REVIEW ARTICLE
https://doi.org/10.1038/s41558-018-0315-6

nature climate change

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

Camilo Mora[1*], Daniele Spirandelli[2,3], Erik C. Franklin[1,4], John Lynham[5,6], Michael B. Kantar[7], Wendy Miles[8,9], Charlotte Z. Smith[10], Kelle Freel[4], Jade Moy[11], Leo V. Louis[12], Evan W. Barba[4], Keith Bettinger[13], Abby G. Frazier[13,14], John F. Colburn IX[15], Naota Hanasaki[16], Ed Hawkins[17], Yukiko Hirabayashi[18], Wolfgang Knorr[19], Christopher M. Little[20], Kerry Emanuel[21], Justin Sheffield[22,23], Jonathan A. Patz[24] and Cynthia L. Hunter[11]

The ongoing emission of greenhouse gases (GHGs) is triggering changes in many climate hazards that can impact humanity. We found traceable evidence for 467 pathways by 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 emmisions are aggressively reduced, or three if they are not, with some tropical coastal areas facing up to six simultaneous hazards. These findings highlight the fact that GHG emissions pose a broad threat to humanity by intensifying multiple hazards to which humanity is vulnerable.

Continuous emissions of GHGs 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 GHGs 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 places that are commonly dry, in turn ripening conditions for wildfires and heatwaves when heat transfer from water evaporation ceases. There are opposite responses in places that are usually humid where constant evaporation leads to more precipitation, which is commonly followed by floods due to soil saturation. The oceans have the added effect of warming waters, which enhance evaporation and wind speeds, intensifying downpours and the strength of storms; storm surges can be aggravated by sea-level rise resulting from the larger volume occupied by warmed water molecules and melting land ice. Other interrelated changes in the ocean include acidification as CO_2 mixes with water to form carbonic acid, and reduced oxygen due to (1) reduced oxygen solubility at higher temperatures and (2) changes in ocean circulation that affect 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 GHG emissions, as demonstrated by active research on detection and attribution (discussed under Caveats in the Methods). 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 probably underestimates the impacts of climate change because: (1) one hazard may be important in one place but not another, (2) strong CO_2 reductions may curb some, but not all, hazards (see Supplementary Fig. 1), and (3) not all aspects of human systems are equally challenged by climate hazards. A narrow focus on one or a few hazards may therefore 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 GHG 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

[1]Department of Geography and Environment, University of Hawai'i at Mānoa, Honolulu, HI, USA. [2]Department of Urban and Regional Planning, University of Hawai'i at Mānoa, Honolulu, HI, USA. [3]Sea Grant College, University of Hawai'i at Mānoa, Honolulu, HI, USA. [4]Hawai'i Institute of Marine Biology, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Kāne'ohe, HI, USA. [5]Department of Economics, University of Hawai'i at Mānoa, Honolulu, HI, USA. [6]University of Hawai'i Economic Research Organization, University of Hawai'i at Mānoa, Honolulu, HI, USA. [7]Department of Tropical Plant and Soil Science, University of Hawai'i at Mānoa, Honolulu, HI, USA. [8]Pacific Islands Climate Change Cooperative, Honolulu, HI, USA. [9]Center for Conservation Research and Training, University of Hawai'i at Mānoa, Honolulu, HI, USA. [10]Department of Natural Resources and Environmental Management, University of Hawai'i at Mānoa, Honolulu, HI, USA. [11]Department of Biology, University of Hawai'i at Mānoa, Honolulu, HI, USA. [12]Department of Natural Resources, Cornell University, Ithaca, NY, USA. [13]East-West Center, Honolulu, HI, USA. [14]Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, HI, USA. [15]School of Architecture, University of Hawai'i at Mānoa, Honolulu, HI, USA. [16]Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan. [17]National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, UK. [18]Department of Civil Engineering, Shibaura Institute of Technology, Tokyo, Japan. [19]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden. [20]Oceanography Department, Atmospheric and Environmental Research, Inc., Lexington, MA, USA. [21]Lorenz Center, Massachusetts Institute of Technology, Cambridge, MA, USA. [22]School of Geography and Environmental Science, University of Southampton, Southampton, UK. [23]Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA. [24]Global Health Institute, University of Wisconsin, Madison, WI, USA. *e-mail: cmora@hawaii.edu

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 to different concurrent hazards. Integration of these two components revealed that humanity has already been impacted by climate hazards that are projected to intensify even under a best-case scenario. Furthermore, we showed that projected exposure to multiple climate hazards will be very similar between rich and poor countries, but variations in adaptive capacity will probably result in different types of impacts (for example, 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 multimodel uncertainty (see further discussion under Caveats in the Methods). We also provide definitions for certain terms as used here (that is, hazard, exposure, impact, sensitivity, vulnerability and adaptation; see 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 (warming, precipitation, floods, drought, heatwaves, fires, sea level, storms, changes in natural land cover and ocean chemistry) were listed in columns and six aspects of human systems (health, food, water, infrastructure, economy and security) were listed in rows (see Methods). This table was used as a guide for all possible combinations of keywords to search for publications reporting the 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 systems. Our criteria for the selection of impacts required that impacts be observed and supported with traceable evidence (that is, 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 (for example, death, disease within human health; see Fig. 1 and Methods). In total, we found case examples for 89 attributes of human health, food, water, infrastructure, economy and security impacted by the ten climate hazards. Of 890 possible combinations (10 climate hazards × 89 attributes of human life), we found case examples for 467 interactions or pathways by 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[4] during heatwaves (for example, from 1980 to 2014, over 780 events of excess human mortality were reported during heatwaves worldwide[5]), drowning during floods (approximately 3,000 deaths in the 1998 floods in China[6]), starvation during droughts (approximately 800,000 famine deaths attributed to the Ethiopian drought in the 1980s[7]), blunt injury during storms (roughly 140,000 deaths occurred in the 1991 Cyclone Gorky in Bangladesh[8]) and asphyxiation during fires (approximately 173 deaths occurred in the 2009 Australian Black Saturday fire[9]). The loss of natural land cover impaired coastal protection, probably 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 (such as cardiac and respiratory disorders) due to heat illness occurred during heatwaves[12], whereas 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], mould following storms[15], organic pollutants released from melting ice[16] and pollen released during extended flowering periods caused by warming[17]. By increasing the 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 disease[1] and campylobacteriosis[22]. Similarly, warming facilitated the 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 the proximity of vectors 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 the Hendra and Nipah viruses[28], drought mobilized livestock near cities, causing outbreaks of haemorrhagic 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 the water supply due to storms and floods resulted in outbreaks of cholera, malaria, leptospirosis[32] and diarrhoeal illness[21]. Changes in ocean chemistry have favoured 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 diarrhoea, cholera and dysentery[38]. By increasing the 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 United States[40], floods in the United Kingdom[41] and heatwaves in France[39]. People experienced existential distress during drought in Australia[42], increased substance abuse after storms in the USA[43] and poor mental health due to climate change in Canada (for example, the loss of sea ice has inhibited cultural practices such as hunting and fishing, leading to depression among Inuit people[44]). Furthermore, suicidal ideation occurred in victims of drought[45], heatwaves[46], storms[40] and floods[47].

Climate hazards were implicated in pre- and post-natal health problems. Children born to pregnant women exposed to floods exhibited increased bedwetting, aggression towards other children[48] and below-average birth weight, juvenile height and academic performance[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[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 both the mother and fetus[51].

