McKinsey Global Institute

Climate risk and response: Physical hazards and socioeconomic impacts

Reduced dividends on natural capital?

Case study

June 2020

McKinsey Global Institute

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Reduced dividends on natural capital?

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Introduction to case studies

In January 2020, the McKinsey Global Institute published *Climate risk and response: Physical hazards and socioeconomic impacts*. In that report, we measured the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. We explored risks today and over the next three decades and examined specific cases to understand the mechanisms through which climate change leads to increased socioeconomic risk. This is one of our case studies, focused on natural capital.

We investigated cases that cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of McKinsey Global Institute research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We found these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds (Exhibit 1). As such, these cases represent leading-edge examples of climate change risk. Each case is specific to a geography and an exposed system, and thus is not representative of an "average" environment or level of risk across the world. Our cases show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). We typically define the climate state today as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. Such an "inherent risk" assessment allows us to understand the magnitude of the challenge and highlight the case for action. (We also choose a sea level rise scenario for one of our cases that is consistent with the RCP 8.5 trajectory). Our case studies cover each of the five systems we assess to be directly affected by physical climate risk, across geographies and sectors. While climate change will have an economic impact across many sectors, our cases highlight the impact on construction, agriculture, finance, fishing, tourism, manufacturing, real estate, and a range of infrastructure-based sectors. The cases include the following:

— For livability and workability, we look at the risk of exposure to extreme heat and humidity in India and what that could mean for that country's urban population and outdoor-based sectors, as well as at the changing Mediterranean climate and how that could affect sectors such as wine and tourism.

— For food systems, we focus on the likelihood of a multiple-breadbasket failure affecting wheat, corn, rice, and soy, as well as, specifically in Africa, the impact on wheat and coffee production in Ethiopia and cotton and corn production in Mozambique.

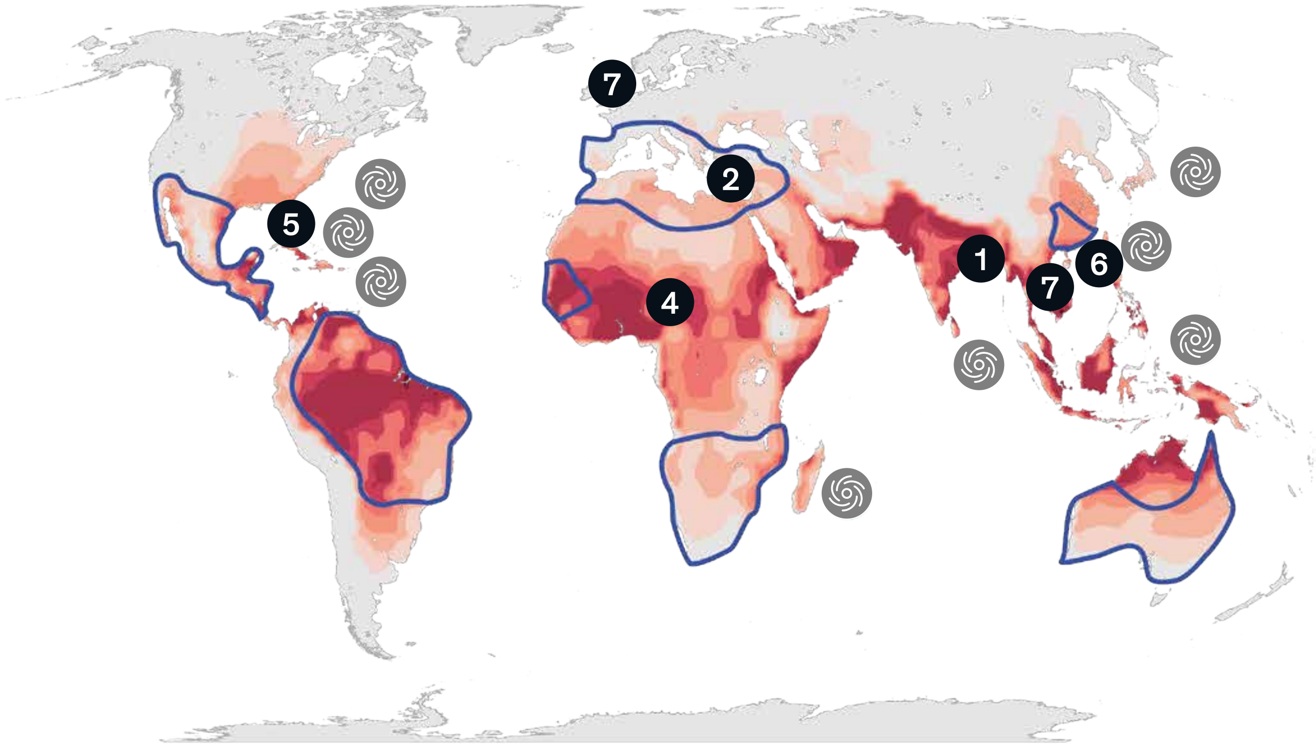
— For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

— For infrastructure services, we examine 17 types of infrastructure assets, including the potential impact on coastal cities such as Bristol in England and Ho Chi Minh City in Vietnam.

