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REVIEW

Water remains a blind spot in climate change policies

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Abstract

For the first time in the latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), water has been the focus of dedicated chapters in both Working Group 1 (Chapter 8) and 2 (Chapter 4). Nevertheless, we argue here that water has not yet received the full attention it deserves from both scientists and policymakers for several reasons. Firstly, the historical focus on temperature change has been further increased with the use of global warming levels motivated by an aim to be consistent with current policy framings. Secondly, an increasing attention paid to extreme weather has sometimes overshadowed longer time-scale changes such as the aridification of an increasing fraction of arable land and the increasing variability of the water cycle from month to month, season to season, and year to year that also yield cascading impacts on all water use sectors. Thirdly, a stronger focus is needed on understanding the effectiveness of current and future adaptation strategies in reducing water-related climate risks. Finally, the role of water has not been adequately recognized in the assessment of mitigation strategies although the compliance with the Paris Agreement and the current pledges all require a massive deployment of land-based strategies whose feasibility and efficiency heavily depend on water resources. It is thus essential to develop a more integrated approach to water and climate change, that would allow scientists and policymakers to "close the loop" between mitigation options, water cycle changes, hydrological impacts and adaptation.

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1. Introduction

Water-related risks are increasing as Earth continues to warm in response to human-caused emissions of greenhouse gases (GHGs), with the vulnerability of human societies varying within and across countries and over time. Yet, the linkages between global water cycle changes, associated impacts and mitigation policies are not well integrated. Water has always been a central concern of the Intergovernmental Panel on Climate Change (IPCC), but has long been the focus solely of impacts and adaptation as part of the Working Group 2 (WG2) assessments (e.g., [1]), rather than an integral part of the scientific understanding found in Working Group 1 (WG1). Indeed, it was not until the recent sixth IPCC assessment report (AR6) that water cycle changes were the subject of a specific chapter in WG1, while a chapter entitled "hydrology and water resources" was already included in the first WG2 report back in 1990. Yet, precipitation and evaporation had been highlighted by WG1 in their first assessment report as critical scientific topics where efforts were needed to narrow uncertainties in climate projections. And the first assessment report from WG2 stated that climate change can be expected to lead to changes in soil moisture and water resources, but that water cycle changes, especially precipitation, cannot be predicted well at the regional scale.

More than thirty years later, substantial progress has been made in the understanding and quantification of water cycle changes, which have been comprehensively evaluated in Chapter 8 of the AR6 WG1 [2], while their multiple impacts and consequences for adaptation policies have been assessed in Chapter 4 of the AR6 WG2 [3]. As coauthors of these two IPCC chapters, we are well placed to highlight progress made since the first IPCC report and to recommend future directions to fellow scientists and decision-makers. Our synthesis is organized into four main sections. Water cycle projections remain highly uncertain in many respects and there is no quick and simple solution to this long-standing issue (Section 2). Human-induced water cycle changes can emerge abruptly and at multiple scales due to the compound effect of GHG and aerosol, the increasing water cycle variability, and the growing water demand from both the atmosphere and the global population (Section 3). Water is therefore at the center of adaptation policies and of socio-economic development in many countries, but more focus is needed on understanding and evaluating the effectiveness of current and future adaptation in reducing climate risks (Section 4). Moreover, water should probably receive more attention from the IPCC Working Group 3 (WG3) since all mitigation scenarios compatible with the Paris Agreement partly rely on land-based mitigation options which are potentially water-limited (Section 5). A final synthesis is provided in Section 6, claiming for a more integrated approach to water in both climate change assessments and policies.

2. Model uncertainty in global water cycle projections

Global and regional climate projections are increasingly used for adaptation, mitigation and resilience planning. During the sixth phase of the Coupled Model Intercomparison Project (CMIP6), more than 50 (not fully independent) global climate models were assessed and compared, in terms of idealized, past, historical and future climates. The overall ensemble mean structure of projected water cycle changes has remained stable since CMIP1, illustrating the remarkable skill of the early coupled climate models. Yet, and despite significant progress made in model performance, individual models still diverge in their projections of water cycle changes at both global and regional scales [2, 4, 5]. This long-standing issue remains a major difficulty for the design of climate change policies [3]. A growing number of climate scientists therefore call for a stronger focus on low-likelihood, high-impact outcomes (e.g., [6–8]), suggesting that uncertainties (and plausible worst case scenarios) should be an additional lever for both adaptation and mitigation actions.

Some prominent scientists have recently expressed their "*deep dissatisfaction with the ability of our models to inform society about the pace of global warming, how this warming plays out regionally, and what it implies for the likelihood of surprises*" [9]. This self-criticism highlights the on-going debate about what a policy-relevant and tractable climate change information should look like. It obviously takes time, computing and human resources to improve climate models and make them fitted for purpose, or to develop and run ultra-high resolution global climate models that may limit the use of empirical representations (the so-called "parameterizations") of sub-grid processes. Conversely, it only takes a few hours of reading the latest IPCC Working Group (WG) 1 and WG2 summaries for policymakers [10, 11] to become convinced that climate change is occurring faster than ever, because of human activities, and with multiple adverse consequences in most if not all regions at the Earth's surface. Such key findings should be sufficient to trigger much more ambitious climate change policies. Yet, the questions of exactly where, when and how severe these water cycle impacts will occur remain partly unanswered [2, 3, 9].

It is therefore crucial that researchers agree on the best way to use climate projections to provide consistent information about our future climate and its most detrimental manifestations. For the first time in IPCC history, global projections of temperature have not been based on raw model outputs, but on constrained projections based on multiple evidence including understanding of feedback processes, paleo-climate records, and the observed historical warming [5, 12]. In other words, a subset of CMIP6 models have been thus considered as "too hot" over recent decades to be reliable across the 21st century. This silent revolution signals the end of "model democracy", at least for global surface temperature, ocean warming and sea level rise. Internationally renowned scientists recently called on the rest of the climate research community to "*do the same*" for other variables [13], and their proposed common-sense recommendations deserve further discussion.

