idea that adaptive capacity changes over time, and in response to exogenous factors, is not new. Twenty years ago, Smit and Pilifosova (2003) observed that a community's "coping range" may increase or decrease in line with socio-economic changes or as a consequence of increasing frequencies of extreme events. Similarly, Smit and Wandel (2006) note the dynamic nature of adaptive capacity. They draw on examples of resource depletion, war, or the loss of a key decision-maker as factors that may narrow a community's coping range in the future, whereas economic growth or improvements in technology or institutions are likely to increase it. They also observe that cumulative effects of increasingly frequent extreme events can lower the threshold beyond which the system is no longer able to cope with further impacts. Besides temporal variation, Smith et al. (2003) note that adaptive capacity is unequally distributed around the world, with developing countries often displaying comparably low levels.

Quantitative assessments of potential future developments of adaptive capacity remain in their infancy. On dimensions of socio-economic development, Andrijevic et al. (2019) utilize the Shared Socio-conomic Pathways (SSPs) framework to project indicators for governance and the "adaptation readiness" component of the Notre Dame Global Adaptation Initiative index (Chen et al. 2015) as a proxy for governance constraints. Andrijevic et al. (2020b) do the same for gender equality as a proxy for socio-cultural constraints. Their results show vast differences in levels of adaptive capacity across regions and scenarios. Developments of adaptive capacity in selected developing countries, such as Nigeria or Somalia, range from stagnation at current levels to threefold increases towards the end of the century.

Assumptions about the future level of adaptive capacity are inherently made when the potential for adaptation to reduce risks in the future is estimated. For example, the IPCC's Reasons for Concern (RFC) qualify "very high risk" as "risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks" (O'Neill et al. 2022). The AR6 cycle reports have introduced some nuance on these assumptions. The Special Report on the Ocean and Cryosphere in a Changing Climate RFC assessments differentiate risk levels between a "no to moderate response" and a "maximum potential response" scenario (IPCC 2019). The Special Report on Climate Change and Land provides RFC for different SSP scenarios (Shukla et al. 2019). While these mostly reflect differing levels of exposure, some consideration on adaptive capacity appears reflected when the risk of rising food prices is considered for divergent levels of income. In the AR6 WG2 assessment of RFC, adaptation is considered to be low or absent compared to today (O'Neill et al. 2022). However, in the absence of a coherent framework linking climate impact projections and socio-economic scenarios to adaptive capacity, these nuanced approaches to the level or risk reduction through adaptation continue to rely on highly stylized scenarios.

As another case in point, most feasibility assessments of discrete adaptation options assume present levels of adaptive capacity. The multidimensional feasibility assessments carried out across the AR6 WG2 report build on a protocol designed by Singh et al. (2020). The authors of this protocol acknowledge the dynamic and spatially variable nature of what they call feasibility dimensions. Yet, potential changes to conditions affecting feasibility (adaptive capacity in our framing) are not considered when casting judgment about the feasibility of discrete adaptation options. This leads to a chronological mismatch where the state of adaptive capacity is assessed for the present, while the worst of climate impacts are expected in the future.

The dynamic nature of adaptive capacity also has important implications for transformational adaptation and limits to adaptation. As climate risks rise due to increasing global average temperatures, IPCC reports have increasingly called for a shift from incremental adaptation to transformational adaptation — adaptation that changes the fundamental attributes of a system (IPCC 2018b, 2022a). Such adaptation is deemed necessary to respond to the escalating risks of climate change, but the levels of adaptive capacity that it requires have not been subject to scrutiny.

At the same time, our knowledge on the human impacts of climate change has increased considerably. Climate impacts manifest in direct costs to human lives and wellbeing, destruction of assets, and other economic damages, as well as indirectly through impacts on sectors such as agriculture, water, or biodiversity, which can trigger effects on economies, human health, education, and human mobility (IPCC 2022b). Each of these impact dimensions has been investigated and summarized in consecutive IPCC reports. The assessments provide clear indications that climate impacts will affect key dimensions of adaptive capacity. The IPCC's report of WG2 provides a first step in linking the evidence of human impacts to adaptive capacity by showing that climate risks increase financial adaptation constraints (O'Neill et al. 2022). However, this information is not yet incorporated where assumptions on adaptive capacity are made.

A more systematic consideration of the evolution of adaptive capacity is thus needed if we are to more realistically estimate the residual risks of climate change (Andrijevic et al. 2023). This is particularly the case for developing countries where exposure to climate hazards is high (Thomas et al. 2020) and adaptation constraints and limits are most prevalent (Thomas et al. 2021).

We here propose a methodological approach for reviewing evidence of climatic risks to adaptive capacity. Complementing the analysis on financial constraints as presented in AR6 WG2 (O'Neill et al. 2022), we expand this methodology to cover the determinant of human resources. To apply our insights to comprehensive risk assessments, we sketch ways of constraining plausible levels of adaptive capacity in climatic risk assessments that rely on expert-based judgments.

