Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

| Citation | Mora, Camilo et al. “Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions.” Nature Climate Change 8, 12 (November 2018): 1062–1071 © 2018 Springer Nature Limited |
|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| As Published | http://dx.doi.org/10.1038/s41558-018-0315-6 |
| Publisher | Springer Science and Business Media LLC |
| Version | Author’s final manuscript |
| Citable link | https://hdl.handle.net/1721.1/126779 |
| Terms of Use | Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use. |
Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions

Camilo Mora¹, Daniele Spirandelli²-³, Erik C. Franklin¹⁴, John Lynham⁵-⁶, Michael B. Kantar⁷, Wendy Miles⁸-⁹, Charlotte Z. Smith¹⁰, Kelle Freel¹, Jade Moy¹¹, Leo V Louis¹², Evan W. Barba¹³, Keith Bettinger¹³, Abby G. Frazier¹³-¹⁴, John F. Colburn IX¹⁵, Naota Hanasaki¹⁶, Ed Hawkins¹⁷, Yukiko Hirabayashi¹⁸, Wolfgang Knorr¹⁹, Christopher M. Little²⁰, Kerry Emanuel²¹, Justin Sheffield²²-²³, Jonathan A. Patz²⁴, Cynthia L. Hunter¹¹

¹Department of Geography and Environment, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
²Department of Urban and Regional Planning, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
³Sea Grant College, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
⁴Hawai‘i Institute of Marine Biology, School of Ocean and Earth Science and Technology, University of Hawai‘i at Mānoa, Kāne‘ohe, Hawai‘i, 96744, USA
⁵Department of Economics, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
⁶University of Hawai‘i Economic Research Organization, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
⁷Department of Tropical Plant and Soil Science, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
⁸Pacific Islands Climate Change Cooperative, Honolulu, Hawai‘i, 96813, USA
⁹Center for Conservation Research and Training, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
¹⁰Department of Natural Resources and Environmental Management, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
¹¹Department of Biology, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
¹²Department of Natural Resources, Cornell University, Fernow Hall, Ithaca, New York, 14853, USA
¹³East-West Center, Honolulu, Hawai‘i, 96848, USA
¹⁴Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, Hawai‘i, 96720, USA
¹⁵School of Architecture, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i, 96822, USA
The ongoing emission of greenhouse gases is triggering changes in many climate hazards that can impact humanity. 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 concurrently to the equivalent of the largest magnitude in one of these hazards if greenhouse gasses are aggressively reduced or three if they are not, with some tropical coastal areas facing up to six hazards concurrently. These findings highlight that greenhouse gas emissions pose a broad threat to humanity by simultaneously intensifying many hazards that have been harmful to numerous aspects of human life.
Ongoing greenhouse gas emissions are simultaneously shifting many elements of Earth’s climate beyond thresholds that can impact humanity\(^1\). 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\(^1\). Given interconnected physics, warming can affect other aspects of the Earth’s climate system\(^2\). For instance, by enhancing water evaporation and increasing the air’s capacity to hold moisture, warming can lead to drought in commonly dry places, in turn ripening conditions for wildfires and heatwaves when heat transfer from water evaporation ceases. There are opposite responses in commonly humid places where constant evaporation leads to more precipitation, which is commonly followed by floods due to soil saturation. The oceans have the added effect of sea warming, which enhances evaporation and wind speeds, intensifying downpours and the strength of storms, whose surges can be aggravated by sea level rise resulting from the larger volume occupied by warmed water molecules and melting land ice. Other inter-related changes in the ocean include acidification as CO\(_2\) mixes with water to form carbonic acid, and reduced oxygen due to warming reducing oxygen solubility and affecting circulation patterns and the mixing of surface waters rich in oxygen with deeper oxygen-poor water. 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 on detection and attribution (discussed under Caveats in the Methods section). With few exceptions\(^3\), changes in these hazards have been studied in isolation whereas impact assessments have commonly focused on specific aspects of human life. Unfortunately, the failure to integrate available information most likely underestimates the impacts of climate change because \(i\) one hazard may be important in one place but not another, \(ii\) strong CO\(_2\) reductions may curb some but not all hazards (See Fig. S1), and \(iii\) not all aspects of human systems are equally challenged by climate hazards. 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\(^3\).

Here we highlight the broad and heightened threat to humanity from ongoing greenhouse gas emissions intensifying multiple climate hazards, to which humanity is currently vulnerable. To build our case, we carried out a systematic literature search to identify observed impacts on people from climate hazards and developed a global map of a cumulative index of projected changes in these hazards to evaluate the extent that humanity 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 adaptive capacity will likely result in different types of impacts (e.g., higher economic loss for developed nations
and higher 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 (further discussion under Caveats in the Methods section). We also provide definitions for how certain terms are used in this paper (i.e., hazard, exposure, impact, sensitivity, vulnerability, and adaptation; Supplementary Note 1).

**Observed Impacts on Human Systems**

A systematic review of observed impacts was conducted by creating 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 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 from hyperthermia during heatwaves [e.g. from 1980 to 2014, over 780 events of
excess human mortality were reported during heatwaves worldwide\(^5\), drowning during floods [e.g., ~3,000 deaths in the 1998 China floods\(^8\)], starvation during droughts [e.g., ~800,000 famine deaths attributed to the 1980s Ethiopian drought\(^7\)], blunt injury during storms [e.g., ~140,000 deaths in the 1991 Cyclone Gorky in Bangladesh\(^8\)], and asphyxiation during fires [e.g., ~173 deaths in the 2009 Australian Black Saturday fire\(^9\)]. Loss of natural land cover impaired coastal protection likely contributing to increased mortality during storms and floods\(^{10,11}\). Warming and changes in precipitation and ocean chemistry caused human death through increased transmission of pathogenic diseases.

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\(^{12}\), while injuries were common during floods, storms and fires. Respiratory problems were associated with increased ozone pollution from heatwaves and fires\(^{13}\), dust from droughts\(^{14}\), mold following storms\(^{15}\), organic pollutants released from melting ice\(^{16}\), and pollen from elongated flowering periods caused by warming\(^{17}\). By increasing habitat suitability of pathogens and vectors, warming and precipitation changes contributed to epidemics of malaria\(^{18}\), diarrhea\(^{19}\), dengue fever\(^{20}\), salmonellosis\(^{21}\), cholera\(^{21}\), leptospirosis\(^1\), bluetongue virus\(^1\), and campylobacteriosis\(^{22}\). Similarly, warming facilitated range expansion of vectors implicated in outbreaks of plague transmitted by rodents\(^{23}\), West Nile virus by birds\(^{24}\), schistosomiasis by snails\(^{18}\) and encephalitis by ticks\(^{25}\). 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\(^{26}\) and encephalitis\(^{27}\), fires drove fruit bats closer to towns causing outbreaks of Hendra and Nipah viruses\(^{28}\), drought mobilized livestock near cities causing outbreaks of hemorrhagic fever\(^{27}\), and melting ice due to warming caused voles to find shelter in homes increasing hantavirus infections\(^{29}\). Likewise, floods\(^{30}\), heatwaves\(^{31}\) and intense rain\(^{31}\) 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\(^{32}\), and diarrheal illness\(^{21}\). Changes in ocean chemistry have favored pathogen growth and harmful algal blooms related to seafood poisoning\(^{21}\), cholera\(^{33}\), and ciguatera\(^{34,35}\). Drought was associated with outbreaks of West Nile virus\(^{24}\), leishmaniasis\(^{36}\) and chikungunya virus\(^{37}\), and hantavirus when interacting with floods\(^{36}\). Drought forced the use of unsafe drinking water resulting in outbreaks of diarrhea, cholera and dysentery\(^{38}\). By increasing concentration of particulates during dust storms, drought was also linked to valley fever, a disease caused by a fungal pathogen\(^{39}\).

Climate hazards affected mental health. For instance, depression and post-traumatic stress disorder were reported after storms in the USA\(^{40}\), floods in the UK\(^{41}\), and heatwaves in France\(^{39}\). People experienced existential distress during drought in Australia\(^{42}\), increased substance abuse after storms in
the USA\textsuperscript{43}, 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\textsuperscript{44}]. Further, suicidal ideation occurred in victims of drought\textsuperscript{45}, heatwaves\textsuperscript{46}, storms\textsuperscript{40}, and floods\textsuperscript{47}.

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\textsuperscript{48}, and below average birth weight, juvenile height, and academic performance\textsuperscript{49}. 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\textsuperscript{50}. 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\textsuperscript{51}.

