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Observations of climate change among subsistence-oriented communities around the world

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The study of climate change has been based strongly on data collected from instruments, but how local people perceive such changes remains poorly quantified. We conducted a meta-analysis of climatic changes observed by subsistence-oriented communities. Our review of 10,660 observations from 2,230 localities in 137 countries shows that increases in temperature and changes in seasonality and rainfall patterns are widespread (≈70% of localities across 122 countries). Observations of increased temperature show patterns consistent with simulated trends in surface air temperature taken from the ensemble average of CMIP5 models, for the period 1955–2005. Secondary impacts of climatic changes on both wild and domesticated plants and animals are extensive and threaten the food security of subsistence-oriented communities. Collectively, our results suggest that climate change is having profound disruptive effects at local levels and that local observations can make an important contribution to understanding the pervasiveness of climate change on ecosystems and societies.

The climate is changing on a global scale, with profound effects on local marine and terrestrial ecosystems across continents[1,2]. Although the spatial resolution of global climate models is increasing, there remains considerable uncertainty about the local and regional environmental consequences of the changing climate. This is especially true for regions with complex topography, or in relation to the secondary effects of climate on species distributions and interactions[3,4]. Moreover, although most regions of the world will be affected by these global processes, some areas and types of ecosystems — such as mature forests and coral reefs — will experience the effects of climate change more dramatically[5–7]. Assembling observations of these changes by members of subsistence-oriented communities can provide an effective way of documenting the multiple fine-scale environmental responses to climate change[8] and can contribute to designing effective strategies to deal with these changes at a local level[9]. Such local observations provide first-hand and detailed descriptions of the complex interactions among the physical and biological components of the environment under climate change stresses, often in places where few or no instrumental data are available[10].

Subsistence-oriented communities include indigenous and non-indigenous people who depend on natural resources for their livelihood and cultural identity[11]. Their cultural knowledge of ecological systems can reflect great time depth[12,13]. This is true whether or not they attribute causality of environmental changes to climate change. Such knowledge, generally referred to as traditional ecological knowledge (TEK), builds on long-term intergenerational sharing of observations, experiences and learning about environmental processes[12,14]. As documented in many areas spanning from the Arctic to the tropics, TEK can deepen our understanding of climate change by providing insights into its effects on ecosystems and people[8,14].

For this Review, we performed a meta-analysis of the observations of climatic changes by subsistence-oriented communities around the world. We analysed literature that explores the multi-dimensional relationships (cultural, psychological, economical, ecological and so forth) between subsistence-oriented communities and the climate, allowing us to extrapolate more specific information about observations of weather and the environment. Our objective was to synthesize these observations and qualitatively compare their spatial distribution to the results of global studies and historical climate model simulations documenting climate change. We drew on literature from 137 countries, highlighting the geographical gaps in research and global trends, as well as commonalities and differences in observations of climatic changes. Although the sources used in this Review date between 1994 and 2013, the climate observations documented within them have greater time depth and thus reflect climate-related changes emerging over the past few decades.

Our data set considerably expands on several general reviews that collate observations of climatic changes by indigenous and subsistence-oriented communities[8,14,15], providing the most comprehensive meta-analysis of these observations so far. Researchers have verified much of the data used in this Review, demonstrating that the observations from individual case studies are consistent with climate data[16,17]. Furthermore, because our conclusions represent multiple observations of diverse phenomena from locations distributed widely across the globe, they have significance beyond the specifics of individual studies with respect to data collection methods, season of data collection[18,19], and gender or culture of the observers[20]. Finally, we recognize the importance of culture- and person-specific differences and values about climate change[20], especially when dealing with specific case studies. However, because our observations span a wide range of peoples, cultures and geographies, we are able to identify broad spatial similarities in observations that are more likely to represent widespread changes in the environment.

We compare the spatial distribution of these human observations with historical model simulations of climate change. Specifically, we conducted a qualitative comparison of our collated observations of changes in temperature and rainfall with simulated trends in annual precipitation and average annual surface temperature between 1955 and 2005. We used ensemble averages estimated from model

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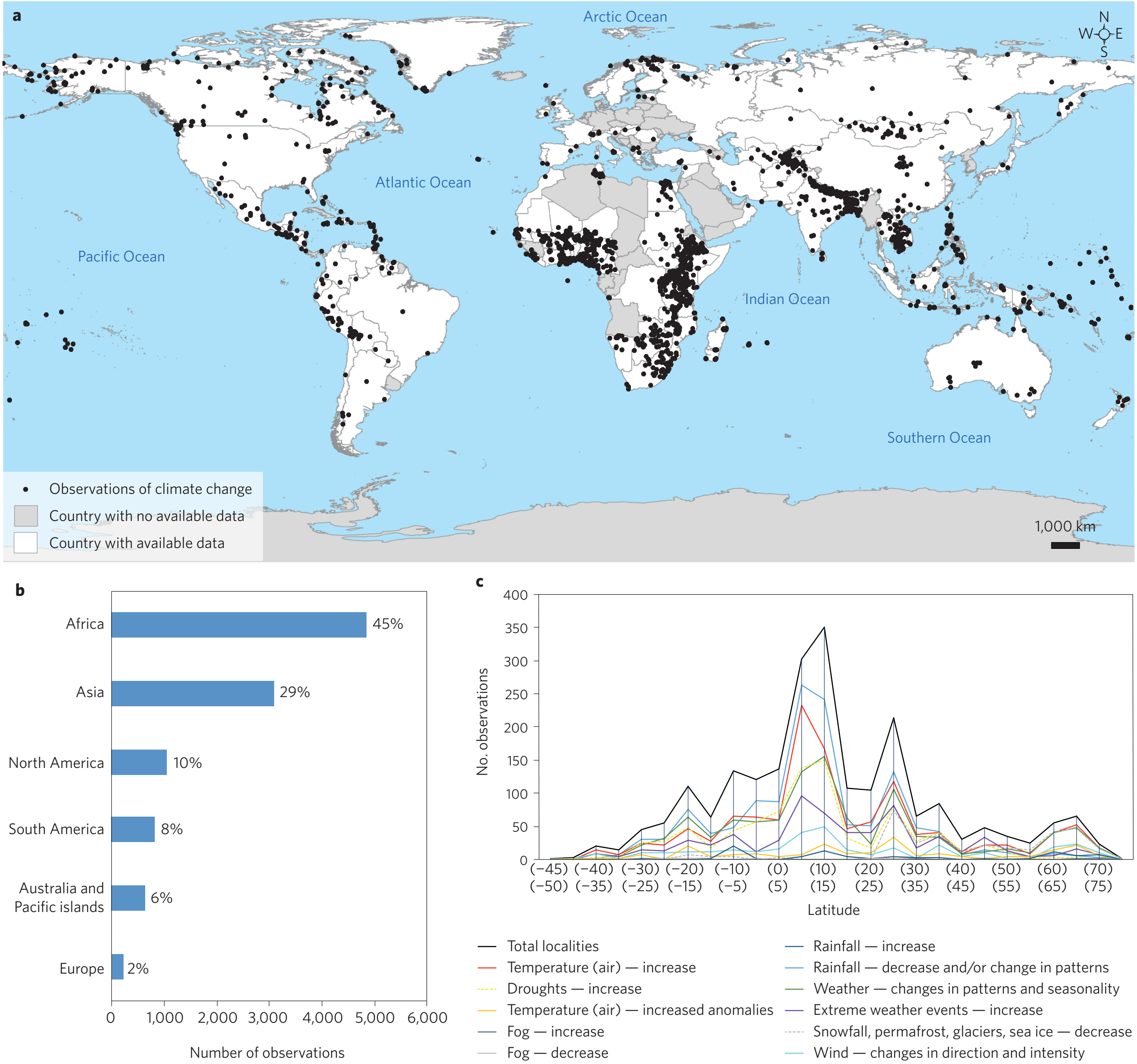

Figure 1 | Geographical distribution of data. a, Observations (*N* = 10,660) of climate and weather changes and climate-driven environmental changes made by subsistence-oriented people in the 137 countries with reported data. Countries with no available data are shaded in grey. **b**, Number of observations in each continent. **c**, Number of observations of climatic changes per latitude ranges.

simulations comprising the IPCC Fifth Assessment Report Atlas subset taken from the Coupled Model Intercomparison Project Phase 5 (CMIP5)[21]. This comparison was aimed at identifying areas where communities are already observing changes, but where simulations are not projecting changes.

Observed climatic changes

We report 10,660 observations from subsistence-oriented communities in 2,230 localities across 137 countries (Fig. 1a–c). These observations can be grouped into three main categories, which we further divide into sub-categories: (i) changes in climate and weather (Fig. 2a); (ii) changes in physical components of the environment (for example, floods and erosion; Fig. 2b); and (iii) changes in biological components of the environment (for example, distributional shifts in plant and animal species; Fig. 3). Some changes are reported frequently (such as changes in seasonality and in crop yields and quality), whereas others are less common (for example, changes in the temperature of salt and/or fresh water) (Figs 2a,b and 3).