— Finally, for natural capital, we examine the potential impacts of glacial melt and runoff in the Hindu Kush region of the Himalayas; what ocean warming and acidification could mean for global fishing and the people whose livelihoods depend on it; as well as potential disturbance to forests, which cover nearly one-third of the world's land and are key to the way of life for 2.4 billion people.

Exhibit 1

We have selected nine case studies of leading-edge climate change impacts across all major geographies, sectors, and affected systems.



Global case studies 3 8 9

Heat stress[1] Low High | Highest drought risk in 2050[2] | Increase in hurricane/cyclone severity

Livability and workability	1	Will India get too hot to work?
	2	A Mediterranean basin without a Mediterranean climate?
Food systems	3	Will the world's breadbaskets become less reliable?
	4	How will African farmers adjust to changing patterns of precipitation?
Physical assets	5	Will mortgages and markets stay afloat in Florida?
	6	Could climate become the weak link in your supply chain?
Infrastructure services	7	Can coastal cities turn the tide on rising flood risk?
	8	Will infrastructure bend or break under climate stress?
Natural capital	9	Reduced dividends on natural capital?

1. Heat stress measured in wet-bulb temperatures.
2. Drought risk defined based on time in drought according to Palmer Drought Severity index (PDSI).
Source: Woods Hole Research Center; McKinsey Global Institute analysis

Climate change due to global warming degrades the health of coral reefs, Pacific Ocean.

Natural capital

Reduced dividends on natural capital?

The world's stock of natural resources—its natural capital—performs a range of services that are essential to human well-being. One type of these so-called ecosystem services is providing goods such as food, fiber, fuel, water, and wood. Another type involves regulating environmental conditions in various ways: controlling pollution, protecting against natural hazards like floods and forest fires, and purifying water, among others. A third type of ecosystem service is supporting recreation, spiritual fulfillment, aesthetic enjoyment, and other cultural practices.

Human activities are depleting natural capital and curtailing ecosystem services at an unprecedented rate. Some of these activities involve the intentional conversion of natural capital into other forms of productive capital, such as clear-cutting forestland so it can be farmed. Others degrade natural capital stock without direct socioeconomic benefit. Even if natural capital conversion can propel economic development, economists note that care should be taken when making decisions about converting natural capital. This is because natural capital is not fungible—that is, rebuilding natural capital stock by conversion of other forms of capital is not straightforward. A stark example is species extinction, which is all but impossible to reverse, but the caution also applies to forms of natural capital such as forests, which can be replanted but may take decades or centuries to regain their previous levels of biodiversity and carbon content.

Climate change accelerates depletion of natural capital and ecosystem services because it is altering major geophysical conditions—average surface temperatures, ocean body temperatures, precipitation patterns, the oxygen content and acidity of seawater—too quickly for natural systems to adapt. When these changes reach thresholds that ecosystems can no longer sustain, natural capital and ecosystem services often degrade along a nonlinear path.[1]

It is particularly hard to manage natural capital losses. The time between human actions that affect natural capital and the environmental and ecological responses to those actions can be long. Problems that occur within ecosystems can be hard to diagnose and understand because the systems are so complex. And traditional economic measures discount natural capital by recording only positive outcomes from the depletion of natural capital (for example, the GDP contributions of the fishing industry), and none of the negative outcomes (such as the impact on marine species).

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1 Virginia R. Burkett et al, "Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications," *Ecological Complexity*, December 2005, Volume 2, Number 4.

These trends have had a significant impact on three major types of natural capital that we examine in this case study: glaciers, oceans, and forests (Natural capital-1). Determining the potential socioeconomic impact from natural capital destruction is challenging due to the manifold and complex ways that societies depend on the natural world. As result, in this case study, we highlight the enormous dependency many communities have on natural capital, for example on the water people drink or on fishing and tourism to provide livelihoods, identify the pace of natural capital destruction in parts of the world such as the Himalayas, and how that might continue in the next few decades. We also explore possibilities for combating natural capital destruction.