## 2 Methodological approach for reviewing evidence of climatic risks to adaptive capacity

Factors influencing a society's capacity to adapt to climate change can be described either positively as determinants of adaptive capacity (Smit and Pilifosova 2001) or negatively as adaptation constraints and limits (Dow et al. 2013; Klein et al. 2014). For example, we treat the financial and human resource constraints as presented in AR5 (Klein et al. 2015) and AR6 (O'Neill et al. 2022) as the detriments of resources that elsewhere are described as determinants (Cinner et al. 2018; Nelson et al. 2007; Smit and Pilifosova 2001; Smith et al. 2003; Yohe and Tol 2002). An increase in respective resources would imply that constraints are being overcome. Our analytical framework thus jointly considers both framings on constraints/limits and determinants of adaptive capacity.

To identify potential causal pathways from climate impacts to adaptive capacity, we select the keywords that are used to describe respective determinants of adaptive capacity from selected publications that we see as paradigmatic because they cover different scales of assessment, from household (Cinner et al. 2018) to generic (Smit and Pilifosova 2001); reflect the resilience framework (Nelson et al. 2007); include considerations on specific situations in developing countries (Smith et al. 2003); and describe determinants that have been practically applied in feasibility assessments (Yohe and Tol 2002). We focus our attention on human and financial resources as necessary though not sufficient conditions for adaptation.

Keywords for each determinant mirrored by constraints are grouped in Table 1. Subsequently, we use these keywords to screen the regional and sectoral chapters of the AR6 WG2 report, qualitatively treating the keywords and descriptions from Table 1 as the dependent variable, and climatic effects as the independent variable.

## 3 Evidence of climatic risks to adaptive capacity

Table 2 reproduces the substance of Table 16.5. from the IPCC's AR6 WG2 report on climatic risks to financial resources (O'Neill et al. 2022), and shows the effects on human resources that we identified throughout our additional review.

On risks to financial resources, most literature with regionally specific information focuses on industrialized countries (Table 2). At the same time, evidence shows the disproportionate effect that climate change has on developing countries' economies, as they register negative macroeconomic responses to higher temperatures in the form of decreases in aggregate economic output and growth (Burke et al. 2015; Kahn et al. 2021) and following extreme events (Hsiang and Amir 2014). The most severe impacts of climate-related disasters on economic growth per capita have been observed in developing countries, although authors note a publication bias in the reporting of negative effects (Klomp and Valckx 2014). Estimates of the duration of negative effects of climate-related disasters differ, with some analyses suggesting that on average economies recover after 2 years (Klomp 2016) and others finding negative effects specifically of cyclones to persist 15–20 years following an event (Hsiang and Amir 2014) (IMF 2017) (Krichene et al. 2020).

Developing countries are also subject to a specific causal pathway from climate change to their financial capacities, as mounting climate vulnerability increases their cost of debt (Kling et al. 2018). This means that climate change negatively affects developing countries' access to financial markets or risk insurance (e.g. Fuller et al. 2018) (Cevik and Jalles 2020). Better understanding and disclosure of climatic risks may result in capital flight (Cooper 2020), further limiting the availability of financial resources. Many island nations such as the Caribbean

**Table 1** Mirroring adaptation constraints with determinants of adaptive capacity and keywords as described in Cinner et al. (2018); Nelson et al. (2007); Smit and Pilifosova (2001); Smith et al. (2003) and Yohe and Tol (2002)

| Determinants of adaptive capacity | Keywords | Adaptation constraint |
|---|---|---|
| Economic resources; wealth; financial capital; assets | Economic assets, capital resources, financial means, wealth, level, variability and diversity of income sources, access to credits or savings | Financial constraints |
| Information and skills; ability of decision-makers to manage information; education; human capital; learning | Skills, health and education of individuals; strong, unifying vision; scientific understanding of the problems; community involvement; commitment at highest political level | Human resource constraints |

**Table 2** Summary of regional evidence of climatic effects on financial and human resources as key dimensions of adaptive capacity. Chapter numbers refer to the IPCC's AR6 WG2 report

| Region | Climatic impacts on financial resources | Climatic impacts on human resources |
|---|---|---|
| Africa | Negative consequences for economic growth and GDP growth rate from higher average temperatures and lower rainfall (chapter 9) | Significant correlation between increased temperature and children's wasting (observed between 1993 – 2012 and projected) (chapters 5 and 7) |
| | Economic losses from damage to infrastructure in the energy, transport, water supply, communication services, housing, health, and education sectors (observed) (chapter 9) | Increase in dengue risk in Tanzania (chapter 7) |
| | | Increase in waterborne diseases (chapter 7) |
| | | Increased human morbidity and mortality (chapter 9) |
| | | Climate variability and change undermine educational attainment with negative impacts on later life earning potential (chapter 9) |
| | | Long-term behavioural and developmental deficiencies associated with exposure to high temperatures during pregnancy (chapter 9) |
| | | Access to health and education hindered by flooding (chapter 9) |
| Asia | Loss of coastal ecosystem services (Bangladesh) (chapter 5) | Increase in dengue exposure in China, Korea and Nepal under high warming (chapter 7) |
| | High coastal damages due to sea level rise (China, India, Korea, Japan, Russia) (chapter 10) | Projected increase in heat-related cardio vascular mortality in Beijing, China (chapter 7) |
| | | Projected reductions in labour capacity due to heat stress in China (chapter 7) |
| | | Increasing vector-borne and water-borne diseases, undernutrition, mental disorders and allergic diseases (chapter 10) |
| | | Daily maximum wet-bulb temperature is expected to exceed survivability threshold across most of South Asia under high warming towards end of century (chapter 10) |
| | | Increases in undernourishment (projected for Southeast Asia) (chapter 10) |
| | | Increase in deaths related to circulatory, respiratory, diabetic and infectious disease. as well as infant mortality (chapter 10) |