The reported observations span the globe (Fig. 1a–c), but their distribution among countries is uneven. The majority of observations come from a few regions, with the Pacific Islands, central Africa and the North American Arctic being especially well represented. This distribution of observations parallels the distribution of areas where climate change is thought to have the greatest social and environmental impacts (for example, in northern latitudes and developing countries). There are few published studies from Central and Eastern Europe and the Mediterranean, despite the fact that climate change in these regions is predicted to have severe impacts on subsistence activities[22]. There is no published

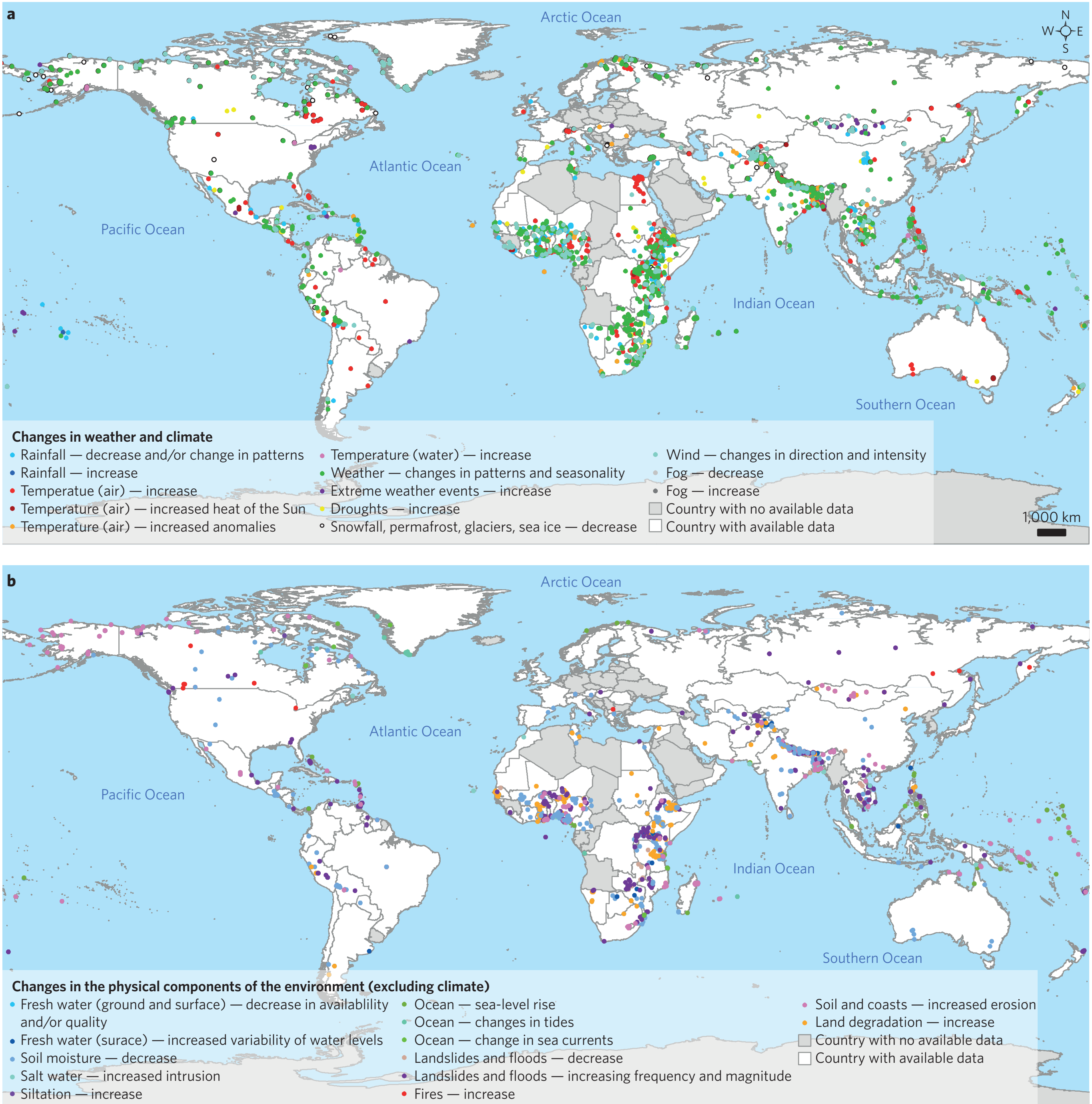

Figure 2 | Detailed observations of climate and climate-driven changes. a, Changes in weather and climate (number of points = 5,976). **b**, Changes in the physical components of the environment (N = 1,799).

research from several small countries such as Aruba and Bahrain, and areas lacking a stable human population, such as Bouvet Island and Antarctica, have no applicable data.

We note that observations about current climatic conditions, resource abundance and weather patterns relate to experiences across multiple time frames. Individual observations are generally accumulated within a lifetime, whereas collective observations are longer term and multi-generational[12]. We consider both individual and collective observations because together they provide an overview of qualitative changes in relation to what are considered normal environmental conditions and incorporate an understanding of the normal local range of variability[23].

There are broad similarities in the changes observed at a local scale in a given biome, even when the locations of those observations are separated by large distances and occur on different continents (Table 1). Some changes, such as increases in temperature, are reported in many localities in different biomes whereas others are common only at certain latitudes (Fig. 1c) and in specific biomes. Increases in temperature and decreases in snowfall and ice formation, for example, are reported in almost all Arctic and sub-Arctic northern locations. Observations of sea-level rise are prevalent in tropical and subtropical biomes — 80% of the localities where sea-level rise was observed. Changes in tide levels and patterns are also prevalent in the tropics (64% of the localities) as

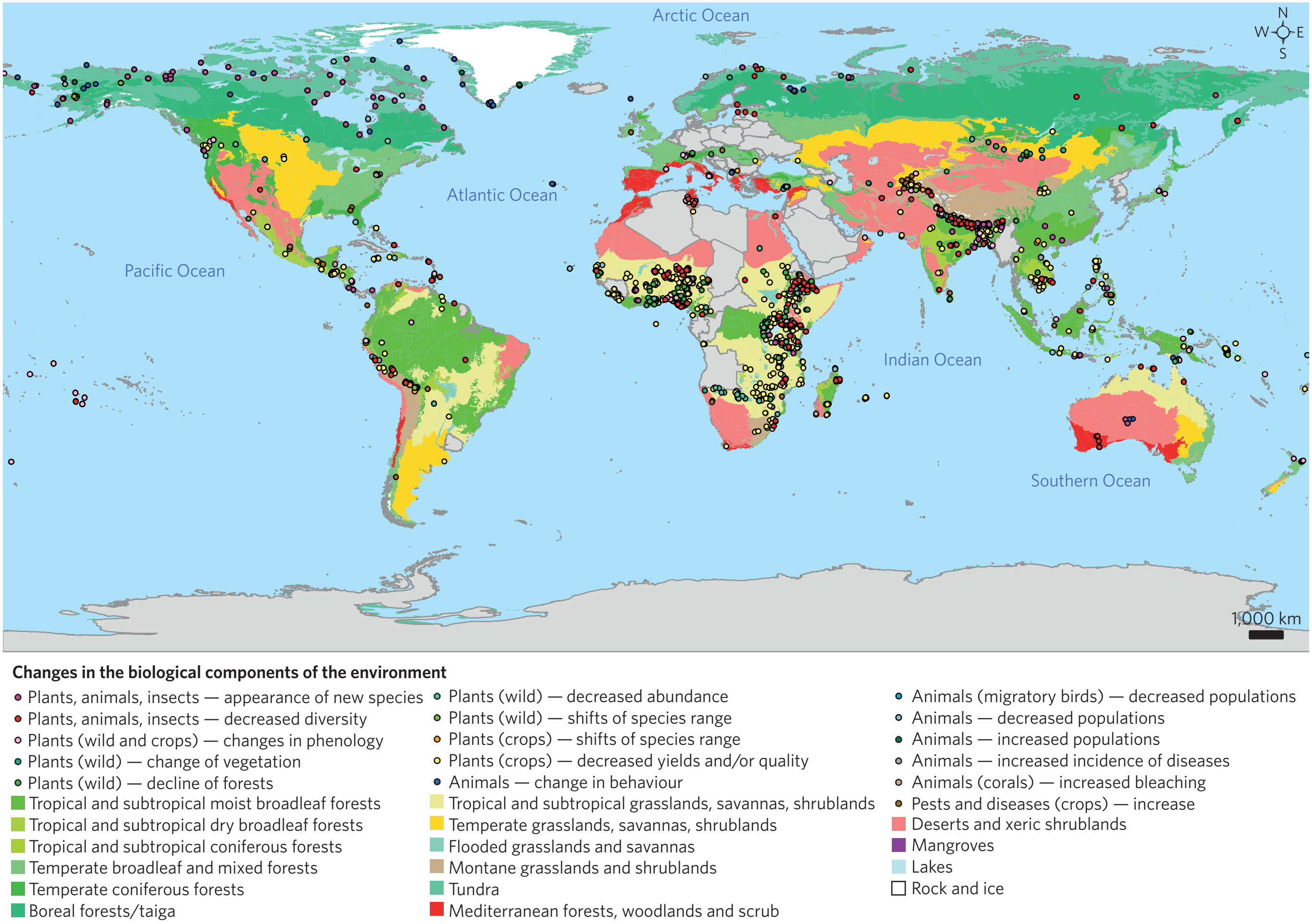

Figure 3 | Detailed observations of climate and climate-driven changes in the biological components of the environment ($N = 2,899$) overlying the biome global map. Biomes are from the WWF terrestrial ecoregions of the world spatial layer (www.worldwildlife.org/WildFinder).

well as in northern Arctic regions (20%). In all these biomes, local people are observing multiple, linked environmental changes. For example, coastal communities in the Arctic link changes in sea ice cover and dynamics to coastal erosion. People also recognize that these changes have ramifying consequences, such as effects on animal migration patterns — for example, if animals formerly migrated across sea ice, which now melts by the time of migration, they would need to find new routes.