**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\textsuperscript{52}], precipitation [e.g., a 10 mm rainfall increase caused a 0.3 ton loss of paddy per hectare in the Mekong Delta\textsuperscript{53}], floods [e.g., over 7,600 ha of agricultural land were destroyed by floods in Vietnam in 2009\textsuperscript{54}], sea level rise [e.g., agricultural land has been lost to saltwater intrusion in Bangladesh\textsuperscript{1}], fires and drought [e.g., \(~33\%\) of grain production was lost to a mixture of fires and drought in Russia in 2010\textsuperscript{55}], Indirect losses due to hazards exceeding crop physiological tolerances were caused by warming [e.g., 3-10\% wheat yield lost per 1°C increase in China\textsuperscript{56}], drought [e.g., \(~36\%\) yield decrease during the 2003 drought in Italy\textsuperscript{57}], heatwaves [e.g., one single day above 38°C reduced annual yields by 5\% in the USA\textsuperscript{58}], changes in ocean chemistry [e.g., drought in Australia caused by variability in ocean temperature in the Indian Ocean\textsuperscript{59}], 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\textsuperscript{60}]. 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\textsuperscript{61} and heatwaves\textsuperscript{61}, whereas floods\textsuperscript{62} and permafrost thawing due to warming\textsuperscript{39} 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\textsuperscript{62}. 
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\textsuperscript{63}], drought [e.g., in 2000, three quarters of livestock died due to drought in Kenya\textsuperscript{64}], heatwaves [e.g., >5,000 cattle deaths occurred each year there were strong heatwaves in the USA Great Plains\textsuperscript{65}], floods [e.g., livestock losses totaled >236,000 during major floods in Bangladesh in 1987 and 1988\textsuperscript{66}], and natural land cover change [e.g., in Sudan, land cover change reduced suitable grazing land\textsuperscript{67}]. Heatwaves were related to a reduction in grazing, reproduction, and milk production in cattle and high mortalities in chickens and turkeys\textsuperscript{68}. 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\textsuperscript{69}. Meat quality was also impacted through contamination [e.g., higher than normal temperatures were associated with 30% of reported cases of salmonellosis in Europe\textsuperscript{63}].

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\textsuperscript{70} and high water temperatures reduced oxygen content severely impacting salmonid reproduction\textsuperscript{71}] and indirectly [e.g. warmer temperatures altered food webs by reducing primary productivity\textsuperscript{70}]. Direct stock mortality and changes to reproduction were caused by drought [e.g., by favoring bivalve predators that decreased shellfish populations\textsuperscript{72}], heatwaves [e.g. a 1953 heatwave warmed Lake Erie triggering nutrient pollution that caused a large fish kill\textsuperscript{73}], and floods [e.g., floods decreased reproductive capacity of anadromous fish\textsuperscript{74}]. 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\textsuperscript{75}], precipitation [e.g. rains increased sediment and nutrient loading in lagoons\textsuperscript{76}], sea level [e.g., sea level rise changed dynamics of coastal lagoons\textsuperscript{76}], ocean chemistry [e.g. changes in ocean chemistry increased coral bleaching, which decreased fish habitat\textsuperscript{77}], and natural land cover [e.g., introduced water hyacinth in Lake Victoria reduced fish quantity\textsuperscript{78}]. The quality of fish was also impacted. Warming increased mercury methylation and has favored the growth of pathogens involved in food poisoning\textsuperscript{79}. 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\textsuperscript{73}.

**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\textsuperscript{38,39,80}. Drought, for instance, led to temporary drinking
water shortages for over 200,000 people in Puerto Rico in 1997-98 and 33 million people in China in 2001. 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, and desertification, which led to losses in water storage in areas like the Sahel. In mountainous regions, warming resulted in less snow accumulation and retreat of glaciers causing lower groundwater levels and drinking water shortages. Temporary water shutdowns were also experienced as a result of intense storms, such as Hurricane Mitch in 1998 which left over 4 million residents in Honduras without water.

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. Heavy rains and flooding also increased nutrients, heavy metals, and pesticides as well as turbidity and fecal pathogens in water supplies, especially when sewage treatment plants were overwhelmed by runoff. For instance, the 2010 Indus flood in Pakistan increased waterborne and infectious diseases, such as *Cryptosporidium*, whereas torrential rains in upstate New York in 1999 washed wastewaters into aquifers, sickening over 1,100 adults and killing several children. Sea level rise has led to seawater contamination of drinking supplies globally, including areas in Bangladesh, Spain, New England, and the Pacific Islands.

**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. Heatwaves also reduced the efficiency of power conductance and hydroelectric production from a loss of generator cooling. Droughts reduced hydroelectric generation due to low water supplies, and dry soil conditions acted as an insulator causing overheating and melting of underground cables. 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, ~35 million in the Saudi Kingdom in 2010, ~500,000 in Southern Australia in 2009, ~200,000 in Buenos Aires in 2014 and ~50 million affected in the Northeast USA and Canada in 2003. Extreme rainfall, flooding, and large storms also caused widespread power outages, and
affected electricity markets due to damaged offshore oil and gas structures.\footnote{39,105}

Impacts on transportation infrastructure were common. Storms have flooded roads, railway lines, and wiped out bridges, ports, and levees. Floods have crippled national transport networks, halted rail service, shut down freight transport, and stranded city residents. Heatwaves caused railways and roads to buckle, asphalt to melt, and concrete roads and bridge joints to crack due to thermal expansion. 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. Fires have repeatedly disrupted land, air, and sea transport [e.g., across Southeast Asia] whereas drought has hampered river navigation [e.g., across Europe in 2003]. Warming, and associated permafrost thawing, has destroyed roads and other critical infrastructure in northern latitudes.\footnote{35,39}

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, 8.7 million in China, 1.8 million in Pakistan, 450,000 in Jakarta, 425,000 in the USA, 45,000 in France, 30,000 in Australia, and 30,000 in Jamaica]. Fires from extreme droughts and heat also destroyed homes [e.g., >5,500 homes in Australia, 3,500 in California, 2,500 in Texas, and 2,000 in Russia]. Glacial lake outbursts due to fast retreating glaciers in Nepal and landslides swept away entire areas including villages. Critical “lifeline” infrastructures such as sewerage and water lines have been disrupted by storms, and electrical supply by heatwaves, with cascading impacts on business districts, hospitals, schools, communications, and access to clean water and food. Loss of cultural heritage sites was attributed to rising seas, flooding, and thawing of permafrost, whereas droughts and increased salinity due to rising sea level damaged irrigation infrastructure. Rising temperatures and CO\textsubscript{2} concentrations led to corrosion and concrete deterioration of infrastructure.\footnote{129}

Global loss of beaches and coastal infrastructure resulted from increasing sea level, storms, ocean swells, and associated flooding, erosion, and slumping. Loss of coastal land was related to storms and sea level rise, which claimed entire islands. Warming and subsequent melting of ice forced the relocation of native villages in Alaska. Loss of natural cover in coral reefs, mangroves and wetlands reduced coastal protection, intensifying the effects of storms and tsunamis on infrastructure.\footnote{131}

\textbf{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 California132], storms [e.g., USD 130 billion in damage from Hurricane Katrina107], floods [e.g., EUR 9.1 billion in losses from the 2002 Elbe flood in Germany133], and fires [e.g., USD 4.1 billion in costs in 1997 in Indonesia119]. 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 USA134]. Extreme events also had indirect costs, which can have long-term impacts, as in the case of Hurricane Iniki, where the local economy in Kaua‘i, Hawai‘i was still suffering losses over a decade later135. 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 globally1. Storms affected access to and the price of insurance. For instance, Hurricane Andrew led to the insolvency of 12 insurance companies136 and many firms now refuse to issue new policies for properties within a mile of the ocean on the east coast of the USA17. Further, lack of insurance, has made it difficult to obtain a mortgage for coastal properties in the Bahamas136. 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 Exchange137, damages to oil rigs during Hurricane Katrina temporarily increased fuel prices35, while drought in Brazil reduced sugar crop production, leading to record high sugar prices and a decline in ethanol production138.

Climate hazards impacted job availability as well as work capacity. Heatwaves lowered labor productivity as observed in Australia where absenteeism increased during heatwaves139, and in India and Vietnam where heatwaves led to longer workdays to compensate for periods of rest during the hottest hours of the day140. Storms and floods141 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 economy142], warming [e.g., in North America where timber jobs were lost due to warm temperatures resulting in pine beetle infestations91] and ocean chemistry [e.g., in Peru where direct and indirect job losses are often linked to climatic impacts on marine fisheries143].

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 temperatures144, and in Taiwan due to storms145. 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 statewide146], as well as other sectors [e.g., USD 2.5 billion revenue lost to the cattle industry in Mexico147]. 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\textsuperscript{148} and Australia\textsuperscript{149}. Changes in ocean chemistry degraded coral reef conditions which were associated with in a decline in recreational dives in Thailand\textsuperscript{150}, and affected annual whale migrations that caused early closure of the whale watching season in Australia\textsuperscript{151}.