**Table 2** (continued)

| Region | Climatic impacts on financial resources | Climatic impacts on human resources |
|---|---|---|
| Central and South America | High costs of extreme events relative to GDP (observed in Guatemala, Belize) (chapter 12) | Growing evidence on the impacts of climate change on human health in NES [northeastern South America] (chapter 12) |
| | Decrease in growth of total GDP per capita and total income and labour income from one standard deviation in the intensity of a hurricane windstorm (chapter 12) | |
| Australasia | Loss of wealth and negative impacts on GDP (chapter 11) | Health loss due to extreme weather in Australia and New Zealand (chapter 11) |
| | High disaster costs (observed in Australia) (chapter 11) | Heightened anxiety and increased self-perceived risks of depression and suicide (observed in Western Australia) (chapter 11) |
| Europe | Negative combined effect of multiple risks on economy for Europe in total (chapter 13) | Large increase in distribution of vectors of Lyme disease and tick-borne encephalitis in second half of the century (chapter 7) |
| | Negative combined effect of multiple risks on economy for Southern Europe (chapter 13) | Expected decrease in access to affordable and nutritious food for European citizens (chapter 13) |
| | High economic costs in agriculture and construction following heat waves and flooding (chapters 6 and 7) | Rising mortality due to heat (chapter 13) |
| North America | Small but persistent negative economy wide effect on GDP (observed in United States and Mexico) (chapter 14) | Increasing risk of mosquito-borne diseases including West Nile Virus, chikungunya, and dengue (chapters 7 and 14) |
| | Economic risks associated with high temperature scenarios (chapter 14) | Projected increase the number of Lyme disease cases in the United States (chapter 7) |
| | Small but persistent positive economy wide effect on GDP (observed in Canada) (chapter 14) | Negative impacts on human health and wellbeing in observed in North America (chapter 14) |
| | Significant economic costs for urban, natural and ecosystem infrastructure (USA) (chapter 14) | Negative impacts on mental health (chapter 14) |
| | High economic damages for a subset of sectors from high warming (southern and southeastern US) (chapter 14) | |
| | Adverse effects on municipal budgets due to costly liabilities, and disruption of financial markets (chapter 14) | |

**Table 2** (continued)

| Region | Climatic impacts on financial resources | Climatic impacts on human resources |
|---|---|---|
| SIDS | High economic costs relative to GDP from extreme events, particularly tropical cyclones (observed) (chapter 15) | Worry, anxiety and sadness from fear of cultural loss (observed in Tuvalu, Fiji and other Pacific islands) (chapter 15) |
| | Negative long-term implications of extreme events for state budgets (chapter 8) | Tropical and sub-tropical islands face risks from vector-borne diseases, such as malaria, dengue fever, and the Zika virus (chapter 15) |
| | Inundation of almost all port and harbour facilities (Caribbean) (chapter 15) | Increase in dependence on imported food and increase rates of malnutrition and non-communicable diseases (chapter 15) |

SIDS are already suffering high levels of debt and require substantial funds to service their debts (Thomas and Theokritoff 2021).

On risks to human resources, our review shows adverse effects in all world regions, primarily through negative impacts on human health and educational attainment. Negative effects on the latter can be pronounced particularly in the case of subsistence livelihoods, as prolonged periods of drought and high temperatures during the growing season can result in poor schooling outcomes if children are taken out of school to help with income generation. Observations show girls to be particularly affected by such practices (UNESCO 2020) or if crop declines lead to poor nutrition which in turn can result in stunting and impaired cognitive development (WHO, UNICEF, and WBG 2019). Analysis from Argentina suggests that exposure to extreme events in early life can also negatively affect years of schooling and employment levels in later life (González et al. 2021).

While many health outcomes have registered improvements over the recent decades (Cissé et al. 2022, Figure Box 7.2.1), climate change poses a clear and recognized risk to human health. Observed and expected effects range from expanding transmission zones of vector-borne diseases, including for example malaria in China (Ren et al. 2016) and dengue fever in Latin America (Colón-González et al. 2019), to growing risk of hunger (Hasegawa et al. 2018) and malnutrition, with high variance across socio-economic scenarios (Nelson et al. 2018). Climate change negatively affects the amount of micro- and macronutrient content of foods, with negative outcomes for health and cognitive development (Ebi and Loladze 2019). Diet- and heat-related morbidity and mortality are projected to increase (Springmann et al. 2016), (Smith et al. 2014). Increases in childhood risks of malnutrition and infectious diseases are expected particularly in low-income countries (Food and Agriculture Organization of the United Nations (FAO et al. 2018). Climate change has further been shown to negatively affect mental health, for example in the form of post-traumatic stress and anxiety (Van Der Geest and Schindler 2016).