[13] first suggest following the lead of the AR6 to base analyses on global warming levels (GWLs) rather than on emission scenarios and time horizons. For example, instead of assessing changes in rainfall for a given emissions scenario by the year 2100, researchers can report changes at GWLs of 1.5, 2, 3 and 4°C. This option would not only mirror the dominant policy discourse surrounding the Paris Agreement targets, but it is also a means of comparing model results independently of emissions scenarios. Moreover, this avoids the need to select or weight CMIP6 models depending on whether their global temperature response to CO2 increase is deemed within an acceptable range, yet does not circumvent the problems of gauging when and how quickly regional hydroclimatic changes are realized and thresholds breached. All models are deficient to a greater or lesser extent, but nevertheless can still provide information relevant to exploring the multi-dimensional aspects of climate change that should be considered in the context of available observational constraints [14, 15].

If the warming trajectory—rather than just the GWL—is important for a particular climate outcome, a second option is to focus on the subset of CMIP6 models that is most consistent with AR6 assessed-warming projections. [13] therefore recommend screening out models with a transient climate response (TCR) that lies outside the "likely" range (1.4–2.2°C). However, there are multiple cases where global warming is not very informative about the water cycle response, even at the global scale (cf. panels b-d in Fig 1). Model versions within an acceptable range of climate sensitivity may poorly represent regional water cycle changes compared with models exhibiting climate sensitivity that is deemed too high or too low, and there is increasing evidence that narrowing climate sensitivity will not help constrain future hydroclimate changes in most regions [16]. Therefore, the AR6 advances in constraining global temperature projections have not so far resulted in more robust water cycle projections.

The third and last option is to pick climate models that are best suited to the task at hand. [13] recognize that, in cases in which model spread is not clearly related to the spread in climate sensitivity, alternative metrics might be more appropriate. Yet, the fit-for-purpose strategy of the AR6 WG1 illustrates the difficulty of such an option. There is for instance no

