**The broad threat to humanity from ongoing greenhouse gas emissions**

**We found traceable evidence for 467 pathways in which human health, water, food, economy, infrastructure and security have been recently impacted by climate hazards such as warming, heatwaves, precipitation, drought, floods, fires, storms, sea level rise, and changes in natural land cover and ocean chemistry. By 2100, the world’s population will be exposed to the equivalent of the largest magnitude in one of these hazards if greenhouse gasses are aggressively reduced or three if they are not. These findings highlight that greenhouse gas emissions pose a broad threat to humanity by simultaneously intensifying many hazards, which humanity is vulnerable to.**

Ongoing greenhouse gas emissions are simultaneously shifting many elements of Earth’s climate beyond thresholds that can impact humanity[1-13](#_ENREF_1). By affecting the balance between incoming solar radiation and outgoing infrared radiation, man-made greenhouse gases are increasing the Earth’s energy budget ultimately leading to warming. Given interconnected physics, warming can affect other aspects of the Earth’s climate system. For instance, by enhancing soil water evaporation, warming can lead to extreme precipitation and floods in commonly wet-places or drought in commonly dry places also increasing risk of wildfires and heatwaves when heat transfer from water evaporation ceases. In the oceans, CO2 emissions interact with water to produce carbonic acid leading to ocean acidification whereas warming of water molecules increases the volume they occupy adding to the sea-level rise from melting land ice. Ocean warming can also supply moisture increasing the strength of storms. These climate hazards and their impacts on human societies occur naturally but are being non-trivially intensified by man-made greenhouse gas emissions as demonstrated by an active research in detection and attribution, which is discussed at length under Caveats in the Methods section. With few exceptions[1](#_ENREF_1), changes in these hazards have been studied in isolation [e.g., warming[2](#_ENREF_2), drought[3](#_ENREF_3), fire[4](#_ENREF_4), floods[5](#_ENREF_5), heatwaves[6](#_ENREF_6), sea level[7](#_ENREF_7)] whereas impact assessments have commonly focused on specific aspects of human life [e.g., health[8](#_ENREF_8), mental health[9](#_ENREF_9), food production[10](#_ENREF_10), livelihoods[11](#_ENREF_11), economy[12](#_ENREF_12),[13](#_ENREF_13)]. Unfortunately, the failure to integrate available information most likely underestimates the impacts of climate change because *i*) spatial patterns of change differ strongly among climate hazards[2](#_ENREF_2) (e.g., one hazard may be important in one place but not another), *ii*) these hazards may respond differently to mitigation (e.g., strong CO2 reductions may curb warming but may not curtail sea level rise[14](#_ENREF_14)) and *iii*) not all aspects of human systems are equally challenged by climate hazards (e.g., thermoregulation may be relevant to heatwaves, while buildings may be to storms). Therefore, a narrow focus on one or a few hazards may mask the changes and impacts of other hazards, giving an incomplete or misleading assessment of the consequences of climate change[1](#_ENREF_1).

Here we show that ongoing greenhouse gas emissions pose a heightened threat to humanity by intensifying multiple climate hazards, which humanity is highly vulnerable to, and which are projected to affect rich and poor countries alike even under a best case climate scenario. To build our case, we carried out a systematic literature search to identify observed impacts on people from climate hazards (this was intended to indicate the broad human vulnerability to climate hazards) and developed a global map of a cumulative index of projected changes in these hazards (this index was intended to evaluate the extent that humanity overall will be exposed concurrently to different hazards). Integration of these two components revealed that humanity has already been impacted by climate hazards which are projected to intensify even under a best case scenario. Further, we showed that projected exposure to multiple climate hazards will be very similar between rich and poor countries, but variations in adaptation capacity will likely result on different types of impacts (e.g., economic for developed nations and loss of life for developing countries). Our conclusions are not without limitations and we include a description of likely problems from biases in the literature, attribution uncertainty, and multi-model uncertainty (discussed at length under Caveats in the Methods section).

**Observed Impacts on Human Systems**

We created a table in which ten climate hazards (i.e., warming, precipitation, floods, drought, heatwaves, fires, sea level, storms, changes in natural land cover and ocean chemistry) were listed by columns and six aspects of human systems (i.e., health, food, water, infrastructure, economy and security) were listed by rows (see Methods). This table was used as a guide for all possible combinations of keywords to search for publications reporting impacts of climate hazards on key aspects of human life. From over 12,000 references assessed, we identified 3,280 relevant papers that were read in full to find case examples of climate hazards impacting human system. Our criteria for selection of impacts required that impacts be observed and supported with traceable evidence (i.e., there was a reference to a place and time that could be traced to where and when a given impact occurred). Impacts were subcategorized within each of the six primary aspects of human life to reflect the variety of documented impacts (e.g., death, disease within human health, Fig. 1) (see extended details in Methods). In total, we found case examples for 89 attributes of human health, food, water, infrastructure, economy and security impacted by the 10 climate hazards. Of 890 possible combinations (i.e., 10 climate hazards times 89 attributes of human life), we found case examples for 467 interactions or pathways through which humanity has been impacted by climate hazards. For brevity, pathways are described and supported with at least one case example; however, very commonly we found numerous similar case examples of impacts which are listed with their associated paper in a publicly available online database (<http://impactsofclimatechange.info>). This list is intended to document the vulnerability of human systems to changes in climate hazards.

***Health impacts***

We found 27 attributes of human health impacted by climate hazards (Fig. 1), of which death, disease and mental health were the most commonly observed. Death was associated with multiple damaging physiological pathways due to hyperthermia[15](#_ENREF_15) during heatwaves [e.g. >70,000 deaths during the 2003 European heatwave[16](#_ENREF_16)], drowning during floods [e.g., ~3,000 deaths in the 1998 China floods[17](#_ENREF_17)], starvation during droughts [e.g., ~800,000 famine deaths attributed to the 1980s Ethiopian drought[18](#_ENREF_18)], blunt injury during storms [e.g., ~140,000 deaths in the 1991 Cyclone Gorky in Bangladesh[19](#_ENREF_19)], and asphyxiation during fires [e.g., ~173 deaths in the 2009 Australian Black Saturday fire[20](#_ENREF_20)]. Loss of natural land cover impaired coastal protection likely contributing to increased mortality during storms and floods[21](#_ENREF_21),[22](#_ENREF_22). Warming and changes in precipitation and ocean chemistry caused human death through increased transmission of pathogenic diseases (described below).