Another causal pathway how climate change can affect human resources is through damages to critical infrastructure, which can hinder access to water, sanitation, and hygiene services (Kohlitz et al. 2017). Waterborne disease outbreaks are expected to increase as a result of sewage overflow following heavy rainfall (Khan et al. 2015). As a positive effect, decreases in cold-related mortality are expected in regions where such risks currently exist (Vardoulakis et al. 2015).

In sum, we find climatic risks to human resources in nearly all world regions. Least evidence currently exists for Central and South America. As the respective chapter in IPCC WG2 observes that the literature on human impacts of climate change is generally scarce for the region, this lack of evidence may point to an important research gap.

Other regions are subject to various causal pathways, with Asia and Africa most prone to risks related to heat, while the spread of diseases is identified as a risk across developed and developing country regions alike. Such risks can undermine adaptive capacity by placing additional burden on governance structures and budgets. Other causal pathways are through adversely affecting economic activity for example through negative long-term earning effects of reduced educational attainment (Lutz et al. 2014) or reduced labour capacity and cognitive functioning (Kjellstrom et al. 2016).

## 4 Discussion

Our assumption that the climatic impacts captured in Table 2 translate into risks to adaptive capacity is more founded in some cases than in others. For example, it is sound to assume that negative effects on income or GDP will limit the availability of financial resources, as one by definition implies the other. Other links, for example between climatic effects on educational attainment and adaptive capacity, are intuitive but less straight-forward. Do negative climatic effects on education add up to raising adaptation constraints in human resources? Here, much depends on the distribution of roles and responsibilities across actors engaged in adaptation (Petzold et al. 2023). As national leaders and administrative staff are often educated in elite institutions, they may be less likely to suffer from adverse climatic effects on education, leading to negligible impacts on adaptive capacity at the national or sub-national level. However, for individuals and households, adverse educational effects may limit their ability to diversify their livelihoods if the necessary skills are underdeveloped.

The above challenges also relate to the questions of scale. At what point does case-study-based evidence add up to systemic risks to adaptive capacity? This area of research remains underexplored. Yet, particularly in developing countries, where the resource base is low and crucial sectors of the economy are highly exposed to climate change, climate-driven upper limits on the availability of human and financial resources needs to be seriously considered. For example, while national governments might be expected to buffer adverse economic effects at the household level to some extent, this becomes increasingly unfeasible where national budgets are continuously strained by adverse climatic effects.

Identifying evidence for other dimensions of adaptive capacity would necessitate yet more assumptions and uncertainties. Yet, it might be worthwhile to dedicate further analytical resources on this question, as, in the worst case, adverse effects on governance could potentially most drastically reduce levels of adaptive capacity. Currently, ten countries are listed as under high or very high alert in the Fragile State Index (The Fund for Peace 2022). Among those, Syria has exhibited high vulnerability to drought, and saw a decrease in indicators of governance in the past (Andrijevic et al. 2019). The political stability in such fragile states may be severely at risk in a scenario of recurring extreme events and declining resources, tipping them into a condition of adaptive inability that may persist over many years. The multifactorial nature of conflict and governance stability renders a simple identification of risks to governance epistemically challenging. At the same time, these risks cannot be excluded.

Despite efforts at generating an evidence base on climate impacts for different levels of projected global warming (Rosenzweig et al. 2017; Warszawski et al. 2014), our analysis is not yet able to capture levels of risks to adaptive capacity at different levels or rates of warming. This is likely due to the pool of evidence that we considered. More fine-grained analysis including individual publications and regional grey literature can likely ameliorate this shortcoming. Given the recognition that impacts substantively scale with every degree of warming (IPCC 2018a), increasingly adverse impacts on adaptive capacity and resultant disproportionately high residual risks need to be reckoned with.

Decreases to or limited increase in adaptive capacity means that adaptation constraints and limits persist over longer timeframes compared to scenarios that do not consider climate impacts (Theokritoff et al. 2023). The extent to which early action can overcome such negative feedback is unclear as conceptually we confront a chicken-or-egg problem: With effective risk reduction through adaptation, impacts are less severe, enabling adaptive capacity to improve and hence adaptation to become more effective. Conversely, if adaptation is not sufficient, climate change impacts may erode future adaptive capacity, lowering future prospects of effective adaptation. Yet, observations show that already today climatic impacts lower adaptive capacity, for example by increasing the cost of borrowing (Kling et al. 2018). There is thus limited reason to err on the optimistic side and every reason to critically question the plausibility of steady improvements to adaptive capacity in the twenty-first century.

