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The hazard components of representative key risks. The physical climate perspective

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A B S T R A C T

The framework of Representative Key Risks (RKRs) has been adopted by the Intergovernmental Panel on Climate Change Working Group II (WGII) to categorize, assess and communicate a wide range of regional and sectoral key risks from climate change. These are risks expected to become severe due to the potentially detrimental convergence of changing climate conditions with the exposure and vulnerability of human and natural systems. Other papers in this special issue treat each of eight RKRs holistically by assessing their current status and future evolution as a result of this convergence. However, in these papers, such assessment cannot always be organized according to a systematic gradation of climatic changes. Often the big-picture evolution of risk has to be extrapolated from either qualitative effects of "low", "medium" and "high" warming, or limited/focused analysis of the consequences of particular mitigation choices (e.g., benefits of limiting warming to 1.5 or 2C), together with consideration of the socio-economic context and possible adaptation choices.

In this study we offer a representation – as systematic as possible given current literature and assessments – of the future evolution of the hazard components of RKRs.

We identify the relevant hazards for each RKR, based upon the WGII authors' assessment, and we report on their current state and expected future changes in magnitude, intensity and/or frequency, linking these changes to Global Warming Levels (GWLs) to the extent possible. We draw on the

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assessment of changes in climatic impact-drivers relevant to RKRs described in the 6th Assessment Report by Working Group I supplemented when needed by more recent literature.

For some of these quantities - like regional trends in oceanic and atmospheric temperature and precipitation, some heat and precipitation extremes, permafrost thaw and Northern Hemisphere snow cover - a strong and quantitative relationship with increasing GWLs has been identified. For others - like frequency and intensity of tropical cyclones and extra-tropical storms, and fire weather - that link can only be described qualitatively. For some processes - like the behavior of ice sheets, or changes in circulation dynamics - large uncertainties about the effects of different GWLs remain, and for a few others - like ocean pH and air pollution - the composition of the scenario of anthropogenic emissions is most relevant, rather than the warming reached. In almost all cases, however, the basic message remains that every small increment in CO_2 concentration in the atmosphere and associated warming will bring changes in climate phenomena that will contribute to increasing risk of impacts on human and natural systems, in the absence of compensating changes in these systems' exposure and vulnerability, and in the absence of effective adaptation. Our picture of the evolution of RKR-relevant climatic impact-drivers complements and enriches the treatment of RKRs in the other papers in at least two ways: by filling in their often only cursory or limited representation of the physical climate aspects driving impacts, and by providing a fuller representation of their future potential evolution, an important component – if never the only one – of the future evolution of risk severity.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC)'s Working Group II (WGII) – tasked with the assessment of Impacts, Adaption and Vulnerability – has used the concept of representative key risk (RKR) as an organizing label to categorize a large number of sectoral and regional risks identified as becoming potentially severe with climate change (Oppenheimer et al., 2014; O'Neill et al., 2022). In the latest report, Chapter 16 of the WGII contribution to the IPCC Sixth Assessment Report (AR6) (O'Neill et al., 2022) clusters more than 100 key risks identified through the assessment of the regional and sectoral chapters of the same report into eight RKRs. Quoting the chapter description, "The RKRs are intended to capture the widest variety of Key Risks to human or ecological systems with a small number of categories that are easier to communicate and provide a manageable structure for further assessment.".

The established risk framework that informs the whole IPCC AR6 identifies more than just *climatic conditions* (usually called hazards in this detrimental role) as the drivers of current and future risks (Reisinger et al., 2020). *Exposure* of systems or assets to adverse climatic conditions and their level of *vulnerability* are also critical determinants of the potential outcome, as well as any adaptation or mitigation *responses* undertaken to reduce any of these components of risk. Accordingly, risk assessment needs to be informed by a complete evaluation of all these components. In this paper, we offer the limited but necessary perspective of the physical climate science, by identifying climatic impact-drivers (CIDs, Ranasinghe et al., 2021; Ruane et al., 2022) that have the potential to become hazards relevant to the various risks constituting the eight RKRs. Once identified, the relation between the CIDs/hazards and the magnitude of global warming is characterized and, where possible, quantified. This focus on the climatic conditions potentially driving impacts has at least two functions. The first is to fill in the picture of future outcomes by drawing a more explicit representation of the physical conditions that are associated to the various risks. The second, especially when the quantification of the relation to global warming is possible, is to provide a scale along which future risk levels may grow in severity, all else being equal, as the determination of what constitute a potentially severe risk is in part driven by the expected changes in the climatic conditions affecting the system at risk.

Our work in this paper rests upon the assessment published as part of IPCC AR6 Working Group I (WGI) Chapter 12 – titled "Climate change information for regional impact and for risk assessment" – a chapter that was conceived as facilitating linkages and consistency between WGI and WGII. While the bulk of the chapter connects to the regional chapters of the WGII report, the chapter's section titled "A global perspective on climatic impact-drivers" (12.5) includes a cross-chapter box (Tebaldi et al., 2021a) summarizing the current state and future projections of a set of metrics describing hazards relevant to the assessment of Representative Key Risks (RKRs) and Reasons For Concern (RFCs), i.e., aiming to connect specifically to WGII chapter 16, "Key risks across sectors and regions" (O'Neill et al., 2022), and its synthetic view of climate-related risks. The cross-chapter box is essentially a large table listing CIDs/hazards and their connection to the eight RKRs. By necessity, the table is succinct and states the connections between CIDs and RKRs without further elaboration. In this paper we elaborate on the RKR descriptions and the CID connections further. The relevance of CIDs to specific sectoral impacts was further elaborated in WGI Chapter 12 Section 12.3 (Table 12.2).

We structure the remainder of the paper as follows. In Section 2 we describe the individual RKRs and identify the CIDs relevant to their assessment. Section 3 systematically covers these CIDs and their relation to global warming levels. Section 4 concludes with a discussion of the findings, also restating the need for an integrated treatment of physical climate conditions and socio-economic and/or natural drivers of risk.

As a last introductory note, on occasion in the paper we may use the terms CID and hazard interchangeably as here we are concerned with drivers of risk, by definition detrimental and therefore hazardous. We need to underline, however, that the CID framework has deliberately chosen a neutral term (impact-driver) recognizing that climatic changes may carry benefits and not only negative impacts (Ruane et al., 2022). This is true in at least two ways: what may be hazards for some actors or in some contexts may be construed as opportunities for other actors or in other contexts (e.g. storm damage impacts have very different implications for home owners, for the insurance industry and for the construction industry); in terms of adaptation, what may be hazardous events today might offer opportunities in the future if adaptive measures are capable of exploiting the changed conditions.

Once again, this is an important reminder that the ultimate outcome is not a direct function of climatic changes alone, but crucially depends on the non-climatic characteristics of the system they affect.

2. Representative key risks and their relevant climatic impact-drivers

The WGII Chapter 16 authors started from a large set of key risks (i.e., risks with the potential of becoming severe) identified by the sectoral and regional chapters of the report, and clustered them into eight broad categories, the Representative Key Risks (RKRs).

Each of these eight categories was described in individual subsections of the chapter, where also the hazards that the literature identified as potentially driving an increase in risk severity were listed. Most of the RKRs are now individually the subject of a paper in this special issue. These papers, however, do not treat the climatic impact-drivers/hazard changes in detail and do not explicitly draw a relation between them and increasing global warming levels, which is the central purpose of our paper.

Table 1 gives a snapshot view of the eight RKRs. In the following we describe them further and identify the CIDs/hazards relevant to the risks becoming severe as assessed by O'Neill et al. (2022). We note here that the categorization into eight RKRs of the many sectoral and regional risks is not mutually exclusive, i.e., the same risks may belong to more than one RKR. This aspect is also key to the possibility of compounded risk across RKR categories, which however we do not address in this paper.

2.1. RKR-A: Risk to the integrity of low-lying coastal socio-ecological systems

This RKR is concerned with physical, human and ecological components of low-lying coastal socio-ecological systems, where 'low-lying' is defined as land within 10 m of elevation and hydrologically connected to the ocean. RKR-A comprises risks to (i) natural coastal protection and habitats; (ii) lives, livelihoods, culture and well-being; and (iii) critical physical infrastructure. Cities and settlements by the sea are home to a large fraction of the global population, leading to high exposure to hazards in this zone (Glavovic et al., 2022). The level of vulnerability varies widely, linked to the level of development and therefore resources to protect from and respond to hazards. The physical environment itself may be more or less conducive to negative outcomes, for example as a function of general environmental degradation.