We start by highlighting the link between the melting of glaciers from rising temperatures and the effect on communities. Scientists observe that glaciers in most parts of the world are shrinking faster than ever, increasing risks of flooding and in the longer term disrupting the flow of glacier-fed rivers that provide one-sixth of the world's people with freshwater for drinking and irrigation. In the Hindu Kush Himalayan region, where glaciers provide water for more than 240 million people, models project substantial glacial mass and area losses in the coming decades for most parts. The greatest relative reductions in glacial area are likely to be for the Salween (losses of 44 to 67 percent) and Mekong (losses of 39 to 68 percent), as their current glacial areas are the smallest. For the Indus basin, a loss in glacier extent ranging from 20 to 28 percent is projected.[2]

Next, we highlight the link between warmer oceans and fishing and tourism. Ocean warming is expected to reduce fish catches by about 8 percent by 2050, and associated revenue by about 10 percent, affecting the livelihoods of approximately 650 million to 800 million people globally who directly or indirectly rely on these revenues. Catch potential in many tropical regions may decline by up to 50 percent, hitting fishing communities even harder.[3] Tourism will also be affected. The Great Barrier Reef, which supports a $5 billion-a-year tourism industry and has suffered four mass bleaching events since 1998 (with half of its reef corals bleaching and dying in 2016–17), is likely to experience bleaching twice each decade by 2035 and annually by midcentury.[4] Finally, we highlight how climate change is increasing the risk of forest wildfires and how that might affect the 1.6 billion people dependent on forests for their livelihood.

As climate change accelerates, losses of natural capital are expected to mount, reducing ecosystem services and affecting local and national economies. Nevertheless, some solutions can help protect natural capital from climate risks, restore depleted natural capital, and limit the socioeconomic impacts of natural-capital losses (see Box 1, "Protecting and restoring natural capital"). Maintaining natural capital and ecosystem services will require more than the protection of individual stocks of natural capital, such as single species. It will require measures to protect and restore entire ecosystems and, critically, in many instances a coordinated international response, for example in the case of ocean warming.

[2] Arun Bhakta Shrestha et al., eds., *The Himalayan climate and water atlas: Impact of climate change on water resources in five of Asia's major river basins*, CIMOD, GRID-Arendal, and CICERO, 2015.
[3] Vicky W. Y. Lam et al., "Projected change in global fisheries revenues under climate change," *Scientific Reports*, 2016, Volume 6, Article 32607.
[4] Terry P. Hughes et al., "Global warming impairs stock—recruitment dynamics of corals," *Nature*, April 2019, Volume 568.

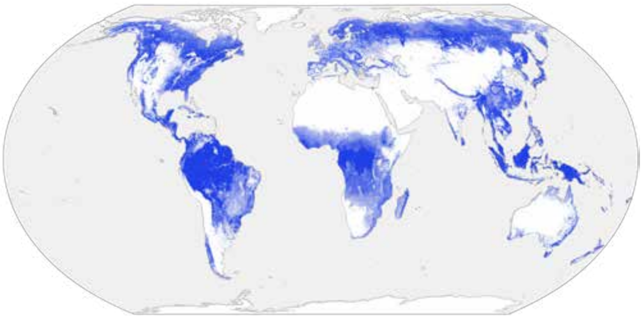
Case study India-1

Natural capital can be found all over the globe.

Forest

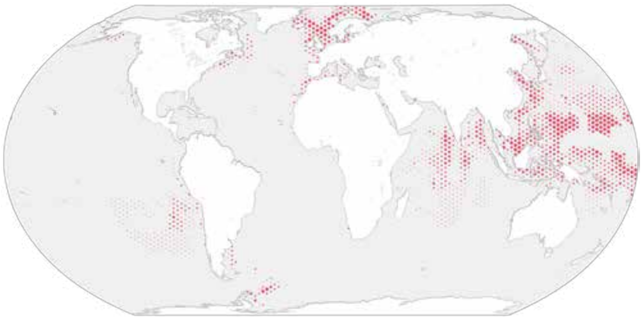
Tree density (%)

0 100

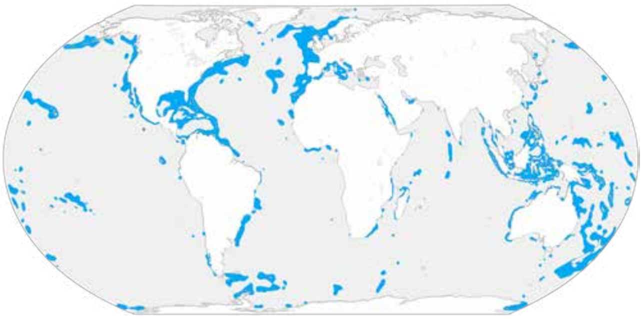


Fish stocks[1]