Recognition that climate impacts themselves have the potential to reduce adaptive capacity further complexifies the shift to transformational adaptation — already viewed as requiring a whole of society effort with the need for far more financial resources, governance capacities, and potential changes to social and cultural norms as compared to incremental adaptation. If indeed adaptive capacity declines with increasing climate impacts, then transformational adaptation may be even more of an elusive goal for those with already low capacities. This may then lead to limits of adaptation and potential tipping points, beyond which intolerable risks may materialize (Klein et al. 2014; O'Neill et al. 2022; Thomas et al. 2021). Research on transformational adaptation and limits to adaptation should also incorporate these considerations of adaptive capacity dynamics, for more realistic assessments of how much we can rely on adaptation, both incremental and transformative, in the future.

We next propose ways for considering such information when casting expert judgment on the feasibility of discrete adaptation options and when qualitatively assessing climatic risks.

## 5 Towards plausible boundaries on future adaptive capacity in expert judgments

Information on climatic risks to adaptive capacity can be used to confine assumptions of future adaptive capacity to plausible levels. Ideally, information would distinguish between impacts at different levels of warming, as both the effectiveness of adaptation and adaptive capacity can be expected to decrease with rising temperatures. Where different Shared Socio-economic Pathways are considered in assessments, available projections of proxies of adaptive capacity (e.g. Andrijevic et al. 2020a; Andrijevic et al. 2020b) should accompany this information.

Our proposed approach necessitates interdisciplinary exchange among experts of the socio-economic dimensions of adaptive capacity (e.g. economists, public health experts) and sectoral experts of the climatic risks that are assessed (e.g. hydrologists, agricultural experts). In principle, two routes for testing plausibility assumptions of adaptive capacity exist: (1) sectoral experts are presented with information on climatic risks to adaptive capacity or (2) socio-economic experts are presented with descriptions of the assumed levels of adaptation (type and scale) at a given time, place, and warming scenario.

For each route, experts would be expected to conduct a consistency check to judge whether the level of adaptive capacity necessary for adaptation to reduce future risks can plausibly be assumed in light of climatic risks to its key determinants. Where necessary levels of adaptive capacity cannot plausibly be assumed given the information we have, adaptation options would need to be excluded from the portfolio of possible risk reduction measures. As a consequence, in the case of RFC, the transition from "high" to "very high" risks could be more accurately defined. In the case of multidimensional feasibility assessments, the feasibility of a given adaptation option may decrease in the future compared to today. Figure 1 summarizes our conceptual understanding of the dynamics of adaptive capacity and the steps needed to consider it in the context of expert judgment assessments.

In most cases, such a consistency check would be far from simple as the levels of adaptive capacity that will be necessary for any given adaptation are rarely made explicit. Nor can adaptive capacity and its interactions with climate hazards be quantitatively projected

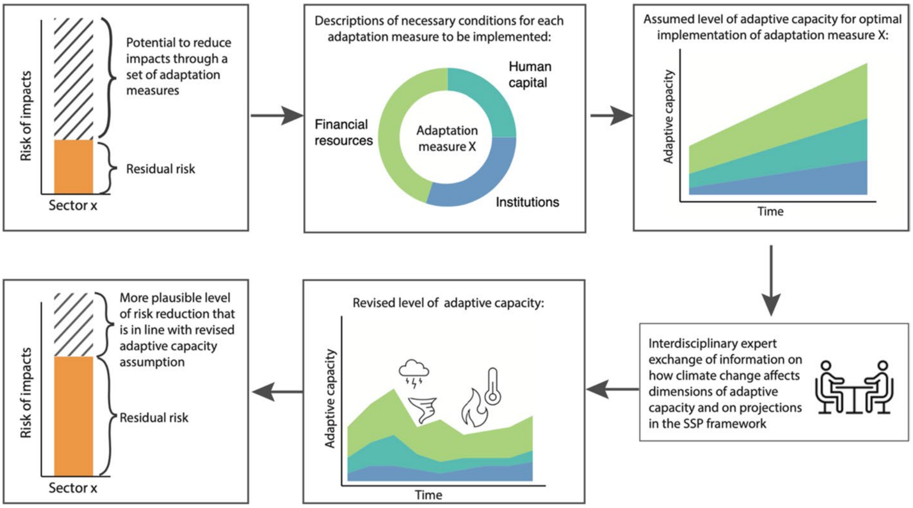


**Fig. 1** Steps towards reflecting more plausible levels of assumed adaptive capacity in climate risk assessments that are based on expert judgment

under the currently available scenario framework. And yet, a critical testing of the plausibility of assumed risk reduction through adaptation would not introduce new assumptions but rather transparently lay open existing ones and qualitatively check for their consistency with the available literature on societal climate impacts.

## 6 Conclusions

Our review has shown that adaptive capacity can be expected to be negatively affected by climate change itself. Different regions display vastly differing levels of adaptive capacity to date and face different types of adaptation constraints and limits (Thomas et al. 2021). As these regions are also differently exposed to climate hazards, their levels of future adaptive capacity are likely to further diverge. For example, due to the high exposure of economies in Small Island States, availability of financial resources can be expected to further decline. Based on our analysis, we have argued that the assumptions of adaptive capacity that underlie assessments of adaptation feasibility and residual risks ought to be tested against the available literature on relevant climate impacts.