A wide range of potential hazards are relevant to this RKR. These may be gradual climatic changes like sea level rise, the warming of sea surface temperatures (SSTs), the thawing of permafrost in Arctic coastal regions, the decrease in extent and thickness of sea ice, ocean acidification. Alternatively, they may be episodic extreme events like marine heatwaves, storm surges, and winds from tropical and extratropical cyclones. Hazards can also compound, for example when storm surges are made higher by sea level rise.

2.2. RKR-B: Risk to terrestrial and ocean ecosystems

This RKR is concerned with significant changes in structure, functioning, and/or loss of a substantial fraction of species richness and therefore biodiversity. These risks present themselves as consequences both of unfolding trends in mean climate variables like temperature and precipitation and of episodic extreme phenomena. Atmospheric CO_2 concentrations at the surface can trigger differential responses in various organisms within an ecosystem, challenging its structure (Parmesan et al., 2022), but since CO_2 is not dependent on warming but actually responsible for it, depending in turn strongly on future scenarios of anthropogenic emissions, we do not treat it further here.

Hazards discussed in Section 2.1, as relevant for RKR-A, such as SST warming, sea ice loss and ocean acidification are also relevant for ocean/coastal ecosystems as are tropical cyclones and marine heatwaves. Heat extremes (Seneviratne et al., 2021; Ranasinghe et al., 2021) on land or water (including marine heatwaves) can with time under increased warming exceed upper thermal limits for living organisms. These thermal limits can vary greatly across species and ecosystem context, leading to complex and uneven risk to ecosystem structure. In addition, general patterns of warming and precipitation change (Douville et al., 2021; Gulev et al., 2021; Gutiérrez et al., 2021; Lee et al., 2021; Ranasinghe et al., 2021) and the pace at which they unfold can pose stresses on ecosystems or individual species. Fire weather conditions conducive to wildfires are also significant drivers of this type of risk. All these are particularly hazardous when affecting limited area domains (islands, mountains, inland and marginal seas, and biodiversity hotspots) by changing the suitability of regions for species that have adapted to cooler and wetter (or drier) conditions and have nowhere to go to regain them, demonstrating the critical role in determining exposure of the physical environment other than climate conditions.

2.3. RKR-C: Risks associated with critical physical infrastructure, networks and services

This RKR comprises risks to physical infrastructure and networks providing critical goods and services. The most consequential hazards driving this type of risks are acute extreme events, like cyclones, floods, droughts or fires, extreme precipitation and heat

Table 1
The eight Representative Key Risks identified by O'Neill et al. (2022).

RKR-A	risk to the integrity of low-lying coastal socio-ecological systems
RKR-B	risk to terrestrial and ocean ecosystems
RKR-C	risks associated with critical physical infrastructure, networks, and services
RKR-D	risk to living standards
RKR-E	risk to human health
RKR-F	risk to food security
RKR-G	risk to water security
RKR-H	risks to peace and to human mobility

events (O'Neill et al., 2022). For example, as described in Ranasinghe et al. (2021), Section 12.3, extreme heat can warp roads and airport runways, cause buckling of railways and require a lower take-off weight for aircraft; both energy transmission and energy production in plants that use stream water for cooling can be impaired by high air and water temperatures. At the other end of the spectrum, extreme cold temperatures, possibly with frequent freezing and refreezing episodes, can cause pipes to burst or damage roads. Inland flooding from heavy rains, or coastal flooding caused by gradual sea level rise in isolation or combined with storm surges, threatens roads and other transportation networks, and key infrastructure assets that are often located along river ways or in coastal areas. Winds from tropical or extratropical storms can damage buildings, and transportation and energy infrastructure. Other long-term trends besides those of sea level rise, like permafrost thaw, threaten the stability of buildings and infrastructure in high latitude or high altitude regions, and can favor the conditions for landslides.

2.4. RKR-D: Risk to living standards

This RKR comprises risks linked to economic impacts at all scales, from Gross Domestic Product to individual livelihoods. Poverty within countries as well as inequality across countries are potentially exacerbated by this type of risk. The degrees of exposure and vulnerability of different economies and segments of society varies with factors such as geography, level of development and sector of employment.

Economic impacts would be driven by hazards that endanger industries and laborers exposed to heat extremes, coastal flooding and storms. Poverty could be exacerbated by the frequent occurrence of extremes causing physical damages or imperiling the growth of crops. Livelihoods can be threatened for systems relying on agriculture, fisheries and other climate-sensitive activities exposed to shifting climatologies and more frequent and intense extremes. El-Nino Southern Oscillation (ENSO) variability may play an additional role in modifying future risks to livelihoods.

2.5. RKR-E: Risk to human health

This RKR comprises risks of human mortality and morbidity, with the assessment having a particular focus on heat-related mortality and morbidity, and on water- and vector-borne diseases.

Extreme events triggering excessive heat and flooding are identified as hazards relevant to this risk. For vector-borne diseases, shifts in insects' habitat range have been identified because of warming trends in temperature and changes in either direction in precipitation patterns. As for other risks, additional conditions that are not directly imputable to climatic changes can increase the severity of these risks, for example the urban environment can exacerbate heat stress (e.g., waste heat from buildings has been found to add more than 1^{o}C to urban temperatures, especially at nighttime, Vahmani et al., 2022). For human health, effects from air pollution play an additional role in the hazard component (Sillmann et al., 2021; Cisse' et al., 2022). Changing climate affects pollution in a complex manner through multiple interactions affecting emissions, chemical processes, deposition and involving numerous climate parameters (e.g., temperature, precipitation, circulation patterns). Extreme air pollution events can be favored by specific meteorological conditions (e.g. heatwaves, temperature inversions and atmospheric stagnation episodes) over highly polluted areas.

2.6. RKR-F: Risk to food security

This RKR comprises risks of breakdown of food systems (relying on land and/or ocean resources) thus engendering food insecurity because of threats to crop, livestock, fishery and agroforestry production as well as the distribution networks underlying international food markets (Kerr et al., 2022; Mbow et al., 2019).

Drivers of risks to food security have been identified in extreme heat and precipitation events and droughts, but also in an increase in overall precipitation variability, and in changes in expected average precipitation and its geographic patterns. The Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) has been used as a descriptor of agricultural and ecological drought conditions relevant to a variety of managed and natural systems, including crop cultivation. Compound extremes like concurrent heatwaves and droughts, and flooding events (for example by the convergence of pluvial flooding with coastal storm surge in a river estuary) are relevant to agricultural productivity, and additional risks to low-lying agricultural lands, including major agricultural river deltas, are expected from increasing flooding frequencies, especially from tropical storms and cyclones, whose surges will be exacerbated by sea level rise even in the absence of changes in the intrinsic characteristics of the storms. Slower, gradual changes in mean temperature and precipitation (and CO_2 concentrations) are expected to create new interactions among pests, weed infestations and diseases. Last, food security also involves trade, transportation and access, therefore hazards relevant to RKR-C (Risks to critical physical infrastructure, network and services) are also relevant here.

2.7. RKR-G: Risk to water security

This RKR comprises risks from water-related hazards (floods and droughts) and induced by water quality deterioration. The category is especially focused on water scarcity, water-related disasters and risk to indigenous and traditional cultures and ways of life. Again, it is the convergence of hazards with population exposure and vulnerability, often the result of both environmental conditions and safety and governance issues, that determines the evolution of these risks. Ultimate impacts are as varied as loss of lives, property, livelihoods and culture, and impacts on human health and nutrition, ecosystems and water-related conflicts, which in turn can drive forced human displacement.

For these types of risks a wide range of hazards related to the water cycle may be relevant, from changes in the average patterns of precipitation causing stress on water availability, to extreme precipitation events causing flooding and related damages, to severe droughts. In addition, expected changes in snow cover and mass loss of glaciers are hazards not only affecting water availability, whose quantity and duration is in some region strongly dependent on snowfall magnitudes and timing, but endangering ways of life, identity, and culture for the local population.