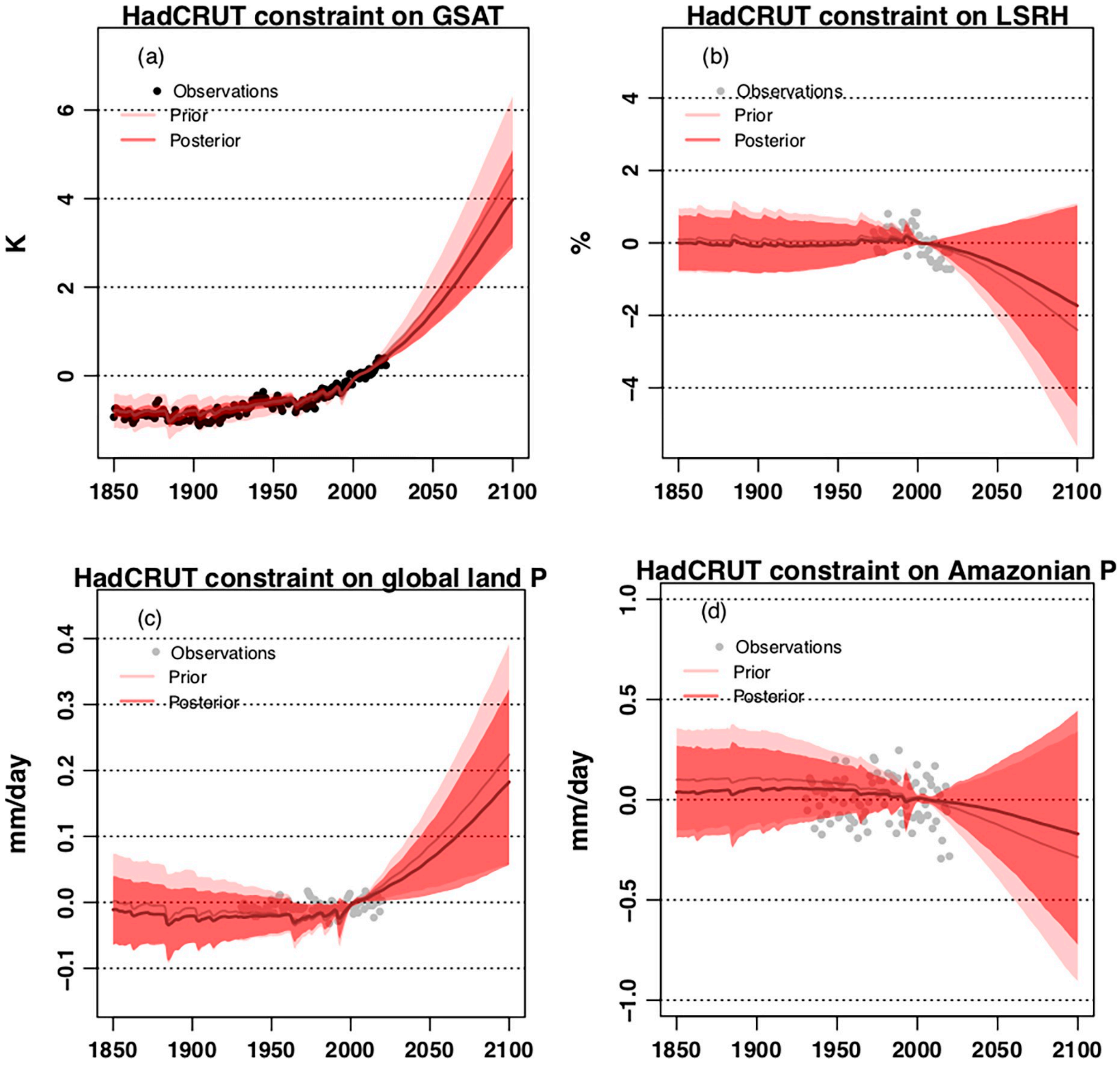

Fig 1. Constrained versus unconstrained annual mean changes in a) global mean surface air temperature (GSAT in K), b) global mean land surface relative humidity (LSRH in %), c) global land precipitation (mm/day), and d) Amazonian precipitation (mm/day). Mean (solid lines) and 5–95% range (shading) of the *prior* (unconstrained projections) and *posterior* (projections constrained by the observed global warming) distributions of the forced response to natural and anthropogenic radiative forcings in historical simulations and SSP5-8.5 projections from thirty-two CMIP6 models. Although based on a blending of sea surface temperature over ocean and near-surface air temperature over land, the HadCRUT observations are here used as a surrogate for observed GSAT to constrain all projections using the Kriging for Climate Change method developed by [14]. Compared to the *prior*, the *posterior* 5–95% interval at the end of the 21st century is reduced by 33% for GSAT projections, but only by 12% for LSRH, 20% for global land precipitation and 6% for Amazonian precipitation, respectively. The observed anomalies are shown as black (gray) filled circles when they are (not) used for constraining the model response. Note that the global warming observational constraint does not necessarily shift the ensemble mean response in the same direction as the observed water cycle changes in panels b and d. Source: inspired from [15].

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comprehensive list of eligible criteria for a climate model to be trusted in water cycle projections and, if such a list was to be established, how many models could still be used? The problem may be thus more complex than anticipated, especially given the difficulty in applying observational constraints once such observations have been used in the tuning process [17]. The IPCC scoping decision to assess the model fit-for-purpose in individual WG1 chapters may therefore not be the best option to deliver consistent guidelines and best practices about the use of global climate models.

To sum up, climate scientists are still facing multiple challenges when it comes to providing useful and usable information about water cycle changes. Despite a better understanding of the underlying mechanisms and a growing consensus on the expected changes, there are many cases where the quantification of such changes is still very uncertain, even for a given emission scenario. In some cases (e.g., hail, ice storms, sting jets, mesoscale convective storms, tropical cyclones), observations are short term or lack homogeneity, and models do not have sufficient resolution or accurate parameterization to adequately simulate the relevant phenomena, making model assessment problematic. Convection-permitting regional or even global climate models may then be needed to provide more reliable projections. However, available projections can be constrained with observations as long as water cycle changes can be partly attributed to GHG emissions in multidecadal quality-checked observations. Such observational constraints are generally based on Bayesian statistical methods and can be more reliable than more empirical emergent constraints based on linear regression techniques. Improved bias-adjustment and dynamical or statistical downscaling techniques are also needed to provide usable climate information at the local scale where most adaptation strategies are dimensioned.

3. Increasing water cycle perturbations due to human activities

Observational records and climate projections, in the context of physical understanding, provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems [1]. Despite this early recognition, the detection and attribution of water cycle changes have long been compromised by the lack of sufficiently reliable observed series and the high natural variability of the water cycle [18]. Substantial advances have been made in this field over recent years, which further support, at least qualitatively, the future changes expected from theoretical understanding and/or projected by global climate models.

According to Chapter 8 of the AR6 WG1 [2], there is high confidence that the global water cycle has intensified since at least 1980, expressed by, for example, increased atmospheric moisture fluxes and amplified patterns of precipitation minus evaporation (P-E). Global total column water vapor content has increased since the 1980s [2, 4] and it is also likely that human influence has contributed to tropical upper tropospheric moistening and, thus, to a strongly positive water vapor feedback on global warming. Near-surface specific humidity has increased over the ocean (likely) and land (very likely) since at least the 1970s, with a detectable human influence. Human influence has also been detected in amplified surface salinity and P–E patterns over the ocean. Global land precipitation has likely increased since 1950, with a faster increase since the 1980s and a likely human contribution to patterns of change, particularly for increases in high-latitude precipitation over the Northern Hemisphere.

The expected increase in global mean precipitation is determined by a robust response to global surface temperature (very likely 2–3% per ˚C) that is partly offset by fast atmospheric adjustments to atmospheric heating by GHGs and aerosols [4, 19, 20]. The overall effect of anthropogenic aerosols is to reduce global precipitation through surface radiative cooling effects. More anthropogenic aerosols lead to less solar radiation absorbed at the land surface and less evapotranspiration. Over much of the 20th century, opposing effects of GHGs and aerosols on precipitation have been observed for some regional monsoons [2]. The strong influence of anthropogenic aerosols on the global water cycle, including their counteracting effect on GHG-induced increases in monsoon precipitation and mid-latitude aridity in the

Northern Hemisphere, is one of the key findings of the AR6 WG1 Chapter 8. It explains why global warming has had so far a limited impact on water resources. Yet, the overall decline in aerosol emissions since the mid 1980's has led to a reversal of the anthropogenic aerosol forcing on the global water cycle, a reduced inter-hemispheric asymmetry in global warming, a partial recovery of monsoon precipitation over the Sahel, but also an increased aridity over the northern mid-latitudes.