0 100



Coral reefs



Land ice

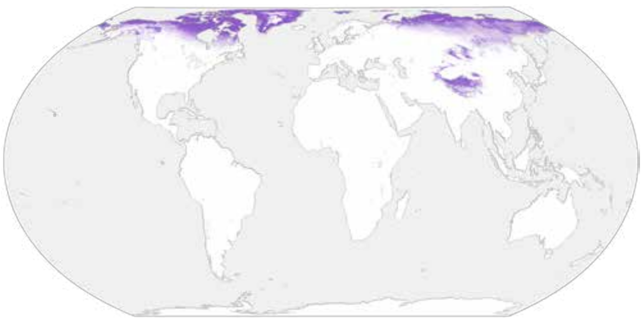
Freshwater

Regions with high freshwater availability

Permafrost

Permafrost coverage (%)

0 100



1. Index of global fishing activity used as proxy for fish stocks.

Source: Data Basin, 2016; FAO, 2010; Halpern et al., 2015; Hughes et al., 2019; James, *National Geographic*, 2018; Lam et al., 2016; NASA Earth Observatory; UNEP, 2014; Wester et al., 2018; Witt et al., 2014; Zemp et al., 2019; McKinsey Global Institute analysis

Box 1.

Protecting and restoring natural capital

Several types of measures can help protect natural capital against climate change. The first type focuses on preventing environmental changes resulting from higher surface temperatures and helping nature withstand changes that do happen. One important measure is sustaining important ecological functions by means of interventions like altering hydrology to help ecosystems during droughts, maintaining and restoring soil quality and nutrient cycling in forests, and maintaining and restoring coastal vegetation.

The second type of protection measures involves making ecosystems more adaptable. Maintaining and enhancing genetic diversity within and among species is one way to do this. For example, using genetic material from other places can increase the resilience of forests. Genetically engineered corals that can resist rising temperatures could help protect the Great Barrier Reef. Wildlife biologists can facilitate species migration and movements with proper landscape-scale planning and design. Authorities can also allow nature to restore itself after damaging events. Following a wildfire, monitoring “control” areas of natural revegetation help identify species that can grow back without assistance.

Third, developing better mechanisms for monitoring natural capital and the impact of climate change can help authorities to make more informed decisions. Experts could create metrics, data, and tools to measure nature’s benefits to people, provide tangible ways to identify trade-offs, and better understand complex ecosystem system dynamics, including feedbacks and the impact of climate change. More sophisticated methods for calculating the value of natural capital and ecosystem services would help as well.

Fourth, certain types of natural capital, such as forests, can be restored, although their full range of ecosystem services might not recover. Designing and building so-called green infrastructure can help. This approach consists of integrating natural processes with spatial planning and territorial development. Green infrastructure projects include planting trees, creating parks, and putting planted walls or roofs on buildings. Other projects aim to restore natural habitats and improve biodiversity. For example, the Netherlands developed five projects to create shallows and increase water-retention capacity in areas where approximately four million people are at risk of catastrophic flooding. As a secondary objective, these projects would also help enhance biodiversity.

Finally, where losses of natural capital and ecosystem services cannot be avoided, communities may need help adapting. Economic-diversification strategies can help communities that depend on sectors threatened by climate change, such as tourism, agriculture, fisheries, and forestry. Pacific Island countries use aggregating devices to adapt to changing fish migration patterns. They lower socioeconomic costs because fishermen can collect fish from the anchored devices rather than searching widely for them. Some communities will need help adapting to the physical risks of climate change as well. In Mongolia, authorities implemented sustainable land-use methods and water-resource monitoring to help communities maintain water supply.

Disaster relief funds and other types of financial support can also help alleviate the socioeconomic consequences of natural-capital loss. A program in Ethiopia provided cash and food to families that ran out of food because of drought, delayed rains, and flooding. To earn the benefits, families needed to participate in local land-rehabilitation efforts and other initiatives intended to enhance agricultural productivity. Risk-transfer and insurance mechanisms can also boost communities’ socioeconomic resilience to climate change. A weather-insurance program for small-scale producers in Burkina Faso was developed to protect their income against crop damage caused by climate change.