\textbf{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)\textsuperscript{85,152,153}. For example, hundreds of thousands of people were displaced after floods in China and Pakistan\textsuperscript{93,152}, and storms in Central America, the USA and Bangladesh\textsuperscript{85,154,155}, to name a few. The recurrence of climate hazards also caused temporary displacement to become permanent\textsuperscript{39,85}; in Bangladesh recurring floods forced some rural inhabitants to move to urban squatter settlements\textsuperscript{156}. We found several cases of planned migration of coastal communities due to permafrost melting\textsuperscript{8} and recurring flooding and sea-shore erosion due to sea level rise and storms [e.g., indigenous communities in the USA\textsuperscript{39}, the Solomon Islands\textsuperscript{130} and India\textsuperscript{157}]. Multiple cases of mass migration have occurred due to droughts, natural land cover change, and extreme precipitation\textsuperscript{153,158}. Extreme heat was also the lead driver of rural Pakistani migration due to the loss of crops and farming income\textsuperscript{126}.

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\textsuperscript{147,159}. Ocean chemistry was linked to shifts in the distribution of commercial fish stocks\textsuperscript{1,16} and the uncovering of new resources under melting sea ice\textsuperscript{84,160} generating geopolitical tensions over their use, including military buildup in the Arctic region\textsuperscript{161}. 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\textsuperscript{162}. 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\textsuperscript{163}, increased food prices associated with violence across Africa\textsuperscript{164}, and food shortages that facilitated rebel
recruitment in Burundi. Drought was also an influencing factor in the migration to urban areas adding to unemployment and political instability that contributed to bloodshed in Syria and Somalia. Excess rainfall has also correlated with violent conflict in Africa. The probability of civil conflicts was nearly double during El Niño years compared with La Niña years. 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.

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, which can aggravate acts of interpersonal violence and violent crimes during heatwaves. In the USA, for instance, warming by 1°F aggravated rates of rapes by 0.20, robberies by 0.84, burglaries by 8.16, and larcenies by 10.65 per 100,000 people. The breakdown of law and order during extreme rainfall and storms has been linked to interpersonal violent behaviors including battering and rape. Likewise anomalously high or low rainfall was tied to a two-fold increase in the number of “witches” murdered in Tanzania. Hydrometeorological disasters have also been associated with increased instances of domestic violence; for example, after the 1993 flood in the midwestern USA, a significant increase in cases of battered women was reported. It is worth noting that there has been considerable discussion over the relative role of the climate hazards on human conflict.

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, heatwaves, precipitation, floods, droughts, fires, sea level, storms, natural land cover, and ocean chemistry; we also included projections on freshwater scarcity (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 (Supplementary Note 2). Commonly, the largest
losses of human life during extreme climatic events have occurred in developing nations whereas developed nations commonly face a high economic burden of damages and requirements for adaptation (Supplementary Note 2). Thus, while it is commonly noted that developing nations will face most of the burden of current and projected climate change\textsuperscript{181-183}, 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 small number of positive and neutral responses of human systems to climate hazard exposure (reviewed in Supplementary Note 2). We surmise 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 these impacts are related to the loss of human lives, basic supplies like food and water, and undesired states for human welfare like access to jobs, revenue and security.

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. 2) 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 finds 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 21\textsuperscript{st} 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 heightened threat to humanity, which will be greatly aggravated if substantial and timely reductions of greenhouse gas emissions are not achieved.

**References**
1 Field, C. et al. *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. 1132 (Cambridge University Press, 2014).
2 Trenberth, K. E. Framing the way to relate climate extremes to climate change. *Clim. Chang.* **115**, 283-290 (2012).
3 Piontek, F. et al. Multisectoral climate impact hotspots in a warming world. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3233-3238 (2014).
4 Mora, C., Counsell, C. W. W., Bielecki, C. R. & Louis, L. V. Twenty-seven ways a heat wave can kill you: Deadly heat in the era of climate change. *Circ. Cardiovasc. Qual. Outcomes* **10**, e004233 (2017).
5 Mora, C. et al. Global risk of deadly heat. *Nat. Clim. Change* **7**, 501-506 (2017).
6 Lugeri, N., Kundzewicz, Z. W., Genovese, E., Hochrainer, S. & Radziejewski, M. River flood risk and adaptation in Europe—assessment of the present status. *Mitig. Adapt. Strat. Gl.* **15**, 621-639 (2010).
7 Baro, M. & Deubel, T. F. Persistent hunger: Perspectives on vulnerability, famine, and food security in sub-Saharan Africa. *Annu. Rev. Anthropol.* **35**, 521-538 (2006).
8 Brown, O. *Migration and climate change*. (International organization for migration, 2008).
9 Alston, M. Gender and climate change in Australia. *J. Soc.* **47**, 53-70 (2011).
10 Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B. & Silliman, B. R. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Clim. Chang.* **106**, 7-29 (2011).
11 Day, J. W. et al. Restoration of the Mississippi Delta: lessons from hurricanes Katrina and Rita. *Science* **315**, 1679-1684 (2007).
12 Gronlund, C. J., Zanobetti, A., Schwartz, J. D., Wellenius, G. A. & O’Neill, M. S. Heat, heat waves, and hospital admissions among the elderly in the United States, 1992–2006. *Environ. Health Persp.* **122**, 1187-1188 (2014).
13 Hurteau, M. D., Westerling, A. L., Wiedinmyer, C. & Bryant, B. P. Projected effects of climate and development on California wildfire emissions through 2100. *Environ. Sci. Technol.* **48**, 2298-2304 (2014).
14 Prospero, J. M. & Lamb, P. J. African droughts and dust transport to the Caribbean: Climate change implications. *Science* **302**, 1024-1027 (2003).
15 Solomon, G. M., Hjelmroos-Koski, M., Rotkin-Ellman, M. & Hammond, S. K. Airborne mold and endotoxin concentrations in New Orleans, Louisiana, after flooding, October through November 2005. *Environ. Health Persp.* **114**, 1381-1386 (2006).
16 Larsen, J. N. et al. Polar regions. *Clim. Chang.*, 1567-1612 (2014).
17 Frumhoff, P. C., McCarthy, J. J., Melillo, J. M., Moser, S. C. & Wuebbles, D. J. Confronting climate change in the US Northeast. *A report of the northeast climate impacts assessment. Union of Concerned Scientists, Cambridge, Massachusetts* (2007).
18 McMichael, T., Montgomery, H. & Costello, A. Health risks, present and future, from global climate change. *Br. Med. J.* **344**, e1359 (2012).
19 Rose, J. B. et al. Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. *Environ. Health Persp.* **109**, 211 (2001).
20 Epstein, P. R. et al. Biological and physical signs of climate change: Focus on mosquito-borne diseases. *Bull. Amer. Meteor. Soc.* **79**, 409-417 (1998).
21 Tirado, M., Clarke, R., Jaykus, L., McQuatters-Gollop, A. & Frank, J. Climate change and food safety: A review. *Food Res. Int.* **43**, 1745-1765 (2010).
22 Kendrovski, V. & Gjorgjiev, D. in *Structure and Function of Food Engineering* (ed A. Ayman) 151-170 (InTech, 2012).
23 Comrie, A. Climate change and human health. *Geogr. Comp.* **1**, 325-339 (2007).
24 Epstein, P. R. Climate change and emerging infectious diseases. *Microbes Infect.* **3**, 747-754 (2001).
25 Kovats, R., Campbell-Lendrum, D., McMichel, A., Woodward, A. & Cox, J. S. H. Early effects of climate change: do they include changes in vector-borne disease? *Philos. Trans. R. Soc. Lond. B* **356**, 1057-1068 (2001).
26 Patz, J. A., Olson, S. H., Uejio, C. K. & Gibbs, H. K. Disease emergence from global climate and land use change. *Med. Clin. N. Am.* **92**, 1473-1491 (2008).
27 Gale, P., Drew, T., Phipps, L., David, G. & Wooldridge, M. The effect of climate change on the occurrence and prevalence of livestock diseases in Great Britain: a review. *J. Appl. Microbiol.* **106**, 1409-1423 (2009).
28 Potera, C. Climate change: challenges of predicting wildfire activity. *Environ. Health Persp.* **117**, A293 (2009).
29 Butler, C. D. & Harley, D. Primary, secondary and tertiary effects of eco-climatic change: the medical response. *Postgrad. Med. J.* **86**, 230-234 (2010).
30 Faiz, M. & Islam, Q. T. Climate change and health. *J. Bangladesh Coll. Phys. Surg.* **28**, 1-3 (2010).
31 Pradhan, B. Key sector analysis: Health adaptation in Nepal. (Mimeo Kathmandu, 2010).
32 Gubler, D. J. *et al.* Climate variability and change in the United States: potential impacts on vector-and rodent-borne diseases. *Environ. Health Persp.* **109**, 223 (2001).
33 Marques, A., Nunes, M. L., Moore, S. K. & Strom, M. S. Climate change and seafood safety: human health implications. *Food Res. Int.* **43**, 1766-1779 (2010).
34 Miraglia, M. *et al.* Climate change and food safety: an emerging issue with special focus on Europe. *Food Chem. Toxicol.* **47**, 1009-1021 (2009).
35 Parry, M., Canziani, O., Palutikof, J. & Linden, P. v. d. *Climate change 2007: Impacts, Adaptation and Vulnerability.* (Cambridge University Press, 2007).
36 Magrin, G. *et al.* Latin America. *Clim. Chang.*, 581-615 (2007).
37 Gould, E. A. & Higgs, S. Impact of climate change and other factors on emerging arbovirus diseases. *Trans. R Soc. Trop. Med. Hyg.* **103**, 109-121 (2009).
38 Calow, R. C., MacDonald, A. M., Nicol, A. L. & Robins, N. S. Ground water security and drought in Africa: linking availability, access, and demand. *Ground Water* **48**, 246-256 (2010).
39 Melillo, J. M., Richmond, T. T. & Yohe, G. *Climate change impacts in the United States, Third National Climate Assessment.* (U.S. Global Change Research Program, 2014).
40 Fritze, J. G., Blashki, G. A., Burke, S. & Wiseman, J. Hope, despair and transformation: Climate change and the promotion of mental health and wellbeing. *Int. J. Ment. Health Syst.* **2**, 13 (2008).
41 Blaikie, P., Cannon, T., Davis, I. & Wisner, B. *At risk: Natural hazards, people's vulnerability and disasters.* (Routledge, 2014).
42 Horton, G., Hanna, L. & Kelly, B. Drought, drying and climate change: emerging health issues for ageing Australians in rural areas. *Australas. J. Ageing.* **29**, 2-7 (2010).
43 Rohrbach, L. A., Grana, R., Vernberg, E., Sussman, S. & Sun, P. Impact of Hurricane Rita on adolescent substance use. *Psychiatry* **72**, 222-237 (2009).
44 Willox, A., Harper, S., Ford, J., Edge, V. & Landman, K. Climate change and mental health: an exploratory case study from Rigolet, Nunatsiavut, Canada. *Clim. Chang.* **121**, 255-270 (2013).
45 Carrington, K., McIntosh, A., Hogg, R. & Scott, J. Safeguarding rural Australia: addressing masculinity and violence in rural settings: suicide and other violent self-harm in an Australian rural context: analysis of secondary data. (Centre for Law and Justice, Queensland University of Technology, 2011).
46 Page, L. A., Hajat, S. & Kovats, R. S. Relationship between daily suicide counts and temperature in England and Wales. *Br. J. Psychiatry* **191**, 106-112 (2007).
Kunkel, K. E., Pielke Jr, R. A. & Changnon, S. A. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bull. Amer. Meteor. Soc.* **80**, 1077-1098 (1999).

