International Journal of Disaster Risk Reduction 108 (2024) 104488

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Global hotspots of climate-related disasters

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A B S T R A C T

Climate change mitigation is crucial to prevent excessive temperature rise, a primary contributor to climate-related impacts. However, even if net zero emissions were achieved immediately, the carbon locked in the atmosphere will continue to impact ecosystems, people, settlements and infrastructure, as observed in the past several decades. Despite the urgent need to minimize climate change impacts, climate adaptation has not kept pace with escalating risks. Data on disaster occurrences and impacts can guide action to where it is most needed. We used data on climate-related disasters recorded between 2000 and 2020 in the Emergency Events Database (EM-DAT) to 1) discern disparities in climate-related disaster impacts across countries and continents, and 2) pinpoint administrative areas where people have been highly impacted from those types of disasters. During this period, over 4,600 occurrences of climate-related disasters were documented, directly impacting over 3.3 billion people. Highly developed countries experienced fewer impacts despite not having a lower number of climate-related events. African countries showed an increase in the number of people impacted through time, despite a decrease in the number of climate-related events. Areas in Central America and the Caribbean, Eastern North America, Eastern Africa and Madagascar, and Southern and Eastern China, India and Southeast Asia had the highest numbers of people impacted per km^2. Identifying locations with disproportionally high numbers of impacted people can lead to action and policy shifts, from local to international levels. Some of the approaches to adapt to climate change impacts that can be cost-effective and readily available are those based on nature and the benefits that nature provides to people. Therefore, nature conservation, restoration and management could be important interventions to help people adapt to the impacts of climate change, especially in areas of low human development and where people have experienced high and very high climate impacts. In the policy sphere, synthesizing information on historical occurrences of climate-related disasters could guide efforts to address losses and damages and to promote climate justice.

1. Introduction

Climate change impacts are cascading and compounding, increasing climate risk and underscoring the urgent need for actions. In the Horn of Africa, droughts in 2020–2022 have surpassed the devastating droughts of 2016–2017, with an estimated 26 million people facing acute food insecurity [1]. In 2020, Australia experienced its worst-ever wildfire season that destroyed 24 million hectares of land [2]. In 2021, a third of Bangladesh was underwater due to a cyclone. In 2023 alone, the United States experienced 25 climate disasters, causing US$ 1 billion in damages [3]. However, climate adaptation has not been keeping up with those, and many others, risks and needs (EEA 2019, [4]). Climate adaptation receives insufficient funding (UNEP 2023), has been implemented at a much slower pace than required to meet climate policy goals (Global commission on Adaptation 2019[5], IPCC 2022 [6]) and is unevenly

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https://doi.org/10.1016/j.ijdrr.2024.104488
Received 27 September 2023; Received in revised form 20 February 2024; Accepted 17 April 2024
Available online 18 April 2024

distributed (IPCC 2018 [7]). Therefore, supporting adaptation actions where most needed allows the strategic use of those limited resources. Prioritization of climate adaptation actions at both global and sub-national levels can be done by understanding future projections of changes and by assessing spatial patterns of historical impacts from climate-related disasters [8].

Estimates of the number of people impacted by climate change exist (CRED 2020 [9]) and have been important to shed light on the magnitude of climate change impacts on people. However, those estimates are done per country and do not specify areas where people have been impacted the most at sub-national levels. Having access to synthesized spatial information based on historical data is instrumental for decision makers to act where climate adaptation is needed now [10] and to identify targeted strategies for people and ecosystems to adapt to specific climate change impacts, guiding strategic allocation of limited funds.

Databases on occurrence and impacts of disasters have been primarily established to improve preparedness and responses to humanitarian emergencies but can also be used to understand the location and magnitude of disasters. In this study, we used data recorded between 2000 and 2020 in the Emergency Events Database (EM-DAT/CRED, UCLouvain 2023 [11]), the only publicly available global disaster database. Despite the limitations of this database, including entry criteria that may lead to an underestimation of deaths and affected people [12] and reliance on various entities for reporting, which can result in data gaps in certain regions [13], this database remains the most comprehensive global compilation of disaster data available to date.

From this database, we selected a set of disasters most related to climate change and, for each of those disaster types, we extracted information on the number of people impacted (the total number of people that have been injured, that become homeless, that required immediate assistance and that died) per year, per country and per administrative area to 1) assess differences across countries and continents regarding the number of people impacted by climate-related disasters, 2) identify administrative areas at the sub-national level where people have been highly impacted from climate-related disasters and 3) indicate actions that could be implemented where people are highly impacted by climate change. The results of this paper can help prioritize areas where adaptation actions are needed by identifying where people have been most impacted by climate-related disasters. For example, this information could help prioritize areas for the implementation of the "Climate Impacts and Response Fund", a historical agreement that aims to support climate adaptation in countries that have suffered the most from the impacts of climate change but have contributed the least to cause them.

2. Methodology

2.1. The emergency events database

The Emergency Events Database (EM-DAT) (hereafter "EM-DAT") is an international disaster database that includes information on impacts of disasters disaggregated by countries and identifies administrative areas that were impacted (using the Global Administrative Unit Layer, GAUL, as a reference). EM-DAT was founded in 1988 by the Centre for Research on the Epidemiology of Disasters (CRED) at the Université catholique de Louvain (UCLouvain, Belgium) with support from the Bureau for Humanitarian Assistance (BHA), the United States Agency for International Development (USAID), the World Health Organization (WHO) and the Belgium Government. The EM-DAT has a compilation of data on disasters that have happened since 1900. Data included in the database has been assembled from various sources including the United Nations, governmental and non-governmental agencies, insurance companies, research institutes and press agencies. EM-DAT has a set of entry criteria that specify what substantial impact means. Disasters listed in the EM-DAT meet at least one of the following inclusion criteria: a) at least ten deaths (including dead and missing); b) at least 100 people affected and c) a call for international assistance or an emergency declaration.

We used this database, downloaded on June 2nd, 2021, to access data on "total affected" people and the "total deaths" per disaster event impacting a country (i.e., an entry in the EM-DAT), which were combined in this study to create the variable "total people impacted". In the EM-DAT database, "total affected" represents the sum of people "injured," "affected," and "homeless" resulting from a particular event. "Injured" were considered those that have suffered from physical injuries, trauma, or an illness requiring immediate medical assistance, including people hospitalized, as a direct result of a disaster, "affected" were considered people requiring immediate assistance during an emergency and "homeless" were considered those whose homes were destroyed or heavily damaged and therefore needed shelter after an event. "Total deaths" include people that have died or were considered missing, those whose whereabouts since the disaster were unknown and presumed dead based on official figures. More details can be found under "documentation, data structure and content description" at emdat.be.

Despite the limitations of the EM-DAT, such as missing data on events and impact variables [13,14], due to its reliance on various sources for information collection, the database management team has implemented measures for data control and validation, including significant oversight [15]. The team systematically performs additional quality control or comparison with other databases as necessary, has developed protocols for collecting information from sources, and ensures that a disaster event is only validated in the database if it has been reported by at least two sources.

2.2. Disaster types considered

The EM-DAT disaster typology is based on the Peril Classification and Hazard Glossary (IRDR, 2014 [16]). As we were primarily interested in understanding the impacts of climate change, we focused our study on the meteorological, hydrological and climatological disaster groups or subgroups. Those disasters are more strongly associated with changes in climate, compared to the other types of disasters recorded in the dataset, and were selected because the focus of the study is on climate-related disasters only. In the EM-DAT, "meteorological disaster subgroup" is "a hazard caused by short-lived, micro and mesoscale extreme weather and atmospheric conditions that last from minutes to days." "Hydrological disaster subgroup" refers to "hazards caused by the occurrence, movement and distribution of surface freshwater and saltwater." "Climatological disaster group" refers to "hazards caused by long-lived, meso- and macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability." The following disasters ("disaster main type" and "disaster sub-types" in the EM-DAT, see Annex 1) were included in this study: drought, tropical cyclones, flash flood, riverine flood, forest fire, land fire, heat wave, landslide and mudslide. Data on coastal flood was not included because the database only had recordings until 2013. Data on disaster sub-types "landslide" and "mudslide" as presented in the EM-DAT were further combined as one single climate-related disaster ("land and mudslides") for the analyses. Likewise, data on disaster sub-types "forest fire" and "land fire" were further combined as one climate-related disaster ("wildfire"). These disaster types and disaster sub-types were selected because they were classified as meteorological, climatological or hydrological disasters in the EM-DAT database and can be associated with changes in climate (World Meteorological Organizational 2021 [17]). In this paper, we refer to the selected disaster types and sub-types as "climate-related disasters." We extracted all data available for those 7 climate-related disasters that occurred between 2000 and 2020 (including those years) to be used in the analyses. All results presented in this paper are therefore related to this period. We opted to start our data analysis period in 2000 because disaster loss databases were able to assemble more data during this decade compared to the previous ones [18] due to the advent of the internet.

2.3. People impacted and number of climate-related disaster events per country and level of human development

Differences on impacts from climate-related disasters that occurred between 2000 and 2020 were assessed using the percentages of people impacted per country and per climate-related disaster, which were calculated using a world population dataset from the United Nations Department of Economic and Social Affairs (UNDESA) published in 2021. All 172 countries for which there were recorded events of climate-related disasters in the EM-DAT were included in the analyses. Cumulative percentages of people impacted, i.e., the sum of the country's percentage of people impacted per year by all types of climate-related disasters, were used to identify the most impacted countries (in terms of population impacted) between (and including) 2000 and 2020. The number of climate-related disaster events reported for each country between 2000 and 2020, i.e., the number of entries in the EM-DAT referent to each one of the climate-related disasters, was extracted directly from EM-DAT.