Changes in weather and climate

Changes in rainfall are the most frequent type of observation in our data set (Fig. 2a). These observations are widely distributed among continents, representing 58% of all localities (97 countries). These changes are especially frequent in mountainous areas and equatorial zones (Figs 1c, 2a and 4), and include shifts in the initiation and/or termination of rains, increasing unpredictability of rainfall events and atypical interruptions during the rainy season. People observe that such changes are sometimes associated with declines in precipitation and increasing periods of drought, as well as an increase in the intensity of rainfall events over short periods. However, these observed differences in the patterns of rainfall are not always coupled with an observed decrease in total annual rainfall[24]. Moreover, some observers reported that spatial variability in rainfall is increasing at a local scale (described as patchy or spotty rainfall[25]), leading to potential errors when generalizing over larger areas from quantitative measurements at gauging stations.

We identify some divergence between the simulated historical trends in average annual rainfall (ensemble average of the CMIP5 historical models) and local observations. Generally, people have observed decreased rainfall in many regions. In contrast, in many places the simulated trends in rainfall between 1955 and 2005 are smaller (<1 standard deviation) than the model estimates of present-day natural variability. In other words, either the simulated change in precipitation is very small or there is little agreement among models in places where humans are rather consistently observing drying trends.

Several factors could contribute to these differences between simulated and observed historical changes in precipitation. The first relates to a potential mismatch in the temporal scale of the comparison. Our analysis assumes that human observations represent an approximate period of about fifty years, whereas, in reality, they could represent much longer or shorter time periods. But comparisons with simulated precipitation trends over ranges of 30 to 75 years (not shown) suggest that the time period alone is not responsible for the mismatch. This comparison, however, does not account for possible cases where humans are observing changes due to short-term (for example, <30 years) natural rather than long-term anthropogenic influences. The second factor relates to a potential mismatch in the spatial scale and resolution of the records. The scale of human observations is very local, whereas models are capturing much broader patterns of change. We note that this problem is exacerbated when comparing precipitation patterns, and that temperature trends and observations are much more congruent. Third, factors

Table 1 | Examples of changes reported in each biome.

Biome and changes that are cited most often among its sites	Example of a locality within the biome	Changes in weather reported in the locality	Changes in the biological components of the environment reported in the locality	Changes in the physical components of the environment reported in the locality
Tundra: Reduction in snowfall and permafrost. Recession of glaciers. Changes in sea ice cover and dynamics.	Kugluktuk village, Nunavut, Canada[17]	Unpredictable weather. Increase in winter freezing rain. Change in wind direction and intensity. Increase in temperature. Increase in storms. Freeze-up is delayed and ice breakup is earlier. Decrease in snowfall. Change in the quality of snow. Snow melts earlier. Increase in permafrost melt.	Changes in animal behaviour and migration and hibernation patterns. Increased incidence of diseased and unhealthy animals. Increase in mosquitoes. New southern species. Changes in the range of grizzly bears.	Drying up of tundra ponds. Lower water levels in lakes and rivers. Coastal erosion.
Boreal forests/taiga: reduction in snowfall, and permafrost. Recession of glaciers. Changes in sea ice cover and dynamics.	Viliui Sakha watershed, Siberia, Russia[91,92]	Seasons have changed (earlier spring, longer autumn). Reduction of permafrost. Huge change in the quality, quantity and timing of snowfall. Warm winters and cool summers. Extreme temperature changes. Increase in rainfall and change in its patterns ("it rains at the wrong times").	New species from the south. Increase in animal diseases. Earlier blooming of plants. Decrease in berries. Migratory birds arrive at the wrong time. Fewer birds and animals. Reduction of the quality of hay and vegetables in home gardens.	Increased rainfall keep larger areas under water (increase in swamps). Increase in floods.
Temperate coniferous forests: increase in temperatures.	Quileute reservation, Washington state, USA[93]	Storms with greater intensity and frequency. Changes in weather. Winds are arriving at different times of the year when they are not expected. Wind directions are changing. Increase in rainfall and timing of rainfall is changing. Less snowfall and a reduction of snowpack on the mountains. Increase in temperatures.	New species (for example, brown pelicans, Humboldt squids, turtles). Increases in warm-water fish (for example, mackerel, tuna, sardines, sunfish). Shift in timing of the smelt run. Reduction of the population of some fish, seafood and bird species. Decline in forests. Delay in the ripening of berries.	Increase in flooding events.
Temperate broadleaf and mixed forests: changes in seasonality, weather patterns and predictability.	Pasighat village, East Siang district, Arunachal Pradesh, India[94]	Erratic rainfall. Increased temperatures. Changes in weather patterns. More frequent heavy rains.	Changes in flowering time. Changing behaviour of animals due to changes in phenology. Shrinking of some plant communities. Fewer wild animals (including freshwater fish in the forest). More insect and pest problems. Lower biodiversity (terrestrial and aquatic).	Unpredictable floods. Increased siltation in rivers. Increasingly erratic hydrogeological regime in streams. Increased soil erosion from heavy rains. Reduced soil moisture.
Temperate grasslands, savannas and shrublands: increase in droughts.	Little Bighorn River Valley, Crow Reservation, Montana, USA[95]	Less snow. Milder winters and warmer summers. Drier weather.	Berries flower earlier and are vulnerable to cold snaps. Changed phenology of several other plants. Changes in brown trout location (a species that prefers cooler waters). Freshwater mussel and frog populations have declined.	Reduced stream flows. More fires.
Montane grasslands and shrublands: changes in rainfall patterns and amounts	Fanzhuang, Huachi County, Gansu Province, Loess Plateau, China.[66]	More drought events, particularly spring droughts. Warmer winter temperatures. Less snow. Less rain and rains are irregular and unpredictable. Weather is more uncertain.	Poor agricultural productivity. Increase in pests and diseases.	Water shortage for both drinking and farming.

Continued

Table 1 | (continued)

Biome and changes that are cited most often among its sites	Example of a locality within the biome	Changes in weather reported in the locality	Changes in the biological components of the environment reported in the locality	Changes in the physical components of the environment reported in the locality
Mediterranean forests, woodlands and shrublands: changes in seasonality, weather patterns and predictability.	Amalfi Coast, Italy[68,83]	Increase in summer droughts. Increased temperatures. Seasons are unpredictable. Decrease in rain and changes in rainfall patterns. Increase in extreme rains. Less snow.	Reduction of crop yields and quality. Altitudinal shifts of crops. Increase in crop diseases and pests.	Increase in fires. More landslides.
Tropical and subtropical dry broadleaf forests: changes in seasonality, weather patterns and predictability.	Virudhunagar district, Vaippar basin, Tamil Nadu, India[97]	Rainfall is unpredictable. Less rainfall. More intense rains. Changes in temperatures. Increase in warmer days. Longer dry spells. Increase in droughts. Late onset of the Monsoon season.	Extirpation of plant and animal species. Changes in flowering and fruiting time. New plant species. Changes in fish species in ponds.	Water amounts and availability are decreasing. Increase in floods.
Tropical and subtropical moist broadleaf forests: changes in rainfall patterns and amounts.	Trieu Van commune, Trieu Phong district, Quang Tri province, Vietnam (Phuong)[98]	Increased temperatures. Decrease in rainfall during the dry season. Rainfall is concentrated over a limited period. Rainy seasons are shifted. More heavy rainfall over short periods. Drought lasts longer and is more intense and more unpredictable. Stronger southern–western winds.	Decrease in crop yields and crop quality. Increase in pests and diseases. Increase in animal diseases.	Water level in the summer is lower in many ponds and lakes. Saltwater intrusion into the fields (including rice fields).
Flooded grasslands and savannas: changes in rainfall patterns and amounts.	Mbutu village, Mambali ward, Nzega District, Tabora Region, Tanzania[45]	Late onset and short period of rainfall and unpredictable rains. Dry season is longer. Warmer temperatures. Stronger winds. Changes in seasonality.	Reduction of crop yields. Increase in crop pests and diseases.	Fewer beneficial floods.
Tropical and subtropical grasslands, savannas and shrublands: changes in rainfall patterns and amounts.	Biidi village, Burkina Faso[48,49]	Changes in rainfall patterns (too little or too much). Colder in the cold season and hotter in the hot season. Rain is less predictable. Changes in the rainy season. Winds are stronger and carry more dust (dust storms). Increase in droughts. Increase in extreme rainfall events.	Appearance of new plant species (grass). Some tree species have disappeared. More crop pests. Decrease in crop yields.	Decrease in water in ponds, wells and water bodies. More floods. Sand is filling up river beds. Decrease in grass cover. Land is eroded and harder to work, and the rain does not penetrate the soil.
Deserts and xeric shrublands: changes in rainfall patterns and amounts.	Mandalgovi area, Mongolia[25]	Change in weather. Rains start later, rain is patchy and there is less. Seasons have changed. More droughts. More storms. More heavy rains.	Grass cover is thinner each year. Mongol (*Stipa tianschanica* Roshev.) flowers in August instead of June and now flowers only once. Increase in insect infestations.	
Mangrove: increase in temperatures.	Keti Bunder town, Thatta District, Pakistan[99]	Increased temperatures. Winters are shorter. Shifts in rainfall. Increase in sea temperatures. More storms.	Reduction of fish. Fish go further out to sea. More diseases (humans).	Decline in freshwater flows. Lack of water. Soil infertility. Rising sea. Saltwater intrusion.