Bosworth, B., Collins, S. & Virmani, A. Sources of growth in the Indian economy. (National Bureau of Economic Research, Cambridge, MA, 2007).

Rosales, M. F. Impact of early life shocks on human capital formation: El Niño floods in Ecuador. (IDB Working Paper Series, 2014).

Jayachandran, S. Air quality and early-life mortality evidence from Indonesia’s wildfires. *J. Hum. Resour.* **44**, 916-954 (2009).

Khan, A. E. *et al.* Salinity in drinking water and the risk of (pre)eclampsia and gestational hypertension in coastal Bangladesh: A case-control study. *PLoS ONE* **9**, e108715 (2014).

Mainville, D. Y. Disasters and development in agricultural input markets: Bean seed markets in Honduras after hurricane Mitch. *Disasters* **27**, 154-171 (2003).

Nhan, D. K., Trung, N. H. & Sanh, N. V. in *Environmental Change and Agricultural Sustainability in the Mekong Delta* Vol. **45** (eds M. Stewart & P. Coclanis) 437-451 (Springer, 2011).

Chau, V. N., Holland, J., Cassells, S. & Tuohy, M. Using GIS to map impacts upon agriculture from extreme floods in Vietnam. *Appl. Geogr.* (2013).

Rossati, A. Global Warming and Its Health Impact. *Int. J. Occup. Environ. Med.* **8**, 963-967-920 (2017).

Yu, Q. *et al.* Proposing an interdisciplinary and cross-scale framework for global change and food security researches. *Agric. Ecosyst. Environ.* **156**, 57-71 (2012).

Easterling, W. E. *et al.* Food, fibre and forest products. *Clim. Chang.*, 273-313 (2007).

Schlenker, W. & Roberts, M. J. Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 15594-15598 (2009).

Ummenhofer, C. C. *et al.* What causes southeast Australia's worst droughts? *Geophys. Res. Lett.* **36**, L04706 (2009).

Bagley, J. E., Desai, A. R., Dirmeyer, P. A. & Foley, J. A. Effects of land cover change on moisture availability and potential crop yield in the world’s breadbaskets. *Environ. Res. Lett.* **7**, 014009 (2012).

Dwivedi, S., Sahrawat, K., Upadhyaya, H. & Ortiz, R. Food, nutrition and agrobiodiversity under global climate change. *Adv. Agron.* **120**, 1-128 (2013).

Marvin, H. J. *et al.* Proactive systems for early warning of potential impacts of natural disasters on food safety: Climate-change-induced extreme events as case in point. *Food Control* **34**, 444-456 (2013).

Patz, J. A., Campbell-Lendrum, D., Holloway, T. & Foley, J. A. Impact of regional climate change on human health. *Nature* **438**, 310-317 (2005).

Chantarat, S. *et al.* Insuring against drought related livestock mortality: Piloting index based livestock insurance in Northern Kenya. *SSRN*, 1-25 (2010).

Mader, T. L. Animal welfare concerns for cattle exposed to adverse environmental conditions. *J. Anim Sci.* **92**, 5319-5324 (2014).

Richard Eckard, M. B., Karen Christie, Richard Rawnsley. in *From living in a warmer world* (ed J. Salinger) 144-157 (CSIRO, 2013).

Sulieman, H. M. & Elagib, N. A. Implications of climate, land-use and land-cover changes for pastoralism in eastern Sudan. *J. Arid Environ.* **85**, 132-141 (2012).

St-Pierre, N., Cobanov, B. & Schnitkey, G. Economic losses from heat stress by US livestock industries. *J. Dairy Sci.* **86**, E52-E77 (2003).

Doney, S. C. *et al.* Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.* **4**, 11-37 (2012).
Portner, H. O. & Knust, R. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* **315**, 95-97 (2007).

Jonsson, B. & Jonsson, N. A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water. *J. Fish Biol.* **75**, 2381-2447 (2009).

Wetz, M. S. & Yoskowitz, D. W. An 'extreme' future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology. *Mar. Pollut. Bull.* **69**, 7-18 (2013).

Smoyer-Tomic, K. E., Kuhn, R. & Hudson, A. Heat wave hazards: An overview of heat wave impacts in Canada. *Nat. Hazards* **28**, 465-486 (2003).

Nikolic, N. *et al*. Bibliometric analysis of diadromous fish research from 1970s to 2010: A case study of seven species. *Scientometrics* (2011).

Benotti, M. J., Stanford, B. D. & Snyder, S. A. Impact of drought on wastewater contaminants in an urban water supply. *J. Environ. Qual.* **39**, 1196-2000 (2010).
Shahid, S. Vulnerability of the power sector of Bangladesh to climate change and extreme weather events. *Reg. Environ. Change* (2012).

Ibàñez, C., Canicio, A., Day, J. W. & Curcó, A. Morphologic development, relative sea level rise and sustainable management of water and sediment in the Ebre Delta, Spain. *J. Coast. Conserv.* 3, 191-202 (1997).

Nunn, P. D. The end of the Pacific? Effects of sea level rise on Pacific Island livelihoods. *Singap. J. Trop. Geogr.* 34, 143-171 (2013).

Bollinger, L. A. & Dijkema, G. P. J. Evaluating infrastructure resilience to extreme weather – The case of the Dutch electricity transmission network. *Eur. J. Transport Infrastruct. Res.* 16, 214-239 (2016).

Sabbag, L. Temperature impacts on health, productivity, and infrastructure in the urban setting, and options for adaptation., (Institute for Social and Environmental Transition-International, 2013).

Lyster, R. & Byrne, R. Climate change adaptation and electricity infrastructure. (Sydney Law School, 2013).

Oliver, E., Martin, D., Krause, O., Bartlett, S. & Froome, C. How is climate change likely to affect Queensland electricity infrastructure into the future? Report No. 9781467381321, (2016).

Zampieri, M. *et al.* Global assessment of heat wave magnitudes from 1901 to 2010 and implications for the river discharge of the Alps. *Sci. Total Environ.* 571, 1330-1339 (2016).

Reeves, J. *et al.* Impacts and adaptation response of infrastructure and communities to heatwaves : the southern Australian experience of 2009. Report No. 192160915X, (2010).

Procupez, V. The perfect storm: Heat waves and power outages in Buenos Aires. *Publ. Cult.* 28, 351-357 (2016).

Klinger, C., Landeg, O. & Murray, V. Power outages, extreme events and health: A systematic review of the literature from 2011-2012. *PLoS Curr.* 6 (2014).

Schaeffer, R., Szklo, A., Lucena, A. d. & Borba, B. Energy sector vulnerability to climate change: a review. *Energy* 38, 1-12 (2012).

Mcguirk, M., Shuford, S., Peterson, T. C. & Pisano, P. Weather and climate change implications for surface transportation in the USA. *WMO Bull.* 58, 84-93 (2009).