As climate change can disproportionally impact the most vulnerable and poor, we computed the Spearman correlation between the cumulative percentage of people impacted by all types of climate-related disasters per country and both the country's Human Development Index (HDI) in 2019 and the country's change in the HDI values between 2000 and 2019 [19]. We also calculated the Pearson correlation between the total number of events from climate-related disasters that occurred in each country between 2000 and 2020 and the country's HDI in 2019. The HDI is a summary measure of average achievement in three key dimensions of human development: a long and healthy life, being knowledgeable and having a decent standard of living, and calculated as the geometric mean of normalized indices for each of those dimensions [20]. The HDI scores were used to define the level of human development of each country, based on the classification by the United Nations Development Programme in 2019 [19], which includes: very high human development (HDI >0.8), high human development ($0.8 \geq$ HDI >0.7), medium human development ($0.7 \geq$ HDI >0.55) and low human development (HDI ≤ 0.55) (UNDP 2000).

We opted to use the HDI from 2019 as countries' indexes in 2020 were affected by the COVID-19 pandemic. Whereas the pandemic has driven reversals in human development in almost every country in the world, some countries were more affected than others [21]. We therefore opted to use the 2019 HDIs. The correlations did not include The Demographic People's Republic of Korea, Somalia and Tuvalu as there was no information on HDI in 2019 for those countries. HDI in 2000 for Bhutan, Eritrea, Grenada, Guinea-Bissau, Lebanon, Marshall Islands, Montenegro, Nigeria, Palestine, Sant Kitts and Nevis, Somalia, South Sudan, Suriname and Vanuatu were not available, so those countries were excluded from the correlations between the cumulative percentage of people impacted by all types of climate-related disasters per country and the country's change in the HDI values between 2000 and 2019.

The average percentages of people impacted by all climate-related disasters combined, in countries of different levels of development and in countries located on different continents, were compared using one-way ANOVA, followed by pairwise Wilcoxon rank sum tests. The same analysis was done to compare the average number of events from all climate-related disasters across countries from different levels of development and across countries located on different continents.

2.4. Temporal trends on people impacted and on the number of climate-related disasters events

Trends in the percentages of the global population impacted through time and in the total number of climate-related disaster events through time, combining all climate-related disasters, were done using the Mann-Kendall trend test. Percentages of the global population impacted, combining all climate-related disasters, were calculated by summing the number of people impacted by all climate-related disasters that happened in each year between (and including) 2000 and 2020 and dividing it by the global population at that year. The number of events from all climate-related disasters was calculated by summing the total number of climate-related disaster events that happened in each year between (and including) 2000 and 2020. Trends in the percentages of the population impacted and in the number of events through time in countries of different levels of human development and in countries located on different continents were also assessed using Mann-Kendall trend tests.

2.5. Impacts from climate-related disasters at the sub-national level

We ranked each administrative area based on the number of people impacted per km^2 by each climate-related disaster, as well as by all types of climate-related disasters combined, as low impact, medium impact, high impact and very high impact. All analyses and data processing were performed using the function quantile in R. The first quartile, or lower quartile (here considered as "low impact"), is the value that cuts off the first 25 % of the data when it is sorted in ascending order. The second quartile (here considered as "medium impact"), or median, is the value that cuts off the first 50 %. The third quartile, or upper quartile (here considered as "high impact"), is the value that cuts off the first 75 %, with the values higher than that were considered as "very high impact." Administrative areas that have experienced climate-related disaster events but did not have anyone impacted were labeled as “no impact on people” and were not included in the quartile calculations.

The maps of impacts from climate-related disasters at the administrative level were created using the “geo codes” listed in the EM-DAT dataset for each event and the Food and Agriculture Organization (FAO)’s Global Administrative Unit Layer (GAUL). As the total number of people “injured,” “affected,” homeless” and number of “deaths” per event (i.e. per entry) in the EM-DAT database are not separated by administrative area, the number of people impacted in each administrative area by each event was estimated based on the proportion of the total population that each administrative area represented in the year of the event.

3. Results

3.1. Global impacts from climate-related disasters

Between 2000 and 2020, there were 4,623 climate-related disaster events recorded in the EM-DAT. They directly impacted over 3.39 billion people, which is equivalent to 44 % of the global population in 2020. Over 472,000 people died because of those events. The climate-related disasters that have impacted the highest number of people were droughts, with over 1.4 billion people impacted, followed by riverine floods, with over 1.2 billion people impacted, and tropical cyclones, with over 501 million people impacted between 2000 and 2020 (Table 1).

3.2. Global differences on impacts from climate-related disasters and on the number of climate-related disaster events

Of the 172 countries included in the EM-DAT database, 19 had cumulative percentages of people impacted higher than 100 % between 2000 and 2020 (Fig. 2, Annex 2). There was a negative and significant correlation between the cumulative percentage of people impacted by all types of climate-related disasters between 2000 and 2020 and countries’ Human Development Index (HDI) in 2019 ($r = -0.44$, $p < 0.01$, $df = 167$, Fig. 1), showing that the percentage of the population impacted decreases with an increase in human development. The association between number of events by all types of climate-related disasters in countries and the country’s HDI in 2019 was not significant ($r = 0.0009$, $p = 0.89$, $df = 167$). The correlation between the cumulative percentage of people impacted by all types of climate-related disasters and changes in countries’ HDI between 2000 and 2019 was also not significant ($r = 0.14$, $p = 0.06$, $df = 153$).

The average cumulative percentage of people impacted by all climate-related disasters differed by countries’ levels of human development ($X = 65.8$, $df = 3$, $p < 0.001$, Fig. 3A). The average cumulative percentage of population impacted in countries of very high human development was significantly lower than the average cumulative percentage of population impacted in countries of high, medium and low human development. The average cumulative percentage of people impacted by all climate-related disasters also differed by countries that are in different continents ($X = 51.28$, $df = 5$, $p < 0.001$, Fig. 3B). The cumulative percentage of people impacted by climate-related disasters in European countries was significantly lower than the cumulative percentage of people impacted in countries located in Australia, Africa, North America, Asia and South America. The average number of events did not significantly differ by country’s level of development ($X = 3.22$, $p = 0.35$, $df = 3$) or by countries located on different continents ($X = 7.66$, $p = 0.178$, $df = 5$).

3.3. Trends on people impacted and on the number of climate-related disaster events through time

The percentage of countries’ populations impacted by all types of climate-related disasters did not significantly change through time (z-value = 0.19, $p = 0.84$, $df = 171$) and the same was found when conducting the analysis by countries with different levels of human development. Countries in Africa and Australia showed significant increases in the percentages of populations impacted by climate-related disasters through time, countries in Europe and Asia showed significant decreases and countries in North and South America did not show any statistically significant changes (Fig. 3C).

The number of events from climate-related disasters per country, as well as the total number of events per year, showed significant and negative changes through time ($z = -3.82$, $p = < 0.001$, $df = 1832$ and $z = -2.56$, $p < 0.05$, $df = 19$, respectively). When conducting the analysis by countries with different levels of development, countries with a low and very high level of development, showed a significant decrease in the number of events through time, whereas countries with medium and high levels of human development did not. Countries in Africa, Europe and North America showed significant decreases in the number of events from

Table 1
Total number of people impacted and number of deaths, total number of events, number of people impacted per event and number of deaths per event for each climate-related disaster between 2000 and 2020. Number of impacted people include the number of people that have died, that have become homeless, that required immediate assistance and that got injured.

Climate-related disaster	N. of people impacted	N. of deaths	Number of events	N. of people impacted*/event	N. of deaths/event
Drought	1,441,038,477	21,291	341	4,225,919	62.43
Riverine flood	1,265,219,766	69,667	1,964	644,205	35.47
Tropical cyclone	501,227,733	188,812	1,020	491,399	185.1
Flash flood	178,721,860	19,795	583	306,555	33.95
Landslide and Mudslide	4,910,747	15,910	334	14,702	47.63
Wildfire	2,316,409	170	238	9,732	0.71
Heat wave	476,975	157,320	143	3,335	1,100.13
Total	**3,393,911,967**	**472,965**	**4,623**	**734,136**	**102.31**

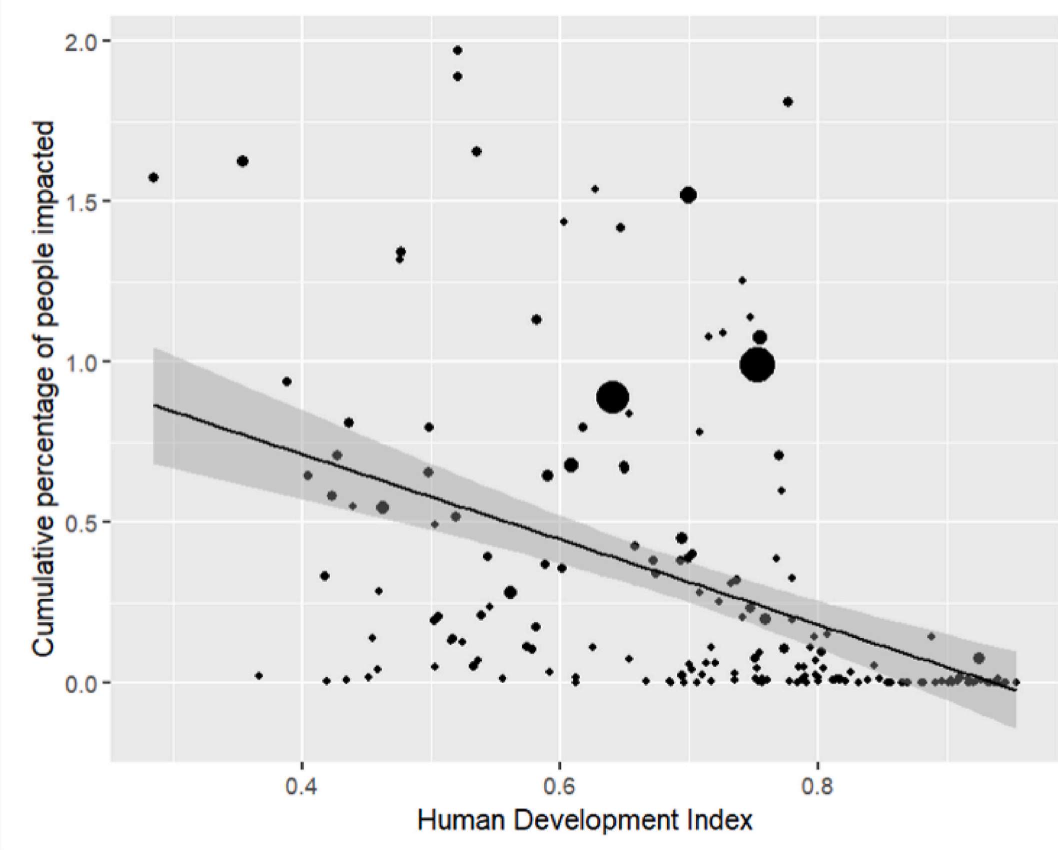


Fig. 1. Correlation between the cumulative percentage of people impacted per country by all climate-related disasters combined, from 2000 to 2020 and country's Human Development Index in 2019. The sizes of the dots represent the total number of people impacted per country between (and including) 2000 and 2020.