There are currently more AR6 regions with observed human-induced increases in the frequency and intensity of heavy precipitation events than with attributable increases in drought severity since the mid-20th century (AR6 Fig SPM.3, [10]). Nevertheless, there is high confidence that anthropogenic warming over land drives an increase in atmospheric evaporative demand and in the severity of hydrological and agricultural drought events. Longer dry spells are projected to occur under continued climate warming, particularly during the annual dry season, which may negatively impact perennial crops and forests [21]. Greater warming over land than over the ocean alters atmospheric circulation patterns and reduces continental near-surface relative humidity, which also contributes to regional drying. A very likely decrease in relative humidity has occurred over much of the global land area since 2000 and some studies suggest that this land surface drying could be underestimated by many global climate models [22, 23] though homogeneity of the global observing system remains questionable. There is also growing evidence that sub-daily to daily precipitation intensities associated with short-lived convective storms will increase with continued global warming, lead to a stronger runoff to precipitation ratio and, thus, decrease soil moisture availability in areas and seasons with no overall increase in precipitation [24].

As long as global warming is not stabilized, global annual precipitation over land is projected to increase but at a much lower rate than atmospheric total precipitable water (Fig 2). As a consequence, there is no overall acceleration of the global water cycle but a global intensification, including more variability and extremes, which will lead to a stronger volatility of water resources at the regional scale [25, 26]. In the tropics year-round (Fig 2) and in the summer season elsewhere, interannual variability of precipitation and runoff over land is projected to increase at a faster rate than changes in seasonal mean precipitation. Projected patterns of precipitation change exhibit substantial regional differences and seasonal contrast as global surface temperature increases over the 21st century. Sub-seasonal precipitation variability is also projected to increase, with fewer rainy days but increased daily mean precipitation intensity over many land regions. While the widely used paradigm that "wet gets wetter and dry gets drier" appears as an oversimplification of the complex water cycle response over land, the expectation that water becomes even more abundant when it is in excess and even scarcer when it is in deficit (more severe wet and dry extremes) remains generally well founded [2].

Over the 21st century, and with more or less amplitude depending on future GHG emissions or GWLs, projected increases in evapotranspiration due to growing atmospheric water demand will decrease soil moisture over the Mediterranean region, south-western North America, South Africa, south-western South America and south-western Australia (Fig 3). Some tropical regions are also projected to experience enhanced aridity, including Central America and the Amazon, and regional decreases in precipitation additionally contribute to aridification as well as compound hot-dry events [27]. The total land area subject to increasing drought frequency and severity will expand, and future aridification will far exceed the magnitude of change seen in the last millennium in the Mediterranean, south-western South America, and western North America. Moreover, there is high confidence that mountain glaciers will diminish in all regions and that seasonal snow cover duration will generally decrease with continued global warming. Runoff from small glaciers will typically decrease through loss of ice mass, while runoff from large glaciers is likely to increase with increasing global warming