Hunt, A. & Watkiss, P. Climate change impacts and adaptation in cities: A review of the literature. *Clim. Chang.* 104, 13-49 (2011).

Illes, M. C. *et al.* High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. *Adv. Geosci* 23, 47-55 (2010).

Wardhana, K. & Hadipriono, F. C. Analysis of recent bridge failures in the United States. *J. Perform. Constr. Fac.* 17, 144-150 (2003).

Revi, A. *et al.* Urban areas. *Clim. Chang.*, 535-612 (2014).

Climate change impacts and adaptation for international transport networks. 1-223 (UN Economic Commission for Europe, 2013).

Anderson, D. M. *et al.* in *U.S. Global Change Research Program* (eds T R Karl, J M Melillo, & T C Peterson) (2009).

Nolte, R., Kamburov, C. & Rupp, J. Adaptation of railway infrastructure to climate change. 1-60 (International Union of Railways, 2011).

MacArthur, J. *et al.* in *Transportation Research and Education Center*. 287.

Peterson, T., McGuirk, M. & Houston, T. Climate variability and change with implications for transportation. (Transportation Research Board, 2008).

Dobney, K., Baker, C. J., Chapman, L. & Quinn, A. D. The future cost to the United Kingdom’s railway network of heat-related delays and buckles caused by the predicted increase in high summer temperatures owing to climate change. *Proc. Inst. Mech. Eng.* 224, 25-34 (2010).
Moorty, S. & Roeder, C. Temperature-dependent bridge movements. *J. Structural Eng.*, **118**, 1090-1105 (1992).

Davies, A. *Why planes can't fly in extreme heat*, <http://www.businessinsider.com/why-planes-cant-fly-in-extreme-heat-2013-7> (2013).

Quah, E. & Varkkey, H. M. The political economy of transboundary pollution: Mitigation forest fires and haze in southeast Asia. *323-358* (2013).

Parry, M., Canziani, O., Palutikof, J., Van Der Linden, P. & Hanson, C. Cross-chapter case study. *Clim. Chang.*, 843-868 (2007).

Bhandari, G. & Gurung, G. B. Integrated approach to climate change adaptation. *J. For. Livelihood*, **8**, 91-99 (2009).

Webb, R. H., Magirl, C. S., Griffiths, P. G. & Boyer, D. E. in *Open-File Report*. (U.S. Dept. of the Interior).

Tsai, H.-T., Tseng, C.-J., Tzeng, S.-Y., Wu, T.-J. & Day, J.-d. The impacts of natural hazards on Taiwan's tourism industry. *Nat. Hazards* **62**, 83-91 (2011).

Bigger, J. E., Willingham, M. G., Krimgold, F. & Mili, L. Consequences of critical infrastructure interdependencies: lessons from the 2004 hurricane season in Florida. *Int. J. Crit. Infrastruct.*, **5**, 199 (2009).

Tierney, K. J., Nigg, J. M. & Nigg, J. M. Business vulnerability to disaster-related lifeline disruption. (University of Delaware, Disaster Research Center, Newark, DE, 1995).

Rehman, J. Heat not wet: Climate change effects on human migration in rural Pakistan. 5 (University of Illinois at Chicago, College of Medicine, 2015).

Scott, D., Simpson, M. C. & Sim, R. The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *J. Sustainable Tour.*, **20**, 883-898 (2012).

Banerjee, O., Bark, R., Connor, J. & Crossman, N. N. D. An ecosystem services approach to estimating economic losses associated with drought. *Ecol. Econ.*, **91**, 19-27 (2013).

Wang, X., Stewart, M. G. & Nguyen, M. Impact of climate change on corrosion and damage to concrete infrastructure in Australia. *Clim. Chang.*, **12**, 1-15 (2017).

Albert, S. *et al.* Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environ. Res. Lett.*, **11**, 054011 (2016).

Mooney, H. *et al.* Biodiversity, climate change, and ecosystem services. *Curr. Opin. Env. Sust.*, **1**, 46-54 (2009).

Howitt, R., Medellín-Azuara, J., MacEwan, D., Lund, J. & Sumner, D. Economic analysis of the 2014 drought for California agriculture. (2014).

Mechler, R. & Weichselgartner, J. (IR-03-021).

Costanza, R. *et al.* The value of coastal wetlands for hurricane protection. *AMBIO*, 241-248 (2008).

Coffman, M. & Noy, I. Hurricane Iniki: measuring the long-term economic impact of a natural disaster using synthetic control. *Environ. Dev. Econ.*, **17**, 187-205 (2012).

Wilbanks, T. J. *et al.* Industry, settlement and society. *Clim. Chang.*, 357-390 (2007).

Pechan, A. & Eisenack, K. The impact of heat waves on electricity spot markets. *Energ. Econ.*, **43**, 63-71 (2014).

Urbanchuk, J. Contribution of biofuels to the global economy. (Global Renewable Fuels Association, 2012).

Zander, K. K., Botzen, W. J. W., Oppermann, E., Kjellstrom, T. & Garnett, S. T. Heat stress causes substantial labour productivity loss in Australia. *Nat. Clim. Change*, **5**, 1-6 (2015).

Berry, H. L., Bowen, K. & Kjellstrom, T. Climate change and mental health: a causal pathways framework. *Int. J. Public Health*, **55**, 123-132 (2010).
Dewan, T. H. Societal impacts and vulnerability to floods in Bangladesh and Nepal. *Weather Clim. Extrem.* **7**, 36-42 (2015).

Caldwell, J. C., Reddy, P. H. & Caldwell, P. Periodic high risk as a cause of fertility decline in a changing rural environment: Survival strategies in the 1980-1983 south Indian drought. *Econ. Dev. Cult. Change.* **34**, 677-701 (1986).

Roessig, J. M., Woodley, C. M., Cech, J. J. & Hansen, L. J. Effects of global climate change on marine and estuarine fishes and fisheries. *Rev. Fish Biol. Fish.* **14**, 251-275 (2004).

Buckley, L. B. & Foushee, M. S. Footprints of climate change in US national park visitation. *Int. J. Biometeorol.* **56**, 1173-1177 (2012).

Liu, T.-M. Analysis of the economic impact of meteorological disasters on tourism: the case of typhoon Morakot's impact on the Maolin National Scenic Area in Taiwan. *Tourism Econ.* **20**, 143-156 (2014).

Scott, D. & Lemieux, C. Weather and climate information for tourism. *Procedia Environ. Sci.* **1**, 146-183 (2010).

Liverman, D. M. Vulnerability and adaptation to drought in Mexico. *Nat. Resour. J.* **39**, 99-115 (1999).

Scott, D., Mcboyle, A. G., Ae, D. S. & Mcboyle, G. Climate change adaptation in the ski industry. *Mitig. Adapt. Strat. Gl.* **12**, 1411-1431 (2007).

Pickering, C. M., Castley, J. G. & Burtt, M. Skiing less often in a warmer world: Attitudes of tourists to climate change in an Australian ski resort. *Geogr. Res.* **48**, 137-147 (2009).

Wilkinson, C. R. Global change and coral reefs: impacts on reefs, economies and human cultures. *Glob. Chang. Biol.* **2**, 547-558 (1996).

Meynecke, J. O., Richards, R. & Sahin, O. Whale watch or no watch: the Australian whale watching tourism industry and climate change. *Reg. Environ. Change* **17**, 1-12 (2016).

Black, R., Arnell, N. W., Adger, W. N., Thomas, D. & Geddes, A. Migration, immobility and displacement outcomes following extreme events. *Environ. Sci. Pol.* **27**, S32-S43 (2012).

Campbell, B. K. M. et al. The age of consequences: The foreign policy and national security implications of global climate change. *Security*, 1-119 (2007).

Christoplos, I. et al. Learning from recovery after Hurricane Mitch. *Disasters* **34**, 202-219 (2010).

Brennan, T. The impact of increasing severe weather events on shelter. 1-11 (U.S. Environmental Protection Agency, 2010).

Raleigh, C., Jordan, L. & Salehyan, I. Assessing the impact of climate change on migration and conflict. *World* **24**, 1-57 (2008).

Hazra, S., Ghosh, T., Dasgupta, R. & Sen, G. Sea level and associated changes in the Sundarbans. *Sci. Cult.* **68**, 309-321 (2002).

McLeman, R. & Smit, B. Migration as an adaptation to climate change. *Clim. Chang.* **76**, 31-53 (2006).

AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T. & Lund, J. Recognize anthropogenic drought. *Nature* **524**, 409-411 (2015).

Gupta, A. Geopolitical implications of Arctic meltdown. *Strategic Anal.* **33**, 174-177 (2009).

Johnson, L. The fearful symmetry of Arctic climate change: Accumulation by degradation. *Environ. Plann. D* **28**, 828-847 (2010).

Hsiang, S. M. & Burke, M. Climate, conflict, and social stability: what does the evidence say? *Clim. Chang.* **123**, 39-55 (2014).