climate-related disasters through time, whereas the number of events from climate-related disasters that happened in countries in Asia, Australia and South America did not significantly change through time. The summary of those trends can be found in Table 2.

3.4. Impacts from climate-related disasters at the sub-national level

Combining impacts from all 7 climate-related disasters, Eastern and Central Mexico and the Caribbean, South of Guatemala, El Salvador, Northwestern Colombia, Central Bolivia, Northeast of Brazil, Eastern United States, Western Senegal, Gambia, Northern Mauritania, South of Niger and North of Nigeria, South Sudan, Eritrea, South of Mali and Burkina Faso, Central Angola, Ethiopia, South of Somalia, Mozambique, Malawi and Zimbabwe, Southeastern and Northern of South Africa, Lesotho and Eastern Madagascar, Eastern Portugal, Central Georgia, Armenia, Central Syria, India, most of Afghanistan and Southern and Eastern China, most of Thailand, Central of Myanmar, Southwestern of Cambodia, Vietnam, most of the Philippines and Southern Japan have been the most impacted areas (Fig. 4A). Regional patterns of impacts from tropical cyclones, droughts, flash floods, riverine floods, heatwaves, mudslides and landslides, and wildfires can be found in Fig. 4B–H.

Please note that many areas experienced events of climate-related disasters without having people directly impacted (i.e., people that have died, people that became homeless, people that needed immediate assistance or people that got injured) (areas in green in Fig. 4A–H). In some areas, those events were likely included due to an emergency declaration but did not end up having any direct human impact in terms of deaths, injuries, homelessness and immediate assistance needed. It is also possible that people may have been impacted in other ways that were not captured by the variables included in the database. For example, several developed countries did not appear as highly impacted by droughts. However, people in those countries could have been impacted by water shortages and by decreases in crop production, which could have had indirect impacts on people's wellbeing and overall country's economy. In other areas, however, the implementation of proper and effective adaptation measures and the increased adaptive capacity of people are likely protecting them from the impacts of climate change as events have occurred, but no one was reported to be directly impacted. In others, population density is small and therefore, the chances of people being impacted in recorded climate-related events are also small compared to more populated areas.

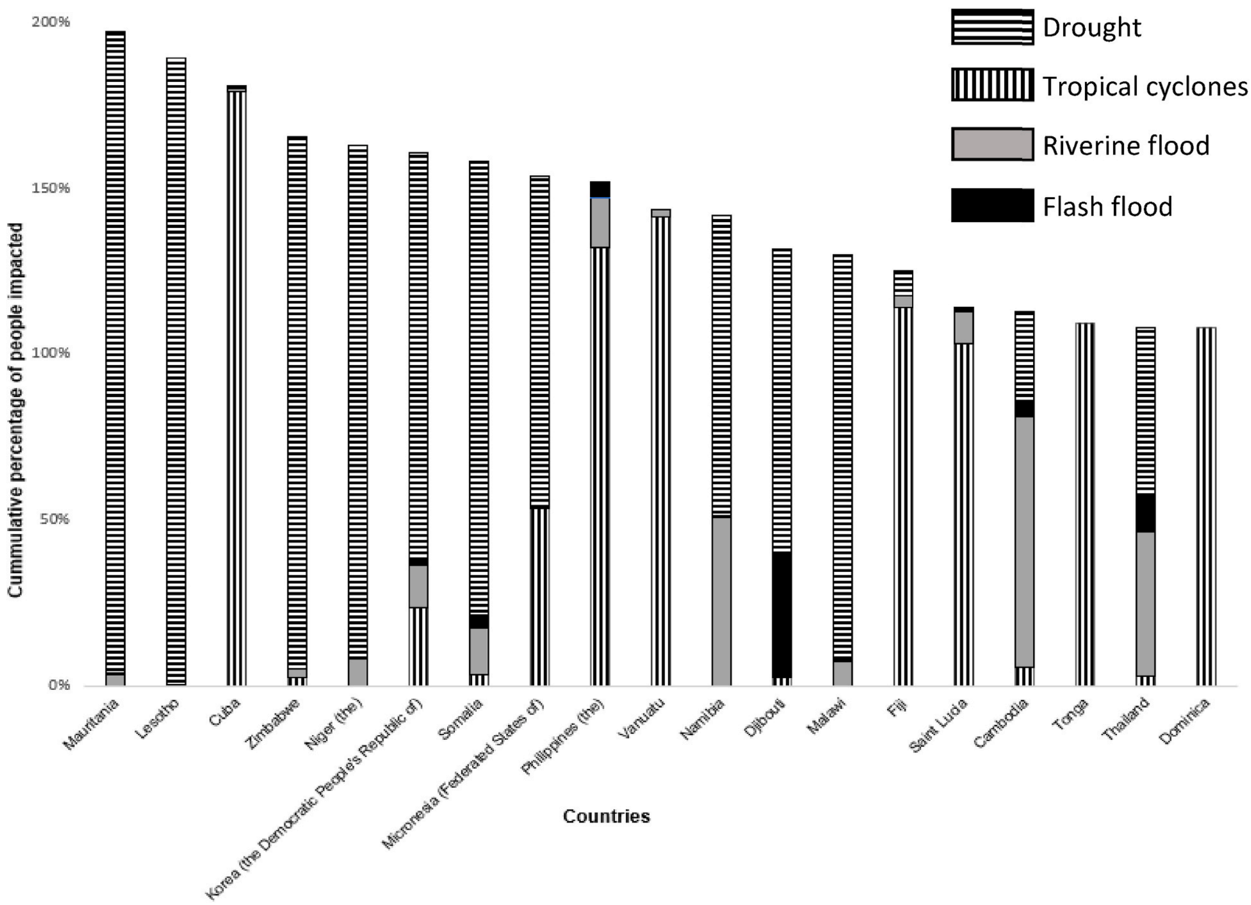


Fig. 2. Countries with the highest cumulative percentage of population (>100 %) impacted between (and including) 2000 and 2020 by each climate-related disaster recorded. Cumulative percentages of people impacted by landslides and mudslides, wildfires and heat waves are relatively too small to be shown in the graph.

4. Discussion

4.1. Countries with high levels of human development were the least impacted by climate-related disasters

Countries with high levels of human development had the lowest percentage of people impacted by climate-related disasters, even though the average number of disaster events did not significantly differ in countries with different levels of human development. There was a negative and significant correlation between the cumulative percentage of people impacted by all types of climate-related disasters combined and countries' HDI. Although the linear trend is significant, it shows a threshold behavior where countries with HDI lower than about 0.78 had a higher impact. Similarly, the cumulative percentages of the population impacted by climate-related disasters in countries with very high human development was statistically and significantly lower than in countries with high, medium and low human development. The cumulative percentages of the population impacted by climate-related disasters in European countries were significantly lower compared to countries in Australia, Africa, North America, Asia and South America.

The lowest percentage of people impacted by climate-related disasters in countries with high levels of human development and in European countries could be explained by the high capacity of people to implement adaptation strategies in those countries. Those strategies include, for example, access to early warning systems and evacuation plans and finance to support needed changes, which are known to be more common in countries with high levels of human development ([22], World Bank 2013 [23–25][25], O'Neill 2015 [26]). Furthermore, people living in countries with higher human development are more likely to face specific regulations and increased access to information related to avoiding settlements in areas that are at high risk of climate change impacts [19]. They may also be able to follow those regulations and have more advanced healthcare systems to receive immediate medical assistance after disasters [27]. Even though those countries could have experienced events with lower intensity compared to countries with medium and low levels of human development, it is likely that people's education and financial resources, combined with appropriate resources allocated to prevention and responses to climate change play an important role in minimizing the impacts of climate-related disasters on people.