Climate hazards were related to numerous conditions that disrupt body function. Increased morbidity (e.g., cardiac and respiratory disorders) due to heat illness occurred during heatwaves[23](#_ENREF_23), while injuries were common during floods, storms and fires. Respiratory problems were associated with increased ozone pollution from heatwaves and fires[24](#_ENREF_24), dust from droughts[25](#_ENREF_25), mold following storms[26](#_ENREF_26), organic pollutants released from melting ice[27](#_ENREF_27), and pollen from elongated flowering periods caused by warming[28](#_ENREF_28). By increasing habitat suitability of pathogens and vectors, warming and precipitation changes contributed to epidemics of malaria[29](#_ENREF_29), diarrhea[30](#_ENREF_30" \o "Rose, 2001 #7162), dengue fever[31](#_ENREF_31" \o "Epstein, 1998 #8766), salmonellosis[32](#_ENREF_32" \o "Tirado, 2010 #7163), cholera[32](#_ENREF_32), leptospirosis[33](#_ENREF_33), bluetongue virus[34](#_ENREF_34), and campylobacteriosis[35](#_ENREF_35" \o "Kendrovski, 2012 #7171). Similarly, warming facilitated range expansion of vectors implicated in outbreaks of plague transmitted by rodents[36](#_ENREF_36), West Nile virus by birds[37](#_ENREF_37), schistosomiasis by snails[29](#_ENREF_29) and encephalitis by ticks[38](#_ENREF_38). Outbreaks also resulted from climate hazards increasing vector proximity to people. For instance, forest fragmentation increased the density of ticks near people triggering outbreaks of Lyme disease[39](#_ENREF_39) and encephalitis[40](#_ENREF_40), fires drove fruit bats closer to towns causing outbreaks of Hendra and Nipah viruses[41](#_ENREF_41), drought mobilized livestock near cities causing outbreaks of hemorrhagic fever[40](#_ENREF_40), and melting ice due to warming caused voles to find shelter in homes increasing hantavirus infections[42](#_ENREF_42). Likewise, floods[43](#_ENREF_43), heatwaves[44](#_ENREF_44) and intense rain[44](#_ENREF_44) have been related to increases in snake bites due to inhospitable conditions forcing animals to move closer to people. Poor sanitation and contamination of water supply due to storms and floods resulted in outbreaks of cholera, malaria, leptospirosis[45](#_ENREF_45), and diarrheal illness[32](#_ENREF_32). Changes in ocean chemistry have favored pathogen growth and harmful algal blooms related to seafood poisoning[32](#_ENREF_32), cholera[46](#_ENREF_46),[47](#_ENREF_47) and ciguatera[48](#_ENREF_48),[49](#_ENREF_49). Drought was associated with outbreaks of West Nile virus[37](#_ENREF_37), leishmaniasis[50](#_ENREF_50" \o "Magrin, 2007 #7167) and chikungunya virus[51](#_ENREF_51), and hantavirus when interacting with floods[50](#_ENREF_50). Drought forced the use of unsafe drinking water resulting in outbreaks of diarrhea, cholera and dysentery[52](#_ENREF_52). By increasing concentration of particulates during dust storms, drought was also linked to valley fever, a disease caused by a fungal pathogen[53](#_ENREF_53).

Climate hazards affected mental health. For instance, depression and post-traumatic stress disorder were reported after storms in the USA[54](#_ENREF_54),[55](#_ENREF_55), floods in the UK[56](#_ENREF_56),[57](#_ENREF_57) and heatwaves in France[53](#_ENREF_53). People experienced existential distress during drought in Australia[58](#_ENREF_58), increased substance abuse after storms in the USA[59](#_ENREF_59), and poor mental health due to climate change in Canada [e.g., loss of sea ice has inhibited cultural practices such as hunting and fishing leading to depression among Inuit people[60](#_ENREF_60)]. Further, suicidal ideation occurred in victims of drought[61](#_ENREF_61), heatwaves[62](#_ENREF_62), storms[55](#_ENREF_55), and floods[63](#_ENREF_63).

Climate hazards were implicated in pre- and post-natal health problems. Children born to pregnant women exposed to floods exhibited increased bedwetting, aggression toward other children[64](#_ENREF_64), and below average birth weight, juvenile height, and academic performance[65](#_ENREF_65). Similarly, exposure to smoke from fires during critical stages of pregnancy may have affected brain development and resulted in preterm delivery, small head circumference, low birth weight, and fetal death or reduced survival[66](#_ENREF_66). Finally, salinity in drinking water caused by saltwater intrusion and aggravated by sea level rise was linked to gestational hypertension, which created serious health issues for the mother and fetus[67](#_ENREF_67).

***Food impacts***

We found ten attributes of food systems impacted by climate hazards, of which impacts on quantity and quality of food from agriculture, livestock, and fisheries were most commonly noted (Fig. 1). Agricultural yields were impacted by direct physical loss and indirectly by exceeding crop physiological thresholds. Direct physical losses occurred due to storms [e.g., ~35% of bean production was lost to Hurricane Mitch in Honduras in 1998[68](#_ENREF_68)], precipitation [e.g., a 10 mm rainfall increase caused a 0.3 ton loss of paddy per hectare in the Mekong Delta[69](#_ENREF_69)], floods [e.g., over 7,600 ha of agricultural land were destroyed by floods in Vietnam in 2009[70](#_ENREF_70)], sea level rise [e.g., agricultural land has been lost to saltwater intrusion in Bangladesh[11](#_ENREF_11)], fires and drought [e.g., ~33% of grain production was lost to a mixture of fires and drought in Russia in 2010[71](#_ENREF_71)]. Indirect losses due to hazards exceeding crop physiological tolerances were caused by warming [e.g., 3-10% wheat yield lost per 1oC increase in China[72](#_ENREF_72)], drought [e.g., ~36% yield decrease during the 2003 drought in Italy[73](#_ENREF_73)], heatwaves [e.g., one single day above 38oC reduced annual yields by 5% in the USA[74](#_ENREF_74)], changes in ocean chemistry [e.g., drought in Australia caused by variability in ocean temperature in the Indian Ocean[75](#_ENREF_75)], and natural land cover change [e.g., crop yields around the world have been reduced by natural land cover change increasing evaporation and reducing soil moisture[76](#_ENREF_76)]. Climate hazards also impacted the quality of crops by altering nutrient content and increasing the risk of contamination. For instance, protein content in some grains declined due to drought[77](#_ENREF_77) and heatwaves[77](#_ENREF_77), whereas floods[78](#_ENREF_78) and permafrost thawing due to warming[79](#_ENREF_79) resulted in soil contamination and food spoilage rendering plant material unfit for consumption. Finally, changes in precipitation and drought were linked to crop infections by molds harmful to people[78](#_ENREF_78).