Ide, T. & Scheffran, J. On climate, conflict and cumulation: suggestions for integrative cumulation of knowledge in the research on climate change and violent conflict. *Global Change Peace Secur.* **26**, 263-279 (2014).
Raleigh, C., Choi, H. J. & Kniveton, D. The devil is in the details: An investigation of the relationships between conflict, food price and climate across Africa. *Glob. Environ. Chang.* **32**, 187-199 (2015).

Von Uexkull, N. Sustained drought, vulnerability and civil conflict in Sub-Saharan Africa. *Polit. Geogr.* **43**, 16-26 (2014).

Gleick, P. H. Water, drought, climate change, and conflict in Syria. *Weather Clim. Soc.* **6**, 331-340 (2014).

Maystadt, J., Ecker, O. & Mabiso, A. Extreme weather and civil war in Somalia: Does drought fuel conflict through livestock price shocks?, (Intl Food Policy Res Inst, 2013).

Hendrix, C. S. & Salehyan, I. Climate change, rainfall, and social conflict in Africa. *J. Peace Res.* **49**, 35-50 (2012).

Hsiang, S. M., Meng, K. C. & Cane, M. A. Civil conflicts are associated with the global climate. *Nature* **476**, 438-441 (2011).

Hsiang, S. M., Burke, M. & Miguel, E. Quantifying the influence of climate on human conflict. *Science* **341**, 1235367 (2013).

Larrick, R. P., Timmerman, T. A., Carton, A. M. & Abrevaya, J. Temper, temperature, and temptation: Heat-related retaliation in baseball. *Psychol Sci.* **22**, 423-428 (2011).

Anderson, C. A. & Delisi, M. in *The Psychology of Social Conflict and Aggression* (eds J. Forgas, A. Kruglanski, & K. Williams) 249-265 (Psychology Press, 2011).

Rotton, J. & Cohn, E. G. Global warming and U.S. crime rates: An application of routine activity theory. *Environ. Behav.* **35**, 802-825 (2003).

Sims, B. 'The day after the hurricane': Infrastructure, order, and the new orleans police department’s response to hurricane Katrina. *Soc. Stud. Sci.* **37**, 111-118 (2007).

Jenkins, P. & Phillips, B. Battered women, catastrophe, and the context of safety after Hurricane Katrina. *NWSA J.* **20**, 49-68 (2008).

Thornton, W. E. & Voigt, L. Disaster rape: Vulnerability of women to sexual assaults during Hurricane Katrina. *J. Public Manag. Soc. Policy* **13**, 23-49 (2007).

Verwimp, P. Food security, violent conflict and human development: Causes and consequences. (United Nations Development Program 2012).

Lane, K. *et al.* Health effects of coastal storms and flooding in urban areas: a review and vulnerability assessment. *J. Environ. Public Health* **2013** (2013).

Enarson, E. Violence against women in disasters: A study of domestic violence programs in the united states and canada. *Violence Against Wom.* **5**, 742-768 (1999).

Editorial. Don’t jump to conclusions about climate change and civil conflict. *Nature* **554**, 275-276 (2018).

Mora, C. *et al.* The projected timing of climate departure from recent variability. *Nature* **502**, 183-187 (2013).

Mora, C. *et al.* Suitable days for plant growth disappear under projected climate change: Potential human and biotic vulnerability. *PLoS Biol* **13**, e1002167 (2015).

Mora, C. *et al.* Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. *PLoS Biol.* **11**, e1001682 (2013).

Acknowledgements

This study was possible by a grant/cooperative agreement from the National Oceanic and Atmospheric Administration, Project R/IR-31, R/IR-25PD, which is sponsored by the University of Hawaii Sea Grant.
College Program, SOEST, under Institutional Grant No. NA14OAR4170071, NA09OAR4170060 from NOAA Office of Sea Grant, Department of Commerce. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies. UNIHI-SEAGRANT-JC-13-37. E.C.F. was supported by NOAA Fisheries award NA15NMF4520361. L.V.L. was supported by the National Science Foundation Graduate Research Fellowship under grant no. DGE-1650441. A.G.F. was supported by the National Bioclimatology and Climate Change Program, USDA Forest Service, and the Department of Interior Pacific Islands Climate Adaptation Science Center award G16PG00037. E.H. was supported by the National Centre for Atmospheric Science and by the NERC REAL project (Grant: NE/N018591/1). Y.H. and N.H. were supported by ERTDF S-14, ERCA, Japan. C.M.L. acknowledges support from NASA award NNH16CT01C. The funders have not role on conceptualization, design, data collection, analysis, decision to publish, or preparation of the manuscript. We thank the ESRI’s Applications Prototype Lab for their help to create the online mapping application. This paper was developed as part of the graduate course on ‘Methods for Large-Scale Analyses’ in the Department of Geography and Environment at the University of Hawai‘i at Mānoa.

Author contributions

C.M., D.S., E.C.F., J.L., M.B.K., W.M., C.Z.S., K.F., J.M., L.V.L., E.W.B, K.B., A.G.F., J. F.C, J.A.P, C.L.H. collected data on observed impacts, C.M., N.H., E.H., Y.H., W.K., C.M.L., K.E., J.S. provided projections of climate hazards, C.M. did the analysis on cumulative impacts, all authors contributed to the writing and revision of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and request for materials should be addressed to C.M.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
Methods

Synthesis of impacts

To compile the observed impacts on people from climate hazards, we searched Google Scholar from February to March 2017 using a full text search in English for publications on the impacts of 10 hazards of the Earth’s climate system (i.e., warming, heatwaves, precipitation, floods, drought, fires, sea level, storms, natural cover change, ocean climate change) on six aspects of human life (i.e., health, food, water, infrastructure, economy and security). Our assessment of the Earth’s climate system was based not only on mean state changes (e.g., warming, precipitation, sea level, ocean chemistry), and extreme weather events (e.g., heatwaves, flood, drought, storms), but also disturbances (e.g., fire). We included changes in natural land cover as one of the hazards because ecosystems are an intrinsic component of Earth’s climate system being sources and sinks of carbon, affecting other hazards (e.g., warming and precipitation via albedo and evapotranspiration), and directly affecting various aspects of human life\(^1,2\). We also assessed impacts from changes in ocean chemistry given the key role of the oceans on the climate system and human dependency on ocean goods and services\(^3\), especially for coastal and maritime societies. Our assessment of impacts on human systems was based on aspects that we considered essential for human wellbeing. These six aspects, however, represent general categories within which many other aspects of human life were assessed. For instance, we found numerous cases examples of impacts on cultural practices such as the breakdown of traditional hunting and fishing systems among indigenous communities (i.e., a food impact), causing depression or even suicide (i.e., a health impact). The diversity of aspects of human life assessed is reflected by the long list of sub-categories reported in the paper (Fig. 1).

To ensure a systematic process, we scrutinized the first 200 references that resulted from using each possible combination of the ten climate hazards and six aspects of human life as keywords. References included the academic literature, grey literature and popular press news articles. From those references, we selected papers independent of whether reported impacts were positive or negative. Our search also included the references cited in the publications that were read to be as comprehensive as possible. From >12,000 references that were screened, including 72 chapters from the prior five IPCC reports and the most recent National Climate Assessment report for the USA, we identified 3,280 publications that were read to find examples of observed impacts.

For the purpose of quality assurance and standardization, we applied the following approach when searching for impacts in reference abstracts and texts:
1. To ensure standardization, an impact was broadly considered as any case example of “an explicit climate hazard causing a response on an explicit aspect of human life in an explicit or implicit place and time.” The criteria allowed us to identify the climate hazard and human aspect that was affected while ensuring the impact was empirically observed (i.e., any impact could be traced to a place and time as reported in the literature). Mentions to impacts that lacked such traceable evidence were excluded. For instance, a claim such as “increased mortality has been observed during heatwaves” was not considered. This claim lacks the traceable evidence of when and where the heatwave that killed people happened. In turn, a valid entry was: “During the 2003 European heatwave over 70,000 excess human deaths were observed”. This later entry provides traceable evidence that an explicit climate hazard (i.e., a heatwave) impacted an explicit aspect of human life (i.e., mortality) in a given place (i.e., Europe) and time (i.e., 2003).

2. We created a public online-database consisting of ten columns (one for each climate hazard) and six rows (one for each of the six aspects of human life assessed). We created subcategories (i.e., added rows to the online table) within each primary aspect of human life to reflect the variety of documented impacts in the literature (e.g., under the primary heading “food”, entries were separated into “agriculture”, “livestock”, “marine fisheries”, etc.; see Fig. 1). Upon identifying an impact in a given paper, the user will place the reported impact in the online table at the intersection of the climate hazard (column) and attribute of human life (row) explicitly mentioned in the paper. Subcategories were created by the user who read the given paper using the terms provided in the reviewed paper thus avoiding classification biases by the user who entered the data. This initial classification specificity was also intended to prevent “grouping” impacts into broad sub-categories and potentially losing visibility of rare impacts. However, by using a central online database, any created subcategory was automatically available to others entering data thus reducing duplication of subcategories. Upon culmination of data entry, authors met to integrate similar existing sub-categories as much as possible, while careful to not generate broad terms that could risk overlooking rare impacts. For example, we found that climate hazards have numerous types of impacts on the state of mind of people ranging from depression, to addiction, to affective disorder, to PTSD, to even suicide. These subcategories were maintained for better identification of the broad array of psychological consequences from climate hazards. Further, we performed secondary searches combining key words of climate hazard (column name) and specific (i.e., subcategory) attribute of human life (row name) of empty cells in our table to ensure that empty cells represented a lack of evidence.