The biomes are based on the WWF terrestrial ecoregions of the world spatial layer (www.worldwildlife.org/WildFinder).

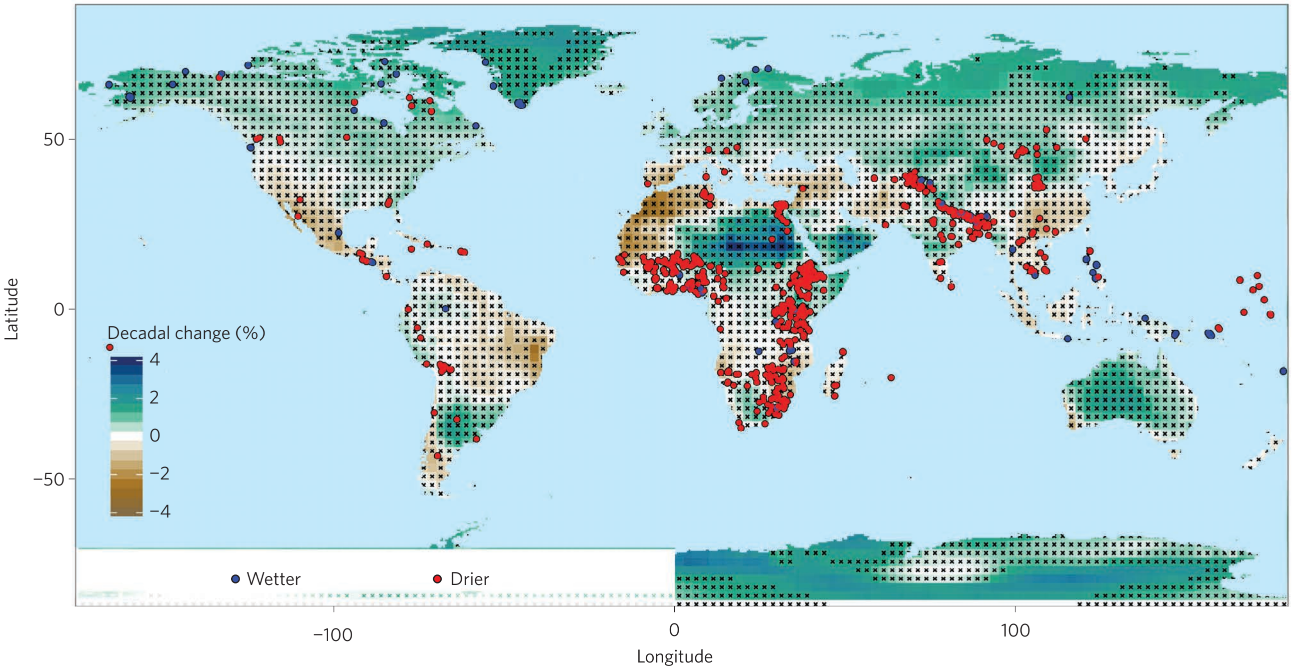

Figure 4 | Observations of changes in rainfall amounts overlaying the decadal trend (%) in annual mean precipitation simulated by the ensemble average of the CMIP5 IPCC AR5 Atlas Subset over the period 1955–2005. Hatching represents areas where the trend signal is smaller than one standard deviation of natural variability. Hatching may exist because the averaged model trends are small relative to natural, internal variability, or there is little agreement between models on the sign of the change in precipitation.

other than precipitation — such as changes in soil moisture — could contribute to the drying that is observed by humans. For instance, changes in rainfall patterns can affect crops and the natural environment in ways similar to overall decreases in precipitation (for example, factors other than the amount of precipitation that can directly contribute to drought[26]).

Differences between simulated and observed historical changes in precipitation could also relate to limitations of either the observations or models. For example, human perceptions might be biased in some way. Although possible, recent work has suggested that even in cases where people are highly exposed to media, public perceptions of temperature changes still correspond with climate records[18,19]. A final possible reason why human observations suggest trends in precipitation that are not seen in the ensemble average of historical model simulations is that people are observing changes in precipitation that are simply not yet captured by model simulations. We anticipate that some combination of these factors is influencing the differences in simulated and observed patterns of rainfall.

Increases in air temperature are more consistent than those of precipitation and have been observed in all continents (47% of localities, 94 countries; Figs 2a and 5). Although observations of warming trends are the most common, in many localities[27] people also observe more generalized anomalies in temperatures (such as extreme temperatures, or increased summer temperatures coupled with a drop in winter temperatures; 10% of localities). Observations of changes in water temperatures are less frequent (2% of localities), but indicate a general warming trend, as noted by the IPCC[28]. Associated with these increased air and water temperatures, melting of glaciers and permafrost and reduction of sea ice have been consistently observed in all Arctic regions and in many alpine ecosystems (15% of localities, 28 countries; Supplementary Fig. 1), leading to a cascade of other effects being observed, as reported in Table 1 (such as coastal erosion, changes in animal behaviour, distributional shifts of plant species and an increase in pests and diseases). However, in some areas of the Arctic, people observe that changes in sea ice conditions are linked most tightly to changes in wind directions rather than temperature[29].

We find almost 100% agreement between our data set of observed changes in temperature and the CMIP5[21,30] ensemble average of simulated historical trends in average annual surface temperature (Fig. 5). In addition to this match between average annual conditions, human observations also reveal increased variability in temperature. Thus, people not only observe a general warming trend[19], but also increases in cold and hot anomalies, including extremes. Locally observed anomalies are not always captured by models that focus on average values[31]. The IPCC[32] highlights the importance of assessing extremes for better defining future scenarios.

People widely report changes in the seasonality and predictability of weather (46% of localities, 96 countries; Supplementary Fig. 2). In our data set, there are few areas globally where people have not observed shifts in the seasons, changes in monsoon patterns, or unpredictable, unseasonal weather events. For example, changes in the arrival of the monsoon season are widely reported in Asia, whereas in Africa many communities observe alterations of the rainy season, describing it as shorter, shifted and interrupted with dry spells. In addition to obvious detrimental consequences for agriculture (including altered cropping calendars and weed and pest cycles[33]), such changes can affect fishing and hunting because these activities are often planned in conjunction with specific seasonal conditions or weather patterns[16]. Observations of changes in weather are often quite detailed and linked to specific bioindicators, such as the arrival of migrating species or the flowering of certain plants[34]. Such bioindicators may provide a useful approach to understanding local changes in weather and their consequences.

Droughts caused by reduced precipitation combined with increasing temperatures are broadly distributed (37% of localities, 85 countries; Fig. 2a and Supplementary Fig. 3). In many arid areas, people observe that droughts now last longer or return more frequently[35]. Collectively these observations suggest that these changes, in conjunction with non-climatic factors, might push biological systems towards dangerous thresholds[36]. Moreover, changing climate is often only one of several interacting factors causing dramatic, cumulative ecosystem change. In many African regions,

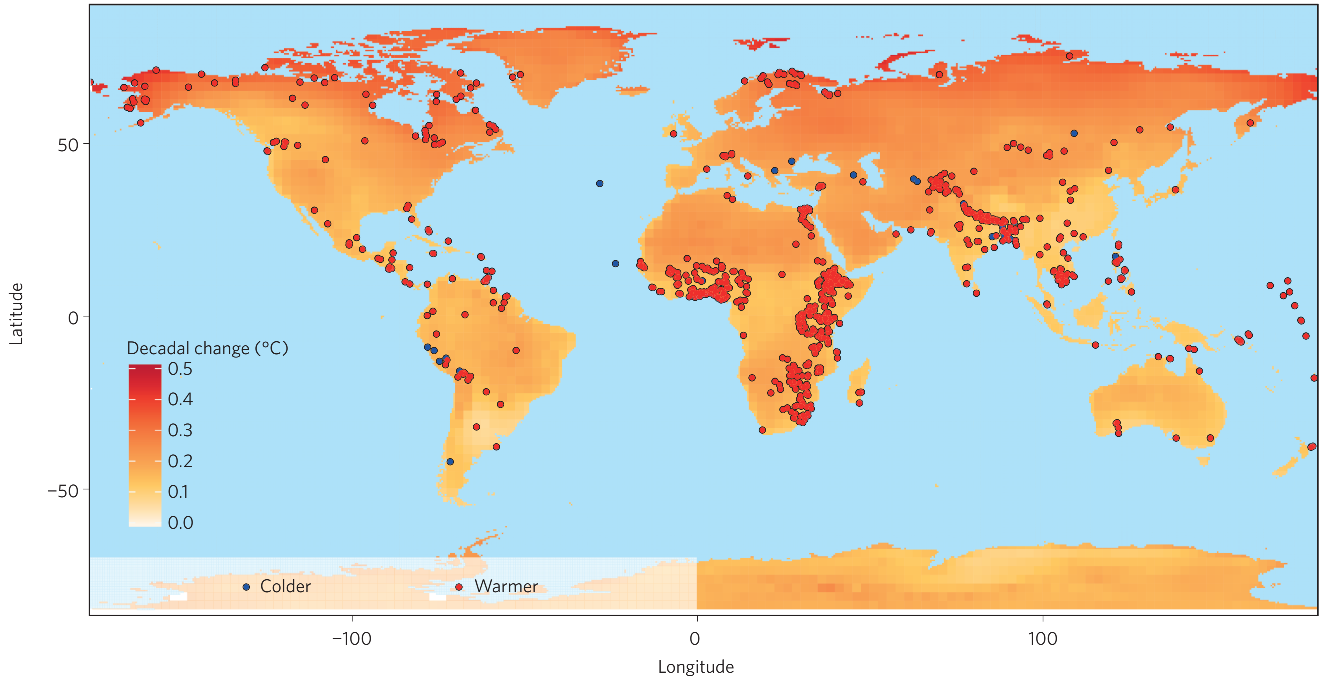

Figure 5 | Observations of changes in temperatures overlaying the decadal trend (°C) in annual mean near-surface temperature simulated by the ensemble average of the CMIP5 IPCC AR5 Atlas Subset over the period 1955–2005. Hatching only exists over the oceans, which we do not examine here.

for example, factors such as deforestation, overpopulation and the spread of diseases are exacerbating negative changes in social–ecological systems[37,38]. Finally, similarly to other recent studies[26,39], our data set indicates that drought is also occurring in areas that have been typically wet, leading to drying of water bodies, die-off of natural vegetation, increase in fires, and disruption of the life cycles of wild animals[40].