Food impacts. We found ten attributes of food systems that were impacted by climate hazards, of which impacts on the 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 physiological thresholds of crop plants. Direct physical losses occurred due to storms (for example, roughly 35% of bean production was lost to Hurricane Mitch in Honduras in 1998[52]), precipitation (a 10 mm

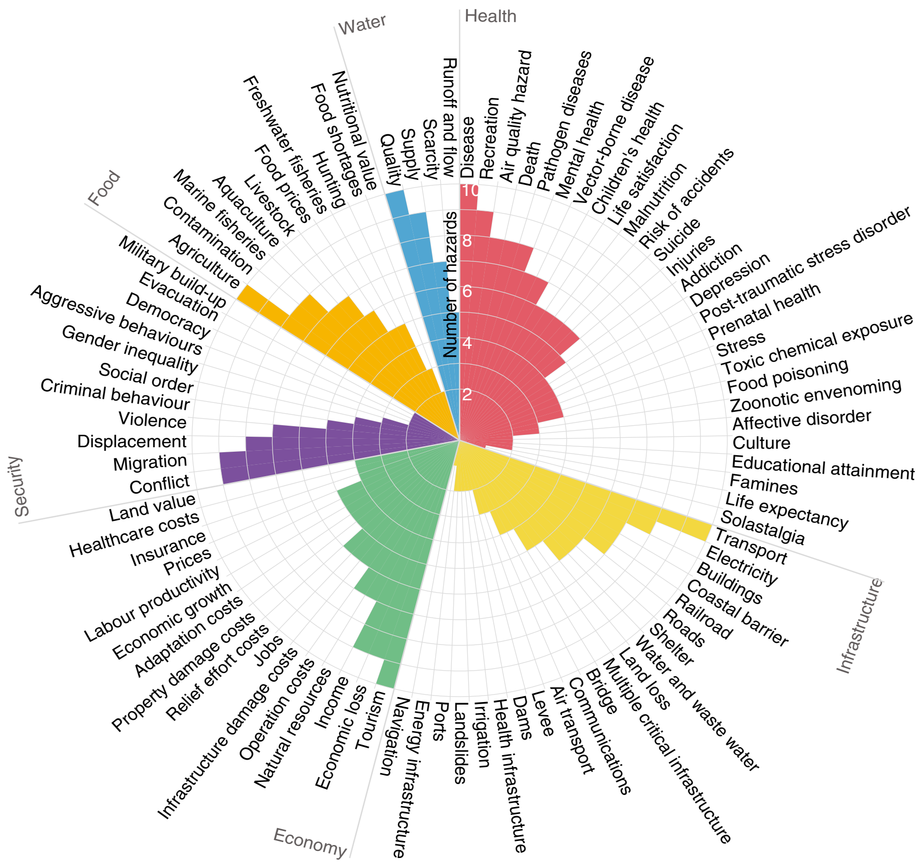

Fig. 1 | Observed impacts on humanity from climate hazards. Six different aspects of human systems are shown (health, food, water, infrastructure, economy and security), with their subcategories for which impacts were observed. The heights of the bars indicate the number of hazards implicated in the impacts. Here we analysed ten climate hazards. The complete table of climate hazards and human aspects impacted is available at http://impactsofclimatechange.info.

increase in rainfall caused a loss of 0.3 t ha^{-1} of paddy rice in the Mekong Delta[53]), floods (over 7,600 ha of agricultural land was destroyed by floods in Vietnam in 2009[54]), sea-level rise (agricultural land has been lost to saltwater intrusion in Bangladesh[1]), fires and drought (approximately 33% of grain production was lost to a mixture of fires and drought in Russia in 2010[55]). Indirect losses due to hazards exceeding crop physiological tolerances were caused by warming (for example, a 3–10% loss of wheat yield per 1 °C increase in China[56]), drought (a yield decrease of roughly 36% during the 2003 drought in Italy[57]), heatwaves (one single day above 38 °C reduced annual yields by 5% in the United States[58]), changes in ocean chemistry (e.g., drought in Australia caused by variability in ocean temperature in the Indian Ocean[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[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[61] and heatwaves[61], whereas floods[62] and permafrost thawing due to warming[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 moulds harmful to people[62].

Climate hazards have impacted animals used for food. Livestock mortality was associated with warming (for example, the livestock disease bluetongue was positively correlated with increasing temperatures in Europe[63]), drought (in 2000, three quarters of livestock died due to drought in Kenya[64]), heatwaves (>5,000 cattle deaths occurred each year there were strong heatwaves in the US Great Plains[65]), floods (livestock losses totalled >236,000 during major floods in Bangladesh in 1987 and 1988[66]) and natural land-cover change (in Sudan, for example, land-cover change reduced suitable grazing land[67]). Heatwaves were related to a reduction in grazing, reproduction and milk production in cattle and high mortalities in chickens and turkeys[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[69]. Meat quality was also impacted through contamination (higher than normal temperatures were associated with 30% of reported cases of salmonellosis in Europe[63]).

Climate hazards were found to impact fisheries through reductions in the quantity and quality of fish populations. There were reductions in fish stocks due to warming both directly (warmer temperatures exceeded the thermal-tolerance of cod[70] and high water temperatures reduced oxygen content, severely impacting salmonid reproduction[71]) and indirectly (warmer temperatures altered food webs by reducing primary productivity[70]). Direct stock mortality and changes to reproduction were caused by drought (by favouring bivalve predators that decreased shellfish populations[72]), heatwaves (a heatwave in 1953 warmed Lake Erie, triggering nutrient pollution that caused a large fish kill[73]) and floods (floods decreased the reproductive capacity of anadromous fish[74]). Climate hazards also impacted the habitats of stocks, including fires (runoff due to fires increased the heavy metal content in lakes and rivers[75]), precipitation (rains increased sediment and nutrient loading in lagoons[76]), sea level (sea-level rise changed the dynamics of coastal lagoons[76]), ocean chemistry (changes in ocean chemistry increased coral bleaching, which decreased fish habitat[77]) and natural land cover (introduced water hyacinth in Lake Victoria reduced fish quantity[78]). The quality of fish was also impacted. Warming increased mercury methylation and has favoured the growth of pathogens involved in food poisoning[79]. Floods, storms and fires were also related to increased heavy metal runoff, causing fish to accumulate mercury and increasing the risk of mercury poisoning in humans[75].

Water impacts. We found that the quantity and quality of fresh water 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[38,39,80]. Drought, for instance, led to temporary drinking water shortages for over 200,000 people in Puerto Rico in 1997–1998[39] and 33 million people in China in 2001[80]. Decreases in water supply were also attributed to land-cover change, including the spread of invasive plant species such as *Tamarix* spp., which increased evapotranspiration, costing US$65–180 million per year in reduced water supplies[81], and desertification, which led to losses in water storage in areas such as the Sahel[82]. In mountainous regions, warming resulted in lower snow accumulation and the retreat of glaciers, causing lower groundwater levels and drinking water shortages[1,39,83,84]. Temporary water shut-downs were also experienced as a result of intense storms, such as Hurricane Mitch in 1998, which left over four million residents in Honduras without water[85].

Water quality was critically impacted by climate hazards. The contamination of drinking water was caused by wildfires and drought that contributed to elevated levels of nutrients (nitrogen, phosphorus and sulfates)[86], heavy metals (lead, mercury, cadmium and chromium)[87], salts (chloride and fluorides)[87], hydrocarbons[88], pesticides[89] and even pharmaceuticals[86]. Heavy rains and flooding also increased nutrients[24], heavy metals[90] and pesticides[90] as well as turbidity[91] and fecal pathogens[92] in water supplies — especially when sewage treatment plants were overwhelmed by runoff[24]. For instance, the 2010 Indus flood in Pakistan increased waterborne and infectious diseases, such as *Cryptosporidium*[93], whereas torrential rains in upstate New York in 1999 washed wastewaters into aquifers, sickening over 1,100 adults and killing several children[24]. Sea-level rise has led to seawater contamination of drinking supplies globally, including areas in Bangladesh[94], Spain[95], New England[17] and the Pacific Islands[96].

Infrastructure impacts. We found 21 attributes of infrastructure impacted by climate hazards (Fig. 1), of which the 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[97]. Heatwaves also reduced the efficiency of power conductance and hydroelectric production from a loss of generator cooling[98,99]. Droughts reduced hydroelectric generation due to low water supplies[99], and dry soil conditions acted as an insulator causing overheating and melting of underground cables[100]. These impacts on electricity generation and conduction frequently coincided with peak demands during heatwaves at times resulting in complete shut-downs. 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[98], ~35 million in the Saudi Kingdom in 2010[101], ~500,000 in Southern Australia in 2009[102], ~200,000 in Buenos Aires in 2014[103] and ~50 million affected in the northeast United States and Canada in 2003. Extreme rainfall[104], flooding[100,104] and large storms[100,104] also caused widespread power outages, and affected electricity markets due to damaged offshore oil and gas structures[39,105].