2.8. RKR-H: Risks to peace and human mobility

O'Neill et al. (2022) defines the scope of this RKR as comprising "risks to peace within and among societies from armed conflict as well as risks to low-agency human mobility within and across state borders, including the potential for involuntarily immobile populations[1]".

This risk is perhaps the hardest to quantifiably link to hazard occurrence, given the socio-economic, demographic, legal and political determinants of exposure and vulnerability that influence any outcome in this category. This RKR is also strongly dependent on risks that belong to other categories: considerable research over the last decade has explored the often complex links between food and water insecurity, migration, and conflict, particularly in urban areas (Von Uexkull and Buhaug, 2021). It is argued however that the increased frequency of extreme events may exacerbate conditions leading to conflict, and even sea level rise (SLR) linked to low warming can add to stress on a population that could find its territory permanently submerged or frequently flooded by the combined effects of storm surges and SLR.

In Table 2 we give a succinct summary of the relevance of different CIDs/hazards to the eight RKRs. In the next section we will address the current and future states of these hazards as they relate to global warming levels, and in doing so we will qualify, as needed, the actual metric(s) used to describe the hazards.

3. Relating relevant hazards to global warming levels

In this section we characterize current state and future changes in the hazards described in Section 2 as a function of global warming levels (GWLs). In some cases, the shape of the response pattern is not evident at low GWLs but becomes apparent at higher GWLs, indicating the direction of likely changes even as the observed signal may not yet have emerged from the background variability (see, e.g., Ranasinghe et al., 2021, Section 12.5.2 which assesses the "Emergence of climatic impact-drivers across time and scenarios", and Arias et al., 2021, Section TS1.2.3). When possible, we discuss a quantitative relation between GWLs and hazard metrics, but in many cases we can only discuss a qualitative relationship between them. In a few cases, the nature of the hazard, or the lack of available literature, force us into a more traditional description of changes by scenario and time horizon, but these remain a minority of instances. Consistent with the treatment of GWLs in the WGI report (IPCC, 2021a), we here define GWLs using Global Surface Air Temperature (GSAT) warming with respect to the pre-industrial baseline of 1850–1900. GSAT is a model-derived quantity based on globally averaging land and marine near-surface temperatures that are available with complete regular coverage from a model simulation. Most of the relationships between hazard metrics and GWLs here described have been identified and, when possible, quantified on the basis of the behavior of climate model output. Specifically, Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring et al. 2016) experiments run under a representative range of uncertain future anthropogenic radiative forcing scenarios (for the most part, ScenarioMIP experiments, O'Neill et al., 2016; Tebaldi et al., 2021b) form the basis of this particular assessment, besides supporting the assessment of IPCC (2021a,b) in general.

The use of GWLs circumvents the uncertainties due to substantial differences between climate model responses to the same scenario (Hausfather et al., 2022), but has the disadvantage of transferring the uncertainty to the time dimension: for most of the discussion in this paper we will not be concerned with *when* GWLs will be reached, and that *when* depends not only on the emission scenario but on the climate model driven by it. Of course, for concerns of exposure and vulnerability the time dimension remains critical.

We organize the following discussion by CID/hazard, and so does Table 3 which summarizes the content of this section.

The material is based on Tebaldi et al., 2021a, i.e., the cross-chapter box in Ranasinghe et al., (2021) specifically intended to support the assessment of RKRs in WGII, but this article allows us to expand on the succinct format of that box.

Mean air temperature warming patterns: Pattern scaling (Santer et al., 1990; Tebaldi and Arblaster, 2014) can fairly accurately represent the scaling of at least basic variables like mean temperature (and precipitation) with GWLs, showing which regions of the world warm more or less than the global average, and which regions will experience wetting rather than drying and by what percentage, per degree of warming. Fig. 1, panel (a), shows normalized patterns of warming for average surface temperature. These geographic features are found to be more sensitive to individual models' characteristics than to individual scenario trajectories, once changes are standardized by the corresponding GSAT changes (Tebaldi et al., 2021b).

Warming trend in the Arctic region: The warming signal averaged over the Arctic region has already emerged from internal variability (Forster et al., 2021), and is projected to continue at a rate between 2 and 2.4 times faster than GSAT, over the 21st century (Lee et al., 2021; Ranasinghe et al., 2021) (see Fig. 2a). We note here that more recent work not assessed by the IPCC WGI report has found the Arctic region warming at a rate close to 4 times faster than GSAT over the last 40 years (Rantanen et al., 2022).

Sea surface temperatures: Sea surface warming has been shown (Gulev et al., 2021; Fox-Kemper et al., 2021; Ranasinghe et al.,

[1] Involuntarily immobile populations are those who aspire to migrate but are unable to do so because of lack of resources.

Table 2
A list of climatic impact-drivers/potential hazards and their relevance (when the cell is filled) to the various RKRs. We use the organization by CID type as in Ranasinghe et al. (2021) and Ruane et al. (2022) then list CID/Hazards as described in the text of Sections 2.1-2.8. Section 3 elaborates further on CID/hazard metrics, when necessary, to draw a relationship to global temperature change. We note here that the judgment of relevance is based on the WG II authors' assessment of "key" risks. Other hazards are or could become relevant, but if the WG II assessment did not identify them as drivers contributing to "key" risks, or chose to assess them as relevant to one of the RKR explicitly but not to another that may be connected to it, the corresponding cells are left blank (and the hazards are not discussed in Sections 2.1-2.8).

CID Type	CID/Hazard	RKR-A (risk to the integrity of low lying coastal socio-ecological systems)	RKR-B (risk to terrestrial and ocean systems)	RKR-C (risks associated with critical physical infrastructure, networks, and services)	RKR-D (risk to living standards)	RKR-E (risk to human health)	RKR-F (risk to food security)	RKR-G (risk to water security)	RKR-H (risks to peace and human mobility)
Heat and Cold	Mean air temperature patterns		■		■	■	■		
	Sea surface temperature	■	■		■		■		
	Extreme heat		■	■	■	■	■		
	Extreme cold		■	■			■		
Wet and Dry	Mean precipitation		■			■	■	■	
	Heavy precipitation		■	■		■	■	■	■
	Drought		■	■	■		■	■	■
	Fire Weather		■	■					
	ENSO variability		■		■				
Wind	Tropical cyclones	■	■	■	■		■		■
	Extra-tropical storms	■	■	■	■		■		■
Snow and Ice	Snow cover							■	
	Permafrost	■		■					
	Sea Ice	■	■					■	
	Glacier mass							■	
Coastal	Sea level rise	■	■	■	■		■		■
	Storm surges	■	■	■	■		■		
Open Ocean	Marine Heatwaves	■	■		■				
	Ocean acidification	■	■		■		■		
Other	Air pollution weather					■			
	Compound events	■	■	■	■	■	■	■	■
	Atmospheric CO_2 at the surface		■				■		

Table 3
Summary of the expected behavior of CID/hazards relevant to the eight RKRs as a function of global surface air temperature (GSAT) warming. When possible, a quantitative relation is specified and those hazards are highlighted by pink shading; when only a direct, qualitative relation is assessed the cells are colored yellow; for those metrics with no robust relation with warming, cells are colored blue. When available, levels of confidence are those assigned by the IPCC AR6 WGI assessment, which constitutes the origin of the information presented here.