Climate hazards have impacted animals used for food. Livestock mortality was associated with warming [e.g., a livestock disease bluetongue was positively correlated with increasing temperatures in Europe[8](#_ENREF_8)], drought [e.g., in 2000, three quarters of livestock died due to drought in Kenya[80](#_ENREF_80)], heatwaves [e.g., >5,000 cattle deaths occurred each year there were strong heatwaves in the USA Great Plains[81](#_ENREF_81)], floods [e.g., livestock losses totaled >236,000 during major floods in Bangladesh in 1987 and 1988[82](#_ENREF_82)], and natural land cover change [e.g., in Sudan, land cover change reduced suitable grazing land[83](#_ENREF_83)]. Heatwaves were related to a reduction in grazing, reproduction, and milk production in cattle and high mortalities in chickens and turkeys[84](#_ENREF_84). There were also impacts on hunting, such as warming and melting sea ice in the Arctic shifting the distribution of walrus leading to the loss of subsistence hunting grounds[85](#_ENREF_85). Meat quality was also impacted through contamination [e.g., higher than normal temperatures were associated with 30% of reported cases of salmonellosis in Europe[8](#_ENREF_8)].

Climate hazards were found to impact fisheries through reductions in quantity and quality of fish populations. There were reductions in fish stocks due to warming both directly [e.g. warmer temperatures exceeded cod thermal-tolerance[86](#_ENREF_86) and high water temperatures reduced oxygen content severely impacting salmonid reproduction[87](#_ENREF_87)] and indirectly [e.g. warmer temperatures altered food webs by reducing primary productivity[86](#_ENREF_86)]. Direct stock mortality and changes to reproduction were caused by drought [e.g., by favoring bivalve predators that decreased shellfish populations[88](#_ENREF_88)], heatwaves [e.g. a 1953 heatwave warmed Lake Erie triggering nutrient pollution that caused a large fish kill[89](#_ENREF_89)], and floods [e.g., floods decreased reproductive capacity of anadromous fish[90](#_ENREF_90)]. Climate hazards also impacted the habitats of stocks, including fires [e.g., run-off due to fires increased heavy metal content in lakes and rivers[91](#_ENREF_91)], precipitation [e.g. rains increased sediment and nutrient loading in lagoons[92](#_ENREF_92)], sea level [e.g., sea level rise changed dynamics of coastal lagoons[92](#_ENREF_92)], ocean chemistry [e.g. changes in ocean chemistry increased coral bleaching, which decreased fish habitat[93](#_ENREF_93)], and natural land cover [e.g., introduced water hyacinth in Lake Victoria reduced fish quantity[94](#_ENREF_94)]. The quality of fish was also impacted. Warming increased mercury methylation and has favored the growth of pathogens involved in food poisoning[95](#_ENREF_95). Floods, storms, and fires were also related to increased heavy metal runoff causing fish to accumulate mercury, increasing the risk of mercury poisoning to humans[91](#_ENREF_91).

***Water impacts***

We found that the quantity and quality of freshwater were critically impacted by climate hazards (Fig. 1). Drought, warming, and heatwaves caused wells to run dry and reduced water levels in reservoirs, forcing water shortages and mandatory water restrictions[52](#_ENREF_52),[79](#_ENREF_79),[96-99](#_ENREF_96). Drought, for instance, led to temporary drinking water shortages for over 200,000 people in Puerto Rico in 1997-98[100](#_ENREF_100) and 33 million people in China in 2001[98](#_ENREF_98). Decreases in water supply were also attributed to land cover change, including spread of invasive plant species such as *Tamarix spp*. which increased evapotranspiration, costing USD 65-180 million per year in reduced water supplies[101](#_ENREF_101), and desertification, which led to losses in water storage in areas like the Sahel[102](#_ENREF_102). In mountainous regions, warming resulted in less snow accumulation and retreat of glaciers causing lower groundwater levels and drinking water shortages[11](#_ENREF_11),[103-106](#_ENREF_103). Temporary water shutdowns were also experienced as a result of intense storms[50](#_ENREF_50),[107](#_ENREF_107),[108](#_ENREF_108), such as Hurricane Mitch in 1998 which left over 4 million residents in Honduras without water[109](#_ENREF_109).

Water quality was critically impacted by climate hazards. Contamination of drinking water was caused by wildfires and drought that contributed to elevated levels of nutrients (nitrogen, phosphorus, and sulfates), heavy metals (lead, mercury, cadmium, and chromium), salts (chloride and fluorides), hydrocarbons, pesticides, and even pharmaceuticals[91](#_ENREF_91),[110-118](#_ENREF_110). Heavy rains and flooding also increased nutrients, heavy metals, and pesticides as well as turbidity and fecal pathogens in water supplies[37](#_ENREF_37),[119](#_ENREF_119),[120](#_ENREF_120), especially when sewage treatment plants were overwhelmed by runoff[49](#_ENREF_49),[110](#_ENREF_110),[121](#_ENREF_121),[122](#_ENREF_122). For instance, the 2010 Indus flood in Pakistan increased waterborne and infectious diseases, such as *Cryptosporidium* [123](#_ENREF_123), whereas torrential rains in upstate New York in 1999 washed wastewaters into aquifers, sickening over 1,100 adults and killing several children[37](#_ENREF_37). Sea level rise has led to seawater contamination of drinking supplies globally, including areas in Bangladesh, Spain, New England, and the Pacific Islands[28](#_ENREF_28),[33](#_ENREF_33),[124-128](#_ENREF_124).