3. To ensure transparency and allow for the capacity to verify entries, records of impacts were taken directly from papers and deposited in the open web-page with the accompanying PDF (i.e., any entry can be read, and if interested the user can review the paper from where the entry was taken). For further
quality evaluation, the online database includes a double review process of each entered impact. Any impact entered by a user will appear automatically as pending in the web-page and awaited validation by a team of at least two authors. Basically, while any registered and authorized user could enter impacts in the database, only those records that met the criteria of an impact and that came from a reliable source as deemed by a reviewing team appear in the main page of the database and were reported in this study.

We envision this web-database as a repository that can be used in future studies to identify knowledge gaps and assess progress in our understanding of the impacts of climate change on people. Our systematic search of the impacts of climate hazards on people yielded numerous case examples of adaptation that reduced the magnitude of such impacts. These case examples were compiled and briefly described in the section on “Adaptation” (Supplementary Note 1). However, we caution that those records are unlikely to reflect the full spectrum of adaptations; as mentioned in the Caveats section, an assessment on human adaptation to climate change likely requires a similar systematic review of the literature dedicated to that topic.

Cumulative index of climate hazards

To assess the exposure of humanity to cumulative climatic hazards, we gathered projections of climate hazards from Earth System Models developed for the Coupled Model Intercomparison Project phase 5 (CMIP5) under alternative emission scenarios. Projections ranged from 1950 to 2005 using the “historical experiment”, which aims to simulate the Earth’s recent climate, and from 2006 to 2100 using the “Representative Concentration Pathways” (RCPs) 2.6, 4.5 and 8.5, which constitute alternative scenarios between strong mitigation or continuous rise of greenhouse gases throughout the 21st century, respectively. We acquired climate projections on floods, fires, sea level, storms, freshwater scarcity, drought, heatwaves and ocean chemistry by reaching out to the lead authors of those papers and obtaining the raw data from their studies. The metric of ocean chemistry change was obtained from Mora et al., and integrates projections of seawater temperature, pH and oxygen. Drought projections were repeated following the same approach as in Sheffield et al. but using data from the CMIP5. We used changes in primary and secondary forest as a surrogate for changes in natural land cover using data from Hurtt et al.; these projections are based primarily on projected deforestation and reforestation and do not include impacts of climate change on forest cover. Warming and precipitation projections were the same as Diffenbaugh and Field. Projected data on sea level and ocean chemistry were extrapolated to the nearest coastal pixels assuming that coastal communities will likely be exposed to those climatic variables. Variables were standardized to a common 1.5 degree global grid using bilinear interpolation
and calculated for each year averaging data over an 11 year window centered on the given year; this was done to avoid aliasing results by inter-annual climate variability. It should be noted that the outputs of the CMIP5 Earth System Models are global in scale and have coarse resolutions that allows for identifying general patterns but should not be used to drive local-scale inference. Downscaling techniques using Regional Climate Models or statistical methods could be more appropriate for local-scale assessments, but such models remain limited in the climate variables analyzed and regions of the world for which they are available.

To generate a cumulative index of the multiple climate hazards, we used an additive approach of standardized variables as developed in similar studies that examined the cumulative effect of human disturbances on land\textsuperscript{13} and sea\textsuperscript{14}. For each hazard, at each pixel in a global grid, we calculated the difference between each year in the time series and 1955 to create global maps of change. Since the intensity of some hazards is projected to decline by comparison to the 1950s period, we separated changes that increased/intensified from those that decreased/lessened. For each climate hazard, we created a distribution of change values (i.e., between 1955 and 2095 under RCP 8.5) across the global grid and selected the grid value at the 95\textsuperscript{th} percentile to be used as reference for the most extreme change in the hazard. All maps of global change were re-scaled from 0 to 1; zero meaning no change and 1 meaning the 95\textsuperscript{th} percentile or greater. In other words, a pixel with a value of zero in a given hazards suggests that that hazard will not change in that pixel. In turn, a pixel with a value of 1 suggests that the most extreme increase of that hazard will occur in that pixel. The matching values of each hazard to the standardized scale are shown on Fig. S2. The re-scaled scores in all hazards were summed at a given pixel to assess the cumulative climatic change projected to occur in the pixel (Fig. 2, Fig. S2-3).

To calculate human exposure to the cumulative changes in all hazards, we used population data consistent with the climate emission scenarios (Fig. 3a-c). Historical population data up to the year 2005 were obtained from the Socioeconomic Data and Applications Center (http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-count-future-estimates/data-download#). Human population projections were obtained from Jones et al.\textsuperscript{15}, who developed global population scenarios consistent with the Shared Socioeconomic Pathways (SSP) from 2006 to 2100. We paired RCP 2.6 with SSP1, RCP 4.5 with SSP3, and RCP 8.5 with SSP5. Human population vulnerability to cumulative climatic changes was also calculated separating countries by country level per capita GDP (Fig. 3d-f). Data on per capita GDP were obtained from the World Bank Database (http://data.worldbank.org/). We grouped low-, medium-, and high-income countries depending on whether annual per capita GDP was smaller than USD 4,000, between USD 4,000 and USD 12,000 and larger than USD 12,000, respectively.
A key source of uncertainty in the reported projections of climatic change is the “precision” with which Earth Climate System Models predict change in the different hazards. Precision is defined here as the variability in projected changes from replicated Earth Climate System Models. To assess the effect of this source of uncertainty, for each hazard we gathered the average projections among Earth Climate System Models and their standard deviations. For each pixel, at each time step, we divided the standard deviation by the mean to calculate the coefficient of variation. We then removed any pixel for which the coefficient of variation was larger than one; that is, pixels for which the multimodel variability was larger than the average projection. We then recalculated the overall cumulative index of climate hazards and compared results from the raw projections and the projections excluding uncertain pixels (Fig. S4). Since the effects of multimodel uncertainty was small (Fig. S4), we reported results based on the raw data. To assess the spatial similarity in the projected change of different hazards, we calculated the cross-correlations between projected changes of all hazards (Table S1).

Caveats

Our search of observed impacts yielded a much larger number of negative impacts than positive ones. This result could reflect a real disparity in the occurrence of impacts but may also reflect a systematic bias of reported impacts. We consider that such bias can emerge from two alternative sources: first, there is a bias in our search of the literature. We minimized this bias by carrying out a comprehensive search of citations on impacts regardless of whether impacts were positive or negative (see Methods). Second, there is a bias in the literature itself toward reporting negative impacts. We consider that this bias could be real, since from a “risk” perspective a critical concern is those impacts with negative consequences on humanity. However, there is no mechanism for us to quantify such bias within our literature review. This is because publications are likely related to issues of novelty and broad public interests as opposed to how common impacts are. However, even if there is a bias towards negative impacts in the literature, this does not invalidate any of the impacts that have already been observed nor their purpose for this paper, which was to highlight the broad threat to humanity from changes in climate hazards.

From this study it is not possible to quantify the temporal or spatial prevalence of impacts that have been reported. Unfortunately, because our paper is based on a compilation of the literature, it is not possible for us to quantify the prevalence of specific impacts as publications are likely related to scientific novelty and interest as opposed to how frequent or important impacts may be. For instance, there may be few examples of impacts of hazards on culture or even loss of islands to sea-level rise because as they may have not gained broad scientific interest or may not be readily quantified, but these impacts are real
and important nevertheless; yet a single report of a case example can reveal that such impacts do occur. Given this limitation, the section on observed impacts on human systems should be taken as descriptive of feasible pathways through which hazards can impact humanity without indicating the prevalence or importance of such impacts.

We caution that our literature search was restricted to impacts on people from climate hazards, and no other aspects related to climate change. Although our survey of the literature yielded some case examples of adaptations, positive and differential impacts (Supplementary Note 2), these are unlikely to reflect the full scope of the adaptations, opportunities and trade-offs associated with climate hazards. The large array of cases that we uncovered with a systematic literature search on only climatic impacts, suggests that a better understanding of those issues (adaptations, positive and differential impacts) will require their own comprehensive analyses. Our assessment of impacts was also restricted to those that occur only on people; we excluded impacts on ecosystems, unless they had ramifications for human life (e.g., food, and water supply, tourism). The broad impacts of climate change on ecosystems have been the topic of similar analysis. We surmise that some aspects of human life lend themselves to more detailed breakdown and analysis, which causes a variable number of subcategories that can be impacted; the more diverse the aspect the more subcategories were apparent. For instance, there were 27 subcategories of human health affected by climate hazards but only four for freshwater (Fig. 1).