Local observers in many localities (29%, 86 countries) report increases in extreme weather events (Fig. 2a and Supplementary Fig. 4) such as heavy rainfall, storms and hurricanes. Furthermore, although some global models project that heavy rainfall events will increase in regions that are already wet (middle and high northern latitudes, Central and Southeast Asia, Indonesia, Central Africa and South America)[6,41], subsistence-oriented communities also report heavy rainfall events in some areas that are not historically wet, such as South Africa[42]. In the hilly and mountainous areas of central Asia and South America, hailstorms are reported to be increasing in frequency and/or intensity[43]. Although hailstorms are difficult to monitor with instrumental systems and therefore are not easy to quantify[32], in some areas, hailstorms have been reported as a novel phenomenon[44]. The increased storminess in the Arctic, coupled with reduced sea ice, is accelerating coastal erosion, especially in Alaska[23]. An increase in the frequency of snowstorms or thunderstorms has also been reported in several regions including Mongolia, Mali, China and Laos. The large number of observations of increases in extreme weather events supports the idea that climate is not changing smoothly, but rather through an intensification of atmospheric phenomena[24].

Alteration in patterns of wind is among the less commonly reported changes (14% of localities, 64 countries; Fig. 2a and Supplementary Fig. 5). Changes in winds include observations of stronger winds[45] or changes in wind direction[46], which often co-occur[17]. Changes in wind direction have been observed especially in the tropical Pacific and Arctic North America. This is notable because the wind shifts in the Arctic are not likely to result from local-scale land use changes. Winds are also reported to be stronger in Central Asia[43]. In parts of sub-Saharan Africa, other studies have shown that changes in atmospheric circulation have increased the occurrence of strong winds[47]. This is corroborated by the high number of observations of stronger winds from these areas[48,49]. However, many communities reporting stronger winds also linked them to deforestation, as they recognize that trees can buffer winds[50]. These examples reflect a general trend in our data of increased wind speeds in the Southern Hemisphere, consistent with instrumental records[51]. Observations of changes in winds in the Northern Arctic show an agreement with measured increases both in wind speed and direction[32].

Changes in the physical components of the environment

Among the most commonly observed changes in abiotic environmental factors is a reduction of fresh water (decreased water quality, declining levels, or the drying of surface and ground water) (21% of localities, 74 countries; Fig. 2a and Supplementary Fig. 6). This is true of arid areas[52], as well as other biomes (from tundra to tropical and subtropical moist broadleaf forests). This widespread reduction may reflect the fact that water availability is often affected by socio-economic (for example, overuse and increased populations) as well as environmental factors (for example, rainfall, temperature and run-off)[53]. People report that water stress is associated with a wide range of impacts, including changes in animal migration patterns (such as ungulates and migratory birds in Africa[54]), increases in waterborne diseases (associated with stagnant small ponds from low flows[55]), reduction of crop yields (in both irrigated and rain-fed agricultural systems; see Table 1) and increased movement to seek water (both humans and animal herds[54]); these all lead to conflicts over a limited number of water sources[56].

Local people are reporting increases in the frequency and severity of floods and landslides in both arid and humid areas (17% of localities, 63 countries; Table 1 and Supplementary Fig. 7). This parallels the IPCC[32] reports of a recent increase in magnitude and frequency of floods. Many observations come from sub-Saharan countries and are consistent with analyses of historical (1900–2000) flood data in Africa[57]. In some areas where floods were a normal phenomenon historically, they are reported to now be less predictable and occur outside of the normal flooding season; this is especially so in Southeast Asia[58]. These changes in flooding seasonality reinforce the observations of increased unpredictability of the weather. Many observations of increased frequency of landslides come from Nepal[59] — where, it must be noted, multiple factors (besides climate) interact to cause slope instability[60]. Floods and landslides have many direct and indirect consequences, including loss of life (of humans and livestock), loss of property and harvests, impacts on potable water (and the consequent spread of waterborne diseases), erosion of topsoil, and salinization of soils in coastal areas[28]. In a few locations (1% of localities), floods and landslides are reported to be decreasing in frequency[61]. However, these observations are scattered and do not show clear geographical patterns.

Observations about the oceans include rising sea level and changes in tides and currents (6% of localities, 35 countries). These changes are observed more often in the Pacific and tropical areas than elsewhere (Fig. 2b), consistent with assessments by the IPCC[32]. Many observations come from tropical islands where sea-level rise is often combined with a reduction in available fresh water as a result of saltwater intrusion into freshwater lenses[46]. In these cases, sea-level rise is also often associated with coastal erosion[62], causing loss of land, property and culturally important sites.

Changes in the biological components of the environment

Subsistence-oriented communities are observing changes in biological systems related to changes in temperature, rainfall and other climate variables (Fig. 3). These changes are observed both in managed ecosystems (for example, orchards and fields) and in untended landscapes.

The most frequently observed change in agricultural systems is a decrease in crop production and/or quality (38% of localities, 78 countries), which is often combined with increases in crop pests and diseases (277 localities, 70% of which are observations of an increase in pests, 33% of which are observations of decreased yields; Fig. 3 and Supplementary Fig. 8). Declines in crop yields are widely reported in Africa (60% of observations), where agriculture is mainly rain-fed[63]. These declines have significant, local consequences for food security as agriculture in this region is primarily for subsistence[63]. Global food security is also threatened by climate-related increases in crop pests and diseases[64]. Here we document the introduction of pests into new areas, as well as an increase in pests that were already present[65,66]. For example, pest populations that formerly were limited by colder winters are now more seasonally persistent[67,68].

Researchers consider climate change to be a powerful trigger for changes in species ranges[2]; many subsistence-oriented communities see a similar relationship between climatic changes and species range (Table 1, Fig. 3 and Supplementary Fig. 9). Changes in species ranges seem to be more evident in northern latitudes and mountainous areas (Supplementary Fig. 9) where plants and animals (including fish, birds and insects) are shifting north or to higher elevations away from warmer latitudes or altitudes[67]. Other changes include shifts in mating season, or migratory and hibernation patterns[17,69]. Changes in migration patterns, in particular, are more commonly observed at higher latitudes[70]. In several areas, fishers observe shifts in the distribution of fish to deeper or higher-latitude waters[71]. For example, in Alaska, fishers increasingly observe sharks, jellyfish and other species typical of southern latitudes[72].

Many communities report alterations to the timing of flowering or fruiting of wild and cultivated plants (9% of localities, 37 countries; Supplementary Fig. 10 and Fig. 3). These phenological observations do not seem to have a distinct geographical pattern. Such changes in phenology are frequently reported in the literature as indicators of climate change[73]. The implications for agriculture, animal feeding patterns and life cycles can be significant[74].

Although the global decline in biodiversity has multiple causes[75], in our synthesis many communities (8% of localities, 39 countries) relate local extirpations of plants and animals to factors such as increased drought or temperature and changes in seasonality (Fig. 3 and Supplementary Fig. 11). The majority (68%) of observations of extirpations are in tropical areas, especially tropical forested ecosystems[76]. Extirpations are reported for piedmont areas (for example, in India and Nepal), consistent with Colwell *et al.*[77] who describe this phenomenon as lowland biotic attrition.

The value of local observations

There is considerable value in integrating local observations of climate into climate studies more generally. Previous research[16] has recognized broad consistency in observations made by local subsistence-oriented communities and local instrumental data. This reinforces their potential value where instrumental data are sparse or not available. Furthermore, local observations can support trends described by global analyses of climate change and can help to fill in gaps in climate research. For example, local observations of sea-level rise in tropical islands are consistent with the IPCC[32] and projections of potential risks[78]. Local observations can be combined with other sources of data (for example, instrumental data[17], remote sensing[79] or surveys of biological communities[80]) to define more precisely the linkages between climatic changes and their direct and indirect effects on the environment[83]. For instance, subsistence-oriented communities may note linkages among winds, animal behaviour and ice conditions[81], which cannot easily be inferred using instrumental data and other kinds of surveys. Local observations can explain how the warming of waters can lead to an increase in fish species diversity in some areas[82], but an increase in fish parasites in others[71]. Such ecological understanding arises from long-term, immersive experience in a particular place. In this sense, TEK has the potential to help formal science disentangle the dynamics of social–ecological systems in their responses to climate change.