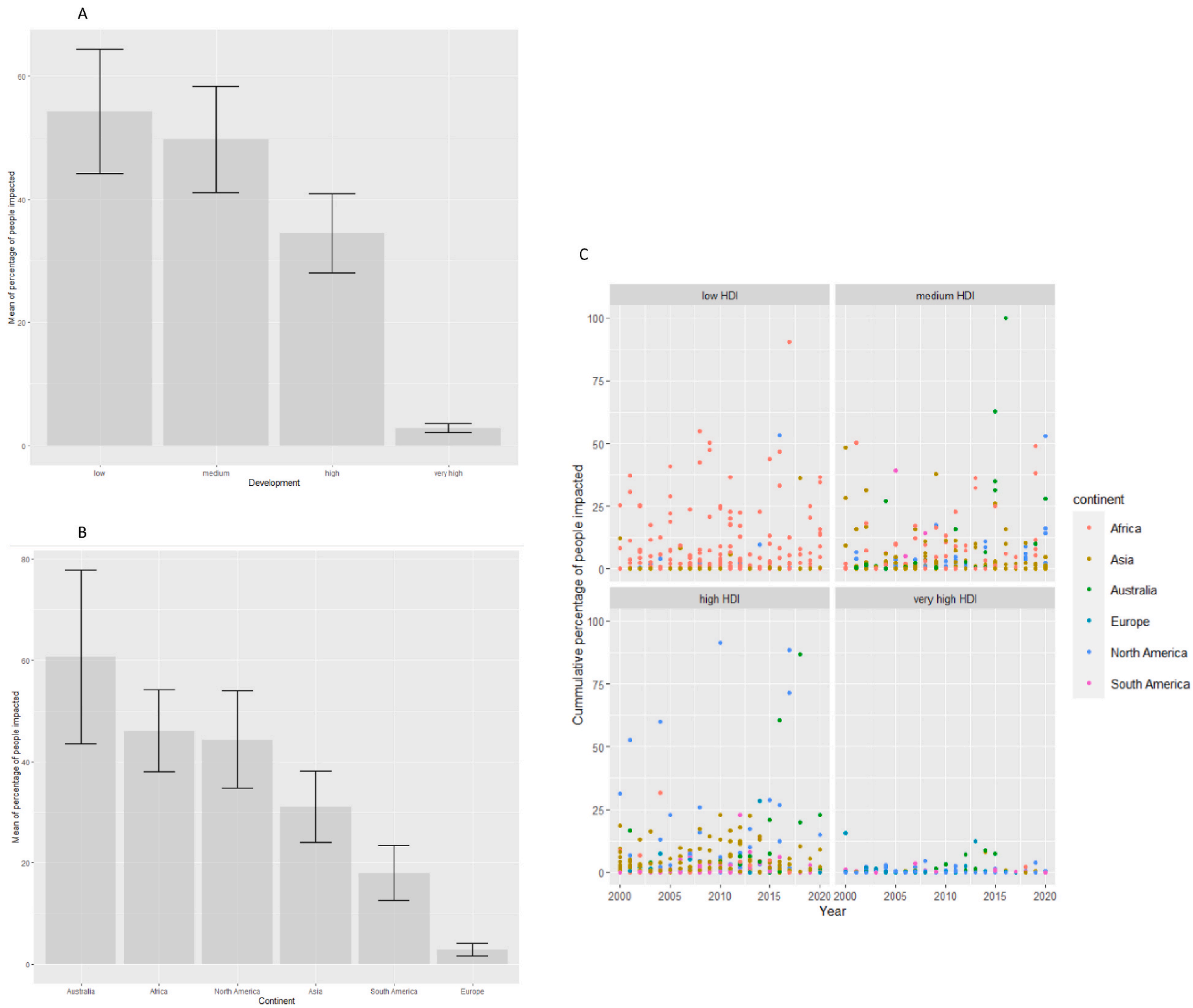
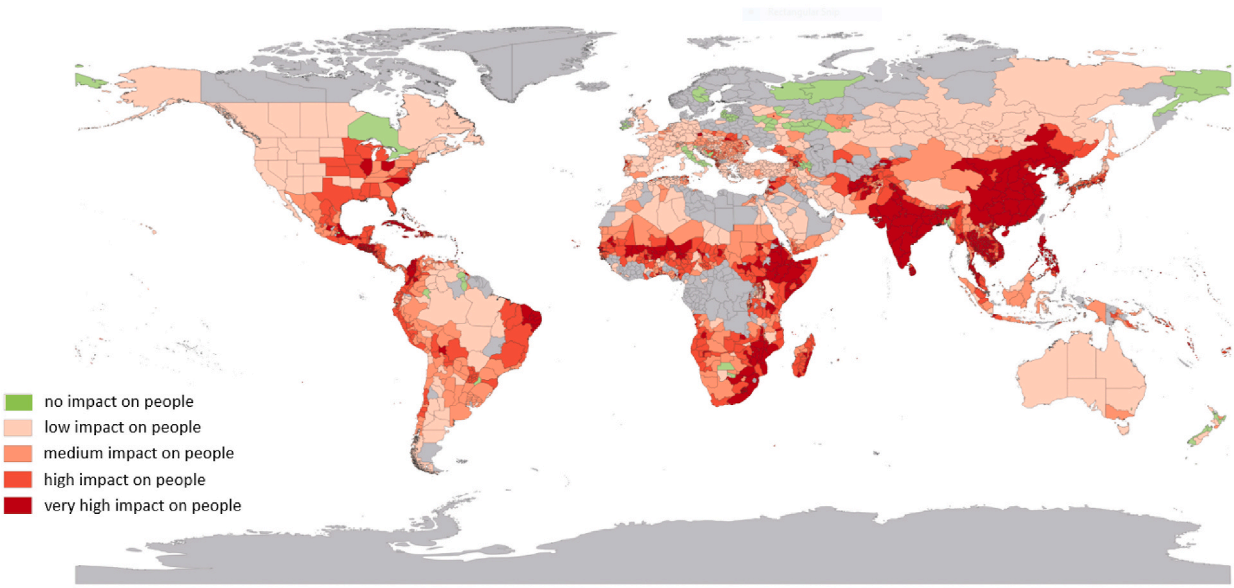


Fig. 3. Fig. 3A. The average percentage (and standard deviation) of the population impacted by all climate-related disasters between (and including) 2000 and 2020 in countries of various levels of development. Fig. 3B. The average percentage (and standard deviation) of people impacted by all climate-related disasters between (and including) 2000 and 2020 in countries on different continents. Fig. 3C. The cumulative percentage of the population impacted by all climate-related disasters between (and including) 2000 and 2020 in countries of various levels of development per year.

Table 2
Direction in the significant trends in the percentages of population impacted by climate-related disasters and in the number of events of climate-related disasters through time (between and including 2000 and 2020) in countries of different levels of development and in countries located in different continents (NS = not statistically significant linear trend through time).

		Temporal trends	
		Percentage of population impacted	Number of events
Continents	Africa	Increase ($z = 2.24$, $p = 0.02$, $df = 509$)	Decrease ($z = -2.63$, $p = 0.008$)
	Australia	Increase ($z = 2.68$, $p < 0.01$, $df = 106$)	NS
	Europe	Decrease ($z = -2.19$, $p = 0.02$, $df = 305$)	Decrease ($z = -2.32$, $p = 0.02$)
	Asia	Decrease ($z = -2.23$. $p = 0.02$, $df = 476$)	NS
	North America	NS	Decrease ($z = -2.51$, $p = 0.01$)
	South America	NS	NS
Level of human development	Low	NS	Decrease ($z = -2.58$, $p = 0.009$)
	Medium	NS	NS
	High	NS	NS
	Very high	NS	Decrease ($z = -3.56$, $p < 0.001$)

A All impacts combined



B Tropical cyclones

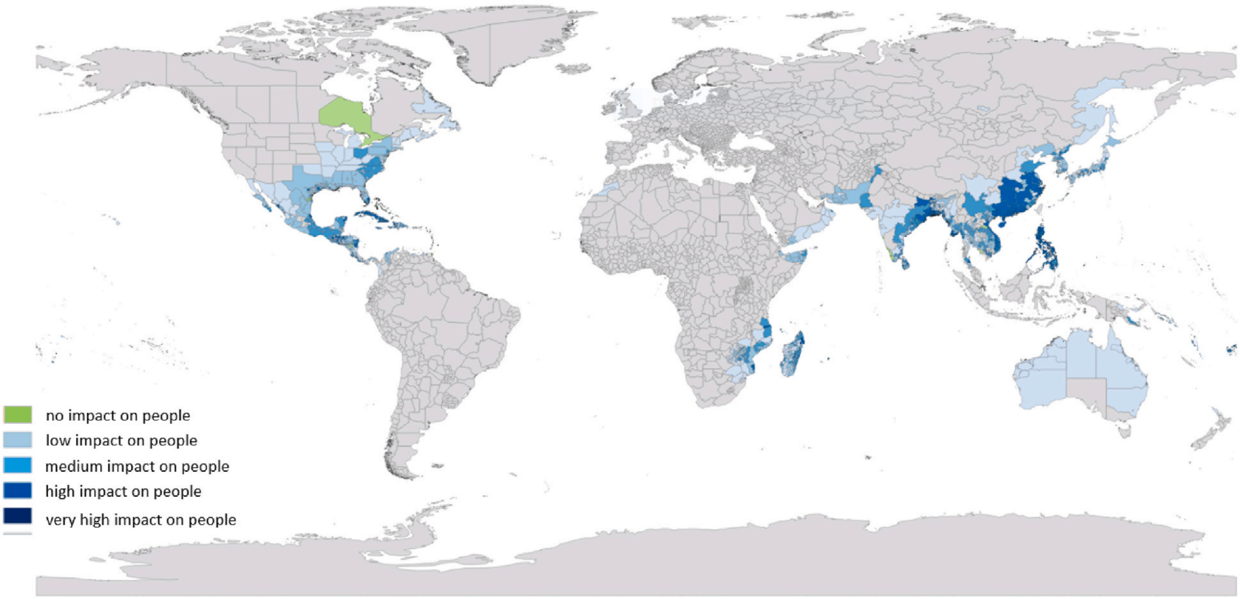
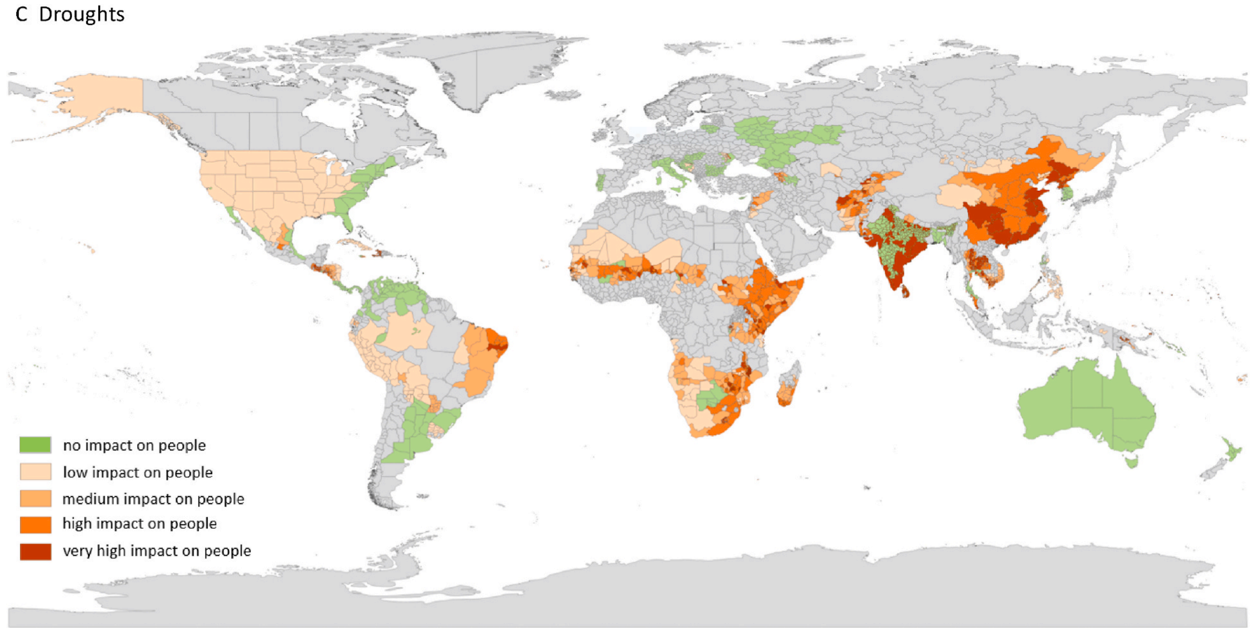