***Infrastructure impacts***

We found 21 attributes of infrastructure impacted by climate hazards (Fig 1), of which electricity, transportation, and building sectors were most critically affected. Impacts to electricity and the electrical grid were commonly cited. Heatwaves, for instance, caused overheated power lines to sag into trees and short out[129](#_ENREF_129),[130](#_ENREF_130). Heatwaves also reduced the efficiency of power conductance and hydroelectric production from a loss of generator cooling[131](#_ENREF_131),[132](#_ENREF_132). Droughts reduced hydroelectric generation due to low water supplies [132](#_ENREF_132), and dry soil conditions acted as an insulator causing overheating and melting of underground cables[133](#_ENREF_133). These impacts on electricity generation and conduction frequently coincided with peak demands during heatwaves at times resulting in complete shutdowns. Blackouts due to heatwaves have impacted millions of people around the world. For example, large-scale blackouts affected ~670 million people in India in 2012[131](#_ENREF_131), ~35 million in the Saudi Kingdom in 2010[134](#_ENREF_134), ~500,000 in Southern Australia in 2009[135](#_ENREF_135), ~200,000 in Buenos Aires in 2014[136](#_ENREF_136) and ~50 million affected in the Northeast USA and Canada in 2003. Extreme rainfall[137](#_ENREF_137),[138](#_ENREF_138), flooding[133](#_ENREF_133),[137](#_ENREF_137), and large storms[133](#_ENREF_133),[137](#_ENREF_137),[139](#_ENREF_139) also caused widespread power outages, and affected electricity markets due to damaged offshore oil and gas structures[140](#_ENREF_140),[141](#_ENREF_141).

Impacts on transportation infrastructure were common. Storms have flooded roads[142](#_ENREF_142), railway lines[143](#_ENREF_143),[144](#_ENREF_144), and wiped out bridges[145](#_ENREF_145), ports[146](#_ENREF_146), and levees[147](#_ENREF_147). Floods have crippled national transport networks[148](#_ENREF_148), halted rail service[149](#_ENREF_149), shut down freight transport[150](#_ENREF_150), and stranded city residents[144](#_ENREF_144),[146](#_ENREF_146),[151](#_ENREF_151). Heatwaves caused railways[135](#_ENREF_135),[152](#_ENREF_152),[153](#_ENREF_153) and roads to buckle[151](#_ENREF_151), asphalt to melt[135](#_ENREF_135), and concrete roads and bridge joints to crack due to thermal expansion[154](#_ENREF_154). Heatwaves have grounded airplanes because hot air is less dense than cold air, thus requiring additional speed which planes may not be able to achieve on short runways[89](#_ENREF_89),[155](#_ENREF_155),[156](#_ENREF_156). Fires have repeatedly disrupted land, air and sea transport [e.g., across Southeast Asia[157](#_ENREF_157)] whereas drought has hampered river navigation [e.g., across Europe in 2003[158](#_ENREF_158)]. Warming, and associated permafrost thawing, has destroyed roads and other critical infrastructure in northern latitudes[79](#_ENREF_79),[159](#_ENREF_159).

Direct and indirect impacts to buildings were significant. Floods and storms damaged or destroyed millions of homes [e.g., ~12.8 million homes in Bangladesh[160](#_ENREF_160), 8.7 million in China[161](#_ENREF_161),[162](#_ENREF_162) , 1.8 million in Pakistan[123](#_ENREF_123), 450,000 in Jakarta[163](#_ENREF_163), 425,000 in the USA[159](#_ENREF_159),[164](#_ENREF_164), 45,000 in France[165](#_ENREF_165), 30,000 in Australia[128](#_ENREF_128), and 30,000 in Jamaica[166](#_ENREF_166)]. Fires from extreme droughts and heat also destroyed homes [e.g., >5,500 homes in Australia[91](#_ENREF_91), 3,500 in California[167](#_ENREF_167), 2,500 in Texas[168](#_ENREF_168), and 2,000 in Russia[169](#_ENREF_169)]. Glacial lake outbursts due to fast retreating glaciers in Nepal[170](#_ENREF_170) and landslides[171](#_ENREF_171) swept away entire areas including villages[172](#_ENREF_172). Storms and heatwaves disrupted critical “lifeline” infrastructures such as sewerage and water lines, as well as electrical supply, with cascading impacts on business districts, hospitals, schools, communications, and access to clean water and food[109](#_ENREF_109),[173-177](#_ENREF_173). Loss of cultural heritage sites was attributed to rising seas, flooding, and thawing of permafrost[146](#_ENREF_146),[178](#_ENREF_178),[179](#_ENREF_179), whereas droughts and increased salinity due to rising sea level damaged irrigation infrastructure[180](#_ENREF_180). Rising temperatures and CO2 concentrations led to corrosion and concrete deterioration of infrastructure[181](#_ENREF_181),[182](#_ENREF_182).

Global loss of beaches and coastal infrastructure resulted from increasing sea level, storms, ocean swells, and associated flooding, erosion, and slumping[33](#_ENREF_33),[178](#_ENREF_178). Loss of coastal land was related to storms and sea level rise, which claimed entire islands[183](#_ENREF_183). Warming and subsequent melting of ice forced the relocation of native villages in Alaska[79](#_ENREF_79). Loss of natural cover in coral reefs, mangroves and wetlands reduced coastal protection, intensifying the effects of storms and tsunamis on infrastructure[184-186](#_ENREF_184).