Human observations and global models have different strengths and weakness. In particular, human observations can integrate climatic changes with their social and environmental consequences (that is, they incorporate direct and secondary impacts). For example, humans may observe increased drought because of direct reductions in rainfall, but also because of changes in their access to water (because of less water in wells or reduced water discharge)[44,84]. Such observations can provide a more complete view of how factors such as drought affect human societies, including their social consequences. In contrast, the strength of global models is in their ability to identify broad patterns and project the effects of well-understood physical processes. Thus, combining local observations with global models will enhance our ability to move beyond the physical changes alone to clarify the social impacts of climate change.

Although climate change often directly affects the lives of subsistence-oriented communities, these effects are not well understood or reflected in the variables currently used in climate model simulations. For example, the effects of change in climate on animal migration patterns or pest distribution and abundance are common observations in our data set, but are still poorly understood by the research community[28,64]. Similarly, though of great local significance, spatially patchy rainfall or short, intense rainfall events, or shifts in the initiation of rainy seasons, can be hard to detect using averaged values from coarse-resolution instrumental networks. Although there have been improvements in the representation of rainfall in climate models, significant uncertainties remain at local and regional scales[32] (Fig. 4).

The social impacts of climate change

Our compilation reveals many of the effects of climate change on communities' lifestyles. Fine-scale environmental changes have enormous consequences for local communities as they not only disrupt crop calendars, destroy harvests and trigger soil erosion, but can increase conflict over limited resources and enhance risk to vulnerable members of society[56,85]. These data are hard to quantify, but in aggregate demonstrate that climate change has significant potential to disrupt the social fabric and culture of many communities. For instance, in response to local climatic changes, people are migrating more, eating less and walking longer distances to get water or reach pastures for their herds (while facing risks such as conflicts and violence[54,56]). In Sweden, Sami herders are abandoning their traditional practices due to changes in temperature, weather and ice formation[86]. In Iran, climatic changes are increasing the divide between rich and poor farmers, as the latter have few options for adaptation other than praying for rain[85].

One potential consequence of climate change (often in combination with other factors) is the reduced ability of people to cope with environmental variability. For instance, various climatic changes are undermining the reliability of long-term ecological knowledge about cyclical and seasonal phenomena, such that people are no longer able to predict the right periods for sowing, harvesting, or recognizing safe conditions to venture on the sea or land for gathering food[17]. In Vietnam, changed weather patterns have forced farmers to reduce the number of farming seasons, impacting crop production[87]. In Bangladesh, the increased number of windy or stormy days is affecting the ability of traditional fishers to go fishing[88].

In some cases, climatic changes are reducing the ability of subsistence-oriented communities to engage in culturally important food gathering practices. This has broad consequences for cultural survival and for food security. In the Arctic, young people have fewer occasions to learn and practice traditional harvesting because the weather is more unpredictable. As a consequence, there is a reduction in the transmission of traditional knowledge and this has been related to an increased consumption of less healthy store-bought foods[11]. In the islands of Torres Strait, Australia, climatic changes are affecting the range distribution of totemic animals and causing the submergence of sites used for gathering culturally important foods[62].

Integrating local observations into climate change research

Our compilation of climate-related observations by subsistence-oriented peoples represents localities from around the globe, but information is still lacking from several regions. It is unlikely that these data gaps represent an absence of local knowledge of climatic phenomena. Moreover, the lack of observations does not mean that climate is not changing: studies are lacking from regions where instrumental data are detecting climate change. Gaps in research could be due to a variety of social and political factors such as the non-recognition or undervaluing of TEK, lack of funding for relevant research, political instability, and underestimation of local vulnerability to climate change.

Local observations of climatic changes made by subsistence-oriented communities are global in distribution and ubiquitous across biomes, ecosystems and modes of local subsistence economy. Such observations should play an important role in mapping the impacts of changing climatic processes and facilitating local adaptations to climate change. Our data set on local observations of climatic changes will provide a foundation for future comparisons of observations and instrumental data. The scientific consensus on the causes and mechanisms of anthropogenic climate change is strong[89] and our analyses show that local subsistence-oriented communities experience the consequences of these changes. However, the debates around the political and policy dimensions of responses to changing climate remain hotly contested[90]. With climate change already profoundly altering social–ecological systems, we need to marshal all the available data on climate processes and their diverse consequences: the local-scale observations of subsistence-oriented communities are a critical part of that process.

There would be tremendous value in initiating community-based programmes in those regions with major data gaps in our synthesis (for example, parts of Europe) and in filling smaller gaps in regions where such work is already under way. In addition to documenting the ecological, social and cultural consequences of climate changes at the local level, these programmes would also be useful for establishing the communities' most pressing priorities and concerns. Finally, it is important to reinforce the need not only for local data and analyses but also for local initiatives that are responsive to the issues and priorities that emerge from these analyses. Local strategies for adaptation to climate change should be developed without waiting for conclusive agreements to emerge from global initiatives.

Methods

Methods and any associated references are available in the online version of the paper.

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References

1. Parmesan, C. Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.* **37,** 637–669 (2006).
2. Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L. & Levin, S. A. Marine taxa track local climate velocities. *Science* **341,** 1239–1242 (2013).
3. Pearson, R. G. & Dawson, T. P. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecol. Biogeogr.* **12,** 361–371 (2003).
4. Schiermeier, Q. The real holes in climate science. *Nature* **463,** 284–287 (2010).
5. Gilman, E. L., Ellison, J., Duke, N. C. & Field, C. Threats to mangroves from climate change and adaptation options: a review. *Aquat. Bot.* **89,** 237–250 (2008).
6. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds Field, C. B. *et al.*) (IPCC, Cambridge Univ. Press, 2012).
7. Mora, C. *et al.* The projected timing of climate departure from recent variability. *Nature* **502,** 183–187 (2013).
8. Galloway McLean, K. *Advance Guard: Climate Change Impacts, Adaptation, Mitigation and Indigenous Peoples — A Compendium of Case Studies* (United Nations University — Traditional Knowledge Initiative, 2010).
A compendium of cases studies that show the value of TEK in relation to research on climate change.
9. Adger, W. N., Barnett, J., Brown, K., Marshall, N. & O'Brien, K. Cultural dimensions of climate change impacts and adaptation. *Nature Clim. Change* **3,** 112–117 (2013).
A study on the different ways in which climate change and culture are interrelated.
10. Alexander, C. *et al.* Linking indigenous and scientific knowledge of climate change. *Bioscience* **61,** 477–484 (2011).
11. Macdonald, P., Harper, S. L., Willox, A. C. & Edge, V. L. A necessary voice: climate change and lived experiences of youth in Rigolet, Nunatsiavut, Canada. *Glob. Environ. Chang.* **23,** 360–371 (2013).
12. Turner, N. J. & Berkes, F. Coming to understanding: developing conservation through incremental learning in the Pacific Northwest. *Hum. Ecol.* **34,** 495–513 (2006).
13. King, D. N. T., Skipper, A. & Tawhai, W. B. Māori environmental knowledge of local weather and climate change in Aotearoa — New Zealand. *Climatic Change* **90,** 385–409 (2008).
14. Nakashima, D. J., Galloway McLean, K., Thulstrup, H. D., Ramos Castillo, A. & Rubis, J. T. *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation* (United Nations University, 2012).
A comprehensive analysis of implications of climate change for indigenous and marginalized communities.
15. Nyong, T., Adesina, F. & Elasha, B. The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitig. Adapt. Strat. Glob. Change* **12,** 787–797 (2007).
16. McNeeley, S. M. & Shulski, M. D. Anatomy of a closing window: vulnerability to changing seasonality in Interior Alaska. *Glob. Environ. Chang.* **21,** 464–473 (2011).
17. Prno, J. *et al.* Community vulnerability to climate change in the context of other exposure-sensitivities in Kugluktuk, Nunavut. *Polar Res.* **30,** 7363 (2011).
18. Howe, P. D., Markowitz, E. M., Lee, T. M., Ko, C. Y. & Leiserowitz, A. Global perceptions of local temperature change. *Nature Clim. Change* **3,** 352–356 (2013).