Fig. 4. Level of impact from climate-related disasters in administrative areas between 2000 and 2020 based on the number of people impacted per km^2. Areas in gray are those that did not have any entries in the EM-DAT database. Areas in green are those that had entries but did not have any people directly impacted by climate change (i.e., people that have died, people that became homeless, people that needed immediate assistance or people that got injured). A. All impacts (tropical cyclones, droughts, flash flood, riverine flood, heatwaves, landslides and mudslides and wildfires combined); B. Tropical cyclones; C. Droughts; D. Flash flood; E. Riverine flood; F. Heatwaves; G. Landslides and Mudslides; H. Wildfires. Thresholds were determined based on quartiles and done independently for each impact. The first quartile or "low impact" is the value that cuts off the first 25 % of the data when it is sorted in ascending order, the second quartile or "medium impact" is the value that cuts off the first 50 %, the third quartile or "high impact" is the value that cuts off the first 75 %, with the values higher than that were considered as "very

high impact." Thresholds for each level of impact for each map can be found in Annex 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.).



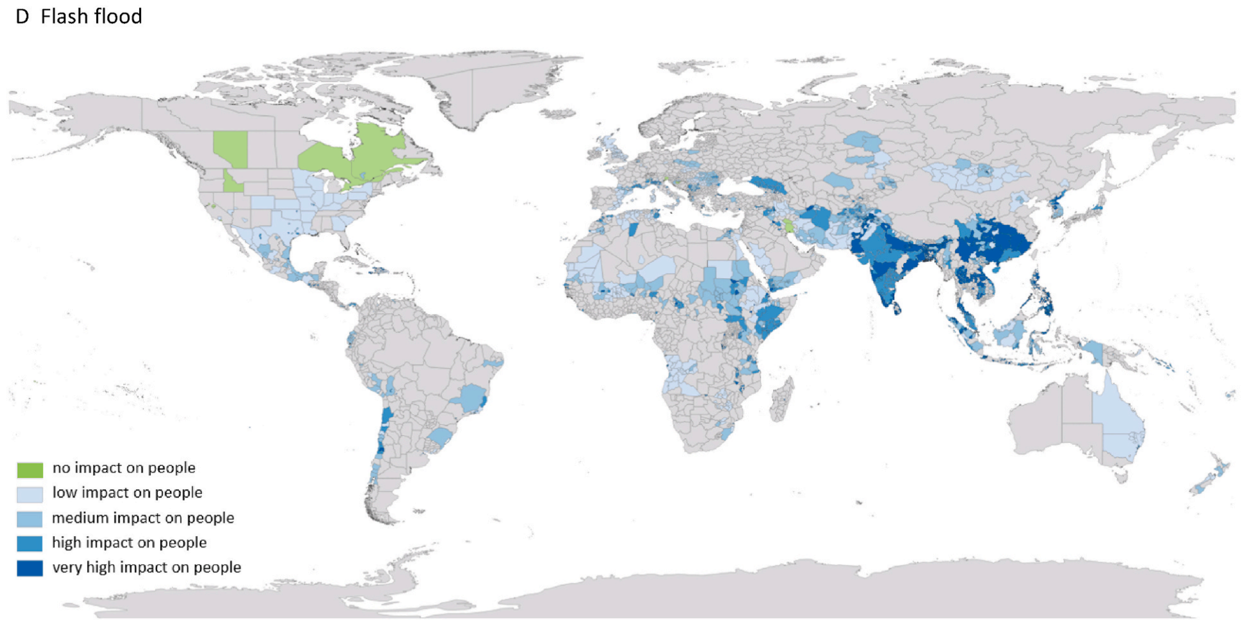
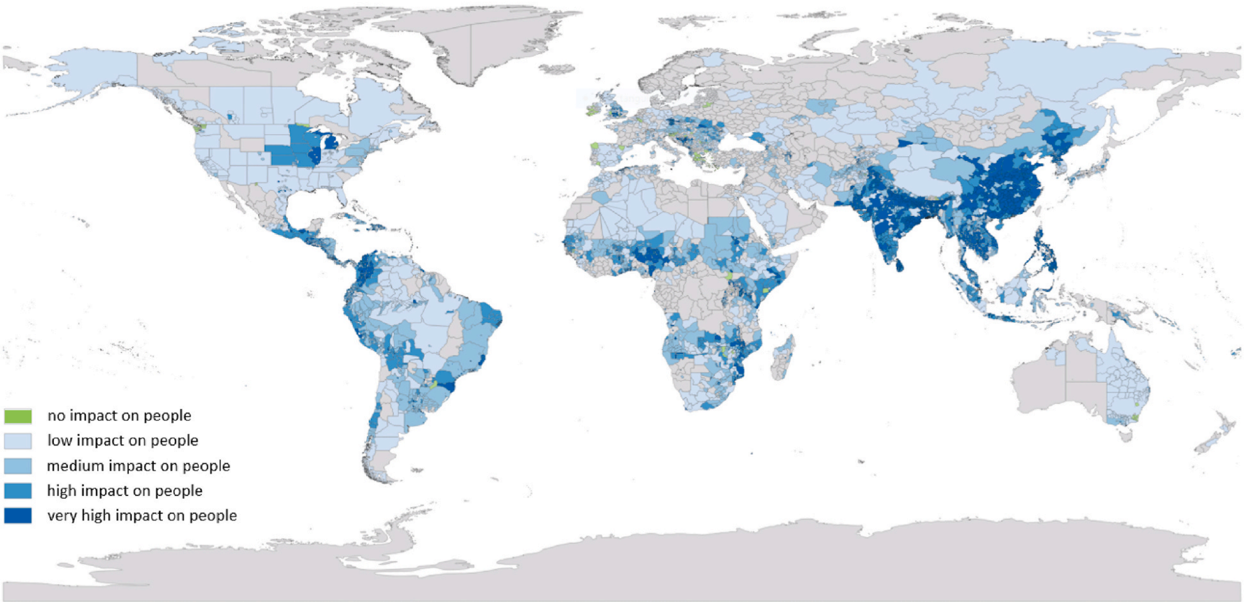


Fig. 4. (*continued*).

4.2. Countries in Africa showed an increase in people impacted by climate-related disasters through time, despite a decrease in the number of climate-related disaster events

Countries in both Africa and Europe showed a decrease in the number of events from climate-related disasters through time between 2000 and 2020. However, countries in Africa showed an increase in the percentage of people impacted by climate-related disasters, whereas countries in Europe showed a decrease. Countries in North America also showed a decrease in the number of events through time, which has not resulted in any significant changes in the percentage of people impacted through time. Those differences show how actions implemented in different countries, and the capacities of countries and their populations to respond to climate change, may have led to different outcomes. Those differences can also imply that the climate-related events are becoming more severe in certain regions, such as in African countries. The severity of impacts was not, however, addressed in this study as this