Another potential issue in our literature review relates to the use of Google Scholar as our sole search engine for the identification of publications. We consider that there may be at least two issues that could emerge from using only this database. One limitation relates to the standards of papers assessed. Curated databases may provide a cleaner set of papers than Google Scholar. The effects of this bias are likely minor in our case because we reviewed the first 200 papers under each pairwise combination of keywords (suggesting that this was a deep search into the literature of specific topics) and because after a given paper was selected, it was read in full and records of reported impacts were curated and validated by our team of authors. The other limitation is that Google Scholar may fail to access records of publications to which other databases may have access. A motivation for using Google Scholar is that it searches over a broad spectrum of the literature as opposed to specialized databases. However, by lacking the potential specificity of specialized databases, Google Scholar may have missed some papers. This effect has been shown to be small in other cases and even if it occurred in our study it would have resulted in us missing some reported impacts, suggesting that our large compilation of observed impacts and conclusions about human vulnerability errs on the side of conservativeness.
The impacts reported here have varying degrees of uncertainty related to their detection and attribution to climate hazards. In this paper, impacts were classified into a given attribute of human life and climate hazard exclusively using the attribution provided in the paper that reported the impact. This was done to avoid any bias on our end, but it should be acknowledged that the issue of attribution can be contentious for several impacts. Some observed impacts have been attributed to a change in climate (e.g., displacement of coastal populations due to sea level rise), some are intuitive (e.g., warming increasing habitat suitability that facilitate the expansion of pathogens) but others may require further analyses to discriminate the contribution of climate to the observed impacts (e.g., drought may lead to a short supply of food, water and livelihoods, but the extent to which this translates to famines and migrations could be aggravated or prevented by, for instance, socio-economic factors). In cases when we found alternative views on attribution, such controversies were cited in the paper (e.g., the role of climate hazards as sole or even main driver of social conflict).

A related uncertainty is the extent to which climate hazards implicated in observed impacts were due to anthropogenic forcing. Since natural variability is large, pinning down human influences on climatic changes requires considerable caution. However, human contribution to recent climatic changes is very likely, given the interconnected physics of the Earth’s climate system, which is critically affected by anthropogenic radiative forcing. There is large certainty that anthropogenic greenhouse gases are affecting the balance between incoming solar radiation and outgoing infrared radiation, which is increasing the Earth’s energy budget ultimately leading to warming, which in turn is enhancing evaporation and air’s capacity to hold moisture. Then, given interconnected physics, warming can affect several other aspects of the Earth’s climate system: “all weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be.” In fact, more than half of the global mean temperature increase since 1951 has been most likely caused by human influence on climate, with over 94% of observed changes in physical systems being concordant with anthropogenic climate change. In turn, several studies have provided support for the human contribution on modern heatwaves, precipitation changes, floods, storms, drought, sea level rise, wildfires and ocean chemistry. As mentioned earlier, however, our compilation of observed impacts was intended to highlight the vulnerability of human systems to climate hazards regardless of their attribution. Our rationale is that the observed impacts of climate hazards, combined with the projected increases of such hazards, reveals a heightened threat to humanity given high human vulnerability to climate hazards that are concurrently projected to intensify.

There are several ways to combine changes in climate hazards into a cumulative index. In our cumulative index of climate hazards, all climate hazards were given equal weight. An alternative
An alternative approach to assessing the broad threat of multiple climate hazards on humanity could be to combine projections of impacts from climate hazards on numerous aspects of humanity at a given site\textsuperscript{36}. However, we choose to focus on cumulative exposure to projected climate hazards as opposed to their cumulative impacts because of the challenges of dealing with uncertainty about social and technological adaptation. Each aspect of the human system will require different types of adaptation, and these will likely vary across space and time\textsuperscript{23}. Combining all of these uncertainties into a cumulative index of projected impacts will render such an index difficult to interpret. Our approach was to quantify the geographical co-occurrence of projected hazards, which can inform where adaptation might be required.

**Methods References**

1. Mahmood, R. et al. Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.* **34**, 929-953 (2014).
2. Mora, C. et al. Suitable days for plant growth disappear under projected climate change: Potential human and biotic vulnerability. *PLoS Biol* **13**, e1002167 (2015).
3. Mora, C. et al. Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. *PLoS Biol.* **11**, e1001682 (2013).
4. Hirabayashi, Y. et al. Global flood risk under climate change. *Nat. Clim. Change* **3**, 816-821 (2013).
5. Knorr, W., Arneth, A. & Jiang, L. Demographic controls of future global fire risk. *Nat. Clim. Change* (2016).
6. Kopp, R. E. et al. Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites. *Earth's future* **2**, 383-406 (2014).
Emanuel, K. A. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 12219-12224 (2013).

Hanasaki, N. *et al.* A global water scarcity assessment under Shared Socio-economic Pathways. *Hydrol. Earth Syst. Sci.* **17**, 2393 (2013).

Sheffield, J. & Wood, E. F. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim. Dynam.* **31**, 79-105 (2008).

Mora, C. *et al.* Global risk of deadly heat. *Nature Climate Change* (2017).

Hurtt, G. C. *et al.* Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Chang.* **109**, 117 (2011).

Diffenbaugh, N. S. & Field, C. B. Changes in ecologically critical terrestrial climate conditions. *Science* **341**, 486-492 (2013).

Sanderson, E. W. *et al.* The human footprint and the last of the wild. *BioScience* **52**, 891-904 (2002).

Halpern, B. S. *et al.* A global map of human impact on marine ecosystems. *Science* **319**, 948-952 (2008).

Jones, B. & O’Neill, B. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ. Res. Lett.* **11**, 084003 (2016).

Scheffers, B. R. *et al.* The broad footprint of climate change from genes to biomes to people. *Science* **354**, aaf7671 (2016).

Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37-42 (2003).

Haddaway, N. R., Collins, A. M., Coughlin, D. & Kirk, S. The role of Google Scholar in evidence reviews and its applicability to grey literature searching. *Plos ONE* **10**, e0138237 (2015).

Gehanno, J. F., Rollin, L. & Darmoni, S. Is the coverage of Google Scholar enough to be used alone for systematic reviews? *BMC Med Inform Decis Mak.* **13**, 10.1186/1472-6947-1113-1187 (2013).

Coumou, D. & Rahmstorf, S. A decade of weather extremes. *Nat. Clim. Change* **2**, 491-496 (2012).

Stott, P. A. *et al.* Attribution of extreme weather and climate-related events. *Wiley Interdiscip. Rev. Clim. Change* **7**, 23-41 (2016).

Trenberth, K. E. Framing the way to relate climate extremes to climate change. *Clim. Chang.* **115**, 283-290 (2012).

IPCC. *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Fifth Assessment Report* (IPCC, 2014).

Huber, M. & Knutti, R. Anthropogenic and natural warming inferred from changes in Earth’s energy balance. *Nat. Geosci.* **5**, 31-36 (2012).

Rosenzweig, C. *et al.* Attributing physical and biological impacts to anthropogenic climate change. *Nature* **453**, 353 (2008).

Stott, P. A., Stone, D. A. & Allen, M. R. Human contribution to the European heatwave of 2003. *Nature* **432**, 610-614 (2004).

Fischer, E. M. & Knutti, R. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Clim. Change* **5**, 560-564 (2015).

Pall, P. *et al.* Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470**, 382-385 (2011).

Min, S.-K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. Human contribution to more-intense precipitation extremes. *Nature* **470**, 378-381 (2011).
Mann, M. E. & Emanuel, K. A. Atlantic hurricane trends linked to climate change. *EOS T. Am. Geophys. Un.* **87**, 233-241 (2006).

Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R. & Kushnir, Y. Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 3241-3246 (2015).

Marcos, M. & Amores, A. Quantifying anthropogenic and natural contributions to thermosteric sea level rise. *Geophys. Res. Lett.* **41**, 2502-2507 (2014).

Gillett, N., Weaver, A., Zwiers, F. & Flannigan, M. Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.* **31** (2004).

Gleckler, P. J. *et al.* Human-induced global ocean warming on multidecadal timescales. *Nat. Clim. Change*** **2**, 524-529 (2012).

Sabine, C. L. *et al.* The Oceanic Sink for Anthropogenic CO$_2$. *Science*** **305**, 367-371 (2004).

Piontek, F. *et al.* Multisectoral climate impact hotspots in a warming world. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3233-3238 (2014).

**Data availability:** Data on cumulative climate hazards are available in an interacting web-app at [https://maps.esri.com/MoraLab/CumulativeChange/index.html](https://maps.esri.com/MoraLab/CumulativeChange/index.html). Records of impacts and related references are provided in an interactive webpage at [http://impactsofclimatechange.info](http://impactsofclimatechange.info). All other data and sources used in this study are available within the article.
Figure captions

**Fig. 1. Observed impacts on humanity from climate hazards.** This figure shows six different aspects of human systems (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 map of cumulative 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/MoraLab/CumulativeChange/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.
Figure 2
Figure 3