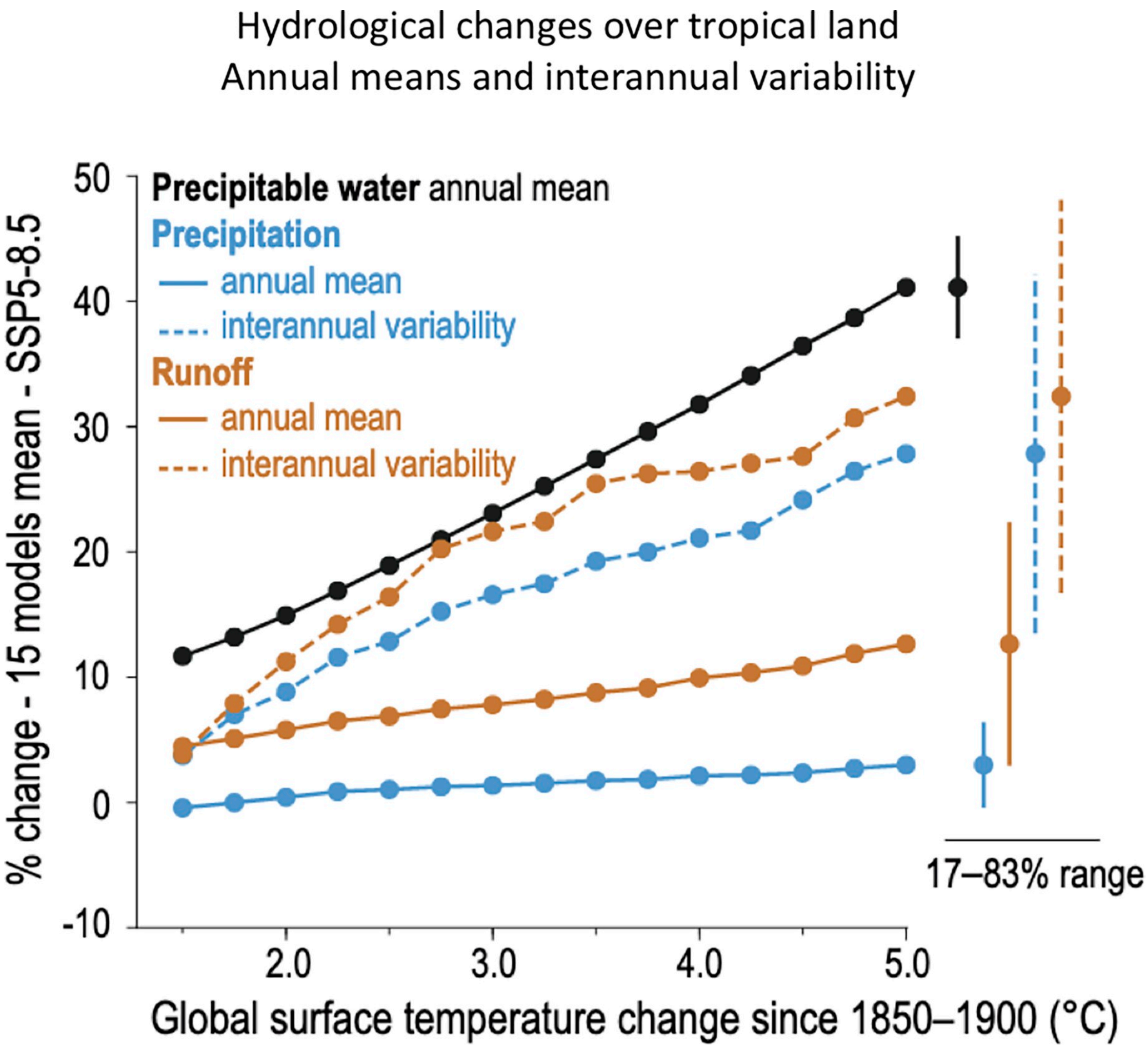

Fig 2. Synthesis of projected hydrological changes over tropical land areas relative to 1850–1900 as a function of increasing global warming levels (GWLs). Relative change (%) and related 66% confidence interval (at a 5˚C GWL only) in annual mean total precipitable water (black lines), precipitation (blue solid lines), runoff (brown solid lines), and in standard deviation (i.e., variability) of precipitation (blue dashed lines) and runoff (brown dashed lines), averaged over tropical land as function of GWLs, using a subset of 15 CMIP6 models that reached a 5˚C GWL above the 1850–1900 average in the SSP5-8.5 scenario. Source: From IPCC, Cycle 6, Working Group 1, Fig TS.12, panel e, 2021.

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until glacier mass becomes depleted, with potential for major loss of water availability in downstream regions [2].

Besides the impact of global warming, land-use change and water extraction for irrigation have already influenced local and regional responses in the water cycle. Large-scale deforestation has likely contributed to a decrease in evapotranspiration and precipitation and an increase in runoff over the deforested regions relative to the regional effects of climate change. Urbanization can increase local precipitation, but mostly reduces soil permeability and increases runoff intensity. While increased precipitation intensities have enhanced groundwater recharge, most notably in tropical regions (medium confidence), there is high confidence that groundwater depletion has occurred since at least the start of the 21st century, as a consequence of groundwater withdrawals for irrigation in agricultural areas in drylands [28].

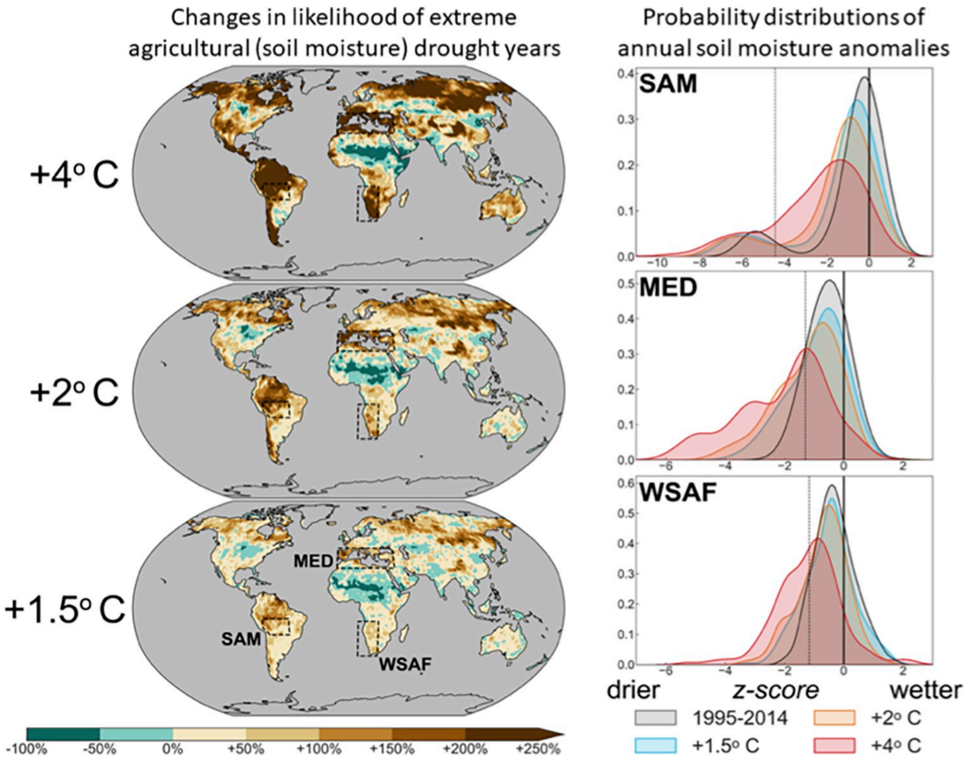

Fig 3. Projected changes in the likelihood of an extreme single-year agricultural drought event at different Global Warming Levels (GWLs), following [51]. left: Percentage change in the likelihood of extreme soil moisture drought at GWLs of 4˚C (top), 2˚C (middle) and 1.5˚C (bottom), with "extreme drought" defined locally as the 10th percentile of anomalies in total soil moisture in individual grid boxes. Likelihoods are calculated using the whole CMIP6 ensemble (, and all ensemble members are treated as equally likely potential outcomes, Right: probability distribution functions of regional mean soil moisture anomalies for the Mediterranean (MED), South American Monsoon (SAM) and West Southern Africa (WSAF) regions [52], at 1.5˚C, 2˚C and 4˚C GWLs. The solid vertical line shows the baseline, i.e., 50th percentile in 1995–2014. The dashed vertical line shows the 10th percentile for 1995–2014, defining "extreme drought" at the regional scale. Projections used the SSP5-8.5 high-emission scenario to maximise the number of ensemble members at higher GWLs, but global patterns of change are very similar for all scenarios (cf. [51]) and for any given GWL. Source: From IPCC, Cycle 6, Working Group 2, Fig 4.18, 2022.