***Economic impacts***

We found 16 attributes of the economy impacted by climate hazards (Fig. 1), including economic losses, diminished labor productivity, jobs and revenue. Economic losses were often most dramatic after extreme events, and encompassed immediate costs such as those associated with property damage as well as indirect costs. Immediate direct losses included those from drought [e.g., USD 1.84 billion in direct agricultural losses in 2015 in California[187](#_ENREF_187)], storms [e.g., USD 130 billion in damage from Hurricane Katrina[143](#_ENREF_143)], floods [e.g., EUR 9.1 billion in losses from the 2002 Elbe flood in Germany[188](#_ENREF_188)], and fires [e.g., USD 4.1 billion in costs in 1997 in Indonesia[157](#_ENREF_157)]. Loss of natural land cover was also related to economic costs [e.g., by reducing coastal protection, storm damages have increased by USD 30,000 for each hectare of destroyed wetland in the USA[189](#_ENREF_189)]. Extreme events also had indirect costs, which can have long-term impacts, as in the case of Hurricane Iniki, where the local economy in Kauaʻi, Hawaiʻi was still suffering losses over a decade later[190](#_ENREF_190). Indirectly, climate hazards increased commodity prices. For instance, heatwaves, droughts, and fires during the 2010 summer in Russia cut local grain production by one third, ultimately doubling wheat prices globally[191](#_ENREF_191). Likewise, drought in Brazil and Argentina drove soybean and corn prices up by 50%[192](#_ENREF_192). Storms affected access to and the price of insurance. For instance, Hurricane Andrew led to the insolvency of 12 insurance companies[193](#_ENREF_193) and many firms now refuse to issue new policies for properties within a mile of the ocean on the east coast of the USA[28](#_ENREF_28). Further, lack of insurance, has made it difficult to obtain a mortgage for coastal properties in the Bahamas[193](#_ENREF_193). Climate hazards also affected the cost and availability of energy resources: heatwaves in 2003 and 2006 in Europe led to a 40-fold increase in the cost per megawatt hour in the European Energy Exchange[194](#_ENREF_194), damages to oil rigs during Hurricane Katrina temporarily increased fuel prices[195](#_ENREF_195), while drought in Brazil reduced sugar crop production, leading to record high sugar prices and a decline in ethanol production[196](#_ENREF_196).

Climate hazards impacted job availability as well as work capacity. Heatwaves lowered labor productivity[135](#_ENREF_135),[197](#_ENREF_197) as observed in Australia where absenteeism increased during heatwaves[198](#_ENREF_198), and in India and Vietnam where heatwaves led to longer workdays to compensate for periods of rest during the hottest hours of the day[9](#_ENREF_9). In China, employees are compensated with a subsidy for each day they work above a temperature threshold[199](#_ENREF_199). Storms and floods[200](#_ENREF_200)disrupted the functioning of industries resulting in an immediate loss of jobs. Job losses were also related to drought [e.g., in areas where agriculture is a large part of the economy[201](#_ENREF_201),[202](#_ENREF_202)], warming [e.g., in North America where timber jobs were lost due to warm temperatures resulting in pine beetle infestations[203](#_ENREF_203)] and ocean chemistry [e.g., in Peru where direct and indirect job losses are often linked to climatic impacts on marine fisheries[204](#_ENREF_204)].

Impacts on revenue-generating activities were documented, with tourism-based economies being particularly sensitive. Climate hazards reduced the number of visitors to national parks in the USA due to increased temperatures[205](#_ENREF_205), and in Taiwan due to storms[206](#_ENREF_206). Droughts had distinct impacts on the recreation industry [e.g., river-rafting outfitters in Colorado lost 40% of their normal business – over USD 50 million to the industry statewide[207](#_ENREF_207)], as well as other sectors [e.g., USD 2.5 billion revenue lost to the cattle industry in Mexico[208](#_ENREF_208)]. The impacts of temperature on winter and ocean-related activities were particularly acute. Although snow can be artificially produced, warmer winters generally meant fewer visitors and revenue to ski resort destinations, as observed in the Alps[209](#_ENREF_209) and Australia[210](#_ENREF_210). Changes in ocean chemistry degraded coral reef conditions which were associated with in a decline in recreational dives in Thailand[211](#_ENREF_211), and affected annual whale migrations that caused early closure of the whale watching season in Australia[212](#_ENREF_212).

***Security impacts***

We identified 11 attributes of human security impacted by climate hazards (Fig. 1), critically related to dislocations, increased conflict and violence, and disruption of the social fabric. Climate hazards forced hundreds of millions of people out of their homes for different reasons and durations, including evacuation (temporary planned movement), displacement (unplanned forced change of residence) and migration (permanent change of residence)[109](#_ENREF_109),[213](#_ENREF_213),[214](#_ENREF_214). For example, hundreds of thousands of people were displaced after floods in China and Pakistan[123](#_ENREF_123),[213](#_ENREF_213), and storms in Central America, the USA and Bangladesh[109](#_ENREF_109),[215](#_ENREF_215),[216](#_ENREF_216), to name a few. The recurrence of climate hazards also caused temporary displacement to become permanent[79](#_ENREF_79),[109](#_ENREF_109); in Bangladesh recurring floods forced some rural inhabitants to move to urban squatter settlements[217](#_ENREF_217). We found several cases of planned migration of coastal communities due to permafrost melting[19](#_ENREF_19) and recurring flooding and sea-shore erosion due to sea level rise and storms [e.g., indigenous communities in the USA[79](#_ENREF_79),[218](#_ENREF_218), the Solomon Islands[183](#_ENREF_183) and India[219](#_ENREF_219)]. Multiple cases of mass migration have occurred due to droughts, natural land cover change, and water scarcity[214](#_ENREF_214),[220-224](#_ENREF_220). Extreme heat was also the lead driver of rural Pakistani migration due to the loss of crops and farming income[175](#_ENREF_175).

Climate hazards contributed to increasing conflict over access to resources and may have acted as a catalyst for violence. Drought, for instance, has triggered conflicts over water rights and access[208](#_ENREF_208),[225](#_ENREF_225). Ocean chemistry was linked to shifts in the distribution of commercial fish stocks[27](#_ENREF_27),[226](#_ENREF_226),[227](#_ENREF_227) and the uncovering of new resources under melting sea ice[104](#_ENREF_104),[228](#_ENREF_228),[229](#_ENREF_229) generating geopolitical tensions over their use, including military buildup in the Arctic region[228](#_ENREF_228). Climate hazards, although not necessarily the sole or even primary driver, have been suggested to ripen conditions leading to violence; however, such pathways remain uncertain and are likely to be diverse including impacts on migration and reduced supply of resources, jobs, and commodity prices, compounded with socio-economic factors, such as inequality and failing governance[230](#_ENREF_230). For instance, changes in precipitation and drought resulted in scarcity of suitable pastoral and crop land, triggering sectarian and inter-communal violence in the Horn of Africa[231](#_ENREF_231),[232](#_ENREF_232), increased food prices associated with violence across Africa[233](#_ENREF_233), and food shortages that facilitated rebel recruitment in Burundi[234](#_ENREF_234). Drought was also an influencing factor in the migration to urban areas adding to unemployment and political instability that contributed to bloodshed in Syria[235-237](#_ENREF_235) and Somalia[238-241](#_ENREF_238). Excess rainfall has also correlated with violent conflict in Africa[242](#_ENREF_242). The probability of civil conflicts was nearly double during El Niño years compared with La Niña years[243](#_ENREF_243). Post-1950, warming or a change in precipitation by one standard deviation increased risk of interpersonal violence by 4% and intergroup conflicts by 14% globally[244](#_ENREF_244).