E Riverine flood



F Heatwaves

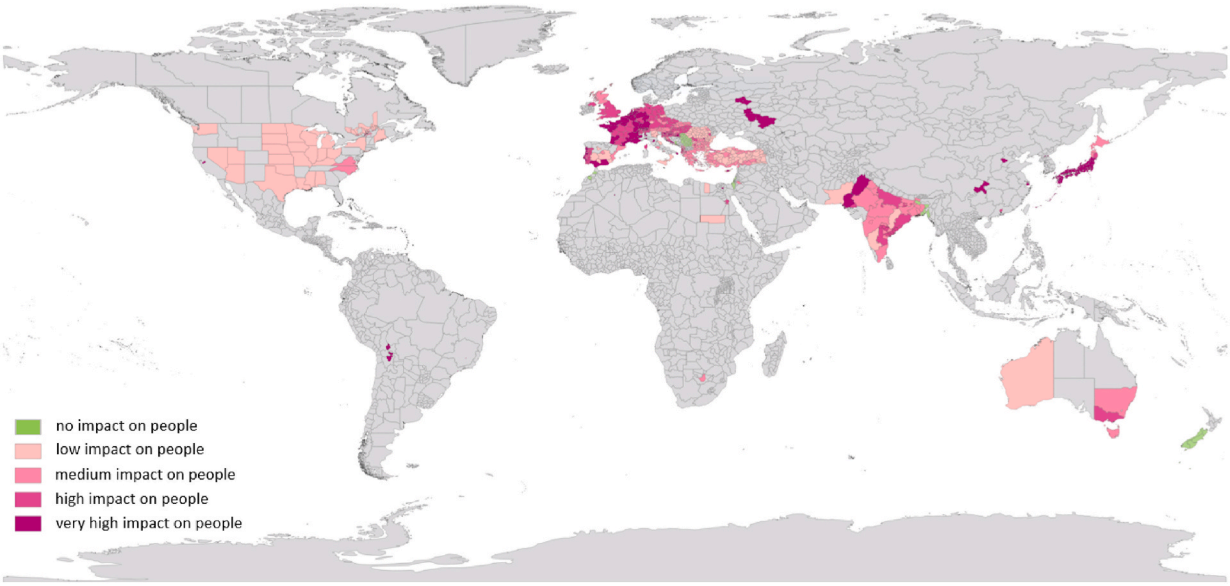
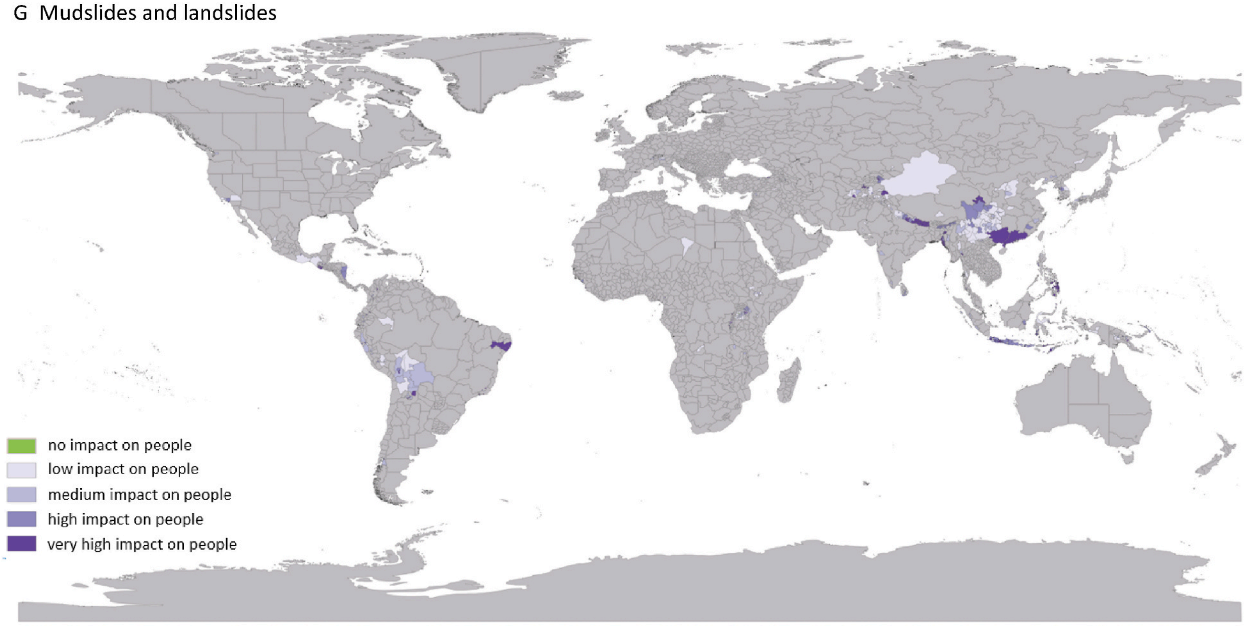


Fig. 4. (*continued*).

information is not included in the EM-DAT. We acknowledge, however, that this is a limitation of the paper, as severity is important and could also be driving the patterns found in this study.

A significant decrease in the number of events from climate-related disasters was found in low and in very high development countries, although these trends have not resulted in a significant change in the percentage of people impacted through time in those countries. A decrease in the number of events found in this study goes against some of the analysis that used global historical data for the last 50 years. However, some of those estimates (e. g., World Meteorological Organization 2021 [17]) are based on disaster loss databases, including the EM-DAT, which were able to assemble more data during the 2000s compared to the previous decades [18] leading to a more comprehensive reporting of disasters compared to the pre-internet era. Furthermore, the number of disasters is an indicator that is conceptually more uncertain and difficult to be reported than the number of people impacted [28,29]. Therefore, our



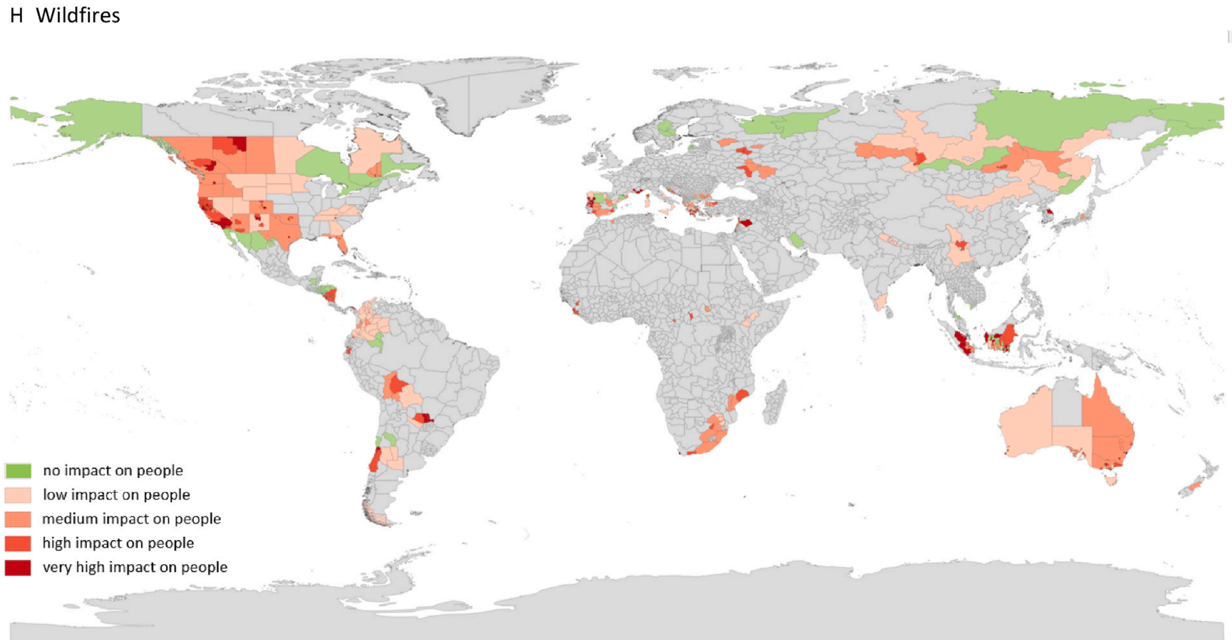


Fig. 4. (*continued*).

results related to the number of events have to be taken with caution.

4.3. The importance of climate adaptation in countries with low levels of human development and the potential role of Nature-based Solutions in those countries

Our analyses show the discrepancies among countries with differing levels of development, as well as the discrepancies in the number of people impacted by climate-related disasters between African and European countries. Many countries in Africa and many countries with low levels of development in other regions are the ones where high percentages of populations have suffered the most. This result is not surprising as those countries often have fewer resources to plan, forecast, prevent and recover from impacts related to climate change [30–32]. In those countries, less costly alternatives, and approaches that not only help people adapt to climate change but also lead to a variety of outcomes, such as the provision of alternative sources of income and building materials [33], may be particularly important.

Nature-based Solutions, actions that aim to restore, protect and manage nature to help people adapt to climate change [34], represent one of those approaches. Nature-based Solutions for climate adaptation can be cost-effective (Narayan et al., 2016 [35], Reguero et al., 2018 [36], Global Commission on Adaptation 2019 [5]) and readily available [37]. They are often considered non-regret options to address climate change impacts because they can provide climate mitigation, biodiversity and human-wellbeing benefits ([38–41], Chausson et al., 2020 [42], [43]), which can be particularly important in areas where resources to address societal challenges are limited, such as those of low human development and where people have experienced high and very high impacts of climate change.

Nature-based Solutions have been effective in addressing the impacts of multiple climate-related disasters, such as those analyzed in this study. For example, the protection of marshes in the Philippines have shown flooding prevention benefits, while providing positive ecological, social and mitigation outcomes [44]. Therefore, this intervention could be implemented in areas that have experienced flooding impacts and where marshes naturally occur. Grazing management and the protection of savannas have shown to be effective in addressing droughts in Kenya and Zimbabwe, and led to positive social outcomes for the local communities [45,46]. The protection of grassland in Ethiopia has shown to be effective in reducing impacts from drought events (Woldie et al., 2019 [47]) and led to positive ecological and social outcomes. Those types of interventions could also be implemented in areas with natural grasslands and rangelands and where people have been highly impacted by droughts.