19. Lehner, F. & Stocker, T. F. From local perception to global perspective. *Nature Clim. Change* **5**, 731–734 (2015).
20. Crona, B., Wutich, A., Brewis, A. & Gartin, M. Perceptions of climate change: linking local and global perceptions through a cultural knowledge approach. *Climatic Change* **119**, 519–531 (2013).
A comparative study, in six countries, of local observations of climate change.
21. Van Oldenborgh, G. J. *et al.* in *Climate Change 2013: The Physical Science Basis.* (eds Stocker, T. F. *et al.*) Annex I (IPCC, Cambridge Univ. Press, 2013).
22. Metzger, M. J., Bunce, R. G. H., van Eupen, M. & Mirtl, M. An assessment of long term ecosystem research activities across European socio-ecological gradients. *J. Environ. Manage.* **91,** 1357–1365 (2010).
23. Gearheard, S. *et al.* "It's not that simple": a collaborative comparison of sea ice environments, their uses, observed changes, and adaptations in Barrow, Alaska, USA, and Clyde River, Nunavut, Canada. *AMBIO* **35,** 203–211 (2006).
24. Karl, T. R. & Trenberth, K. E. Modern global climate change. *Science* **302,** 1719–1723 (2003).
25. Marin, A. Riders under storms: contributions of nomadic herders' observations to analysing climate change in Mongolia. *Glob. Environ. Chang.* **20,** 162–176 (2010).
26. Sherwood, S. & Fu, Q. A drier future. *Science* **343,** 737–739 (2014).
27. Bury, J. T. *et al.* Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change* **105,** 179–206 (2011).
28. Field, C. B. *et al. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectorial Aspects* (IPCC, Cambridge Univ. Press, 2014).
29. Gearheard, S., Pocernich, M., Stewart, R., Sanguya, J. & Huntington, H. P. Linking Inuit knowledge and meteorological station observations to understand changing wind patterns at Clyde River, Nunavut. *Climatic Change* **100,** 267–294 (2010).
30. Prather, M. *et al.* in *Climate Change 2013: The Physical Science Basis.* (eds Stocker, T. F. *et al.*) Annex II (Cambridge Univ. Press, 2013).
31. Rahmstorf, S. & Coumou, D. Increase of extreme events in a warming world. *Proc. Natl Acad. Sci. USA* **108,** 17905–17909 (2011).
32. Stocker, T. F. *et al. Climate Change 2013: The Physical Science Basis* (IPCC, World Meteorological Organization, 2013).
33. Chaudhary, P. & Bawa, K. S. Local perceptions of climate change validated by scientific evidence in the Himalayas. *Biol. Lett.* **7,** 767–770 (2011).
34. Schneider, P. Current and future climate change adaptation of a vulnerable coastal community on the Coromandel Peninsula, New Zealand. MSc thesis, Univ. Massey (2010).
35. Roncoli, C., Ingram, K. & Kirshen, P. Reading the rains: local knowledge and rainfall forecasting in Burkina Faso. *Soc. Nat. Resour.* **15,** 409–427 (2002).
36. Cunningham, S. J., Martin, R. O., Hojem, C. L. & Hockey, P. A. Temperatures in excess of critical thresholds threaten nestling growth and survival in a rapidly-warming arid savanna: a study of common fiscals. *PLOS ONE* **8,** e74613 (2013).
37. Thomson, M. C., Connor, S. J., Ward, N. & Molyneux, D. Impact of climate variability on infectious disease in West Africa. *EcoHealth* **1,** 138–150 (2004).
38. Weiss, R. A. & McMichael, A. J. Social and environmental risk factors in the emergence of infectious diseases. *Nature Medicine* **10,** S70–S76 (2004).
39. Greve, P. *et al.* Global assessment of trends in wetting and drying over land. *Nature Geosci.* **7,** 716–721 (2014).
40. Gudmundsson, L., Rego, F. C. & Seneviratne, S. I. Predicting above normal wildfire activity in southern Europe as a function of meteorological drought. *Environ. Res. Lett.* **9,** 084008 (2014).
41. Sillmann, J. & Roeckner, E. Indices for extreme events in projections of anthropogenic climate change. *Climatic Change* **86,** 83–104 (2008).
42. Thomas, D. S., Twyman, C., Osbahr, H. & Hewitson, B. Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change* **83,** 301–322 (2007).
43. Devkota, R. P., Bajracharya, B. & Narayan, T. The perception of Nepal's Tharu community in regard to climate change and its impacts on their livelihoods. *Int. J. Environ. Stud.* **68,** 937–946 (2011).
44. Hartmann, I. *et al. The Impact of Climate Change on Pastoral Societies of Somaliland* (Candlelight for Health, 2009).
45. Majule, A. E., Kauzeni, A. S., Shishira, E. K., Mwansasu, S. & Gwambene, B. in *Strengthening Local Agricultural Innovations to Adapt to Climate Change in Botswana, Malawi, South Africa and Tanzania* (eds Maro, P. S. & Majule, A. E.) 208–223 (Univ. Dar es Salaam, 2009).
46. Kuruppu, N. & Liverman, D. Mental preparation for climate adaptation: the role of cognition and culture in enhancing adaptive capacity of water management in Kiribati. *Glob. Environ. Chang.* **21,** 657–669 (2011).
47. Nicholson, S. E. Climatic and environmental change in Africa during the last two centuries. *Clim. Res.* **17,** 123–144 (2001).
48. Nielsen, J. Ø. & Reenberg, A. Temporality and the problem with singling out climate as a current driver of change in a small West African village. *J. Arid Environ.* **74,** 464–474 (2010).
49. Nielsen, J. Ø. & Vigh, H. Adaptive lives: navigating the global food crisis in a changing climate. *Glob. Environ. Chang.* **22,** 659–669 (2012).
50. Abiodun, B. J., Salami, A. T., Matthew, O. J. & Odedokun, S. Potential impacts of afforestation on climate change and extreme events in Nigeria. *Clim. Dynam.* **41,** 277–293 (2013).
51. Young, I. R., Zieger, S. & Babanin, A. V. Global trends in wind speed and wave height. *Science* **332,** 451–455 (2011).
52. Sowers, J., Vengosh, A. & Weinthal, E. Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change* **104,** 599–627 (2011).
53. Vörösmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. Global water resources: vulnerability from climate change and population growth. *Science* **289,** 284–288 (2000).
54. Speranza, C. I., Kiteme, B., Ambenje, P., Wiesmann, U. & Makali, S. Indigenous knowledge related to climate variability and change: insights from droughts in semi-arid areas of former Makueni District, Kenya. *Climatic Change* **100,** 295–315 (2010).
55. Hofmeijer, I. *et al.* Community vulnerability to the health effects of climate change among indigenous populations in the Peruvian Amazon: a case study from Panaillo and Nuevo Progreso. *Mitig. Adapt. Strategies Glob. Chang.* **18,** 957–978 (2013).
56. van der Valk, M. R. & Keenan, P. *Climate Change, Water Stress, Conflict and Migration* (UNESCO, 2012).
57. Padi, P. T., Di Baldassarre, G. & Castellarin, A. Floodplain management in Africa: large scale analysis of flood data. *Phys. Chem. Earth* **36,** 292–298 (2011).
58. Nuorteva, P., Keskinen, M. & Varis, O. Water, livelihoods and climate change adaptation in the Tonle Sap Lake area, Cambodia: learning from the past to understand the future. *J. Water Clim. Chang.* **1,** 87–101 (2010).
59. Becken, S., Lama, A. K. & Espiner, S. The cultural context of climate change impacts: perceptions among community members in the Annapurna Conservation Area, Nepal. *Environ. Dev.* **8,** 22–37 (2013).
60. Petley, D. N. *et al.* Trends in landslide occurrence in Nepal. *Natural Hazards* **43,** 23–44 (2007).
61. Diessner, C. *It Will Rain if God Wills it: Local Perceptions of Climate Change in the Futa Tooro of Northern Senegal* MA thesis, Univ. Missouri (2012).
62. O'Neill, C., Green, D. & Lui, W. How to make climate change research relevant for Indigenous communities in Torres Strait, Australia. *Local Environ.* **17,** 1104–1120 (2012).
63. Knox, J., Hess, T., Daccache, A. & Wheeler, T. Climate change impacts on crop productivity in Africa and South Asia. *Environ. Res. Lett.* **7,** 034032 (2012).
64. Gregory, P. J., Johnson, S. N., Newton, A. C. & Ingram J. S. I. Integrating pests and pathogens into the climate change/food security debate. *J. Exp. Bot.* **60,** 2827–2838 (2009).
65. Lama, S. & Devkota, B. Vulnerability of mountain communities to climate change and adaptation strategies. *J. Agric. Environ.* **10,** 76–83 (2009).
66. Wang, L. *The Vulnerability of Social-Environmental Systems and Farmers' Livelihood to Climate Change on China's Loess Plateau* PhD thesis, Univ. New South Wales (2012).
67. Kirrane, C., Sharkey, C. & Naess, L. O. *Shaping Strategies: Factors and Actors in Climate Change Adaptation. Lessons from Two-Year Case Studies in Africa and Latin America* (Trocaire, 2012).
68. Reedy, D., Savo, V. & McClatchey, W. Traditional climatic knowledge: orchardists' perceptions of and adaptation to climate change in the Campania region (Southern Italy). *Plant Biosyst.* **148,** 699–712 (2014).
69. Lescureux, N. *et al.* The king of the forest: local knowledge about European brown bears (*Ursus arctos*) and implications for their conservation in contemporary Western Macedonia. *Conserv. Soc.* **9,** 189–201 (2011).
70. Lavrillier, A. Climate change among nomadic and settled Tungus of Siberia: continuity and changes in economic and ritual relationships with the natural environment. *Polar Rec.* **49,** 260–271 (2013).
71. Keskitalo, E. C. H. & Kulyasova, A. A. The role of governance in community adaptation to climate change. *Polar Res.* **28,** 60–70 (2009).
72. Carter, B. T. & Nielsen, E. A. Exploring ecological changes in Cook Inlet Beluga Whale habitat though traditional and local ecological knowledge of contributing factors for population decline. *Marine Policy* **35,** 299–308 (2011).
73. Menzel, A. *et al.* European phenological response to climate change matches the warming pattern. *Glob. Change Biol.* **12,** 1969–1976 (2006).
74. Cleland, E. E., Chuine, I., Menzel, A., Mooney, H. A. & Schwartz, M. D. Shifting plant phenology in response to global change. *Trends Ecol. Evol.* **22,** 357–365 (2007).
75. Butchart, S. H. *et al.* Global biodiversity: indicators of recent declines. *Science* **328,** 1164–1168 (2010).
76. Ashwill, M., Flora, C. & Flora, J. *Building Community Resilience to Climate Change: Testing the Adaptation Coalition Framework in Latin America* (World Bank, 2011).