Impacts of climate hazards on the social fabric were found, including instances of violence, exacerbated gender inequality, and breakdown of social order. High temperatures can increase anger and arousal affecting how people respond to provocation[245](#_ENREF_245), which can aggravate acts of interpersonal violence and violent crimes during heatwaves[246](#_ENREF_246),[247](#_ENREF_247). In the USA, for instance, warming by 1oF aggravated rates of rapes by 0.20, robberies by 0.84, burglaries by 8.16, and larcenies by 10.65 per 100,000 people[248](#_ENREF_248). The breakdown of law and order during extreme rainfall[244](#_ENREF_244) and storms[249](#_ENREF_249) has been linked to interpersonal violent behaviors including battering[250](#_ENREF_250) and rape[251](#_ENREF_251). Likewise anomalously high or low rainfall was tied to a two-fold increase in the number of “witches” murdered in Tanzania[252](#_ENREF_252). Hydrometeorological disasters have also been associated with increased instances of domestic violence[253](#_ENREF_253); for example, after the 1993 flood in the midwestern USA, a significant increase in cases of battered women was reported[254](#_ENREF_254). It is worth noting that there has been considerable discussion over the relative role of the climate hazards on human conflict[255-257](#_ENREF_255).

**Global Map of Cumulative Climate Hazards**

Our overview of observed impacts reveals the high vulnerability of humanity to climate hazards (Fig. 1). Since different hazards can impact numerous aspects of human systems (Fig. 1) and may require varied types and costs of adaptations, a considerable concern for future societies is the simultaneous exposure to multiple climate hazards. To provide insight into this issue, we collected projections for the same hazards for which impacts were surveyed in our literature review and constructed a cumulative index of their geographical co-occurrence. Specifically, we collected projections for warming[2](#_ENREF_2), heatwaves[6](#_ENREF_6), precipitation[2](#_ENREF_2), floods[5](#_ENREF_5), droughts[3](#_ENREF_3), fires[4](#_ENREF_4), sea level[258](#_ENREF_258), storms[259](#_ENREF_259), natural land cover[260](#_ENREF_260), and ocean chemistry[261](#_ENREF_261); we also included projections on freshwater scarcity[262](#_ENREF_262) (Fig. 2). Hazard projections were based on the recent Coupled Model Intercomparison Project phase 5 under Representative Concentrations Pathways (RCPs) 2.6, 4.5 and 8.5, which represent a range of mitigation scenarios in which greenhouse gasses are considerably slowed (RCP26) or continue to rise throughout the 21st century (RCP85), with RCP45 being in the middle of such extremes. Changes in the projected hazards were rescaled to their largest projected change by 2095 under RCP 8.5, and summed to generate an overall cumulative index of climate hazards (see Methods). The index provides a relative indication of the extent to which the largest projected changes in the hazards will co-occur. The effect of multimodel uncertainty in the cumulative index of climate hazards is shown in Fig. S4.

Among hazards, the geographical distributions of projected changes were poorly correlated, with no single hazard having a predominant role in the overall cumulative index of climate hazards (Table S1). For instance, there was little concordance in the spatial patterns of change in drought, floods, and water scarcity compared to precipitation, despite the latter being an underlying driver of the formers. This reflects the effects of topography, soil type, and human uses acting as modifiers for precipitation patterns. Likewise, warming, which is projected to intensify at higher latitudes, was poorly related to the spatial patterns of change observed in most other hazards (Fig. 2, Table S1). Overall, the geographical variability of projected changes in the different hazards highlights the need for analysis that integrates different climate hazards and the potential for underestimation of projected climatic changes when examining one or a few hazards. Globally, the largest intensification of drought is projected to occur in Europe, North and South America (Fig. 2). Fires are projected to intensify in Australia but decline over the south Sahara. Floods are projected to increase in South America, Southeast Asia and northern Russia. Deadly heatwaves are projected to increase in duration over most tropical areas while storms are projected to increase in intensity over pantropical regions. Precipitation is projected to increase over tropical areas and high-latitudes but decrease at mid-latitudes. Water scarcity will intensify over many regions of Africa and America. When patterns of change in all hazards are combined, cumulatively, the largest co-occurrence of changes is projected in the tropics, generally isolated to coastal regions (Fig. 2). Coastal areas of Southeast Asia, East and West Africa, the Atlantic coast of South and Central America will be exposed concurrently to the largest changes in up to six climate hazards if greenhouse gases continue to rise throughout the 21st century (RCP 8.5, Fig. 2), or three under strong mitigation of greenhouse gases (RCP 2.6, Fig. S3).

When we examined how the cumulative patterns of future change relate to human populations (see Methods), we found that globally, half of the world’s population will be exposed to the equivalent of the largest change in one full hazard under RCP 2.6 and approximately three hazards concurrently under RCP 8.5 (Fig. 3A-C). This suggests that even under strong mitigation scenarios, there will still be significant human exposure to climate change. Patterns of exposure to cumulative climatic hazards showed similar trends among countries with different levels of wealth (Fig. 3D-F). In our bibliographic search of impacts from climate hazards, we found differential responses from exposure to similar climate hazards highlighting variation in adaptation capacity (Box S1). Commonly, the largest losses of human life during extreme climatic events have occurred in developing nations[263](#_ENREF_263),[264](#_ENREF_264) whereas developed nations commonly face a high economic burden of damages and requirements for adaptation. Thus, while it is commonly noted that developing nations will face most of the burden of current and projected climate change[265](#_ENREF_265),[266](#_ENREF_266), our integrative analysis of impacts reveals that developed nations will not be spared from adverse impacts.