The protection, restoration and sustainable use of mangroves in India, Vietnam and the Philippines have had positive impacts in reducing coastal erosion and coastal inundation, providing positive ecological and social outcomes (Badola et al., 2005 [48], [49,50]). The protection of sandy shorelines in Mexico has shown to be effective in minimizing the impacts of coastal erosion [51]. The fire and water management, protection and restoration of montane rainforests in Nepal have had positive effects in reducing mudslides and landslides, while providing positive ecological and social outcomes [52]. Other examples of Nature-based Solutions found to be effective in minimizing specific climate change impacts can be found in the Nature-based Solutions Initiative evidence platform (https://www.naturebasedsolutionsevidence.info/).

4.4. The importance of understanding historical impacts in guiding efforts to address losses and damages related to climate change

The concept of losses and damages, the effects of climate change that are beyond current means of adaptation, has been receiving a lot of attention, especially after the 27th United Nations (UN) Climate Change Conference (COP27). In that climate conference, countries reached a historical decision to establish the "Loss and Damage Fund". At the 28th UN Climate Change Conference (COP28) this fund, now called "Climate Impact and Response Fund" was operationalized, with several countries, including Germany, France, Italy, the United Kingdom and The United Arab Emirates, pledging money to the fund. It is very clear now that the effects and impacts of climate change are not felt evenly around the world, with the most vulnerable countries hit hardest by the impacts of climate change, despite doing the least to cause them. This fund can be an important step towards climate justice, as countries responsible for high carbon emissions will have to mobilize expertise and additional finance for developing countries that have been suffering the most from losses related to climate-related disasters. However, there are still challenges regarding this fund, including that current pledges are well short of the total resources needed, the risk that supposed "additional" funding will simply be taken from other areas and the establishment of clear eligibility criteria.

Our study shows that the cumulative percentage of people impacted by climate-related disasters have been more than 100 % in 19 countries, meaning that large numbers of people in those countries, primarily located in the Caribbean, Africa and Asia, have been impacted year after year by climate-related disasters. This recurrent impact very likely means that adaptation efforts in those countries have been falling short in helping people and ecosystems adapt to climate change. Therefore, this paper provides insights into countries where people have suffered the most from climate change impacts in recent years and could be good candidates for the "Climate Impact and Response Fund".

4.5. Limitations of the dataset used

Even though some studies have highlighted the limitations of using the EM-DAT dataset (e.g., Panwar et al., 2020 [53], [54]), this is still the most comprehensive, global and free disaster database compiled to date. One of the limitations is the lack of reporting for events that had fewer than 10 deaths or that affected fewer than 100 people. Such criteria might exclude significant events that do not meet these thresholds but still have meaningful impacts. So, our results may be biased towards areas with a certain level of population density and may be underestimating the number of deaths and affected people [12]. Therefore, in addition to the areas highlighted in our maps and in the tables showing top impacted countries, there might be populations in low-density areas and countries with low populations that urgently need to adapt. The second limitation of EM-DAT is the limited capacity of certain countries and regions to report impacts leading to the issue of missing data [13]. We are aware that countries with low human development have less reporting capacity than other countries, which could have led to unbalanced representation of those countries and regions in the database, making the results of this paper biased. For example, heatwave data may have less completeness, with no or few records in certain regions, such as in Africa [55]. Even though many developing countries were highlighted as having overall high impacts on people, improving data availability for those countries, placing equal importance on all types of disasters and expanding the suite of information sources used could advance the accuracy of the database (Gall et al., 2015 [56]) and complement the results of this work. The third limitation is the dependency on official records, which could have led to under or overreporting of certain disasters due to political considerations.

5. Conclusion

This study analyzed the occurrence of climate-related disasters over 20 years and illustrated how they are impacting populations across the world depending on their levels of human development. Central America, Caribbean, Eastern Africa including Madagascar and Southern and Eastern Asia had the highest levels of impacts from climate-related disasters. This study did not find statistically significant differences in the total number of events of climate-related disasters among countries of different levels of development and among countries located on different continents. However, this study did find significant differences in percentages of people impacted in countries with very high levels of human development when compared to countries with lower levels of human development. Likewise, this study found significant differences in the percentages of people impacted in African countries compared to European countries. This is consistent with what we would expect given that countries with higher levels of human development have more resources to plan for climate-related disasters, and to warn and educate populations about risks, in addition to having populations with the needed resources to adapt and respond to climate change.

The identification of administrative areas at the sub-national level where disproportionally high numbers of people have been impacted by climate-related disasters can inform action and policy changes at multiple levels. For example, in administrative areas where people have experienced high and very high impacts, and especially for countries with low levels of economic development, Nature-based Solutions could be important interventions to help vulnerable communities adapt to the impacts of climate change, while receiving a variety of ecosystems benefits, including having their basic needs fulfilled [33]. In the international policy sphere, the analysis of historical events of climate-related disasters could help prioritize areas for the implementation of the newly established "Climate Impact and Response Fund", a landmark deal to support vulnerable countries that have suffered the most from the impacts of climate change and to promote climate justice.

CRediT authorship contribution statement

Camila I. Donatti: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Kristina Nicholas:** Data curation, Formal analysis, Writing – review & editing. **Giacomo Fedele:** Conceptualization, Writing – review & editing. **Damien Delforge:** Formal analysis, Writing – review & editing. **Niko Speybroeck:** Formal analysis, Writing – review & editing. **Paula Moraga:** Formal analysis, Writing – review & editing. **Jamie Blatter:** Formal analysis, Writing – original draft, Writing – review & editing. **Regina Below:** Writing – review & editing. **Alex Zvoleff:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Camila Donatti reports financial support was provided by Gordon and Betty Moore.

Data availability

The authors do not have permission to share data.

Acknowledgements

Camila I. Donatti was supported by a gift provided by Betty and Gordon Moore. We would like to thank Patrick Roehrdanz and Gabriel Daldegan for their assistance with data analysis and mapping and 2 anonymous reviewers for their suggestions that helped improve the manuscript.

ANNEXES.

Annex 1
List of disasters included in the EM-DAT dataset. Disaster types, sub-types and sub-sub-types in bold were included in the analysis for this publication.

Disaster Subgroup	Disaster Main Type	Disaster Sub-Type	Disaster Sub-Sub-Type
Meteorological	Storm	Extra-tropical storm	NA
		Tropical cyclone	
		Convective Storm	Derecho
			Hail
			Lightning/thunderstorm
			Rain
			Tornado
			Sand/dust storm
			Winter storm/blizzard
			Storm/surge
			Wind
			Severe storm

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Annex 1 (*continued*)

Disaster Subgroup	Disaster Main Type	Disaster Sub-Type	Disaster Sub-Sub-Type
	Extreme temperature	Cold wave	NA
		Heat wave	NA
		Severe winter conditions	Snow/ice
			Frost/freeze
	Fog	NA	NA
Hydrological	**Flood**	Coastal flood	NA
		Riverine flood	
		Flash flood	
		Ice jam flood	
	Landslide	Avalanche	
		Mudslide	
		Landslide	
	Wave action	Rogue wave	
		Seiche	
Climatological	**Drought**	NA	NA
	Glacial Lake Outburst	NA	
	Wildfire	Forest Fire	
		Land fire: Brush, bush, pasture	

Annex 2

Cumulative percentage of people impacted , the total number of people impacted , number of events and number of people impacted per event by 7 climate-related disaster types between (and including) 2000–2020.

Country	Cumulative percentage of people impacted	Total number of people impacted	Number of events	N. of people impacted per event
Mauritania	196.96 %	7,536,101	16	471,006
Lesotho	188.99 %	3,883,541	8	485,442
Cuba	180.99 %	20,391,089	32	637,221
Zimbabwe	165.49 %	21,666,000	19	1,140,315
Niger (the)	162.82 %	26,414,124	24	1,100,588
Korea (the Democratic People's Republic of)	160.72 %	40,587,475	30	1,352,915
Somalia	157.45 %	20,137,244	44	457,664
Micronesia (Federated States of)	153.68 %	153,684	8	19,210
Philippines (the)	151.91 %	145,641,745	255	571,144
Vanuatu	143.53 %	385,198	11	35,018
Namibia	141.81 %	3,089,358	17	181,726
Malawi	134.36 %	18,875,289	29	650,872
Djibouti	131.63 %	1,108,072	7	158,296
Fiji	125.32 %	1,123,213	28	40,114
Saint Lucia	114.00 %	228,005	7	32,572
Cambodia	112.90 %	15,380,985	22	699,135
Tonga	109.20 %	109,196	10	10,919
Thailand	107.88 %	72,118,289	69	1,045,192
Dominica	107.85 %	107,853	4	26,963
China	99.10 %	1,330,773,654	343	3,879,806
South Sudan	93.96 %	9,255,819	13	711,986
India	89.02 %	1,054,928,730	205	5,145,993
Tuvalu	85.76 %	10,113	3	3,371
Guyana	83.83 %	612,082	6	1,02,013
Mozambique	81.12 %	18,365,957	42	437,284
Haiti	79.82 %	8,378,301	61	137,349
Honduras	79.69 %	7,333,547	37	198,203
Belize	78.23 %	220,980	11	20,089
Mali	70.87 %	12,176,922	21	579,853
Sri Lanka	70.66 %	14,243,769	43	331,250
Bangladesh	68.05 %	97,205,690	68	1,429,495
Guatemala	67.55 %	10,566,650	49	215,645
Tajikistan	66.94 %	4,309,503	25	172,380
Afghanistan	65.45 %	20,799,734	77	270,126
Chad	64.83 %	7,821,444	16	488,840
Kenya	64.80 %	27,362,705	55	497,503
Grenada	60.04 %	60,039	2	30,019
Burkina Faso	58.28 %	10,294,845	17	605,579
Eritrea	55.10 %	1,707,013	3	569,004
Ethiopia	54.80 %	45,886,349	40	1,147,158
Madagascar	51.62 %	10,700,429	51	209,812
Comoros (the)	49.22 %	422,473	5	84,494
Viet Nam	45.16 %	39,469,742	126	313,251
Nicaragua	42.97 %	2,615,456	34	76,925
Paraguay	40.55 %	2,607,195	19	137,220