Increasing awareness among communities and policy makers, along with building and deploying risk management tools, can also help lessen the impact of ecosystem changes. The United Nations Institute for Training and Research develops and shares tools, methods, knowledge, and skills to develop institutional capacities to address specific climate change problems (such as floods and droughts). In Gambia, officials used the UN institute’s adaptation tool kit to perform a vulnerability assessment. This led to the adoption of such adaptation interventions as the construction of waterways to carry heavy storm runoff, the building of concrete structures to prevent infrastructure from collapsing during floods, and the prohibition of encroachment on wetlands. Early-warning systems help reduce risk, improve safety, and raise awareness in regions affected by climate change. Farmers in Cambodia can now access climate bulletins to avoid the costly consequences of floods.

Glaciers are melting, and the change has begun to disrupt crucial supplies of freshwater

Glaciers play an essential part in regulating the supply of freshwater. They collect precipitation that falls during the winter and hold it until warm summer weather sends meltwater coursing down rivers to the many people who need it. Glaciers cover 10 percent of Earth's land surface and contain 75 percent of the world's freshwater. More than one-sixth of the world's people depend on glacier-fed rivers for drinking and irrigation water.[5]

Glaciers are losing mass at an unprecedented rate in most parts of the world. On average, they lose 335 billion tons of snow and ice each year, enough to raise sea levels by almost one millimeter per year.[6] Because glacial response times are decades or longer, the current rate of glacial retreat also reflects both past and current climate variability. Nevertheless, about 70 percent of the loss in glacial mass that occurred from 1991 to 2010 has been attributed to human-induced increases of temperatures.[7] In the near term, melting glaciers increase supplies of freshwater as well as the risk of flooding. Runoff from glaciers could form lakes on the slopes of icy mountains with degrading permafrost (surface and subsurface ice). As permafrost melts, mountain slopes could become less stable and more likely to release outbursts from glacial lakes, which can result in floods. Such hazards can cause significant loss of life as well as damage to land, property, and infrastructure.[8] Floods caused by glacial-lake outbursts have been reported worldwide, with the greatest concentration observed in the middle Himalayas.[9] For this reason, many mountainous countries have established mechanisms for monitoring and forecasting glacial floods and have begun to take cautionary measures.[10]

In the long run, the shrinking of glaciers is expected to reduce freshwater availability, leading to large socioeconomic impacts in sectors such as agriculture, hydroelectricity, and tourism. Global mass loss of all glaciers is projected to be 24 percent by 2100 compared with 2015 and under RCP 6.0; however, loss of glacial mass per glacier and region may vary widely.[11] Alpine glaciers could lose 50 to 90 percent of their current volume by 2100, and the average snow line is expected to rise by 150 meters for each degree of warming.[12] While the overall volume of freshwater released by glaciers is projected to stay the same, that water is expected to flow during shorter periods each year (again, changes per glacier and region may vary widely). The effects of this change could include a reduction in the generation of hydroelectric power during the summer, periodic droughts, and increased water stress which has also been linked to increases in conflict.[13]

The Hindu Kush Himalayan region faces significant physical and socioeconomic risks as a result of glacial melting

The Hindu Kush Himalayan region covers eight countries, from Afghanistan in the west to Myanmar in the east. Its glaciers provide water for irrigation, energy generation, and other economic activities for the region's 240 million residents and about 750 million people in total. The melting of Himalayan glaciers has doubled since 2000, and more than a quarter of glacial

5 *State of the planet*, "The glaciers are going," blog entry by Renee Cho, May 5, 2017.

6 Michael Zemp et al., "Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016," *Nature*, April 2019.

7 Ben Marzeion et al., "Attribution of global glacier mass loss to anthropogenic and natural causes," *Science*, August 2014, Volume 345, Number 6199.

8 Wilfried Haeberli, Yvonne Schaub, and Christian Huggel, "Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges," *Geomorphology*, September 2017, Volume 293, Part B; Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, January 2019.

9 L. Iturrizaga, "Glacier Lake Outburst Floods," in: V. P. Singh, P. Singh, U. K. Haritashya, eds., *Encyclopedia of Snow, Ice and Glaciers,* Encyclopedia of Earth Sciences Series, 2011.

10 Mark Carey, "Disasters, development, and glacial lake control in twentieth-century Peru," in *Mountains: Sources of Water, Sources of Knowledge*, Ellen Wiegandt, ed., Dordrecht, The Netherlands: Springer, 2008; Department of Geography, University of Zurich, *Glacier hazards*, glacierhazards.ch.

11 Regine Hock et al., "GlacierMIP—A model intercomparison of global-scale glacier mass-balance models and projections," *Journal of Glaciology*, June 2019, Volume 65, Number 251.

12 Martin Beniston, "Impacts of climatic change on water and associated economic activities in the Swiss Alps," *Journal of Hydrology*, January 2012, Volumes 412–413.