Impacts on transportation infrastructure were common. Storms have flooded roads[106], railway lines[107,108] and wiped out bridges[109], ports[110] and levees[111]. Floods have crippled national transport networks[112], halted rail service[113], shut down freight transport[114] and stranded city residents[108,110,115]. Heatwaves caused railways[102,116], and roads to buckle[115], asphalt to melt[102], and concrete roads and bridge joints to crack due to thermal expansion[117]. Heatwaves have grounded airplanes because hot air is less dense than cold air, thus requiring additional speed that airplanes may not be able to achieve on short runways[73,118]. Fires have repeatedly disrupted land, air and sea transport (for example, across Southeast Asia[119]) whereas drought has hampered river navigation (across Europe in 2003[120], for instance). Warming, and associated permafrost thawing, has destroyed roads and other critical infrastructure in northern latitudes[35,39].

Direct and indirect impacts to buildings were significant. Floods and storms damaged or destroyed millions of homes (approximately 12.8 million homes in Bangladesh, 8.7 million in China, 1.8 million in Pakistan, 450,000 in Jakarta, 425,000 in the United States, 45,000 in France, 30,000 in Australia and 30,000 in Jamaica). Fires from extreme droughts and heat also destroyed homes (more than 5,500 homes in Australia, 3,500 in California, 2,500 in Texas,and 2,000 in Russia). Glacial lake outbursts due to retreating glaciers in Nepal[121] and landslides[122] swept away entire areas, including villages[123]. 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[124–126]. Loss of cultural heritage sites was attributed to rising seas, flooding and thawing of permafrost[110,127], whereas droughts and increased salinity due to rising sea level damaged irrigation infrastructure[128]. Rising temperatures and CO_2 concentrations led to corrosion and deterioration of concrete infrastructure[129].

Global loss of beaches and coastal infrastructure has resulted from increases in sea level, storms, ocean swells and associated flooding, erosion and slumping[1,127]. The loss of coastal land was related to storms and sea-level rise, which claimed entire islands[130]. Warming and the subsequent melting of ice forced the relocation of native villages in Alaska[39]. Natural cover lost in coral reefs, mangroves and wetlands reduced coastal protection, intensifying the effects of storms and tsunamis on infrastructure[131].

Economic impacts. We found 16 attributes of the economy impacted by climate hazards (Fig. 1), including economic losses, diminished labour 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 (for example, US$1.84 billion in direct agricultural losses in 2015 in California[132]), storms (US$130 billion in damage from Hurricane Katrina[107]), floods (€9.1 billion in losses from the 2002 Elbe flood in Germany[133]), and fires (US$4.1 billion in costs in 1997 in Indonesia[119]). The loss of natural land cover was also related to economic costs (for example, by reducing coastal protection, storm damages have increased by US$30,000 for each hectare of destroyed wetland in the United States[134]). 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 later[135]. Indirectly, climate hazards increased commodity prices. For instance, heatwaves, droughts and fires during the summer of 2010 in Russia cut local grain production by one-third, ultimately doubling wheat prices globally[1]. Storms affected access to and the price of insurance. For instance, Hurricane Andrew led to the insolvency of 12 insurance companies[136] and many firms now refuse to issue new policies for properties within a mile of the ocean on the east coast of the United States[17]. Furthermore, a lack of insurance has made it difficult to obtain mortgages for coastal properties in the Bahamas[136]. Climate hazards also affected the cost and availability of energy resources: heatwaves in 2003 and 2006 in Europe led to a 40-fold increase in the cost per megawatt hour in the European Energy Exchange[137], damages to oil rigs during Hurricane Katrina temporarily increased fuel prices[35] and drought in Brazil reduced sugar crop production, leading to record high sugar prices and a decline in ethanol production[138].

Climate hazards impacted job availability as well as work capacity. Heatwaves lowered labour productivity, as observed in Australia, where absenteeism increased during heatwaves[139], and in India and Vietnam, where heatwaves led to longer workdays to compensate for periods of rest during the hottest hours of the day[140]. Storms and floods[141] disrupted the functioning of industries, resulting in an immediate loss of jobs. Job losses were also related to drought (in areas where agriculture is a large part of the economy[142], for example), warming (in North America timber jobs were lost due to warm temperatures resulting in pine beetle infestations[91]) and ocean chemistry (in Peru direct and indirect job losses are often linked to climatic impacts on marine fisheries[143]).

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 United States due to increased temperatures[144], and in Taiwan due to storms[145]. Droughts had distinct impacts on the recreation industry (for example, river-rafting outfitters in Colorado lost 40% of their normal business — over US$50 million to the industry statewide[146]) as well as other sectors (US$2.5 billion of revenue lost by the cattle industry in Mexico[147]). 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 lower revenue to ski resort destinations, as observed in the Alps[148] and Australia[149]. Changes in ocean chemistry degraded coral reef conditions, which were associated with in a decline in recreational dives in Thailand[150] and affected annual whale migrations, causing early closure of the whale-watching season in Australia[151].

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)[85,152,153]. For example, hundreds of thousands of people were displaced after floods in China and Pakistan[93,152], and storms in Central America, the United States and Bangladesh[85,154,155], to name a few. The recurrence of climate hazards also caused temporary displacement to become permanent[39,85]; in Bangladesh recurring floods forced some rural inhabitants to move to urban squatter settlements[156]. We found several cases of planned migration of coastal communities due to permafrost melting[8] and recurring flooding and sea-shore erosion due to sea-level rise and storms (for example, indigenous communities in the United States[39], the Solomon Islands[130] and India[157]). Multiple cases of mass migration have occurred due to droughts, natural land-cover change and extreme precipitation[153,158]. Extreme heat was also the lead driver of migration in rural Pakistan due to the loss of crops and farming income[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[147,159]. Ocean chemistry was linked to shifts in the distribution of commercial fish stocks[1,16] and the uncovering of new resources under melting sea ice[84,160] generated geopolitical tensions over their use, including military build-up in the Arctic region[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[162]. For instance, changes in precipitation and drought resulted in a scarcity of suitable pastoral and crop land, triggering sectarian and intercommunity violence in the Horn of Africa[163], increased food prices associated with violence across Africa[164] and food shortages that facilitated rebel recruitment in Burundi[165]. Drought was also an influencing factor in migration to urban areas, adding to the unemployment and political instability that contributed to bloodshed in Syria[166] and Somalia[167]. Excess rainfall has also correlated with violent conflict in Africa[168]. The probability of civil conflicts was nearly double during El Niño years compared with La Niña years[169]. 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[170].

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[171], which can aggravate acts of interpersonal violence and violent crimes during heatwaves[172]. In the United States, for instance, warming by 0.5 °C aggravated rates of rapes by 0.20, robberies by 0.84, burglaries by 8.16, and larcenies by 10.65 per 100,000 people[173]. The breakdown of law and order during extreme rainfall[170] and storms[174] has been linked to interpersonal violent behaviours including battering[175] and rape[176]. Likewise, anomalously high or low rainfall was tied to a two-fold increase in the number of 'witches' murdered in Tanzania[177]. Hydrometeorological disasters have also been associated with increased instances of domestic violence[178]; for example, after the 1993 flood in the midwestern United States, a significant increase in cases of battered women was reported[179]. It is worth noting that there has been considerable discussion over the relative role of the climate hazards on human conflict[180].

Global map of cumulative climate hazards

Our overview of observed impacts reveals the high vulnerability of humanity to climate hazards (Fig. 1). As different hazards can impact numerous aspects of human systems (Fig. 1) and may require varied types and costs of adaptation, the simultaneous exposure of future societies to multiple climate hazards constitutes a considerable concern. 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 of freshwater scarcity (Fig. 2). Hazard projections were based on the recent Coupled Model Intercomparison Project Phase 5 under Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5, which represent a range of mitigation scenarios in which GHGs are considerably slowed (RCP 2.6) or continue to rise throughout the twenty-first century (RCP 8.5), with RCP 4.5 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 Supplementary Fig. 4.