**Concluding remarks**

Our assessment of the literature yielded a handful of positive and neutral responses of human system from exposure to climate hazards (reviewed in Box S1). We surmised that the reduced number of positive or neutral impacts may be real but may also reflect a research bias toward the study of detrimental impacts (discussed under Caveats in the Methods section). This small set of positive and neutral impacts, however, can hardly justify any of the many detrimental impacts that were uncovered in our literature search, particularly when many of those impacts are related to the loss of human lives.

Given the vast number of components in coupled human-climate systems, assessing the impacts of climate change on humanity requires analyses that integrate diverse types of information. Contrasting temporal (Fig. S1) and spatial (Fig. 3) patterns of climate hazards, compounded with varying vulnerabilities of human systems (Fig. 1), suggest that narrow analyses may not completely reflect the impacts of climate change on humanity. Our integrative analysis suggests that even under strong mitigation scenarios, there will still be significant human exposure to climate change (Fig. 3D), particularly in tropical coastal areas (Fig. 2); such exposure will be much larger if greenhouse gases continue to rise throughout the 21st century (RCP 8.5, Fig. 3F) and will not differentiate between poor or rich countries (Fig. 3). The multitude of climate hazards that could simultaneously impact any given society highlights the diversity of adaptations that will likely be needed and the considerable economic and welfare burden that will be imposed by projected climate change triggered by ongoing greenhouse gas emissions. Altogether, our analysis shows that ongoing climate change will pose a heighted threat to humanity, which will be greatly aggravated if substantial and timely reductions of greenhouse gas emissions are not achieved.

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**Box. 1. Terms and definitions.** Here we provide a list of terms and definitions as they are meant to be used in this paper. These terms are paraphrased for brevity of what they mean in the latest IPCC report and adjusted for relevance to human systems.

*Hazard*: climate-related event or trend or their impacts on geophysical systems (e.g., floods, droughts and sea level rise) with likely detrimental consequences to human systems.

*Exposure*: the presence of a human system in places where hazards had or are projected to occur.

*Impact*: effects on human systems from exposure to a hazard; effects are mediated by the strength of the hazard and the vulnerability of the exposed society.

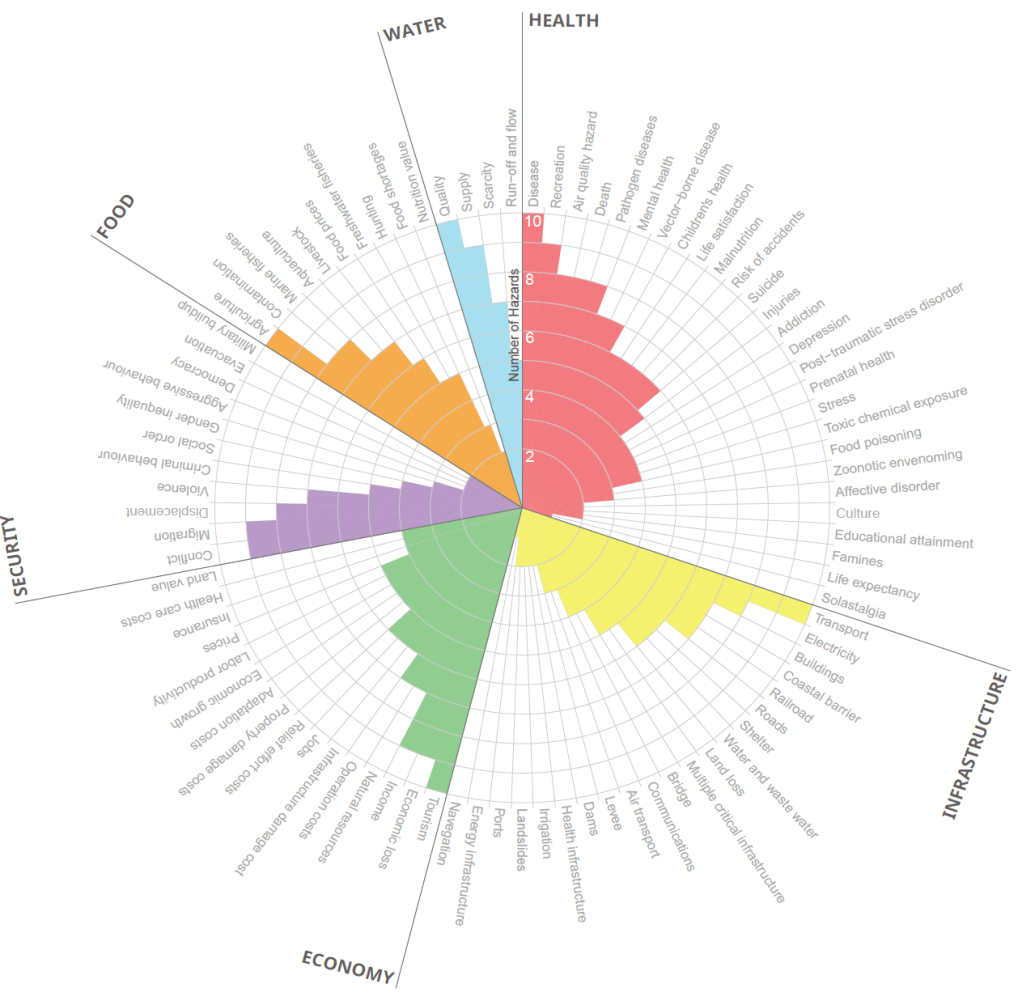
*Sensitivity*: responsiveness (harmful or beneficial) of a human system to a hazard.

*Adaptation*: actions to moderate or avoid harm or exploit beneficial opportunities from exposure to a given change in climate and its effects.