13 Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, January 2019.

ice in negatively affected regions has been lost in the past four decades.[14] Glacial mass in this region could drop by about 10 to 25 percent by 2030, and by 20 to 40 percent by 2050 in some subregions. The region already faces severe danger of catastrophic flooding.[15] Climate change has been the main cause of these developments.[16]

On the Tibetan Plateau, glacial retreat has caused hydrological changes, including an increase in river runoff of more than 5 percent and a 0.2-meter annual rise in water levels.[17] While runoff has already peaked from 45 percent of the world's glaciers, including the source of the Brahmaputra River, runoff from 22 percent of glacier-fed basins is predicted to increase. The headwaters of the Ganges River and the Indus River are expected to peak in 2050 and 2070, respectively.[18] Although annual river flows across major parts of the region are expected not to change greatly, pre-monsoon flows are forecast to decline, compromising irrigation, hydropower, and ecosystem services. Acute climate events, such as the disappearance of expected rainfall, will magnify the effects of changes in river flows.[19]

These changes will have significant consequences, particularly for rural communities that rely on rivers. The risk of floods poses an immediate threat to human populations. Climate-dependent sectors, such as agriculture, will also be threatened.[20] The consequences could be severe for countries such as India, which has the world's 13th-highest level of water stress and a population three times greater than the total population of the 17 other countries with high water stress.[21] Altered river flows are likely to disrupt food and water supplies, and could cause mass population displacements and heighten geopolitical tensions and the risk of conflicts over the management of water and the construction of river dams.

For the Hindu Kush Himalayan region, integrated water planning and management across sectors (such as energy, land, forest, ecosystems, and agriculture) could make water use more efficient and reduce environmental impacts. More water storage could help when discharges are low. Physical protections (such as flood-prevention structures, better irrigation systems, upgraded canals, precision land leveling, and proper implementation and enforcement of building codes) and management tools (such as land-use planning laws and early-warning systems) are also needed to manage risk.[22]

Measures to protect glaciers against continued loss of mass are being explored around the world. For instance, some scientists argue that vulnerable glaciers could be protected with underwater walls built by robots.[23] However, at this stage, measures are being explored on only a relatively small scale and involve immense investment. If at all possible, finding effective long-term solutions will require further research and large-scale experiments.

14 J. M. Maurer et al., "Acceleration of ice loss across the Himalayas over the past 40 years," *Science Advances*, June 2019, Volume 5, Number 6.

15 Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, January 2019.

16 D. Carrington, "Himalayan glacier melting doubled since 2000, spy satellites show," *Guardian,* June 2019.

17 Tandong Yao et al., "Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding regions," *Arctic, Antarctic, and Alpine Research*, November 2007, Volume 39, Number 4; Guoqing Zhang et al., "Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009)," *Remote Sensing of Environment*, July 2011, Volume 115, Number 7.

18 Matthias Huss and Regine Hock, "Global-scale hydrological response to future glacier mass loss," *Nature Climate Change*, January 2018, Volume 8, Number 2.

19 Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, January 2019.

20 Arun Bhakta Shrestha et al., eds., *The Himalayan climate and water atlas: Impact of climate change on water resources in five of Asia's major river basins*, CIMOD, GRID-Arendal, and CICERO, 2015.

21 *Insights*, "17 countries, home to one-quarter of the world's population, face extremely high water stress," blog entry by Rutger Willem Hofste, Paul Reig, and Leah Schleifer, August 6, 2019.

22 Jo-Ellen Parry, Anika Terton, and Hisham Osman, *Making every drop count: Pakistan's growing water scarcity challenge*, International Institute for Sustainable Development, September 2016.

23 Matthew J. Wolovick and John C. Moore, "Stopping the flood: Could we use targeted geoengineering to mitigate sea level rise?," *The Cryosphere*, 2018, Volume 12, Number 9.

Oceans are warming and undergoing chemical changes, with harmful consequences for marine life and coastal communities

Covering more than 70 percent of the Earth's surface, oceans provide important ecosystem services. They transport heat between the equator and the poles, which helps regulate the climate and global weather patterns. They generate over half of the world's oxygen and currently absorb roughly 30 percent of fossil fuel CO_2 emissions, acting as an important carbon sink that slows the rise in atmospheric CO_2.[24] Marine fisheries and aquaculture produce about 15 percent of the animal protein consumed by 4.3 billion people and support the livelihoods of approximately 650 million to 800 million people globally.[25] Coral reefs attract tourists, who generate economic activity, as well as anchoring certain marine ecosystems.