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To sum up, water cycle changes are increasing and are now emerging in some cases abruptly given the combined and time-varying influence of anthropogenic GHG and aerosols in many regions. There is now robust evidence for a reversal of the trend in aerosol effective climate forcing [29], and this decreasing cooling effect is now compounding the water cycle changes due to GHG-induced global warming. These changes will not only manifest as more frequent and more intense short-term heavy rainfall events but will also occur at longer time-scales, including more extreme wet and dry seasons, years and decades. Drought events will be favored by less regular precipitation but also by the retreat of glaciers, a reduced winter snow-pack and a growing atmospheric evaporative demand, and should therefore become faster, longer, larger and more severe. Adaptation policies must consider changes in extreme weather events, but also changes at larger spatial and temporal scales, including dry events and a projected aridification beyond the subtropics, as well as compound events and worst-case scenarios where such water cycle responses to human activities may be reinforced by natural climate variability. Land use and irrigated farming can also contribute to amplify water cycle changes at the regional scale and should be thus managed carefully.

4. Water is central to adaptation

The majority of people, especially in climate-exposed livelihoods like agriculture and particularly in the Global South, experience climate change through water and in turn also use water for adaptation. According to Chapter 4 of the AR6 WG2 [3], half of the world's population already face water scarcity for at least one month in a year due to various reasons, including (but not exclusively) climate change. Global water demand in most sectors, particularly irrigation, is further projected to rise, and that, coupled with poor water governance and regulations is expected to lead to even larger water extraction over the next few decades. Water insecurity will put food and energy security at risk given that 80% of consumptive water usage goes to agriculture, that 50% of global food production is irrigated [30] and that 19% of global thermal electricity generation comes from 10% of the most water stressed basins [31]. Additionally, considering expected and ongoing population growth in cities everywhere, but particularly in the Global South, models show that more than 440 million people in cities globally will be faced with water insecurity by 2050 [32]. Cities in the Global South will be particularly at risk given that most people lack access to water, sanitation and hygiene (WaSH) infrastructures [33]. The water cycle intensification highlighted by WG1 [2] is thus not the main threat to water resources at the regional scale, but it will unquestionably exacerbate existing water-related vulnerabilities caused by other socio-economic factors. Large uncertainties in future changes in hydrometeorological conditions and hence in water availability and/or hazards (eg. drought, Fig 3) further increase the level of challenge for adaptation [3].

Climate change is not experienced equally across populations. Race, gender and socio-economic conditions are constitutive elements of climate change vulnerability. Marginalized communities, such as Indigenous Peoples, relying on natural resource provisions are directly impacted by climate change-induced water disasters through freshwater ecosystems degradation, diminishing availability of fishing and foraging opportunities [34, 35]. Likewise, women, who are globally the chief domestic water providers, have seen an increased burden in water management due to the direct impacts of climate change-induced water cycle intensification, particularly in the form of floods and droughts [36–39].

A huge proportion of people, mainly in the Global South, experience climate change first and foremost through water related hazards such as extreme rainfall events, floods, droughts, rainfall variability etc. It is therefore not surprising that major share (~60%) of all adaptations documented in the literature are about water–those are either about people and communities adapting to water related hazards, or using water for adaptation, e.g. irrigation, soil moisture conservation, rainwater harvesting, water storage [3, 40]. WG2 Chapter 4 on water [3] assesses hundreds of such documented cases about these water-related adaptation strategies (defined as such when either hazard is water, or response involves water) and finds that they have many benefits on multiple dimensions. For example, the adoption of drought resistant crops, or better irrigation and on-farm water management can help in improving incomes and crop production, while better soil moisture conservation measures help in improved soil health and fertility (hence better environmental outcomes). Similarly, a large number of adaptation responses to water hazards that involve collective action (e.g. creation of water user groups; community based early warning systems for floods) can also empower local populations, including women and marginalized groups.

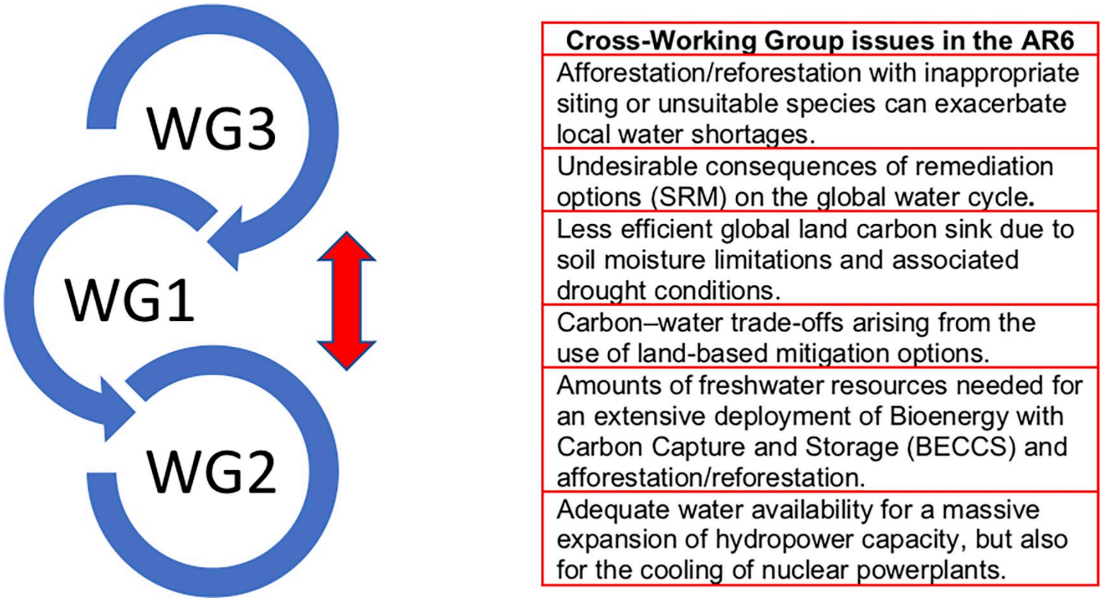
However, whether or not current adaptation measures are reducing climate risks (through reduction in hazard, vulnerability and exposure) is not clear from the existing literature and remains a major blindspot in our current understanding of climate change and adaptation. The water chapter in WG2 [3] also assesses future effectiveness of some of the current adaptation options at higher GWLs, and concludes that majority of the adaptation measures will become less effective at GWL beyond 2˚C and above. This may be true for water-related but also for water-dependent adaptation strategies. For instance, the greening of cities is often cited as an effective strategy to limit the impacts of heatwaves on urban populations, but this effectiveness is highly dependent on the availability of water resources. This example illustrates that space and scope for adaptation becomes seriously constrained in a warmer world, and that it is imperative to remain within the Paris declared climate goals.