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 (Supplementary Table 1). For instance, there was little concordance

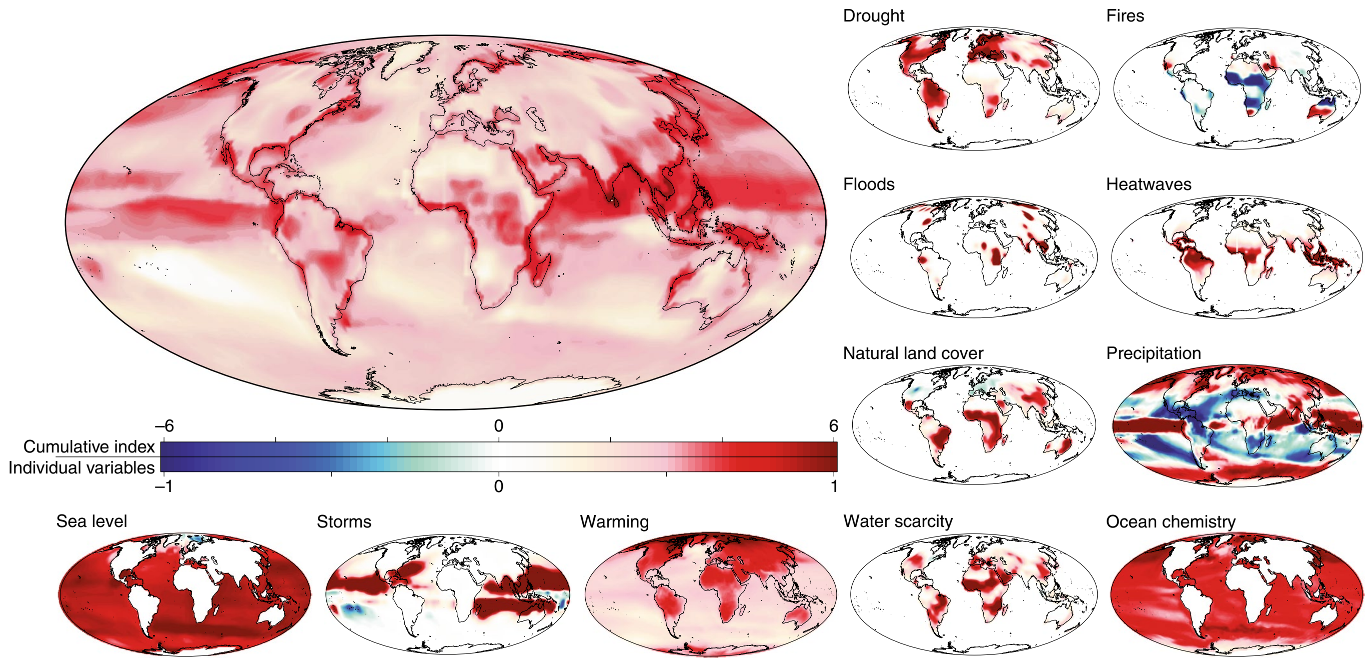

Fig. 2 | Global map of cumulative climate hazards. The main map shows the cumulative index of climate hazards, which is the summation of the rescaled change in all hazards between 1955 and 2095. Smaller maps indicate the difference for each individual hazard for the same time period. Individual hazards were rescaled to be normalized between −1 and 1. Negative values indicate a decrease in the given hazard, whereas positive values represent an increase relative to the 1950s baseline values. The largest value in the cumulative index was six (that is, 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 Supplementary Figs. 1–3. An 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.

in the spatial patterns of change in drought, floods and water scarcity compared to precipitation, despite the latter being an underlying driver of the former. This reflects the effects of topography, soil type and human uses that act 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, Supplementary Table 1). 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 America 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 cumulative patterns of change in all hazards are combined, 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 GHGs continue to rise throughout the twenty-first century (RCP 8.5, Fig. 2), or three under strong mitigation of GHGs (RCP 2.6, Supplementary Fig. 3).

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 the variation in adaptation capacity (Supplementary Note 2). The largest losses of human life during extreme climatic events 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[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 towards the study of detrimental impacts (discussed under Caveats in the Methods). This small set of positive and neutral impacts, however, cannot counterbalance 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 such as food and water, and undesired states for human welfare such as 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

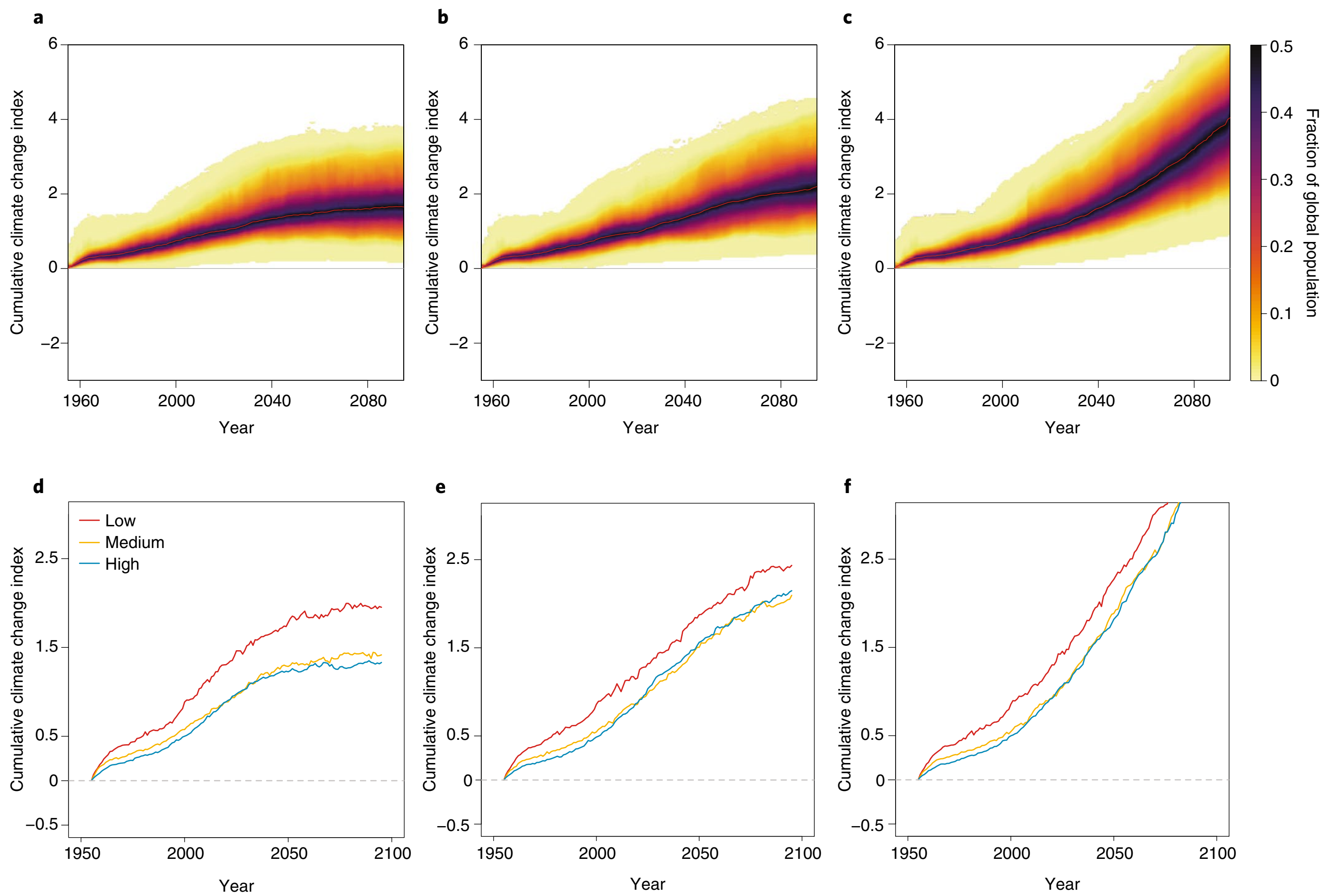

Fig. 3 | Human population exposure to simultaneous climate hazards. a–c, The fraction of the world's human population exposed to varying levels of cumulative hazards under three RCPs: RCP 2.6 (**a**), RCP 4.5 (**b**) and RCP 8.5 (**c**). **d–f**, Exposure to cumulative climatic hazards for half of the total population in countries with low, medium and high incomes under the same scenarios.