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Annex 2 (*continued*)

Country	Cumulative percentage of people impacted	Total number of people impacted	Number of events	N. of people impacted per event
Papua New Guinea	39.51 %	3,138,011	27	116,222
Bosnia and Herzegovina	38.91 %	1,391,944	16	86,996
South Africa	38.71 %	18,885,883	31	609,222
Bolivia (Plurinational State of)	38.51 %	3,860,481	35	110,299
Kyrgyzstan	38.17 %	2,023,712	10	202,371
Zambia	37.32 %	5,051,322	17	297,136
Lao People's Democratic Republic (the)	35.84 %	2,331,096	15	155,406
El Salvador	34.11 %	2,123,018	28	75,822
Burundi	33.51 %	2,522,853	25	100,914
Antigua and Barbuda	32.60 %	32,601	3	10,867
Dominican Republic (the)	32.45 %	3,327,050	42	79,215
Jamaica	31.12 %	864,382	19	45,493
Gambia (the)	28.74 %	548,335	9	60,926
Marshall Islands (the)	28.34 %	28,344	5	5,668
Pakistan	28.31 %	50,888,559	74	687,683
Saint Vincent and the Grenadines	25.35 %	25,347	8	3,168
Solomon Islands	23.86 %	137,808	15	9,187
Colombia	23.18 %	10,303,774	62	166,189
Tanzania, United Republic of	21.51 %	9,130,862	27	338,180
Senegal	20.91 %	2,631,493	14	187,963
Mongolia	20.44 %	500,875	6	83,479
Brazil	20.24 %	40,426,349	79	511,725
Georgia	19.59 %	849,474	12	70,789
Sudan (the)	19.58 %	7,027,215	22	319,418
Angola	17.72 %	4,438,955	39	113,819
Bahamas (the)	15.10 %	53,554	15	3,570
Czech Republic (the)	14.40 %	1,520,532	10	152,053
Seychelles	14.24 %	14,235	3	4,745
Uganda	13.99 %	4,193,312	31	135,268
Guinea-Bissau	13.90 %	190,547	6	31,757
Benin	13.37 %	1,223,202	10	122,320
Rwanda	12.78 %	1,118,616	18	62,145
Nepal	11.38 %	2,960,977	35	84,599
Timor-Leste	11.14 %	133,194	6	22,199
Botswana	11.04 %	190,617	8	23,827
Costa Rica	11.00 %	494,471	25	19,778
Mexico	10.92 %	12,113,103	106	11,4274
Myanmar	10.56 %	5,378,549	33	162,986
Malaysia	10.12 %	2,963,707	32	92,615
Armenia	9.61 %	297,751	3	99,250
Peru	7.95 %	2,309,359	43	53,706
United States of America (the)	7.90 %	23,911,600	219	109,185
Cabo Verde	7.53 %	30,162	3	10,054
Syrian Arab Republic	7.10 %	1,440,191	4	360,047
Palau	6.91 %	1,250	2	625
Samoa	6.36 %	12,725	6	2,120
Suriname	6.31 %	31,553	2	15,776
Moldova (the Republic of)	5.82 %	238,700	6	39,783
Nigeria	5.66 %	9,282,812	30	30,9427
Chile	5.50 %	901,765	27	33,398
Albania	5.14 %	153,719	11	13,974
Panama	4.90 %	172,686	32	5,396
Togo	4.87 %	297,764	5	59,552
Uruguay	4.84 %	160,663	9	17,851
Ecuador	4.70 %	686,899	25	27,475
Gabon	4.32 %	77,846	1	77,846
Guinea	4.07 %	366,655	11	33,332
Ghana	3.62 %	832,801	13	64,061
Argentina	3.33 %	1,342,611	32	41,956
Jordan	2.94 %	150,068	3	50,022
Indonesia	2.76 %	6,569,677	174	37,756
Iran (Islamic Republic of)	2.45 %	1,647,318	29	56,804
Uzbekistan	2.43 %	601,500	2	300,750
Mauritius	2.40 %	31,148	4	7,787
Central African Republic	2.25 %	94,623	10	9,462
Japan	1.96 %	2,508,345	93	26,971
Yemen	1.85 %	505,303	27	18,714
Kiribati	1.81 %	1,805	3	601
Barbados	1.79 %	5,382	5	1,076

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Annex 2 (*continued*)

Country	Cumulative percentage of people impacted	Total number of people impacted	Number of events	N. of people impacted per event
Cameroon	1.61 %	358,029	15	23,868
Australia	1.60 %	358,887	73	4,916
Portugal	1.54 %	159,859	22	7,266
Russian Federation (the)	1.45 %	2,106,783	63	33,441
Korea (the Republic of)	1.42 %	686,721	41	16,749
Montenegro	1.35 %	8,086	5	1,617
Ukraine	1.22 %	574,685	10	57,468
Azerbaijan	1.21 %	106,503	4	26,625
Romania	1.08 %	231,918	41	5,656
Hungary	1.04 %	103,390	12	8,615
Serbia	1.03 %	92,024	15	6,134
Israel	1.02 %	80,245	7	11,463
Venezuela (Bolivarian Republic of)	0.99 %	272,173	21	12,960
Tunisia	0.95 %	105,572	9	11,730
Liberia	0.91 %	33,414	4	8,353
Canada	0.83 %	295,984	38	7,789
Bulgaria	0.82 %	60,143	24	2,505
Austria	0.76 %	61,985	10	6,198
Oman	0.75 %	20,404	7	2,914
Slovenia	0.71 %	14,842	4	3,710
United Kingdom of Great Britain and Northern Ireland (the)	0.71 %	437,350	27	16,198
Kazakhstan	0.70 %	115,081	10	11,508
Sierra Leone	0.64 %	41,661	10	4,166
Algeria	0.60 %	200,904	26	7,727
Maldives	0.55 %	1,649	1	1,649
Iraq	0.52 %	163,637	10	16,363
Saint Kitts and Nevis	0.50 %	500	1	500
Morocco	0.43 %	134,737	18	7,485
Lebanon	0.39 %	17,016	3	5,672
Croatia	0.36 %	15,397	18	855
Palestine, State of	0.34 %	14,505	4	3,626
Poland	0.31 %	120,599	8	15,074
Hong Kong	0.28 %	19,553	11	1,777
Turkey	0.26 %	182,792	37	4,940
Greece	0.22 %	23,581	25	943
New Zealand	0.20 %	8,449	11	768
Bhutan	0.20 %	1,212	3	404
Italy	0.17 %	96,011	38	2,526
France	0.17 %	101,886	30	3,396
Trinidad and Tobago	0.14 %	1,763	4	440
Saudi Arabia	0.10 %	25,020	15	1,668
Switzerland	0.09 %	6,879	5	1,375
Spain	0.06 %	27,587	31	889
Belgium	0.06 %	6,206	14	443
Qatar	0.05 %	1,500	1	1,500
Cyprus	0.05 %	409	4	102
Luxembourg	0.04 %	170	1	170
Libya	0.03 %	2,016	1	2,016
Egypt	0.03 %	24,947	5	4,989
Slovakia	0.02 %	1,285	12	107
Germany	0.02 %	17,774	14	1,269
Norway	0.02 %	1,171	2	585
Ireland	0.02 %	902	3	300
Netherlands (the)	0.02 %	2,765	5	553
Finland	0.01 %	400	1	400
Lithuania	<0.001 %	4	4	1
Latvia	0.00 %	–	1	0
Sweden	0.00 %	–	1	0

Annex 3
Thresholds for each level of impact used to prepare the maps of Impacts from climate-related disasters at the sub-national level for each climate-related disaster.

climate-related disaster	Low impact on people (people per km2)	Medium impact on people (people per km2)	High impact on people (people per km2)	Very high impact on people (people per km2)
all impacts combined	≥1.080710e-07 < 5.853062e-02	≥5.853062e-02 < 1.070379e+00	≥1.070379e+00 < 1.025556e+01	≥1.025556e+01 ≤ 1.980551e+04
tropical cyclone	≥1.200000e-07 < 5.084546e-01	≥5.084546e-01 < 3.731912e+00	≥3.731912e+00 < 2.464409e+01	≥2.464409e+01 ≤ 1.980551e+04

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Annex 3 (*continued*)

climate-related disaster	Low impact on people (people per km2)	Medium impact on people (people per km2)	High impact on people (people per km2)	Very high impact on people (people per km2)
droughts	≥1.080000e-07 < 2.778637e+00	≥2.778637e+00 < 1.492962e+01	≥1.492962e+01 < 5.875317e+01	≥5.875317e+01 ≤ 4.608189e+03
flash floods	≥4.240000e-07 < 2.480567e-02	≥2.480567e-02 < 4.322706e-01	≥4.322706e-01 < 4.484455e+00	≥4.484455e+00 ≤ 8.954104e+02
heatwaves	≥3.060000e-06 < 3.179065e-04	≥3.179065e-04 < 3.222649e-03	≥3.222649e-03 < 2.855217e-02	≥2.855217e-02 ≤ 5.759482e+02
mudslides and landslides	≥6.670000e-06 < 8.387995e-03	≥8.387995e-03 < 7.312105e-02	≥7.312105e-02 < 8.145801e-01	≥8.145801e-01 ≤ 1.332236e+02
riverine floods	≥2.720000e-06 < 1.308372e-01	≥1.308372e-01 < 1.223405e+00	≥1.223405e+00 < 9.152869e+00	≥9.152869e+00 ≤ 5.813410e+03
wildfire	≥1.900000e-07 < 7.157733e-04	≥7.157733e-04 < 1.167326e-02	≥1.167326e-02 < 3.428637e-01	≥3.428637e-01 ≤ 5.809370e+01

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