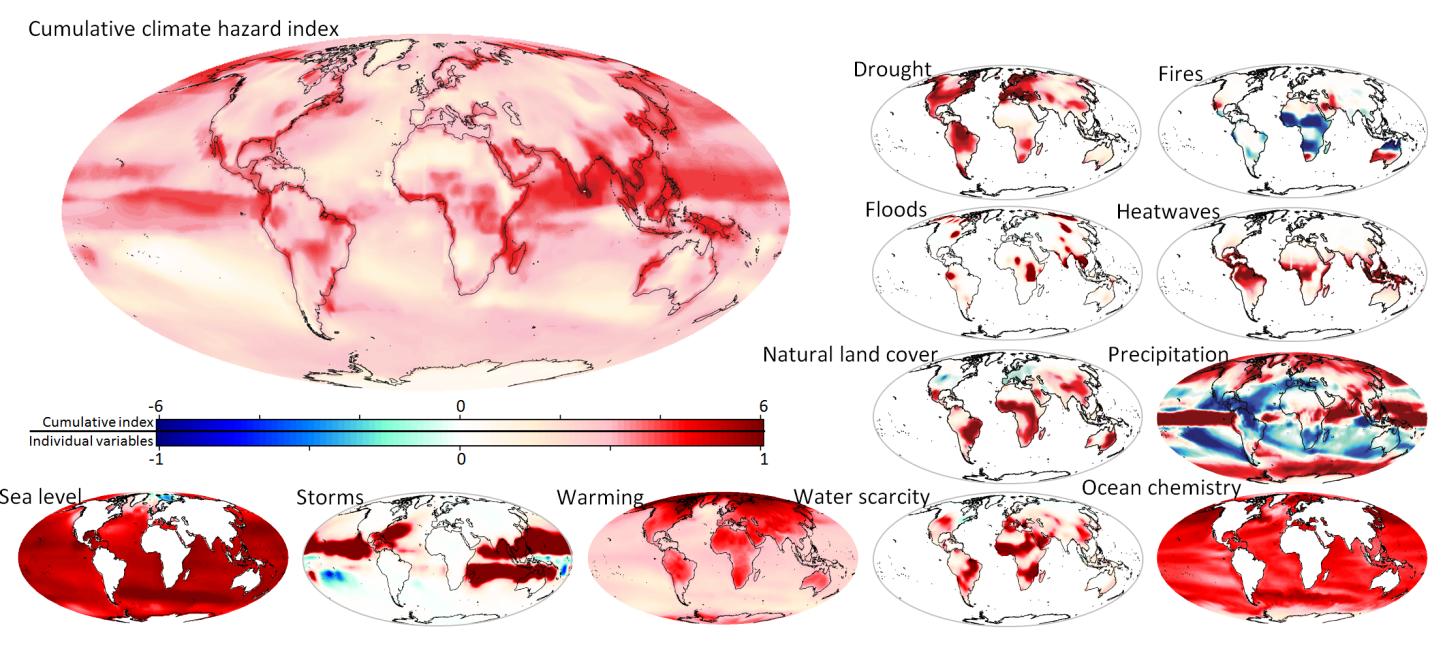
*Vulnerability*: being prone to sustaining damage. The propensity to be adversely affected results from the balance between sensitivity and adaptation capacity.

*Human system*: single or combine attributes of societies such as health, food, water needs, livelihoods, economy, security, cultures, services and/or infrastructure.

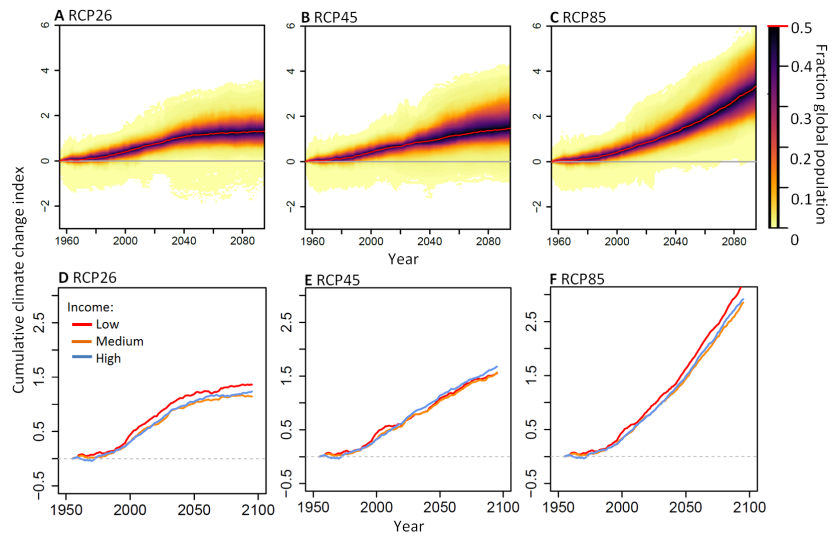
**Fig. 1. Observed impacts on humanity from climate hazards.** The figure shows six different aspects of human life (health, food, water, infrastructure, economy and security) and their subcategories for which impacts were observed. The height of the bars indicates the number of hazards implicated in the impacts. Here we analyzed 10 climate hazards: warming, heatwaves, precipitation, floods, drought, fires, sea level, storms, and changes in natural land cover and ocean chemistry. The complete table of climate hazards and human aspects impacted is found at http://impactsofclimatechange.info



**Fig. 2 Global cumulative index of climate hazards.** The large map shows the cumulative index of climate hazards, which is the summation of the re-scaled change in all hazards between 1955 and 2095. Small plots indicate the difference for each individual hazard for the same time period. Individual hazards were rescaled to be normalized between -1 to 1. Negative values indicate a decrease in the given hazard, while positive values represent an increase relative to 1950s baseline values. The largest value in the cumulative index was six (i.e., cumulatively, the equivalent to the largest change in six climate hazards occurred for any one cell). Plots are based on RCP 8.5, results for all three mitigation scenarios are provided in Fig. S1-S3. Interactive data visualization is available at <https://maps.esri.com/rc/climate-impact/index.html>, and time series animations at <http://impactsofclimatechange.info/HumanImpacts/HeatWaves_rcp26.html>.



**Fig. 3 Human population exposure to simultaneous climate hazards.** A-C, show the fraction of the world’s human population exposed to varying levels of cumulative hazards. D-F, show the exposure to cumulative climatic hazards for half of the total population in countries with low, medium and high income.

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