analyses that integrate diverse types of information. Contrasting temporal (Supplementary Fig. 1) and spatial (Fig. 2) patterns of climate hazards, compounded with varying vulnerabilities of human systems (Fig. 1), suggests 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 greater if GHG concentrations continue to rise throughout the twenty-first century (RCP 8.5, Fig. 3) 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 probably be needed and the considerable economic and welfare burden that will be imposed by projected climate change triggered by ongoing GHG emissions. Overall, our analysis shows that ongoing climate change will pose a heightened threat to humanity that will be greatly aggravated if substantial and timely reductions of GHG emissions are not achieved.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0315-6

Received: 21 December 2017; Accepted: 21 September 2018;
Published online: 19 November 2018

References

1. IPCC *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) (Cambridge Univ. Press, 2014).
2. Trenberth, K. E. Framing the way to relate climate extremes to climate change. *Climatic Change* **115**, 283–290 (2012).
3. Piontek, F. et al. Multisectoral climate impact hotspots in a warming world. *Proc. Natl Acad. Sci. USA* **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. Strateg. Glob. Change* **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. *Climatic Change* **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 Perspect.* **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 Perspect.* **114**, 1381–1386 (2006).
16. Larsen, J. N. et al. Polar regions. *Climatic Change* **28**, 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, 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 Perspect.* **109**, 211–221 (2001).
20. Epstein, P. R. et al. Biological and physical signs of climate change: focus on mosquito-borne diseases. *Bull. Am. Meteorol. 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. & Gjorgjev, D. in *Structure and Function of Food Engineering* (ed. Ayman, A.) 151–170 (InTech, Elsevier, Amsterdam, 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. *Microb. 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? *Phil. 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 Perspect.* **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. K. *Key Sector Analysis: Health Adaptation in Nepal* (UNDP, 2010); https://go.nature.com/2D5mx9Q
32. Gubler, D. J. et al. Climate variability and change in the United States: potential impacts on vector-and rodent-borne diseases. *Environ. Health Perspect.* **109**, 223–233 (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. IPCC *Climate Change 2007: Impacts, Adaptation, and Vulnerability* (eds Parry, M. L. et al.) (Cambridge Univ. Press, 2007).
36. Magrin, G. et al. in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L. et al.) 581–615 (IPCC, Cambridge Univ. Press, 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* (US 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, London, 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. *Climatic Change* **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 Univ. Technology, Brisbane, 2011).
46. Page, L. A., Hajat, S. & Kovats, R. S. Relationship between daily suicide counts and temperature in England and Wales. *Br. J. Psychiat.* **191**, 106–112 (2007).
47. Kunkel, K. E., Pielke, R. A. Jr & Changnon, S. A. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: a review. *Bull. Am. Meteorol. Soc.* **80**, 1077–1098 (1999).
48. Bosworth, B., Collins, S. & Virmani, A. *Sources of Growth in the Indian Economy* (National Bureau of Economic Research, Cambridge, 2007).
49. Rosales, M. F. *Impact of Early Life Shocks on Human Capital Formation: El Niño Floods in Ecuador* (IDB, 2014).
50. Jayachandran, S. Air quality and early-life mortality evidence from Indonesia's wildfires. *J. Hum. Resour.* **44**, 916–954 (2009).
51. 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).
52. Mainville, D. Y. Disasters and development in agricultural input markets: bean seed markets in Honduras after hurricane Mitch. *Disasters* **27**, 154–171 (2003).
53. Nhan, D. K., Trung, N. H. & Sanh, N. V. in *Environmental Change and Agricultural Sustainability in the Mekong Delta* Vol. 45 (eds Stewart, M. & Coclanis, P.) 437–451 (Springer, Dordrecht, 2011).
54. Chau, V. N., Holland, J., Cassells, S. & Tuohy, M. Using GIS to map impacts upon agriculture from extreme floods in Vietnam. *Appl. Geogr.* **41**, 65–74 (2013).
55. Rossati, A. Global warming and its health impact. *Int. J. Occup. Environ. Med.* **8**, 7–20 (2017).
56. 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).
57. Easterling, W. E. et al. in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L., et al.) 273–313 (IPCC, Cambridge Univ Press, 2007).
58. Schlenker, W. & Roberts, M. J. Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proc. Natl Acad. Sci. USA* **106**, 15594–15598 (2009).
59. Ummenhofer, C. C. et al. What causes southeast Australia's worst droughts? *Geophys. Res. Lett.* **36**, L04706 (2009).
60. 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).
61. Dwivedi, S., Sahrawat, K., Upadhyaya, H. & Ortiz, R. Food, nutrition and agrobiodiversity under global climate change. *Adv. Agron.* **120**, 1–128 (2013).
62. 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).
63. Patz, J. A., Campbell-Lendrum, D., Holloway, T. & Foley, J. A. Impact of regional climate change on human health. *Nature* **438**, 310–317 (2005).
64. Chantarat, S. et al. *Insuring Against Drought-Related Livestock Mortality: Piloting Index Based Livestock Insurance in Northern Kenya* (Cornell Univ., 2010).
65. Mader, T. L. Animal welfare concerns for cattle exposed to adverse environmental conditions. *J. Anim. Sci.* **92**, 5319–5324 (2014).
66. Eckard, R. Bell, M., Christie, K. & Rawnsley, R. in *Living in a Warmer World* (ed. Salinger, J.) 144–157 (CSIRO, Auckland, 2013).
67. 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).
68. St-Pierre, N., Cobanov, B. & Schnitkey, G. Economic losses from heat stress by US livestock industries. *J. Dairy Sci.* **86**, E52–E77 (2003).
69. Doney, S. C. et al. Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.* **4**, 11–37 (2012).
70. Portner, H. O. & Knust, R. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* **315**, 95–97 (2007).
71. 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).
72. 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).
73. 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).