The world's oceans are subject to harm from climate change and from greenhouse-gas emissions. Ocean temperatures are rising: from 1950 to 2009, the average surface temperature rose in the Indian Ocean (0.65 degree Celsius), the Atlantic Ocean (0.41 degree), and the Pacific Ocean (0.31 degree).[26] Globally, the rate of ocean warming doubled from 1969–93 to 1993–2017.[27] Ocean warming is increasing the frequency and duration of marine heat waves that can strongly affect marine ecosystems, such as seagrass and kelp forests, which contain significant amounts of carbon.[28] Ocean warming also causes seawater to release stored oxygen. The increasing concentration of CO_2 in the atmosphere causes the ocean to absorb more CO_2, which makes seawater more acidic. The oceans have absorbed roughly 30 percent of the CO_2 emitted by human activities since the preindustrial period, leading to a 0.1 pH decrease, a change that is unprecedented in speed during the past 65 million years.[29] Moreover, rate of CO_2 absorption is slowing due to rising ocean temperatures, reducing the ability of the ocean to slow the rise in atmospheric CO_2 concentrations.[30] Warming, deoxygenation, and acidification change the oceans' circulation patterns and chemistry.

Warmer and more acidic oceans have a direct impact on marine species by altering important ecosystem-level processes (for example, primary productivity, reef building, and erosion) as well as physiological processes of marine species and organisms (such as skeleton formation, gas exchange, reproduction, growth, and neural function). Marine creatures, particularly fish and zooplankton, are migrating to higher latitudes, where they engage in seasonal behaviors such as reproduction at different times than in the past.[31] As a result, fisheries have been put under stress. According to one estimate, ocean warming reduced the maximum sustainable global yield of seafood by 4 percent between 1930 and 2010. Yields have fallen by even more in certain areas: in the Sea of Japan and the North Sea, as much as 35 percent.[32] Climate change is forecast to lower fish catches by about 8 percent and associated revenues by about 10 percent or $6 billion to $15 billion (including ranges) by 2050 under RCP 8.5. Fisheries

24 P. Ciais et al., "Carbon and Other Biogeochemical Cycles," in: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* T. F. Stocker et al., eds., Cambridge, UK, and New York, NY: Cambridge University Press, 2013.

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in certain regions could be hit especially hard. Nigeria and Côte d'Ivoire could experience declines of over 50 percent; Ghana, over 60 percent.[33] These trends would pose particular challenges for developing countries where fish is a major component of the typical diet and for small-scale fisheries with fewer technological and financial means to adapt to change.

Africa and Oceania appear most vulnerable in these respects.[34] Africa's small-scale fishermen are especially likely to need help adjusting to climate change's effects on fisheries.[35] In the short term, better governance mechanisms could protect regional marine ecosystems and the services they provide. Affected fishing communities would also need financial support and opportunities to pursue other ways of making a living. For example, microcredit mechanisms have been set up in four of Senegal's marine protected areas to help fishing communities develop alternative sources of income.

Reductions in fishing incomes and food supplies are not the only significant socioeconomic risks posed by climate change's impacts on oceans. Coral reefs have suffered from bleaching and subsequent dying. These impacts have harmed wildlife communities that occupy coral reefs and diminished the habitats of other species.[36] The destruction of coral reefs could also lessen tourism, depriving coastal communities and related sectors of much-needed income (see Box 2, "Half of the Great Barrier Reef's coral has died, and further dying could impede tourism"). Half of the Great Barrier Reef's coral has died, and further dying could impede tourism.[37] Tourism around coral reefs accounts for an estimated $35 billion a year of economic value, including $19 billion of "on-reef" activities (diving, snorkeling, glass-bottom boating, and the like) and $16 billion of "reef-adjacent" tourism (for example, beachgoing, paddle-boarding, and surfing) permitted by the reefs' sheltering effects.[38]

Experts have suggested that mitigating pressures (such as pollution, commercial fishing, invasive species, and coastal habitat modification) could reduce and delay the effects of climate change on the world's oceans. Increased international cooperation could ease adaptation to variation in the productivity of global fisheries. To increase the resilience of coral reef fisheries, experts recommend managing catchment vegetation to improve coastal water quality, maintaining connectivity of coral reefs with mangrove and seagrass habitats, sustaining and diversifying the catch of coral reef fish, and transferring fishing activity to pelagic fish resources.[39] Scientists are investigating measures to restore coral reefs, such as selective breeding, assisted gene flow, conditioning, epigenetic programming, and manipulation of the coral microbiome.

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Box 2.