CID/Hazard (From Table 2)	Specific Metric (when relevant)	Relation with GSAT warming	Level of confidence	RKR	Comments
Mean Air Temperature Patterns	Average Temperature Change Patterns	Linear relation with GSAT, location specific. See left panel pattern in Figure 1.	High confidence	B,E,F,G	Normalized patterns are model-dependent, but robust across time and scenarios for each model.
	Arctic Warming	2-2.4 times faster than GSAT. See Figure 2a.	High confidence	A,B	Recent work has quantified Arctic amplification as close to 4 times faster than GSAT over the last 43 years (Rantanen et al., 2022)
Sea Surface Temperature	Sea Surface Temperature Warming	Rate of warming ~0.8 of GSAT. See Figure 2a.	High confidence	A,B	Supported by observations and modeling results
Extreme Heat	Heat Extremes	Magnitude and intensity increase linearly with GSAT, Changes twice as large or more (in mid/high-latitude regions)); Frequency of exceedance may show stronger than linear relationships (exponential). Compared to today, changes in extremes at +2°C at least two times larger than at +1.5°C, and four times larger at +3°C. See Figure 2a,c.	High Confidence	B,C,D,E,F,H	Detectable starting at 1.5°C
Extreme Cold	Cold Extremes	Analog but opposite relation in frequency and magnitude trends as for heat extremes.	High Confidence	B,C	
Mean Precipitation	Average Percent Precipitation Change Patterns	Linear relation with GSAT, location specific. See right panel pattern in Figure 1.	High Confidence	B,E,F,G	Normalized patterns are model-dependent, but robust across time and scenarios for each model. Departures from linearity are expected at local scales with the effect of dynamics.
Heavy Precipitation	Precipitation Extremes	Frequency and magnitude increase with GSAT over all continents for events with return period >10year. At the global scale, intensification of heavy precipitation generally follows Clausius–Clapeyron (about 6–7% per °C of GSAT warming; high confidence). Increase in frequency accelerates with warming, higher for rarer events with approximately a doubling and tripling frequency of 10-year and 50-year events, respectively, at 4°C of global warming. See Figure 2c,d.	High Confidence	B,C,D,E,F,G,H	Detectable starting at 2C. Likelihood lower at lower GWLs and for less-rare events.
	Inland Floods	Increase in flood area extent with GSAT; Increase in frequency and magnitude of pluvial flood.	High Confidence	B,C,E,F	Urban areas potentially more affected (larger extent of impervious surfaces)
Drought	Drought	Upward trends with GSAT, See Figure 2d.	High Confidence	B,C,D, F, G, H	
	SPEI	Chances of 3 months/year of drought conditions increasing from 9.4% at 1°C to 20% at 1.5°C, 35% at 2°C and to 60% at 4°C. See Figure 2c.	Not Assessed	F	Chances are computed at the global scale.
Fire Weather	Fire Weather	Likely more frequent with GSAT.	Not Assessed	B,C	Expected increase in hot/dry/windy conditions.

(continued on next page)

Table 3 (*continued*)

ENSO Variability	ENSO Variability	No change in amplitude; Increase in variability of ENSO-related precipitation.	Medium confidence on amplitude; high confidence on precipitation changes	D,F	Likely shift Eastward of teleconnection patterns over N. Pacific and N. America.
Tropical Cyclones	Tropical Cyclones	Wind and Precipitation intensity increase with warming; cyclogenesis constant or decreasing; fraction of more powerful storms increases.	High confidence in wind/precip behavior and increase frequency of stronger storms; medium confidence for overall frequency changes.	A,B,C,D, F,H	Changes in main cyclogenesis regions are not robust, but warming SSTs may sustain tracks over an extended region, bringing more storms northward.
Extra-Tropical Storms	Extra-Tropical Storms	Moving poleward with warming	Medium confidence	A,B,C,D,F ,H	Also seeing enhanced frequency as a consequence of more Tropical Cyclones transitioning to Extra-Tropical Storms over their lengthened track (see above)
Snow Cover	Northern Hemisphere Spring Snow Cover	~8% area loss pr 1°C for GWL < 4°C See Figure 2b.	High confidence	G	
Permafrost	Permafrost Thaw in the Upper 3m Layer	Top 3m losing permafrost volume by 25% (+/-5%) per 1°C of warming. See Figure 2b.	Medium confidence	A,C	
Sea Ice	September Arctic Sea Ice Extent	Ice-free September occurrence at any GWL, episodic for 1.5°C, becoming ~annual for 2°C-3°C, extending to other months annually for 3°C-5°C.	High confidence	A,B	Linearity of Arctic sea ice minimum extent in warming but large uncertainty bounds due to natural and model variability.
	Antarctic Sea Ice	No robust relation	Low confidence	A,B	
Glacier Mass	Mass Loss of Glaciers	For 1.5°C–2°C ~50–60% of glacier mass outside the two ice sheets and excluding peripheral glaciers in Antarctica remaining, predominantly in the polar regions. For 2°C–3°C a ~40–50% of current glacier mass outside Antarctica remaining. For sustained 3°C–5°C ~25–40% of current glacier mass outside Antarctica remaining. Likely nearly all glacier mass lost in low latitudes, Central Europe, Caucasus, western Canada and USA, North Asia, Scandinavia and New Zealand for high level of warming (3°-5°C) See Figure 2b.	Low Confidence	G	Lagged response to warming.
Sea Level Rise	Global Sea Level Rise	At 2050 0.16-0.31m across 1.5°C-5°C GWLs. At 2100 0.34m-0.59m at 1.5°C; 0.40m-0.69m at 2°C; 0.50m-0.81m at 3°C; 0.58m-0.92m at 4°C; 0.69m-1.05m at 5°C. See Figure 2a.	Ranges quoted consider processes in which there is at least medium confidence in our ability to project. Low confidence processes characterized by deep uncertainty could contribute significantly at warming above 2°C	A,C,D, F, H	Currently rising at a rate higher than recorded or inferred for the last 3Ky at least. Lagged response to warming.
Storm Surges	Coastal Flooding events	Increased frequency with warming/SLR	High confidence	A,C,D,E,F ,H	Even if characteristics of storms did not change, SLR alone creates these changes.

(*continued on next page*)

2021) to happen – globally averaged – at a rate of about 80 % that of GSAT warming. Thus, if one focuses on 2081–2100 outcomes, global average SSTs will increase between 2 °C and 4 °C under High warming (SSP5-8.5, reaching GWLS between 3.6 °C and 6.9 °C); but only between 0.4 °C and 1.5 °C under Low warming (SSP1-2.6, reaching GWLs between 1.3 °C and 2.8 °C) (see Fig. 2a).

Extreme heat: On the global scale, the frequency and intensity of heat extremes have increased since the 1950s (corresponding to

Table 3 (*continued*)

Marine Heatwaves	Marine Heatwaves	2-9 times more frequent for 2°C; 3-15 times more frequent for 5°C. See Figure 2c.	Medium confidence	A,B	Spatially heterogeneous, with hot spots in the tropical oceans and in the Arctic Ocean
Ocean Acidification	Ocean Acidification	Increasing proportionally to CO2 concentrations.	High confidence	A,B,E	Only under SSP1-1.9 and SSP1-2.6 ocean acidification stops increasing and may actually decline in the presence of negative emissions.
Air Pollution	Increase in Surface Ozone Pollution	Linear and positive in high ozone production areas	Medium to high confidence	E	Production areas are scenario dependent
	Increase in Surface PM Pollution	No clear relation	Medium confidence	E	
Compound Events	Compound Extremes	Higher frequency with GSAT	High Confidence	B, F	Esp. hot+dry extremes; Pluvial and coastal storm flooding.
Atmospheric CO2 at the Surface	Atmospheric CO2 at the surface	Scenario Dependent		B.F	This CID is not considered a hazard in the context of the RKRs.

Representative Key Risk categories are:
- RKR-A: risk to the low-lying coastal socio-ecological systems;
- RKR-B: risk to terrestrial and ocean ecosystems;
- RKR-C: risks associated with critical physical infrastructure, networks and services;
- RKR-D: risk to living standards;
- RKR-E: risk to human health;
- RKR-F: risk to food security;
- RKR-G: risk to water security;
- RKR-H: risks to peace and to human mobility.