To sum up, water insecurity is already being faced by a majority of the world population and climate change has been shown to worsen further the situation for billions of people. Given the centrality of water for sustainable development goals, adaptation is key to respond to the enhanced risk caused by climate change. Vulnerability varies widely across people both within and between countries. Adaptation is and will be crucial across all contexts to reduce vulnerability to water insecurity. While existing evidence of adaptation in the water sector is prevalent in agriculture, growing world population and urbanization demand that adaptation increasingly takes place in cities and also focuses on the water, sanitation and hygiene (WaSH) sector. Additional research and prompt implementation of these strategies are needed, taking into account potential physical and financial limitations at increasing GWLs. As such, the next assessment report from WG2 will need to focus more on understanding the effectiveness of current and future adaptation in reducing climate risks, for which evidence remains patchy.

5. Water footprint of mitigation is not explicitly considered in climate policies and negotiations

Water security is critical for meeting Sustainable Development Goals (SDGs) and system transitions needed for climate-resilient development, yet many mitigation measures have a high water footprint (Fig 4), which can compromise SDGs and adaptation outcomes [3]. Afforestation/reforestation is an apt example where studies show that inappropriate citing of forests or unsuitable species can exacerbate local water shortages and also create change in local and regional water cycles [41–43]. Nevertheless, global climate policy, as reflected in the international negotiations within the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COPs), is still largely focused on mitigating global warming, regardless of its hydrological impacts and consequences for mitigation options. The Paris Agreement reached at COP21 in 2015 led to ambitious maximum global warming targets, either a 2˚C or even a 1.5˚C level relative to preindustrial times. Since COP21, the Nationally Determined Contributions (NDCs) have been complemented with mid-century strategies for up until 2050. The so-called "net-zero carbon emission" challenge relies on a drastic decarbonization in the energy sector, but also on strong reductions of GHG emissions from land, coming from the agriculture sector and other forms of land-based carbon storage and management. However, "*the current focus of climate policy on energy and land measures leaves behind a third sibling that is critical to addressing local and global climate goals*: *water*" [44].

The feasibility of the illustrative emissions scenarios considered by WG1 and WG2 needs to be assessed by WG3. In its summary for policymakers [45], WG3 highlights that progress on the alignment of financial flows towards the goals of the Paris Agreement remains slow and tracked climate finance flows are distributed unevenly across regions and sectors. Yet, the potential physical limitations to mitigation options are less emphasized. It has been for instance argued that the highest GHG emissions (SSP5-8.5) scenario is misleading since it would require an unprecedented fivefold increase in coal use by the end of the century, an amount larger than some estimates of recoverable coal reserves [46]. Surprisingly, the plausibility of the best-case scenarios (SSP1-1.9 and SSP1-2.6 in the AR6) does not seem to be as controversial despite their bold assumptions on our ability to compensate our unavoidable



Cross-Working Group issues in the AR6
Afforestation/reforestation with inappropriate siting or unsuitable species can exacerbate local water shortages.
Undesirable consequences of remediation options (SRM) on the global water cycle.
Less efficient global land carbon sink due to soil moisture limitations and associated drought conditions.
Carbon–water trade-offs arising from the use of land-based mitigation options.
Amounts of freshwater resources needed for an extensive deployment of Bioenergy with Carbon Capture and Storage (BECCS) and afforestation/reforestation.
Adequate water availability for a massive expansion of hydropower capacity, but also for the cooling of nuclear powerplants.

Fig 4. Closing the IPCC loop. The IPCC assessment is shared among three Working Groups (WGs). WG1 aims at assessing the physical scientific basis of the climate system and climate change. WG2 assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting to it. WG3 focuses on climate change mitigation, assessing methods for reducing GHG emissions, and removing GHGs from the atmosphere. Here, we argue that there is a gap in the IPCC assessment given the potential hiatus between the mitigation options that underlie the GHG emissions scenarios assessed by WG1 and the water-related impacts of the corresponding climate projections. It should be thus a priority to assess whether the proposed mitigation options, including bioenergy with carbon capture and storage or afforestation/reforestation, are truly resilient to the projected climate change.

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residual GHG emissions with negative CO_2 emissions. As WG1 and WG2 authors, our aim here is not to assess the feasibility of such mitigation options (the task of WG3), but to highlight their questionable resilience to the on-going climate change given their potential vulnerability to water cycle changes and related hydrological impacts.