74. Nikolic, N. et al. Bibliometric analysis of diadromous fish research from 1970s to 2010: a case study of seven species. *Scientometrics* **88**, 929–947 (2011).
75. Bladon, K. D., Emelko, M. B., Silins, U. & Stone, M. Wildfire and the future of water supply. *Environ. Sci. Technol.* **48**, 8936–8943 (2014).
76. Anthony, A. et al. Coastal lagoons and climate change: ecological and social ramifications in U.S. Atlantic and Gulf Coast ecosystems. *Ecol. Soc.* **14**, art8 (2009).
77. Carpenter, K. E. et al. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science* **321**, 560–563 (2008).
78. Pejchar, L. & Mooney, H. A. Invasive species, ecosystem services and human well-being. *Trends Ecol. Evol.* **24**, 497–504 (2009).
79. Chateau-Degat, M., Chinain, M., Cerf, N. & Gingras, S. Seawater temperature, *Gambierdiscus* spp. variability and incidence of ciguatera poisoning in French Polynesia. *Harmful Algae* **4**, 1053–1062 (2005).
80. Shen, C., Wang, W.-C., Hao, Z. & Gong, W. Exceptional drought events over eastern China during the last five centuries. *Climatic Change* **85**, 453–471 (2007).
81. Chapin, F. S. et al. Consequences of changing biodiversity. *Nature* **405**, 234–242 (2000).
82. Sahagian, D., Vorosmarty, C. J. & Sahagian, D. Anthropogenic disturbance of the terrestrial water cycle. *BioScience* **50**, 753–765 (2000).
83. Taylor, R. G. et al. Ground water and climate change. *Nat. Clim. Change* **3**, 322–329 (2012).
84. Morton, K. Climate change and security at the third pole. *Survival* **53**, 121–132 (2011).
85. Smith, P. J. Climate change, mass migration and the military response. *Orbis* **51**, 617–633 (2007).
86. 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).
87. van Vliet, M. T. H. & Zwolsman, J. J. G. Impact of summer droughts on the water quality of the Meuse river. *J. Hydrol.* **353**, 1–17 (2008).
88. Mansilha, C., Carvalho, A., Guimarães, P. & Espinha Marques, J. Water quality concerns due to forest fires: polycyclic aromatic hydrocarbons (pah) contamination of groundwater from mountain areas. *J. Tox. Environ. Health* **77**, 806–815 (2014).
89. Sprague, L. A. Drought effects on water quality in the South Platte river basin, Colorado. *J. Am. Water. Resour. Assoc.* **41**, 11–24 (2005).
90. Kovats, R. S. et al. Climate change and human health in Europe. *Br. Med. J.* **318**, 1682–1685 (1999).
91. Embrey, S., Remais, J. V. & Hess, J. Climate change and ecosystem disruption: the health impacts of the North American rocky mountain pine beetle infestation. *Am. J. Public Health* **102**, 818–827 (2012).
92. Chanda Shimi, A., Ara Parvin, G., Biswas, C. & Shaw, R. Impact and adaptation to flood. *Disaster Prev. Manag.* **19**, 298–313 (2010).
93. Mustafa, D. & Wrathall, D. Basin floods of 2010: souring of a faustian bargain? *Water Altern.* **4**, 72–85 (2011).
94. Shahid, S. Vulnerability of the power sector of Bangladesh to climate change and extreme weather events. *Reg. Environ. Change* **12**, 595–606 (2012).
95. 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).
96. 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).
97. Bollinger, L. A. & Dijkema, G. P. J. Evaluating infrastructure resilience to extreme weather — the case of the Dutch electricity transmission network. *Eur. J. Transp. Infrastruct. Res.* **16**, 214–239 (2016).
98. Sabbag, L. *Temperature Impacts on Health, Productivity, and Infrastructure in the Urban Setting, and Options for Adaptation* (Institute for Social and Environmental Transition-International, Boulder, 2013).
99. Lyster, R. & Byrne, R. *Climate Change Adaptation and Electricity Infrastructure* (Sydney Law School, Sydney, 2013).
100. Oliver, E., Martin, D., Krause, O., Bartlett, S. & Froome, C. How is climate change likely to affect Queensland electricity infrastructure into the future? In *2015 IEEE/PES Asia-Pacific Power and Energy Engineering Conference* https://doi.org/10.1109/APPEEC.2015.7380972 (IEEE/PES, 2016).
101. 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).
102. Reeves, J. et al. *Impacts and Adaptation Response of Infrastructure and Communities to Heatwaves: The Southern Australian Experience of 2009* Report No. 192160915X (Queensland Univ. of Technology, Univ. Southern Queensland and Monash Univ., 2010).
103. Procupez, V. The perfect storm: heat waves and power outages in Buenos Aires. *Publ. Cult.* **28**, 351–357 (2016).
104. Klinger, C., Landeg, O. & Murray, V. Power outages, extreme events and health: a systematic review of the literature from 2011–2012. *PLoS Curr. Disasters* **6**, https://go.nature.com/2ORjVn5 (2014).
105. Schaeffer, R., Szklo, A., Lucena, Ad & Borba, B. Energy sector vulnerability to climate change: a review. *Energy* **38**, 1–12 (2012).
106. 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).
107. Hunt, A. & Watkiss, P. Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change* **104**, 13–49 (2011).
108. Llasat, M. C. et al. High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. *Adv. Geosci.* **23**, 47–55 (2010).
109. Wardhana, K. & Hadipriono, F. C. Analysis of recent bridge failures in the United States. *J. Perform. Constr. Fac.* **17**, 144–150 (2003).
110. Revi, A. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) 535–612 (IPCC, Cambridge Univ. Press, 2014).
111. *Climate Change Impacts and Adaptation for International Transport Networks* (UN Economic Commission for Europe, 2013); http://www.unece.org/fileadmin/DAM/trans/main/wp5/publications/climate_change_2014.pdf
112. Karl, T. R., Melilo, J. M. & Peterson, T. C. (eds) *Global Climate Change Impacts in the United States* (Cambridge Univ. Press, New York, 2009).
113. Nolte, R., Kamburow, C. & Rupp, J. *Adaptation of Railway Infrastructure to Climate Change* (International Union of Railways, 2011).
114. MacArthur, J. et al. *Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska* Report No. OTREC-RR-12-01 (Transportation Research and Education Center, 2012).
115. Peterson, T. C., McGuirk, M., Houston, T. G., Horvitz, A. H. & Wehner, M. F. *Climate Variability and Change with Implications for Transportation* (Transportation Research Board, 2008).
116. 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).
117. Moorty, S. & Roeder, C. Temperature-dependent bridge movements. *J. Struct. Eng.* **118**, 1090–1105 (1992).
118. Davies, A. Why planes can't fly in extreme heat. *Business Insider* (1 July 2013); http://www.businessinsider.com/why-planes-cant-fly-in-extreme-heat-2013-7
119. Quah, E. & Varkkey, H. M. in *The Asian Community—Its Concepts and Prospects* (ed. Sei, H. H.) 323–358 (Soso Sha, Tokyo, 2013).
120. Parry, M. L. et al. in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L. et al.) 843–868 (IPCC, Cambridge Univ. Press, 2007).
121. Bhandari, G. & Gurung, G. B. Integrated approach to climate change adaptation. *J. For. Livelihood* **8**, 91–99 (2009).
122. Webb, R. H. et al. *Debris Flows and Floods in Southeastern Arizona from Extreme Precipitation in July 2006—Magnitude, Frequency, and Sediment Delivery* Report No. 2008-1274 (USGS, 2008).
123. 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).
124. 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).
125. Tierney, K. J. & Nigg, J. M. *Business Vulnerability to Disaster-Related Lifeline Disruption* (Univ. Delaware, Disaster Research Center, Newark, 1995).
126. Rehman, J. *Heat not Wet: Climate Change Effects on Human Migration in Rural Pakistan* (College of Medicine, Univ. Illinois at Chicago, 2015).
127. Scott, D., Simpson, M. C. & Sim, R. The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *J. Sustain. Tour.* **20**, 883–898 (2012).
128. 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).
129. Wang, X., Stewart, M. G. & Nguyen, M. Impact of climate change on corrosion and damage to concrete infrastructure in Australia. *Climatic Change* **110**, 941–957 (2017).
130. 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).
131. Mooney, H. et al. Biodiversity, climate change, and ecosystem services. *Curr. Opin. Environ. Sustain.* **1**, 46–54 (2009).
132. Howitt, R., Medellín-Azuara, J., MacEwan, D., Lund, J. & Sumner, D. *Economic Analysis of the 2014 Drought for California Agriculture* (Center for Watershed Sciences, University of California–Davis, 2015).
133. Mechler, R. & Weichselgartner, J. *Disaster Loss Financing in Germany—The Case of the Elbe River Floods 2002* Interim Report No. IR-03-021 (IIASA, 2003).
134. Costanza, R. et al. The value of coastal wetlands for hurricane protection. *AMBIO* **37**, 241–248 (2008).
135. 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).