Half of the Great Barrier Reef's coral has died, and further dying could impede tourism

The Great Barrier Reef, the largest coral reef system in the world, spans more than 2,600 kilometers off the coast of Queensland, Australia. It sustains some 10 percent of the world's fish species, accounts for approximately $5 billion per year in tourism revenue, and supports roughly 69,000 jobs.[1] Since 2016, at least 50 percent of the reef's corals have bleached and died.[2] That year, a strong El Niño event—on top of previous anthropogenic warming—resulted in the bleaching of 93 percent of the reef and the death of 30 percent of its corals.[3] In 2017, unusually warm water led to further bleaching and the deaths of an additional 20 percent of corals. Larval recruitment declined by 89 percent in 2018, which makes the prospect of recovery uncertain, especially with a higher likelihood of extreme climate events in the next 20 years.[4] Recovery is even more imperiled when considering the projection that bleaching might occur twice each decade from 2035 and is expected to repeat every year by midcentury. In addition, even the fastest growing coral species might take a decade or longer to recover, diminishing the reef's ecological resistance.[5] In addition to ocean warming, the occurrence of severe tropical cyclones may increase with a changing climate, causing damage to coral reefs. For instance, Cyclone Yasi affected corals in an area of about 89,000 square kilometers in 2011.[6]

In 2015, a survey of tourists visiting the Great Barrier Reef found that approximately 70 percent came to "see it before it's gone."[7] Although this could lead to a short-term increase in tourist traffic, the number of people visiting the reef declined by more than 5 percent after the 2016 bleaching event. More dying of the reef's corals could further reduce tourism and slow fishing activity. The Australia Institute estimated that roughly $900 million of annual expenditure by visitors is at risk.[8]

Anticipating these challenges, the Australian national and Queensland state governments formed a plan for the protection of the reef in 2015 and updated it in 2018. The national government has committed more than $700 million to address threats to the reef. The plan includes such measures as prohibiting capital dredging in the Great Barrier Reef Marine Park, improving shipping management, reducing the inflow of polluted water, and setting up protected areas.[9] Although some experts have criticized the plan for not providing sufficient protection, the Great Barrier Reef Marine Park Authority has stated, "Only the strongest and fastest possible action on climate change will reduce the risks and limit the impacts of climate change on the reef."[10]

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Climate change is exacerbating the pressure on the world's forests

Approximately 1.6 billion people depend on forests, which cover nearly one-third of the world's land, to make their living. Some studies suggest that forests and trees furnish rural households in developing countries with about 20 percent of their income. Some 2.4 billion people use wood as fuel to cook, boil and sterilize water, and heat their dwellings.[40] Forests also have tremendous ecological importance. They are the habitats for more than three-quarters of the world's species, and they store up to 45 percent of all the carbon found on land.[41] And, like oceans, forests act as important carbon sinks; the biosphere currently absorbs approximately 30 percent of fossil fuel CO_2 emissions, with the majority stored in forests and mangroves.[42]

Several research groups studied the link between climate change and forest disturbances due to wind, snow and ice, fire, drought, insects, and pathogens. This research showed that climate change most likely has a triggering or intensifying effect on disturbances—57 percent of the observations in the studied literature were related to direct impacts of climate change on disturbance processes.[43] Disturbances can also feed back into climate change—wildfires emit large quantities of CO_2 and thus exacerbate the rate of change in the climate.

Intensifying disturbances and the associated damages are projected to be among the most severe impacts of climate change on forests. One study estimated a rate of damage increase of more than 910,000 cubic meters of timber per year until 2030 for European forests, based on harm from wind, bark beetles, and forest fires; trees are often weakened by drought, which may increase the likelihood of insect infestation and ultimately fires.[44]

Because forests take a long time to grow but then live for decades or longer, they are likely to face risks from both changes in mean climate variables and extreme weather events like prolonged drought, storms, and floods.[45] This is especially relevant when considering that fires, drought, and insect activity are likely to increase in warmer and drier conditions.[46]

Climate change, a result of human activity, worsens wildfires by making forests hotter and drier.[47] In 2014, so-called megafires in Canada burned more than seven million acres of forest, releasing more than 103 million tons of carbon, half of what the country's vegetation absorbs in a typical year.[48] Climate change made fires in this region 1 to 6 times more likely.[49] Such major wildfires have become normal in other parts of the world as well. They are also costly. During 2018, the costs of wildfires in the United States totaled $24 billion, primarily from the destruction of property.[50]

Forests can be protected by altering forest structures to reduce the frequency or severity of wildfires.[51] It is also possible to maintain wildlife refuges capable of resisting ecological changes and to protect ecologically significant areas such as spawning grounds and highly biodiverse habitats.

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