GSAT warming of 0.6 °C). Both the number of days and nights exceeding their climatological 90th percentile have increased, and so has the duration of heat waves. These global trends are reflected in most regions of the world where sufficient data are available for assessment. Because of their threshold response, future increases in GSAT can translate non-linearly into increases in length, intensity, and associated impacts of heat extremes, depending on the metrics of extreme considered. Such a non-linear relation is detectable starting at GWLs as low as 1.5 °C. But even those metrics that have been shown to vary linearly in GSAT are projected to see changes more than double the magnitude of GSAT warming (in the mid-latitudes) when not larger (in the high-latitude regions). When heat extremes are defined as exceedances of thresholds, the relation with GSAT warming can become exponential. IPCC (2021) reports assessed changes in characteristics (globally averaged) of pre-industrial 10- or 50-yr events with a range of GWLs. While magnitudes for both types and frequency for the less extreme events show a linear change with warming, the frequency of the rarer events changes exponentially. 10-yr events are already 3 times more frequent than during pre-industrial conditions, becoming about 4, 6 and 9 times more frequent for 1.5 °C, 2 °C and 4 °C respectively. 50-yr events are already 5 times more frequent, and would become about 9, 14 and 40 times more frequent at those GWLs. The magnitude of both these events has changed and will change similarly: they are already 1.2 °C hotter on average, and will become about 2 °C, 2.6 °C and 5 °C hotter at those GWLs (see Fig. 2a).

Extreme cold: In general, for cold extremes, changes go in the opposite direction, i.e., towards a decrease linearly (or more strongly) as GSAT warms (see Fig. 2b). A contrasting effect from Arctic amplification affecting the circulation of what is known as the polar vortex may engender more severe cold episodes over the mid-latitudes of the northern hemisphere but observational and modeling challenges prevent the estimation of a robust relation so far (Cohen et al., 2020).

Mean Precipitation: Pattern scaling (Santer et al., 1990; Tebaldi and Arblaster, 2014) can fairly accurately represent also the scaling of mean precipitation with GSAT showing which regions will experience wetting rather than drying and by what percentage, per degree of GSAT warming. We show in Fig. 1, panel (b), normalized patterns for percent precipitation change derived from CMIP6 projections but, as is the case for temperature patterns, also very consistent with previous generations of climate models and scenario experiments, once changes are standardized by the corresponding GSAT changes (Tebaldi et al., 2021b).

Heavy precipitation: In all regions where sufficient data are available (both in quality and length), increases in frequency and intensity of heavy precipitation episodes has been detected over the historical record, and at the continental scale over North America, Europe and Asia. The strongest signal is that of larger percentage increases over the high latitudes of the Northern Hemisphere in all seasons, and in the mid-latitudes over the cold season. Future warming will be accompanied by increases in precipitation intensity, including precipitation associated to tropical cyclones. It is virtually certain that intense rare events will increase in frequency over all continents for GWLs larger than 2 °C. The increase in frequency does not happen evenly across the range of rare events and is greater for rarer events. While the basic thermodynamics of the Clausius-Clapeyron equation allows us to infer an increase in heavy precipitation of 6–7 % per degree of warming at the global scale, regional outcomes are often affected by changes in circulation in large measure and can therefore manifest themselves as stronger or weaker changes. IPCC (2021) also reports changes in characteristics (globally averaged) of pre-Industrial 10-yr events. The frequency of these types of events is now already 30 % higher than during pre-Industrial conditions, and it is projected to become 1.5, 2 and 3 times more frequent for 1.5 °C, 2 °C and 4 °C respectively. The intensity of these events has increased by about 7 % and will increase further becoming 10.5 %, 14 % and 30 % wetter at those GWLs

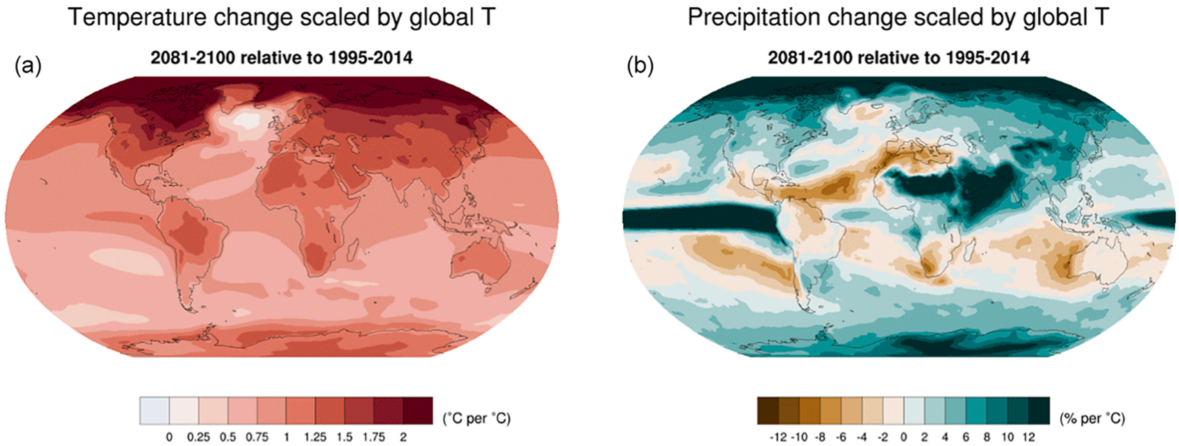

Fig. 1. Normalized patterns of surface temperature, panel (a), and percent precipitation change, panel (b). Values on the maps are changes (in °C or % precipitation compared to 1995–2014 averages) per degree of global (GSAT) warming. Patterns are computed separately for all CMIP6 models/ scenarios documented in Tebaldi et al. (2021b) then averaged.

(Seneviratne et al., 2021; Ranasinghe et al., 2021) (see Fig. 2c and 2d).

Floods: Inland floods induced by heavy precipitation are expected to produce increasing flooded area extent with increasing GWLs, detectable even when comparing 1.5 °C and 2 °C GWLs (Seneviratne et al., 2021; Ranasinghe et al., 2021).

Droughts: Drought events (Seneviratne et al., 2021; Ranasinghe et al., 2021) have already be observed with increased frequency compared to pre-industrial times, having become more likely because of the combined effects of changes in precipitation patterns and warming, which compound to increase frequency and severity of drought episodes in observations over semi-arid regions of the world (Mediterranean, North America, and Africa). The trend continues in future projections, with a direct relation between drought severity and frequency and GSAT warming. IPCC (2021) shows frequency of 10-yr drought events having already increased and continuing to follow GSAT warming, with events being now 1.7 times more frequent, and projected to be 2,2.4 and 4 times more frequent at 1.5 °C, 2 °C and 4 °C respectively. Intensity, here measured as a factor of the climatological standard deviation (sd) of the drought metric utilized is already 0.3sd drier, and will be 0.5sd, 0.6sd and 1sd drier at those GWLs. For drought, regional warming and corresponding effects on soil moisture drying and land–atmosphere feedbacks are especially relevant at local scales (see Fig. 2c and 2d).

Standardized Precipitation-Evapotranspiration Index (SPEI): an index describing drought conditions relevant to a variety of managed and natural systems, including crop cultivation, is at present, i.e., for a 1 °C of warming compared to pre-industrial, indicating a 9.4 % probability of three months' drought conditions as a global average (over land regions), while the probability increases to 20 % (15–30 %) at 1.5 °C of warming, to 35 % (20–45 %) at 2 °C of warming and to 60 % (45–75 %) at 4 °C of warming compared to pre-industrial (Ranasinghe et al., 2021) (see Fig. 2c).

Fire weather: Metrics specifically designed to characterize fire-conducive conditions are so-called indices of fire weather (Seneviratne et al., 2021; Ranasinghe et al., 2021), usually considering not only temperature and (accumulated) precipitation, but also other variables like soil moisture, humidity and winds. Some regions of the world are already seeing more likely occurrences of fire-weather, and the direction of change will continue towards increased occurrence and severity with GSAT warming. However, these indices only measure atmospheric conditions that are more or less conducive to fire developing. The availability of fuel, in part also dependent on climatic conditions, is not considered in these metrics and is another strong determinant of fire risk.

ENSO variability: at present, signals of changes in both ENSO frequency and amplitude do not appear to have emerged from natural variability, neither shifts in patterns and teleconnections can be detected (Gulev et al., 2021). In the future, even if ENSO variability has not been assessed to change robustly, variability of precipitation associated with ENSO is expected to be enhanced for warming under the intermediate emission scenario reaching radiative forcing of 4.5 Wm^{-2} by the end of the 21st century and higher (Lee et al., 2021).