136. Wilbanks, T. J. et al. in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L. et al.) 357–390 (IPCC, Cambridge Univ. Press, 2007).
137. Pechan, A. & Eisenack, K. The impact of heat waves on electricity spot markets. *Energ. Econ.* **43**, 63–71 (2014).
138. Urbanchuk, J. *Contribution of Biofuels to the Global Economy* (Global Renewable Fuels Association, 2012).
139. 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).
140. Berry, H. L., Bowen, K. & Kjellstrom, T. Climate change and mental health: a causal pathways framework. *Int. J. Public Health* **55**, 123–132 (2010).
141. Dewan, T. H. Societal impacts and vulnerability to floods in Bangladesh and Nepal. *Weather Clim. Extremes* **7**, 36–42 (2015).
142. 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).
143. 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).
144. Buckley, L. B. & Foushee, M. S. Footprints of climate change in US national park visitation. *Int. J. Biometeorol.* **56**, 1173–1177 (2012).
145. 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. *Tour. Econ.* **20**, 143–156 (2014).
146. Scott, D. & Lemieux, C. Weather and climate information for tourism. *Proced. Environ. Sci.* **1**, 146–183 (2010).
147. Liverman, D. M. Vulnerability and adaptation to drought in Mexico. *Nat. Resour. J.* **39**, 99–115 (1999).
148. Scott, D., Mcboyle, A. G., Ae, D. S. & Mcboyle, G. Climate change adaptation in the ski industry. *Mitig. Adapt. Strateg. Glob. Change* **12**, 1411–1431 (2007).
149. 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).
150. Wilkinson, C. R. Global change and coral reefs: impacts on reefs, economies and human cultures. *Glob. Change Biol.* **2**, 547–558 (1996).
151. 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).
152. 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).
153. Campbell, B. K. M. et al. *The Age of Consequences: The Foreign Policy and National Security Implications of Global Climate Change* (Center for Strategic and International Studies and Center for a New American Security, 2007).
154. Christoplos, I. et al. Learning from recovery after Hurricane Mitch. *Disasters* **34**, 202–219 (2010).
155. Brennan, T. *The Impact of Increasing Severe Weather Events on Shelter* (US Environmental Protection Agency, 2010).
156. Raleigh, C., Jordan, L. & Salehyan, I. Assessing the impact of climate change on migration and conflict. *World* **24**, 1–57 (2008).
157. Hazra, S., Ghosh, T., Dasgupta, R. & Sen, G. Sea level and associated changes in the Sundarbans. *Sci. Cult.* **68**, 309–321 (2002).
158. McLeman, R. & Smit, B. Migration as an adaptation to climate change. *Climatic Change* **76**, 31–53 (2006).
159. AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T. & Lund, J. Recognize anthropogenic drought. *Nature* **524**, 409–411 (2015).
160. Gupta, A. Geopolitical implications of Arctic meltdown. *Strateg. Anal.* **33**, 174–177 (2009).
161. Johnson, L. The fearful symmetry of Arctic climate change: accumulation by degradation. *Environ. Plann. D* **28**, 828–847 (2010).
162. Hsiang, S. M. & Burke, M. Climate, conflict, and social stability: what does the evidence say? *Climatic Change* **123**, 39–55 (2014).
163. Ide, T. & Scheffran, J. On climate, conflict and cumulation: suggestions for integrative cumulation of knowledge in the research on climate change and violent conflict. *Glob. Change Peace Secur.* **26**, 263–279 (2014).
164. 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. Change* **32**, 187–199 (2015).
165. Von Uexkull, N. Sustained drought, vulnerability and civil conflict in Sub-Saharan Africa. *Polit. Geogr.* **43**, 16–26 (2014).
166. Gleick, P. H. Water, drought, climate change, and conflict in Syria. *Weather Clim. Soc.* **6**, 331–340 (2014).
167. Maystadt, J., Ecker, O. & Mabiso, A. *Extreme Weather and Civil War in Somalia: Does Drought Fuel Conflict Through Livestock Price Shocks?* (International Food Policy Research Institute, 2013).
168. Hendrix, C. S. & Salehyan, I. Climate change, rainfall, and social conflict in Africa. *J. Peace Res.* **49**, 35–50 (2012).
169. Hsiang, S. M., Meng, K. C. & Cane, M. A. Civil conflicts are associated with the global climate. *Nature* **476**, 438–441 (2011).
170. Hsiang, S. M., Burke, M. & Miguel, E. Quantifying the influence of climate on human conflict. *Science* **341**, 1235367 (2013).
171. 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).
172. Anderson, C. A. & Delisi, M. in *The Psychology of Social Conflict and Aggression* (eds Forgas, J. et al.) 249–265 (Psychology, New York, 2011).
173. Rotton, J. & Cohn, E. G. Global warming and U. S. crime rates: an application of routine activity theory. *Environ. Behav.* **35**, 802–825 (2003).
174. 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).
175. Jenkins, P. & Phillips, B. Battered women, catastrophe, and the context of safety after Hurricane Katrina. *NWSA J.* **20**, 49–68 (2008).
176. Thornton, W. E. & Voigt, L. Disaster rape: vulnerability of women to sexual assaults during Hurricane Katrina. *J. Public Manage. Soc. Policy* **13**, 23–49 (2007).
177. Verwimp, P. *Food Security, Violent Conflict and Human Development: Causes and Consequences* (United Nations Development Program, 2012).
178. Lane, K. et al. Health effects of coastal storms and flooding in urban areas: a review and vulnerability assessment. *J. Environ. Public Health* **2013**, 913064 (2013).
179. 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).
180. Don't jump to conclusions about climate change and civil conflict. *Nature* **554**, 275–276 (2018).
181. Mora, C. et al. The projected timing of climate departure from recent variability. *Nature* **502**, 183–187 (2013).
182. Mora, C. et al. Suitable days for plant growth disappear under projected climate change: potential human and biotic vulnerability. *PLoS Biol.* **13**, e1002167 (2015).
183. 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 made 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 nos NA14OAR4170071 and NA09OAR4170060 from NOAA Office of Sea Grant, Department of Commerce. D.S. was supported by the University of Hawaii Sea Grant College Program under UNIHI-SEAGRANT-JC-13-37. E.C.F. was supported by NOAA Fisheries award no. 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 no. G16PG00037. E.H. was supported by the National Centre for Atmospheric Science and by the NERC REAL project (grant no. NE/N018591/1). Y.H. and N.H. were supported by ERTDF S-14, ERCA, Japan. W.K. was supported by BECC. C.M.L. acknowledges support from NASA award no. NNH16CT01C. We thank the ESRI's Applications Prototype Lab for their help with creating 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. and C.L.H. collected data on observed impacts. C.M., N.H., E.H., Y.H., W.K., C.M.L., K.E. and J.S. provided projections of climate hazards. C.M. conducted the analysis of the cumulative impacts. All authors contributed to the writing and revision of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-018-0315-6.

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

Correspondence 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 ten hazards of the Earth's climate system (warming, heatwaves, precipitation, floods, drought, fires, sea level, storms, natural cover change, ocean climate change) on six aspects of human life (health, food, water, infrastructure, economy and security). Our assessment of the Earth's climate system was based not only on mean state changes (such as warming, precipitation, sea level, ocean chemistry) and extreme weather events (heatwaves, flood, drought, storms), but also on disturbances (such as fire). We included changes in natural land cover as one of the hazards because ecosystems are an intrinsic component of Earth's climate system as they are both sources and sinks of carbon, affecting other hazards (for example, warming and precipitation via albedo and evapotranspiration) and directly affecting various aspects of human life[182,184]. We also assessed impacts from changes in ocean chemistry given the key role of the oceans in the climate system and human dependency on ocean goods and services[183], especially for coastal and maritime societies. Our assessment of these impacts on human systems was based on aspects that we considered essential for human well-being. These six aspects, however, represent general categories within which many other facets of human life were assessed. For instance, we found numerous examples of impacts on cultural practices such as the breakdown of traditional hunting and fishing systems among indigenous communities (that is, a food impact), causing depression or even suicide (a health impact). The diversity of the aspects of human life assessed is reflected by the long list of sub-categories reported (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 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 five IPCC assessment reports and the most recent National Climate Assessment report for the United States, 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 (that is, 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, an example of a valid entry is: "During the 2003 European heatwave over 70,000 excess human deaths were observed". This latter entry provides traceable evidence that an explicit climate hazard (a heatwave) impacted an explicit aspect of human life (mortality) in a given place (Europe) and time (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 (that is, added rows to the online table) within each primary aspect of human life to reflect the variety of documented impacts in the literature (for example, under the primary heading 'food', entries were separated into agriculture, livestock, marine fisheries and so on; see Fig. 1). On identifying an impact in a given paper, the user placed 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 that paper, thus avoiding classification biases by the user who entered the data. This initial classification specificity was also intended to prevent 'grouping' of impacts into broad sub-categories and potentially losing the visibility of rare impacts. However, by using a central online database, any created subcategory was automatically available to others entering data thus reducing the duplication of subcategories. When the data entry stage ended, the authors met to integrate similar existing sub-categories as much as possible, while care was taken to avoid generating broad terms that could risk rare impacts being overlooked. For example, we found that climate hazards have numerous types of impacts on the state of mind of people ranging from depression, to addiction, affective disorder, PTSD and even suicide. These subcategories were maintained for better identification of the broad array of psychological consequences from climate hazards. We also performed secondary searches combining key words of climate hazard (column name) and specific (that is, subcategory) attributes of human life (row name) for empty cells in our table to ensure that these 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 (any entry can therefore be read, and if interested the user can review the associated paper). For further quality evaluation, the online database includes a double review process for 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 can 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.