Further research is clearly needed to better understand the interactions between climate change and adaptive capacity. Our framework limits our review to potential effects that have been identified in studies that did not investigate effects on adaptive capacity. Exploring and understanding potential mechanisms and causal pathways from climate change to the development of adaptive capacity remains an open research need.

Yet, sufficient information is available to confine the levels of adaptive capacity that are assumed in various exercises to plausible levels. As Zommers et al. (2020) observe, the scientific robustness and credibility of expert elicitation underlying the burning embers diagrams have increased over the assessment cycles, and AR6 builds upon these improvements. Implementing a consistency check for plausibility of adaptive capacity assumptions as we propose would further add to these recent improvements.

**Author contribution** OS, MA, and CS conceptualized the paper. Review was carried out by CF, IM, OS, and ET. MA designed the figure. All authors contributed to the writing of the manuscript.

**Funding** Open Access funding enabled and organized by Projekt DEAL. Olivia Serdeczny, Carl Schleussner, and Emily Theokritoff were supported by the German Federal Ministry of Education and Research (grant number 01LN1711A).

**Data availability** The entries reflected in Table 2 are publicly available at the IPCC website under https://www.ipcc.ch/report/ar6/wg2/.

## Declarations

**Competing interests** The authors declare no competing interests.



## References

Adger WN et al (2007) Assessment of adaptation practices, options, constraints and capacity. In: Parry ML et al (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ Press, pp 717–743

Andrijevic, M. (2021) Pathways of adaptive capacity for climate impact research. Humboldt-Universität zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät. https://doi.org/10.18452/23304.

Andrijevic M, Crespo Cuaresma J, Lissner T et al (2020b) Overcoming gender inequality for climate resilient development. Nat Commun. Springer US 11(1):6261. https://doi.org/10.1038/s41467-020-19856-w

Andrijevic M, Crespo Cuaresma J, Muttarak R et al (2020a) Governance in socioeconomic pathways and its role for future adaptive capacity. Nat Sustain. Springer US 3:35–41. https://doi.org/10.1038/s41893-019-0405-0

Andrijevic M et al (2019) Governance in socioeconomic pathways and its role for future adaptive capacity. Nat Sustain. Springer US. https://doi.org/10.1038/s41893-019-0405-0

Andrijevic M et al (2023) Towards scenario representation of adaptive capacity for global climate change assessments. Nat Clim Chang. Springer US. https://doi.org/10.1038/s41558-023-01725-1

Berrang-Ford L et al (2021) A systematic global stocktake of evidence on human adaptation to climate change. Nat Clim Chang. https://doi.org/10.21203/rs.3.rs-100873/v1

Burke M, Hsiang SM, Miguel E (2015) Global non-linear effect of temperature on economic production. Nature 527:235–239. https://doi.org/10.1038/nature15725

Cevik S, Jalles JT (2020) Feeling the heat: climate shocks and credit ratings. IMF Working Paper

Chen C, Noble I, Hellman J, Coffee J, Murillo M, Chawla N (2015) University of Notre Dame global adaptation initiative - country index technical report. Available at https://gain.nd.edu/assets/522870/nd_gain_countryindextechreport_2023_01.pdf. Accessed 5 Jan 2024

Cinner JE et al (2018) Building adaptive capacity to climate change in tropical coastal communities. Nat Clim Chang. Springer US 8(2):117–123. https://doi.org/10.1038/s41558-017-0065-x

Colón-González FJ et al (2019) Limiting global-mean temperature increase to 1.5–2 °C could reduce the incidence and spatial spread of dengue fever in Latin America. Proc Natl Acad Sci USA 116(24):12110. https://doi.org/10.1073/pnas.1906969116

Cooper R (2020) Risk of capital flight due to a better understanding of climate change risks. K4D Helpdesk Report 727. Institute of Development Studies, Brighton, UK . Available at https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/15631. Accessed 5 Jan 2024