Tropical cyclones: The rain intensity that accompanies these storms has already increased because of global warming, and the global proportion of the more intense Tropical Cyclones (TCs) has also likely increased in the last four decades (Seneviratne et al., 2021; Ranasinghe et al., 2021). While a quantitative relation with increasing GSAT in the future has not been established, it is expected that a number of TC characteristics will become more severe with increasing GWLs: these characteristics are total precipitation amounts, average peak wind speed, the proportion of intense TCs and their peak wind speed. One global measure that is not expected to change is the overall frequency of TCs, when including all categories. However, SST warming may change TC trajectories, extending the region that supports them beyond latitudes that are now dominated by easterlies, and increasing the chance of landfalls on coastal regions currently less impacted by TCs or heavy tropical storms.

Extra-tropical storms: We lack robust assessment of changes in this type of storm that affects the mid and high latitudes, especially as a function of GWLs, besides the general results that wind and precipitation intensity is projected to increase with warming, and the storm track tends to move polewards. The dynamical aspects of storm genesis and movement, however, are as important as the thermodynamic-driven expectations about their intensities, and still too uncertain under warming experiments for their effects to be

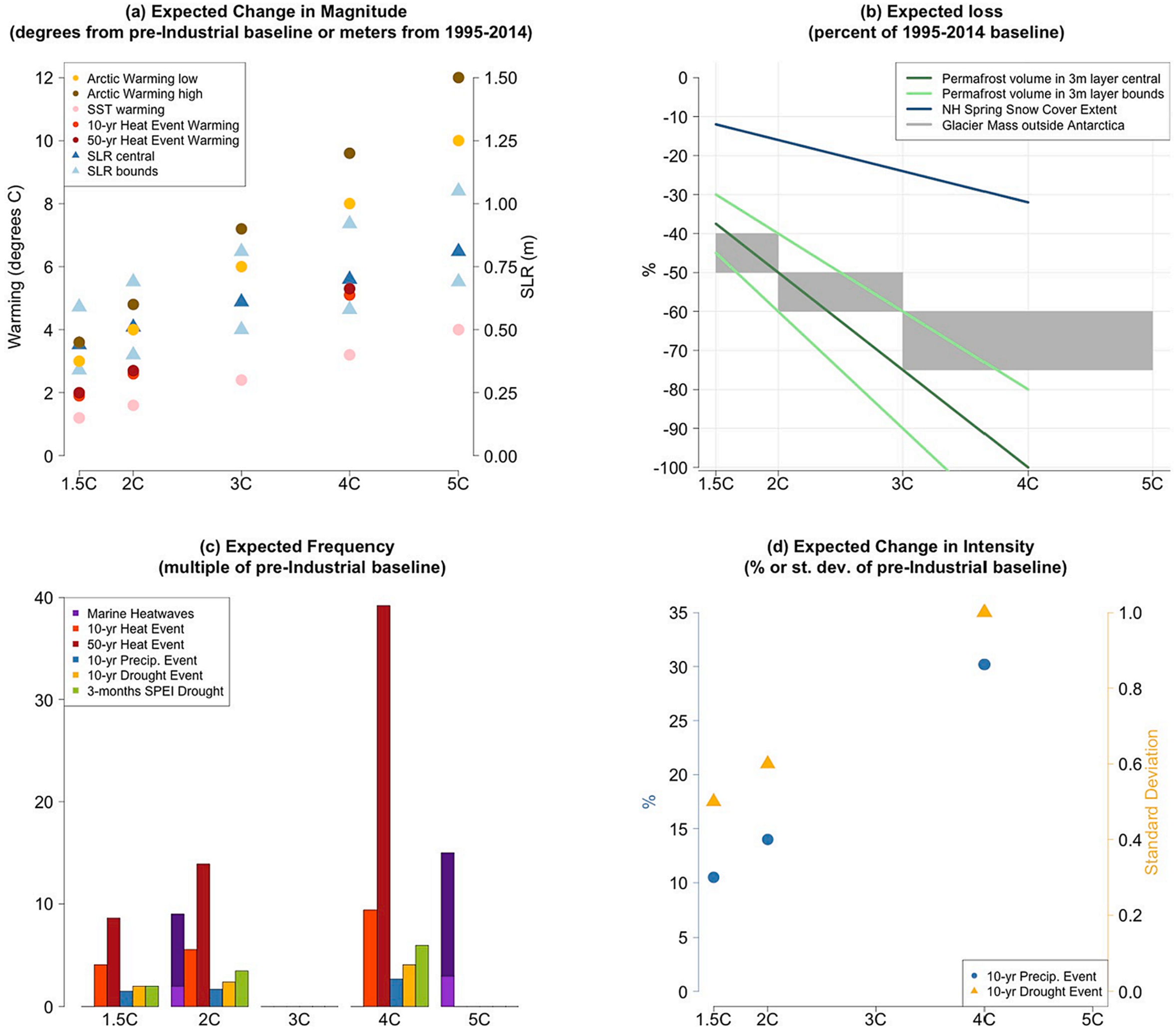

Fig. 2. For all metrics whose future changes were found to have a quantitative relation with GSAT warming we represent such changes for discrete GWLs (1.5 °C, 2 °C, 3 °C, 4 °C and 5 °C, or a subset of them depending on the availability of the corresponding estimates).
Panel (a) shows warming of Arctic region, SSTs, 10-yr and 50-yr heat events (globally averaged) as degrees C with respect to pre-industrial (left axis) and global SLR changes by 2100 in meters with respect to 1995–2014 (right axis).
Panel (b) shows losses in permafrost volume, glacier mass and northern hemisphere snow cover as percentage of 1995–2014 conditions. The latter metric was only evaluated as a central estimate. Permafrost loss has a central estimate and uncertainty bounds. Glacier mass loss is given as a range for intervals of GWLs (1.5 °C–2 °C; 2 °C–3 °C; 3 °C–5 °C).
Panel (c) shows the factor by which the frequency is multiplied for a number of hazards, setting their pre-industrial frequency as 1. Hazards represented are marine heatwave (whose frequency multiplier was assessed only at 2 °C and 5 °C as a range – hence the two different colors of the bar), 10- and 50-yr heat events, 10-yr precipitation events, 10-yr drought events and the SPEI-derived drought metric.
Panel (d) shows changes in intensity for 10-yr precipitation events, globally averaged, as percentage of pre-industrial conditions, and for 10-yr drought events, whose change in severity is shown as standard deviations of the metric's statistical distribution at pre-Industrial times.

robustly characterized (Seneviratne et al., 2021; Ranasinghe et al., 2021).

Snow cover: Since the late 1970s, early 1980s, both spring snow cover extent in the northern hemisphere and spring snow water equivalent have seen substantial decline (Gulev et al., 2021). For the future, a linear decrease of spring snow cover of about 8 % per degree of warming is projected for GWLs up to 4 °C. Thus, relative to 1995–2014, decreases of less than 20 % are projected for warming less than 2 °C, up to 30 % for 2 °C–3 °C of warming, while a lower bound of 25 % is projected for warming above 3 °C (see Fig. 2b).

Permafrost: Permafrost temperatures in the upper 20–30 m have already warmed over the past three-to-four decades (Gulev et al., 2021), and projections indicate that the permafrost volume within the top 3 m will decrease by about 25 % (plus or minus 5 %) per degree of warming (below 4 °C). Accounting for the uncertainties in this relationship and model shortcomings lead the assessment to attribute only medium confidence to this relationship and to characterize the expected decline in a less precise way, as a decrease by less than 40 % (relative to 1995–2014) for GWLs between 1.5 °C and 2 °C; by less than 75 % at GWLs between 2 °C and 3 °C and by more than 60 % for GWLs of 3 °C–5 °C (Fox-Kemper et al., 2021; Ranasinghe et al., 2021) (see Fig. 2b).