(4) 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 of human adaptation to climate change probably 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 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 RCP 2.6, RCP 4.5 and RCP 8.5, which constitute alternative scenarios between strong mitigation or the continuous rise of GHGs throughout the twenty-first century, respectively. We acquired climate projections on floods[185], fires[186], sea level[187], storms[188], freshwater scarcity[189], drought[190], heatwaves[5] and ocean chemistry[183] 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.[183], and integrates projections of seawater temperature, pH and oxygen. Drought projections were repeated following the same approach as in Sheffield et al.[190] but using data from CMIP5. We used changes in primary and secondary forest as a surrogate for changes in natural land cover using data from Hurtt et al.[191]; 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[192]. Projected data on sea level and ocean chemistry were extrapolated to the nearest coastal pixels assuming that coastal communities will probably be exposed to those climatic variables. Variables were standardized to a common 1.5° global grid using bilinear interpolation and calculated for each year, averaging data over an 11-year window centred on the given year; this was done as a low pass filter to allow the variables to better reflect the climate signal without undue influence from interannual variability. It should be noted that the outputs of the CMIP5 Earth system models are global in scale and have coarse resolutions that allow for identification of 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 for the climate variables analysed 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[193] and sea[194]. 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. As 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 (that is, between 1955 and 2095 under RCP 8.5) across the global grid and selected the grid value at the 95th percentile to be used as a reference for the most extreme change in the hazard. All maps of global change were rescaled from 0 to 1; zero meaning no change and 1 meaning the 95th 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 in that hazard will occur in that pixel. The matching values of each hazard to the standardized scale are shown in Supplementary Fig. 2. The rescaled scores in all hazards were summed at a given pixel to assess the cumulative climatic change projected to occur in the pixel (Fig. 2, Supplementary Figs. 2 and 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.[195], who developed global population scenarios consistent with the shared socioeconomic pathways (SSPs) from 2006 to 2100. We paired RCP 2.6 with SSP1, RCP 4.5 with SSP3 and RCP 8.5 with SSP5. The vulnerability of the human population 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 World Development Indicators Database. We grouped low-, medium- and high-income countries depending on whether annual per capita GDP was smaller than US$4,000, between US$4,000 and US$12,000 and larger than US$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 (Supplementary Fig. 4). As the effects of multimodel uncertainty were small (Supplementary Fig. 4), 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 (Supplementary Table 1).

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 towards reporting negative impacts. We consider that this bias could be real, as 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 probably 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 Review, 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 study is based on a compilation of the literature, it is not possible for us to quantify the prevalence of specific impacts as publications are probably 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 not have garnered 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 affect only people; we excluded impacts on ecosystems unless they had ramifications for human life (such as food and water supply, tourism). The broad impacts of climate change on ecosystems have been the topic of similar analysis[196,197]. 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 4 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 tool. 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 probably 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[198]. One motivation for using Google Scholar is that it searches over a broad spectrum of the literature as opposed to specialized databases[199]. 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[199] and even if it did occur 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. Here, 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 (such as the displacement of coastal populations due to sea-level rise), some are intuitive (for example, warming increasing habitat suitability that facilitates the expansion of pathogens) but others may require further analyses to discriminate the contribution of climate to the observed impacts (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 for which we found alternative views on attribution, such controversies were cited in the paper (for example, the role of climate hazards as the ole 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. As natural variability is large, pinning down human influences on climatic changes requires considerable caution[200,201]. However, the 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[2]. There is large certainty that anthropogenic GHGs are affecting the balance between incoming solar radiation and outgoing infrared radiation, which is increasing the Earth's energy budget ultimately leading to warming[202], which in turn is enhancing evaporation and the capacity of the air to hold moisture[2]. Given interconnected physics, this warming can then 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"[2]. In fact, more than half of the global mean temperature increase since 1951 is most likely to have been caused by human influence on the climate[203], with over 94% of observed changes in physical systems being concordant with anthropogenic climate change[204]. In turn, several studies have provided support for the human contribution to modern heatwaves[200,205,206], precipitation changes[200,206–208], floods[207], storms[209], drought[210], sea-level rise[211], wildfires[212] and ocean chemistry[213,214]. 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 approach would be to weight individual hazards depending on the severity of the impacts on people. However, as noted in this study, all climate hazards have shown considerable impacts on humanity that vary across space and time[202], making a ranking of these hazards very speculative. Likewise, climate hazards could be grouped by their physical interconnections (ocean versus terrestrial hazards, hazards related to their connection to water or temperature and so on). However, small correlations in the projected spatial patterns of climate hazards (Supplementary Table 1) support the treatment of all climate hazards independently. A related limitation is the issue of interactions among hazards, which may result in different magnitudes of impacts. For instance, in the presence of deforestation, the impacts of hurricanes may be more damaging to coastal areas. In contrast, drought may reduce vector-borne disease outbreaks that are likely to result from mosquito range expansion brought about by warming. It would be a challenge to document all of the potential and observed interactions, but it certainly highlights the importance of additional studies to investigate the myriad of hazards and responses from ongoing climate change.

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[3]. However, we chose 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 probably vary across space and time[202]. 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.

Data availability

Data on cumulative climate hazards are available in an interactive web app at https://maps.esri.com/MoraLab/CumulativeChange/index.html. Records of impacts and related references are provided at http://impactsofclimatechange.info. All other data and sources used in this study are available within the text.

References

184. Mahmood, R. et al. Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.* **34**, 929–953 (2014).
185. Hirabayashi, Y. et al. Global flood risk under climate change. *Nat. Clim. Change* **3**, 816–821 (2013).
186. Knorr, W., Arneth, A. & Jiang, L. Demographic controls of future global fire risk. *Nat. Clim. Change* **6**, 781–785 (2016).
187. Kopp, R. E. et al. Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites. *Earth Future* **2**, 383–406 (2014).
188. Emanuel, K. A. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc. Natl Acad. Sci. USA* **110**, 12219–12224 (2013).
189. Hanasaki, N. et al. A global water scarcity assessment under Shared Socio-economic Pathways. *Hydrol. Earth Syst. Sci.* **17**, 2393 (2013).
190. 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).
191. 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. *Climatic Change* **109**, 117–161 (2011).
192. Diffenbaugh, N. S. & Field, C. B. Changes in ecologically critical terrestrial climate conditions. *Science* **341**, 486–492 (2013).
193. Sanderson, E. W. et al. The human footprint and the last of the wild. *BioScience* **52**, 891–904 (2002).
194. Halpern, B. S. et al. A global map of human impact on marine ecosystems. *Science* **319**, 948–952 (2008).
195. Jones, B. & O'Neill, B. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ. Res. Lett.* **11**, 084003 (2016).
196. Scheffers, B. R. et al. The broad footprint of climate change from genes to biomes to people. *Science* **354**, aaf7671 (2016).
197. Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37–42 (2003).
198. 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).
199. 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**, 7 (2013).
200. Coumou, D. & Rahmstorf, S. A decade of weather extremes. *Nat. Clim. Change* **2**, 491–496 (2012).
201. Stott, P. A. et al. Attribution of extreme weather and climate-related events. *WIREs Clim. Change* **7**, 23–41 (2016).
202. IPCC *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) (Cambridge Univ. Press, 2014).
203. Huber, M. & Knutti, R. Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nat. Geosci.* **5**, 31–36 (2012).
204. Rosenzweig, C. et al. Attributing physical and biological impacts to anthropogenic climate change. *Nature* **453**, 353 (2008).
205. Stott, P. A., Stone, D. A. & Allen, M. R. Human contribution to the European heatwave of 2003. *Nature* **432**, 610–614 (2004).
206. Fischer, E. M. & Knutti, R. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Clim. Change* **5**, 560–564 (2015).
207. Pall, P. et al. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470**, 382–385 (2011).
208. Min, S.-K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. Human contribution to more-intense precipitation extremes. *Nature* **470**, 378–381 (2011).
209. Mann, M. E. & Emanuel, K. A. Atlantic hurricane trends linked to climate change. *Eos* **87**, 233–241 (2006).
210. 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. USA* **112**, 3241–3246 (2015).
211. Marcos, M. & Amores, A. Quantifying anthropogenic and natural contributions to thermosteric sea level rise. *Geophys. Res. Lett.* **41**, 2502–2507 (2014).
212. Gillett, N., Weaver, A., Zwiers, F. & Flannigan, M. Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.* **31**, L18211 (2004).
213. Gleckler, P. J. et al. Human-induced global ocean warming on multidecadal timescales. *Nat. Clim. Change* **2**, 524–529 (2012).
214. Sabine, C. L. et al. The oceanic sink for anthropogenic CO_2. *Science* **305**, 367–371 (2004).