Dow K et al (2013) Limits to adaptation. Nat Publ Group 3(4):305–307. https://doi.org/10.1038/nclimate1847
Ebi, K. L. and Loladze, I. (2019) 'Elevated atmospheric $CO_2$ concentrations and climate change will affect our food's quality and quantity', Lancet Planet Health. Elsevier, 3(7), e283–e284. https://doi.org/10.1016/S2542-5196(19)30108-1.
FAO, IFAD, UNICEF, WFP, WHO (2018) The state of food security and nutrition in the world 2018. Building climate resilience for food security and nutrition. Rome, FAO. https://www.fao.org/3/I9553EN/i9553en.pdf. Accessed 5 Jan 2024
Fuller F et al (2018) Debt for climate swaps. Caribbean outlook, Berlin Available at: https://climateanalytics.org/media/debt_for_climate_swap_impact_briefing.pdf
Füssel HM (2010) Modeling impacts and adaptation in global IAMs. Wiley Interdiscip Rev Clim Chang 1(2):288–303. https://doi.org/10.1002/wcc.40
Cissé G, McLeman R, Adams H, Aldunce P, Bowen K, Campbell-Lendrum D, Clayton S, Ebi KL, Hess J, Huang C, Liu Q, McGregor G , Semenza J, Tirado MC (2022) Health, wellbeing, and the changing structure of communities. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate change 2022: impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp.1041–1170. https://doi.org/10.1017/9781009325844.009
González FAI, Santos ME, London S (2021) Persistent effects of natural disasters on human development: quasi-experimental evidence for Argentina. Environ Dev Sustain 23:10432–10454
Hasegawa T et al (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang. Springer US 8(8):699–703. https://doi.org/10.1038/s41558-018-0230-x
Holman IP et al (2019) Improving the representation of adaptation in climate change impact models. Reg Environ Chang. Springer Verlag 19(3):711–721. https://doi.org/10.1007/s10113-018-1328-4
Hsiang S, Amir J (2014) The causal effect of environmental catastrophe on long-run economic growth: evidence from 6,700 cyclones. National Bureau of Economic Research Working Paper Series. No. 20352. https://doi.org/10.3386/w20352
IMF (2017) Seeking sustainable growth - short-term recovery, long-term challenges. International Monetary Fund, Washington, DC
IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation, Climate change, disaster risk, and the urban poor. Geneva. https://doi.org/10.1596/978-0-8213-8845-7.
IPCC (2018a) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 3–24. https://doi.org/10.1017/9781009157940.001
IPCC (2018b) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) Global Warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 3–24. https://doi.org/10.1017/9781009157940.001
IPCC (2019) In: Pörtner H-O et al (eds) IPCC special report on the ocean and cryosphere in a changing climate. IPCC, Geneva https://www.ipcc.ch/report/srocc/
IPCC (2022a) Climate change 2022: impacts, adaptation, and vulnerability. H.-O. Pörtner et al (ed) Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge Univ Press, Cambridge & New York. https://doi.org/10.1017/9781009325844
IPCC (2022b) Climate change 2022: impacts, adaptation and vulnerability - summary for policymakers, Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.4324/9781315071961-11.
Kahn ME, Mohaddes K, Ng RN, Pesaran MH, Raissi M, Yang JC (2021) Long-term macroeconomic effects of climate change: A cross-country analysis. Energy Econ 104:105624

Khan SJ et al (2015) Extreme weather events: should drinking water quality management systems adapt to changing risk profiles? Water Res 85:124–136. https://doi.org/10.1016/j.watres.2015.08.018
Kjellstrom T et al (2016) Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. Annu Rev Public Health. Annual Reviews 37(1):97–112. https://doi.org/10.1146/annurev-publhealth-032315-021740
Klein RJT, Midgley GF et al (2014) Adaptation opportunities, constraints, and limits. In: Field CB (ed) et al.Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 899–943
Klein RJT et al (2015) Adaptation opportunities, constraints, and limits. In: Climate change 2014 impacts, adaptation and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp 899–944. https://doi.org/10.1017/CBO9781107415379.021
Kling G, Lo YC, Murinde V, Volz U (2018) Climate vulnerability and the cost of deb
Klomp J (2016) Economic development and natural disasters: a satellite data analysis. Glob Environ Chang. Elsevier Ltd 36:67–88. https://doi.org/10.1016/j.gloenvcha.2015.11.001
Klomp J, Valckx K (2014) Natural disasters and economic growth: a meta-analysis. Glob Environ Chang. Elsevier Ltd 26:183–195. https://doi.org/10.1016/j.gloenvcha.2014.02.006
Kohlitz JP, Chong J, Willetts J (2017) Climate change vulnerability and resilience of water, sanitation, and hygiene services: a theoretical perspective. J Water Sanit Hyg Dev 7(2):181–195. https://doi.org/10.2166/washdev.2017.134
Krichene, H. et al. (2020) 'The impacts of tropical cyclones and fluvial floods on economic growth – empirical evidence on transmission channels at different levels of development', Krichene, Hazem and Geiger, Tobias and Frieler, Katja and Willner, Sven and Sauer, Inga and Otto, Christian, The impacts of tropical cyclones and fluvial floods on economic growth – empirical evidence on transmission channels at different levels of development. https://doi.org/10.1016/j.worlddev.2021.105475.
Lissner T, Moeller T, Caretta MA, Mukherji A (n.d.) 'Adaptation of water-related adaptation decreases with warming', in review, One Earth
Lutz BW, Muttarak R, Striessnig E (2014) Universal education is key to enhanced climate adaptation. Science 346(6213):1061–1062
Mortreux C, Barnett J (2017) Adaptive capacity: exploring the research frontier. Wiley Interdiscip Rev Clim Chang 8(4). https://doi.org/10.1002/wcc.467
Nelson DR, Adger WN, Brown K (2007) Adaptation to environmental change: contributions of a resilience framework. Annu Rev Environ Resour 32(1):395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348
Nelson, G. et al. (2018) 'Income growth and climate change effects on global nutrition security to mid-century', Nat Sustain. Springer US, 1(12), 773–781. https://doi.org/10.1038/s41893-018-0192-z.
O'Neill B et al (2022) Key risks across sectors and regions. In: Poertner H-O et al (eds) Climate change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ Press, Cambridge & New York, pp 2411–2538. https://doi.org/10.1017/9781009325844.025
Otto FEL, Raju E (2023) Harbingers of decades of unnatural disasters. Commun Earth Environ. Springer US 4(1):1–7. https://doi.org/10.1038/s43247-023-00943-x
Owen G (2020) What makes climate change adaptation effective? A systematic review of the literature. Glob Environ Chang 62:102071. https://doi.org/10.1016/j.gloenvcha.2020.102071
Petzold J et al (2023) A global assessment of actors and their roles in climate change adaptation. Nat Clim Chang 13(11):1250–1257. https://doi.org/10.1038/s41558-023-01824-z
Ren Z et al (2016) Predicting malaria vector distribution under climate change scenarios in China: challenges for malaria elimination. Sci Rep. Nature Publishing Group 6(September 2014):1–13. https://doi.org/10.1038/srep20604
Rosenzweig C et al (2017) Assessing inter-sectoral climate change risks: the role of ISIMIP. Environ Res Lett. IOP Publishing 12(1):010301. https://doi.org/10.1088/1748-9326/12/1/010301
Shukla PR, Skea J, Slade R, van Diemen R, Haughey E, Malley J, Pathak M, Portugal Pereira J (eds) Technical Summary, 2019. In: Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick E, Belkacemi M, Malley J (eds) Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://doi.org/10.1017/9781009157988.002