Sea ice: Arctic sea ice extent is already showing a decrease, in every month, since 1970, with stronger decreasing trends in the summer. Current levels (as annual means and in late summer) are unprecedented since reliable records began, around 1850. The ice is also younger, thinner and faster moving (Gulev et al., 2021; Fox-Kemper et al., 2021). It is projected that only by limiting warming to 1.5 °C will the Arctic maintain some ice cover in summer (September) episodically in some years, while all higher warming levels will see it becoming ice-free before 2050. GWLs of 2 °C–3 °C translate into summer ice-free Arctic in most years, while warming of 3 °C–5 °C would translate to several more months of the year being ice-free (Lee et al., 2021; Ranasinghe et al., 2021). A linear relation can be drawn between Arctic sea ice minimum extent and GSAT warming, but there remain large uncertainties in the rate due to internal variability and model differences (Fox-Kemper et al., 2021). Arctic sea-ice sensitivity to global warming stands in contrast to Antarctic sea ice, which has experienced little net-change since 1979, due to the relatively lower warming experienced by the Antarctic region compared to the Arctic, and possibly the influence of ice discharge from the Antarctic ice sheet as the associated meltwater release reduces mixing with warmer water from below. Before 1979 (the start of the satellite era) there is little confidence in all aspects of Antarctic sea-ice behavior (Gulev et al., 2021; Fox-Kemper et al., 2021).

Glacier mass: Since 1850, glaciers are retreating and the current global mass loss is unprecedented in at least the last 2000 years (Fox-Kemper et al., 2021; Ranasinghe et al., 2021). The last 3–4 decades have seen an acceleration of mass loss (Gulev et al., 2021, Hugonnet et al., 2021). Glaciers are not in balance with respect to the current climate conditions (temperatures), and they would continue to lose mass for several decades, even in the absence of further warming (Gulev et al., 2021; Fox-Kemper et al., 2021). Additional warming of 1.5 °C–2 °C would allow only 50–60 % of glacier mass to remain, not including the ice sheets or the glaciers in Antarctica, mainly in the polar regions. Warming of 2 °C–3 °C could allow 40–50 % of glacier mass to remain while higher warming would only see 25 %–40 % of glaciers remaining, with all glaciers in low latitudes, Central Europe, the Caucasus, Western Canada and USA, North Asia, Scandinavia and New Zealand disappearing (Fox-Kemper et al., 2021; Ranasinghe et al., 2021) (see Fig. 2b).

Sea level rise: Gradual SLR has been happening at an accelerated rate since the 19th century, with the past two decades recording a rate almost double that of the preceding decades. Global-mean SLR during the 20th century happened at a faster rate than over any preceding century in at least the last 3,000 years.

SLR depends on global warming in a complex way, due to the long timescales over which GSAT warming translates in warming of the ocean waters and melting of glaciers and ice-sheets. That lagged response compels us to always associate GWLs to specific time periods for this CID. The result is that until mid-century, SLR does not show a strong dependence on scenarios, and will likely (that is, with at least 66 % probability) be between 0.15 and 0.30 m. By 2100 the outcome will depend on the scenario more strongly, with a rise of 0.44 m (0.34–0.59) for a GWL of 1.5 °C; 0.51 m (0.40–0.69) for a GWL of 2 °C; 0.61 m (0.50–0.81) for a GWL of 3 °C; 0.70 m (0.58–0.92) for a GWL of 4 °C; and 0.81 m (0.69–1.05) for a GWL of 5 °C (see Fig. 2a). For warming levels in excess of 2 °C, ice sheet behavior exhibits deep uncertainty, and substantially higher SLR may be possible. For 5 °C of warming, ice sheet processes in which there is limited agreement across modeling approaches and therefore low confidence could drive global mean sea level rise approaching 2 m (Fox-Kemper et al., 2021).

Storm surges: Relative SLR compounds with storm surges and coastal flooding from tropical (hurricane, typhoons) and extra-tropical (mid-latitude, particularly winter-time) storms in increasing the size and reach of episodic flooding events. Increased frequency in these compound flooding events has been already detected (Seneviratne et al., 2021). A newer study (Tebaldi et al., 2021c), not assessed by AR6 WGI, shows how changes in the return period of current 100-yr events are extremely sensitive to warming of even just 1.5 °C, and the relative sea level rise that accompanies it by 2100. Accordingly, a large percentage of coastal locations over the world's ice-free coastal areas see the historical 100-yr event becoming an annual event by 2100, even if warming is strongly limited. This is true in particular, but not exclusively, of locations in the subtropics. Locations where the frequency does not change as significantly are concentrated for the most part in the high latitudes of the Northern Hemisphere, where post-glacial isostatic uplift is expected to continue to slow the relative rising of sea levels (Fox-Kemper et al., 2021; Ranasinghe et al., 2021; Tebaldi et al., 2021c). We show in Fig. 3 the main result of that study: at each location along the world's coastlines, a colored circle indicates a central estimate of the global warming level sufficient to change what is now the 100-yr event at that location into an annual (or more frequent) event.

Marine heatwaves: These phenomena have already seen a doubling of their frequency over the past three or four decades and appear to be getting more intense and longer since the 1980 s with devastating consequences for marine ecosystems such as coral reefs (Hoegh-Guldberg et al., 2018; Bindoff et al., 2019; Cooley et al., 2022). By the end of the century, they are projected to become 2-to-9 times more frequent under SSP1-2.6 (whose corresponding central GWL at that time is close to 2 °C) and between 3 and 15 times more frequent under SSP5-8.5 (whose corresponding central GWL at that time is close to 5 °C) (Fox-Kemper et al., 2021; Ranasinghe et al., 2021) (see Fig. 2c, where we represent these ranges of change corresponding to 2 °C and 5 °C).

Ocean acidification: If not related to warming per se, ocean acidification is a direct consequence of increasing CO_2 concentrations in the atmosphere (Canadell et al., 2021). Surface pH is currently at its lowest (most acidic) level over at least the last 26,000 years, as a consequence of a decline in the last 40 years at the rate of 0.017–0.027 pH units per decade. The decline also extends to the subsurface for at least the last two to three decades (Gulev et al., 2021; Canadell et al., 2021). The decrease of ocean surface pH is expected to continue over the 21st century for all but the two lowest scenarios (SSP1-1.9 and SSP1-2.6) under which, due to negative emissions, surface pH is expected to start slightly increasing in the last two or three decades of the century (Lee et al., 2021; Ranasinghe et al., 2021). Irrespective of the scenario, net ocean carbon flux is expected to increase throughout the century (Canadell et al., 2021).

Air pollution weather: There is no discernible trend, at present, in the effects of warming on large scale air pollution (Szopa et al., 2021). Local air pollution levels are, to first order, controlled by emissions and policies implemented to control air pollution and/or mitigate climate change. Signs and magnitudes of future changes in surface air pollution are mainly driven by anthropogenic emissions