Water is at the front lines of climate change not only because it is the main channel through which global warming impacts are felt across key drivers of the global economy and across many ecosystems, but also because less regular precipitation, enhanced evapotranspiration and more volatile water resources will exert a growing constraint on mitigation policies. Plans for reducing GHG emissions from the energy sector typically rely on the optimistic assumptions of adequate water availability for a massive expansion of generation capacity, regardless of the water limitation constraints on hydropower, but also nuclear sources of energy. Other global warming consequences that are mediated through water include effects on human health and changes in natural habitats, watersheds and biodiversity [3, 47]. Moreover, water has been so far largely ignored in climate change policy interventions. Yet, water resources will become increasingly volatile in many regions and their effective management will be pivotal in addressing the climate challenge, both for adapting to the effects of climate change and for meeting global GHG mitigation goals [48].

Unfortunately, water has not been given a primary importance in the outline of the AR6 WG3 report. Even in the AR6 WG1, the splitting of the energy, water and carbon cycles into three distinct chapters has not favored the assessment of the water-carbon nexus. This has been partly alleviated by a cross-chapter box in the AR6 WG1, but a more comprehensive assessment would be needed given the intense debate on potentially overestimated land-based solutions [49, 50]. Cross-chapter box 5.1 in the AR6 WGI highlighted carbon–water trade-offs arising from the use of land-based climate change mitigation options. It concluded with high confidence that the global net land CO2 sink is reduced on the interannual scale when regional-scale reductions in water availability associated with droughts occur, particularly in tropical regions. There is also high confidence that the global land sink will become less efficient due to soil moisture limitations and associated drought conditions in some regions under high-emissions scenarios.

However, there is only low confidence on how water cycle feedbacks will play out in the future, due to uncertainties in regional rainfall changes and the balance between the CO2 fertilization effect, through water-use efficiency and the radiative impacts of GHGs. Moreover, an extensive deployment of Bioenergy with Carbon Capture and Storage (BECCS) and afforestation/reforestation was found to require larger amounts of freshwater resources than used by the previous vegetation, altering the water cycle at regional scales. Consequences of high-water consumption on downstream uses, biodiversity, and regional climate depend on prior land cover, background climate conditions, and scale of deployment (high confidence). Therefore, a regional approach is required to determine the efficacy and sustainability of Carbon Dioxide Removal (CDR) projects. Unfortunately, such a regional approach may not be conservative enough if based on the most likely water cycle response given the large residual model uncertainties in the projected changes at the regional scale and the possible transient worsening effect of internal climate variability [2, 3].

It is important to highlight that some remediation options do not only rely on water availability for their implementation but may have undesirable or unexpected consequences on the global water cycle. For instance, Chapter 8 of the AR6 WGI [2] finds that it is very likely that abrupt water cycle changes will occur if Solar Radiation Modification (SRM) techniques are abruptly initiated or halted, especially in tropical regions. The impact of SRM is spatially heterogeneous (high confidence), it will not fully mitigate the GHG-forced water cycle changes (medium confidence), and it can affect different regions in potentially disruptive ways (low confidence). Also, the summary for policymakers of the AR6 WG3 [45] indicates that afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including water security, especially if implemented at large scales and where land tenure is insecure.

To sum up, there are multiple ways to reduce our emissions of GHGs with potential social and environmental co-benefits, for instance on air quality. Yet, and beyond financial issues, there are possible physical limits to mitigation scenarios. While finite fossil energy reserves may invalidate the highest-emission scenario assessed in the AR6, the low-emission scenarios compatible with the Paris Agreement not only rely on the sustainability of hydroelectric power generation, but also on the strengthening of natural terrestrial carbon sinks to absorb our residual GHG emissions. By so doing, the socio-economic pathways may not fully consider the hydrological consequences of the related emission pathways and the on-going impacts already observed in the energy, agriculture and forest sectors. This shows the urgent need of considering not only the feasibility of the different mitigation strategies in terms of the required technology or resources but also, and probably more importantly, in terms of their social and environmental impacts, particularly in water-related aspects. It requires a more inter and transdisciplinary view of mitigation.

6. Conclusions

Currently, about half of Earth's 8 billion people are estimated to experience severe water scarcity for at least one month per year due to climatic and non-climatic factors, and there is increasing evidence of observed impacts of water cycle changes on people and ecosystems. A significant share of those impacts is negative and felt disproportionately by already vulnerable communities [3]. Water-related risks are projected to further increase with continued global warming, and more vulnerable and exposed regions and peoples are projected to face greater risks than those responsible for most of the past GHG emissions.

While freshwater resources have always been an integral part of the IPCC assessment reports, they were mainly the focus of WG2 until a chapter on water cycle changes appeared in the 6th assessment report from WG1. Beyond the physical basis of climate change, the key role of water is not fully recognized by WG3, which may still overlook possible water limitations to the assessed mitigation strategies. It is therefore essential to develop a more integrated approach to water and climate change, that would allow scientists and policymakers to "close the loop" between mitigation options, water cycle changes, hydrological impacts and adaptation. Water is central to many Sustainable Development Goals and would therefore benefit from a special IPCC report involving all WGs.

Beyond climate sciences, water is still missing from international climate change negotiations. To the best of the authors' knowledge, none of the COP documents ever mentioned water and, certainly, water does not feature even once in the Paris Agreement. Yet, the feasibility of low-emission scenarios that may be still compatible with this agreement does not only depend on the energy-carbon nexus, but also on water resources and their interactions with both the energy and carbon cycles.

International negotiations on climate change often stall on the compensation of damages and the amount of fundings for the adaptation of countries in the Global South. So far, about 60% of all adaptation responses are about water-related hazards or involve water as an adaptation response. Unfortunately, the effectiveness of current and future adaptation strategies in reducing climate related risks has not been yet assessed thoroughly. Meanwhile, it is quite clear that the effectiveness of most adaptation measures will decline at higher levels of global warming, hence the need to limit global warming to 2˚C and 1.5˚C if still feasible.

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