Singh C et al (2020) Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. Clim Chang 4. https://doi.org/10.1007/s10584-020-02762-x
Smit B, Pilifosova O (2001) Chapter 18: adaptation to climate change in the context of susainable development and equity. In: IPCC 2001, impacts, adaptation, and vulnerability; The Contribution of Working Group II to the Third Scientific Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://doi.org/10.1103/PhysRevD.87.106003
Smit B, Pilifosova O (2003) From adaptation to adaptive capacity and vulnerability reduction. In: Smith JB, Klein RJT, Huq S (eds) Climate change, adaptive capacity and development. Imperial College Press, London, pp 9–28
Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Glob Environ Chang. Pergamon 16(3):282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008
Smith JB, Huq S, Klein RJT (2003) Climate change, adaptive capacity and development. Imperial College Press, London
Smith KR et al (2014) Human health: impacts, adaptation, and co-benefits. In: Confalonieri U, Haines A (eds) Climate change 2014: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 11. Final Draft. IPCC AR5 WGII, Cambridge University Press, Cambridge UK
Springmann M et al (2016) Global and regional health effects of future food production under climate change: a modelling study. Lancet. Elsevier 387(10031):1937–1946. https://doi.org/10.1016/S0140-6736(15)01156-3
The Fund for Peace (2022) Fragile states index annual report 2022. Available at https://fragilestatesindex.org/wpcontent/uploads/2022/07/22-FSI-Report-Final.pdf. Accessed 5 Jan 2024
Theokritoff E et al (2023) Adaptation constraints in scenarios of socio-economic development. Sci Rep 13(1):19604. https://doi.org/10.1038/s41598-023-46931-1
Thomas A, Theokritoff E (2021) Debt-for-climate swaps for small islands. Nat Clim Chang 11(11):889–891. https://doi.org/10.1038/s41558-021-01194-4
Thomas A, Theokritoff E, Lesnikowski A, Reckien D, Jagannathan K, Cremades R, Campbell D, Elphin JT et al (2021) 'Global evidence of limits and constraints to human adaptation', Regional Environmental Change. Reg Environ Chang 21(85). https://doi.org/10.1007/s10113-021-01808-9
Thomas A et al (2020) Climate change and small island developing states. Annu Rev Environ Resour 45(1):1–27. https://doi.org/10.1146/annurev-environ-012320-083355
UNESCO (2020) UN World Water Development Report 2020. https://doi.org/10.1002/9781118786352.wbieg0793.pub2.
World Health Organization, United Nations Children's Fund ( UNICEF) & International Bank for Reconstruction and Development/The World Bank (2019) Levels and trends in child malnutrition: Key findings of the 2019 edition. Available at https://www.unicef.org/media/60626/file/Joint-malnutrition-estimates-2019.pdf. Last Accessed 5 Jan 2024
Van Der Geest K, Schindler M (2016) Brief communication: loss and damage from a catastrophic landslide in Nepal. Nat Hazards Earth Syst Sci 16(11):2347–2350. https://doi.org/10.5194/nhess-16-2347-2016
van Maanen N et al (2023) Representation of adaptation in quantitative climate assessments. Nat Clim Chang 13(4):309–311. https://doi.org/10.1038/s41558-023-01644-1
Vardoulakis S et al (2015) Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. Environ Health Perspect 122(12):1285–1292. https://doi.org/10.1289/ehp.1307524
Warszawski L et al (2014) The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): project framework. Proc Natl Acad Sci 9:3228–3232. https://doi.org/10.1073/pnas.1312330110
Yohe G, Tol RSJ (2002) Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity. Glob Environ Chang 12(1):25–40. https://doi.org/10.1016/S0959-3780(01)00026-7
Zommers Z et al (2020) Burning embers: towards more transparent and robust climate-change risk assessments. Nat Rev Earth Environ. Springer US 1(10):516–529. https://doi.org/10.1038/s43017-020-0088-0