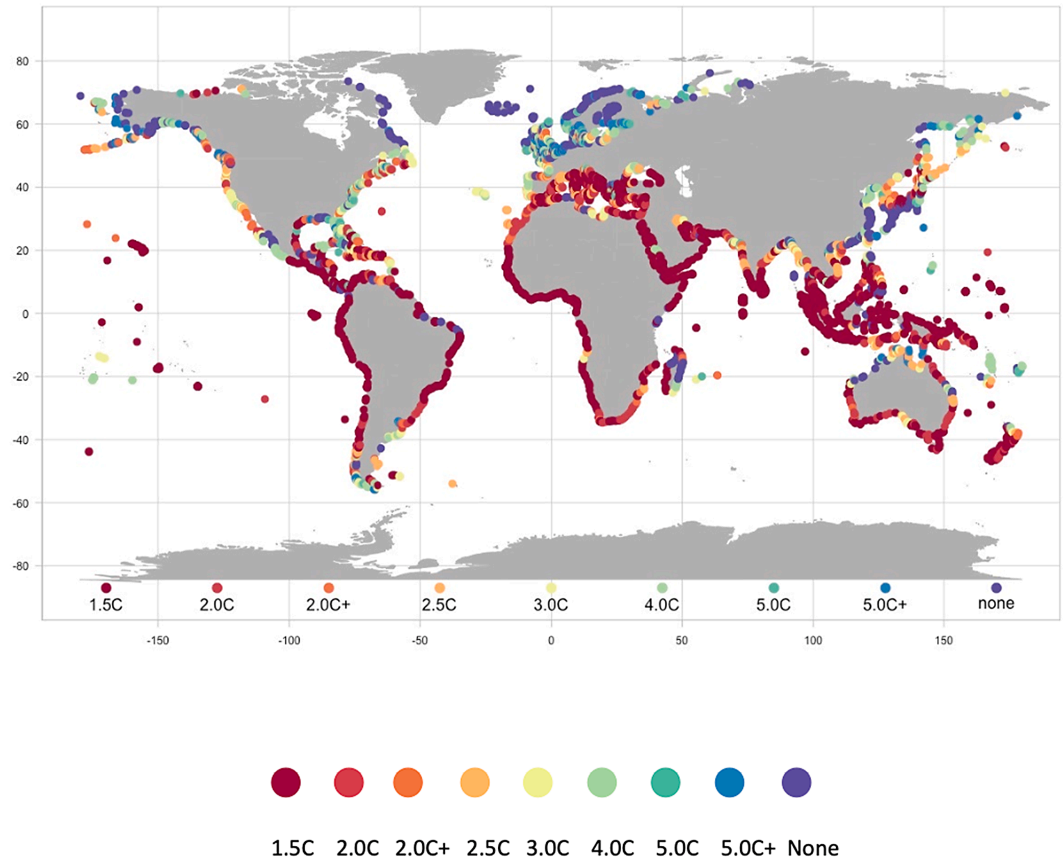

Fig. 3. At each location of the world's ice-free coasts, the color indicates the global warming level that makes the current 100-yr event into an annual (or more frequent) event. The assumption is that the storm surges are enhanced by the amount of relative sea level rise experienced at that location by 2100, if global temperature reaches that GWL by that date. "None" labels those location where such increase in frequency is not projected, even for the highest GWL. The labels 2.0C+ and 5.0C+ indicate sea level rise projections for those two GWLs that also include the effects of ice-sheet instability. Adapted from Tebaldi et al. (2021c).

changes. However, the effects of future climate change on air pollution through changes in natural sources of pollution precursors (for example, by vegetation, fires, lightning) remain very uncertain (Szopa et al., 2021). Changes purely associated with the increase in GWL on air pollution are difficult to assess. The effect on Particulate Matter (PM) global burden could be positive or negative, but is estimated to be small. In contrast, surface ozone levels could respond linearly to GSAT increases but with differing effects depending on the ozone regime. In low pollution regions, decreases of -0.2 to -2 ppbv per degree of warming are expected. In high pollution regions, i.e. regions close to sources of ozone precursors, an increase of the same absolute magnitude is expected, thus implying a regional surface ozone penalty due to global warming (Szopa et al., 2021; Zanis et al., 2022). Extreme air pollution events can be favored by specific meteorological conditions (e.g. heatwaves, temperature inversions and atmospheric stagnation episodes) over highly polluted areas. These conditions are influenced by climate change, but the correlation between such meteorological conditions and high concentrations of ozone and PM2.5 have been shown to be regionally and metric dependent.

Compound extremes: Higher frequency of concurrent heatwaves and droughts, and of compound (sea level rise and storm-driven) flooding events have already been detected and higher frequencies with additional warming are expected of these specific compound extremes and, in general, of concurrent extremes in time and space (Seneviratne et al., 2021; IPCC 2021b, pp. 24, 25).

Table 3 summarizes our findings. We distinguish cases where a quantitative relation was drawn (by a pink shade of the cells), where only a qualitative but robustly unidirectional relation was drawn (by a yellow shade), and cases where no such relation has been characterized (by a blue shade).

4. Discussion and conclusions

With this work we are offering a physical climate perspective on drivers of risk, i.e., we focus on the hazard component, aware that it is only one of multiple factors - including exposure, vulnerability and possible adaptation and mitigation responses - contributing to the ultimate outcome. In particular, we present a catalogue of climatic impact-drivers (CIDs) that, by having the potential to become hazards, can be expected to contribute to the severity of representative key risks (RKRs). The identification of these hazards rests on the work assessed in O'Neill et al. (2022) and other regional and sectoral chapter of the WGII report, but also on the complementary work, based on the climate impact literature, that guided the development of the CID framework in Ranasinghe et al. (2021) and Ruane et al. (2022), in WGI. Our goal with this work is to present how these CIDs/hazards are expected to evolve as a function of global warming. This, we would argue, has value in itself, as physical climate outcomes are in themselves a cogent aspect of future scenarios. In addition, by providing a measure of how these hazards may evolve as a function of global warming we aim to support research on future changes of a wide range of impacts as a consequence of changes in hazards. In this latter regard, however, we recognize that for the other components of risk - exposure, vulnerability and adaptation responses - the time dimension, which the GWL approach de-emphasizes, remains critical.

This work shows that many of the hazards considered can be put in a direct, strong relationship with global temperature changes. This is the case for patterns of regional warming and mean precipitation change, sea surface temperature warming, snow cover, permafrost thawing, but also for several types of extreme events that have been associated with risks across all RKRs, like heat extremes, tropical cyclone intensity, marine heatwaves, droughts and fire weather, storm surges as results of winds and sea level rise combined. Other hazards, like SLR and glacier mass loss are in strong relation to warming, but present a lagged response. Despite increased confidence in associating the behavior of hazards to warming, large uncertainties remain in the character of the changes in individual (or concurrent) hazards in relation to GWLs, particularly with respect to two dimensions: the magnitude and rate of change. First, the relation may be fuzzy, and either wide ranges of future changes are associated to any given GSAT level, or only a qualitative direction of change may be described, as a function of GSAT. This is increasingly the case when downscaling from the global domain to regional to local phenomena. Second, while for some of these changes we can successfully decouple GWLs from specific GSAT trajectories (i.e., we can consider the behavior of hazards at different warming levels independently of the scenario, and therefore independently of the time when the level is reached and the shape of the trajectory followed to get there) this is not always the case. For some hazards, changes may be path-dependent or dependent on the mix of forcings contributing to the warming. For others the response to warming may be non-linear, whether in the form of threshold behavior (i.e. tipping points) or time-lags, associated with complex internal dynamics of the system in question.

We have adopted here a global perspective on changing climatic impact-drivers to serve a synthetic assessment based on global warming levels rather than particular scenarios of emissions and therefore warming. However, individual impacts are and will continue to be determined by the conditions of the system(s) affected in all their specificity and fine spatial and temporal details. Aspects of the physical climate system that vary as a direct function of warming are for the most part aggregated metrics, or coarse patterns, as opposed to small-scale quantities for which local feedbacks can be significant. An example here could be heat extremes affecting semi-arid regions where the combined effects of lack of precipitation will compound with the first order effect of warming in exacerbating dryness and heat by triggering land–atmosphere feedback mechanisms. For these locales the actual heat extremes experienced may well surpass what could be projected based only on warmer global temperatures. The distinction between the thermodynamic nature of change as opposed to its dynamic component is also relevant here: for many quantities, and over the timescale of the current century, the first order effect of warming (and associated increase in water holding capacity of the atmosphere, when precipitation related metrics are concerned) can be considered the dominant source of future changes. For others, changes in the dynamics of a warmer climate, i.e., changes in circulation, are important to consider, and a simple dependence on warming will not explain the major character of future changes. This can be the case for storm paths that can shift their location due to still uncertain effects of warming and precipitation anomalies in the tropics, or blocking events that could become more persistent because of dynamic processes triggered by a warming Arctic and its associated ice loss. For still others a combination of direct and indirect, and likely delayed, effects must be included to complete the picture. The prime examples here are the melting of glaciers and ice-sheets, having their own impacts and also contributing to sea level rise globally and regionally.

Nevertheless, even accounting for the generalization and imprecision of drawing these relations between GSAT and individual hazards, we believe that our summary will facilitate a synthetic view of expected climate risk at increasing levels of warming. In this regard, the message that every increment of global warming matters (IPCC 2021a,b) is further substantiated and reinforced by this work.

Before concluding, however, we would like to reaffirm the importance of considering the hazard component as only one of the determinants, sometimes not even the major one, of climate risks. Citing O'Neill et al. (2022), "climate risk is not a matter of changing climatic impact-drivers (CIDs) only, but of the confrontation between changing CIDs and changing socio-ecological conditions". Therefore, changes in exposure and vulnerability in the future need to be considered jointly with changes in climatic conditions to obtain a realistic assessment of future risk and possibly future opportunities that associated adaptation responses may present.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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