77. Colwell, R. K., Brehm, G., Cardelús, C. L., Gilman, A. C. & Longino, J. T. Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science* **322,** 258–261 (2008).
78. Nicholls, R. J. & Cazenave, A. Sea-level rise and its impact on coastal zones. *Science* **328,** 1517–1520 (2010).
79. Meier, W. N., Stroeve, J. & Gearheard, S. Bridging perspectives from remote sensing and Inuit communities on changing sea-ice cover in the Baffin Bay region. *Ann. Glaciol.* **44,** 433–438 (2006).
80. Danielsen, F. *et al.* Testing focus groups as a tool for connecting indigenous and local knowledge on abundance of natural resources with science-based land management systems. *Conserv. Lett.* **7,** 380–389 (2014).
81. Weatherhead, E., Gearheard, S. & Barry, R. G. Changes in weather persistence: insight from Inuit knowledge. *Glob. Environ. Chang.* **20,** 523–528 (2010).
82. Buijs, C. Inuit perceptions of climate change in East Greenland. *Études/Inuit/Studies* **34,** 39–54 (2010).
83. Savo, V., Caneva, G., McClatchey, W., Reedy, D. & Salvati, L. Combining environmental factors and agriculturalists' observations of environmental changes in the traditional terrace system of the Amalfi Coast (Southern Italy). *AMBIO* **43,** 297–310 (2014).
84. Meze-Hausken, E. Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. *Clim. Res.* **27,** 19–31 (2004).
85. Hayati, D., Yazdanpanah, M. & Karbalaee, F. Coping with drought: the case of poor farmers of South Iran. *Psychol. Dev. Soc.* **22,** 361–383 (2010).
86. Furberg, M., Evengård, B. & Nilsson, M. Facing the limit of resilience: perceptions of climate change among reindeer herding Sami in Sweden. *Global Health Act.* **4,** 8417 (2011).
87. Von Platen-Hallermund, T. & Thorsen, A. M. *Vulnerability and Climate Change Adaptation in Rural Vietnam* MSc thesis, Univ. Roskilde (2010).
88. Chowdhury, S. R., Hossain, M. S., Shamsuddoha, M. & Khan, S. M. M. H. *Coastal fishers' livelihood in peril: sea surface temperature and tropical cyclones in Bangladesh* (CPRD, 2012).
89. Cook, J. *et al.* Quantifying the consensus on anthropogenic global warming in the scientific literature. *Environ. Res. Lett.* **8,** 024024 (2013).
90. Palen, W. J. *et al.* Energy: consider the global impacts of oil pipelines. *Nature* **510,** 465 (2014).
91. Crate, S. A. Gone the bull of winter? Grappling with the cultural implications of and anthropology's role(s) in global climate change. *Curr. Anthropol.* **49,** 569–595 (2008).
92. Crate, S. A. in *Water, Cultural Diversity, and Global Environmental Change. Emerging Trends, Sustainable Futures?* (eds Johnston, B. R., Hiwasaki, L., Klaver, I. J., Castillo, A. R. & Strang, V.) 214–217 (Springer, 2012).
93. Papiez, C. *Climate Change Implications for the Quileute and Hoh Tribes of Washington: A Multidisciplinary Approach to Assessing Climatic Disruptions to Coastal Indigenous Communities* PhD thesis, Evergreen State College (2009).
94. Singh, R. K., Bhowmik, S. N. & Pandey, C. B. Biocultural diversity, climate change and livelihood security of the Adi community: grassroots conservators of Eastern Himalaya Arunachal Pradesh. *Indian J. Tradit. Knowl.* **10,** 39–56 (2011).
95. Doyle, J. T., Redsteer, M. H. & Eggers, M. J. Exploring Effects of Climate Change on Northern Plains American Indian Health. *Climatic Change* **120,** 643–655 (2013).
96. Garcia, D. T. *The Interrelationship of Local and Global Events and the Changing Ecological and Socio-Economic States of the Sierra Tarahumara in Chihuahua, Mexico* BSc thesis, Univ. Arizona (2009).
97. Shimola, K. & Krishnaveni, M. in *On a Sustainable Future of the Earth's Natural Resources* (ed. Ramkumar, M.) 509–516 (Springer, 2013).
98. Phuong, L. T. H. *Climate Change and Farmers' Adaptation: A Case Study of Mixed-Farming Systems in the Coastal Area in Trieu Van Commune, Trieu Phong District, Quang Tri Province, Vietnam* MSc thesis, HUAF (2011).
99. Zaheer, K. *Community Vulnerability Assessment: Kharo Chan, Keti Bunder and Jiwani* (World Wide Fund for Nature, 2012).

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Author contributions

V.S. and D.L. conceptualized the research design and contributed equally to the writing of the manuscript. V.S. conducted the bibliographic search and analysed the data. J.P.B. carried out the GIS elaborations and contributed to the manuscript. K.E.K. and J.B. contributed to the climate model elaborations and the manuscript. K.L. contributed conceptually to the manuscript and helped with writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permission information is available online at www.nature.com/reprints. Correspondence should be addressed to V.S.

Competing financial interests

The authors declare no competing financial interests.

Methods

This paper is based on an extensive review of peer-reviewed papers, books, master and doctoral theses, participatory videos and unpublished reports by governmental and non-governmental agencies. The search only included material written in English or translated into English. However, we carried out preliminary searches in other languages (Chinese, French, Italian and Spanish) to assess the amount of data available in other languages, and found that the vast majority of papers were written in English. The search for pertinent material dealing with climate change, traditional ecological knowledge, communities (fishers, reindeer herders, agro-pastoralists, Saami, Inuit, Borana and Aymara), interviews, observations and so forth, was carried out for each country in the world (including their overseas territories; 250 in total). The initial search led to more than 3,000 sources with various foci (disaster preparedness, mitigation, hazard prevention and so on). These were then culled to include only those observations made by communities who have a direct relationship with natural resources. Thus, we excluded surveys carried out in cities or with local administrative officials such as park managers. The final selection led to a total of 1,017 studies (Supplementary Table 1). The number of informants extrapolated from these sources totals around 92,000 people whose subsistence base is characterized by hunting, gathering, fishing or farming. Data were not available for all countries, potentially due to a lack of studies, a lack of studies in English, and/or a limited stable population (or the lack of one).

Observations were compiled in a database and were divided in three main categories of direct and indirect changes associated with climatic changes: changes in weather and climate; changes in the physical components of the environment (for example, soil, water), changes in the biological components of the environment (that is, plants and animals). These were then organized into 42 subcategories (Supplementary Table 2) based on climate variables such as rainfall or wind, and relative trends (change, increase, decrease). Changes in the physical environment were categorized by the effects of climatic changes on land and water. Changes in biological systems included those changes related to plants and animals (population, abundance, behaviour, shifts in distribution). Of the indirect changes, only those recognized by the communities to be linked to climatic changes were included (land degradation caused by drought was included, but excluded if observers stated that it was caused by deforestation). In the same way that scientists document ecological changes in a specific area or ecosystem, subsistence-oriented communities observe changes in their environments and infer ecological linkages among species and ecological and physical processes. The analysis of cultural specific attributions or causation of these changes (for example, belief systems) is beyond the scope of this paper. We included only direct observations: we did not include second-hand information obtained by media, agronomists, or any other third party. We characterized each observation by the country and locality where the study was based, the main subsistence activity of the observers (for example, agriculture or pastoralism), cultural or ethnic group, the climatic and vegetation features of the study area (when available) and the bibliographic source. We geo-referenced each observation using the name of the locality and the open source GeoNames geographical database (www.geonames.org). If the name of the village was not found in this database, we used the higher administrative division (county, district) or the closest available town.

Data analyses. Most of our data were analysed qualitatively and geographically. Unlike small, regional data sets that lend themselves to quantitative analyses (for example, refs 29,33,40), our large and diverse data compilation is better suited to a more qualitative approach. We used ArcGIS 10.2 to visualize the geo-referenced database of observations, and created separate layers to represent different categories of observations (World Geodetic System (WGS) 1984 geographic coordinate system). The biome map used in Fig. 3 is based on the World Wildlife Fund (WWF) terrestrial ecoregions of the world spatial layer (www.worldwildlife.org/WildFinder).

To visualize the comparison of human observations of temperature and precipitation with historical model simulations of annual trends in near-surface temperature and rainfall (Figs 4 and 5), we used the statistical software package R (www.R-project.org). We obtained historical model simulations from the KNMI climate explorer in the form of Network Common Data Form (NetCDF) files (http://climexp.knmi.nl/plot_atlas_form.py). Specifically, we downloaded the centennial trends in near-surface temperature and precipitation over the period 1955–2005 from the CMIP5 IPCC AR5 Atlas Subset Annex I[21]. In this circumstance, trends were estimated using a 'historical' concentration pathway outlined in the Annex II of the IPCC[30], and we present the average decadal trend from all 42 model simulations used in the CMIP5 IPCC AR5 Atlas Subset under this 'historical' concentration pathway. This approach uses only a single realization of each model and weighs all models equally, where model realizations differing only in model parameter settings are treated as different models. In the case of Fig. 4, we also use hatching to indicate regions where the magnitude of the historically simulated trend in rainfall is less than one standard deviation of model-estimated present-day natural variability. Put simply, areas with hatching suggest the historically simulated trend is relatively small or that there is little agreement between models on the sign of the trend at the hatched locations. For reference, a non-masked version of Fig. 4 is available (Supplementary Fig. 12).