

# CR

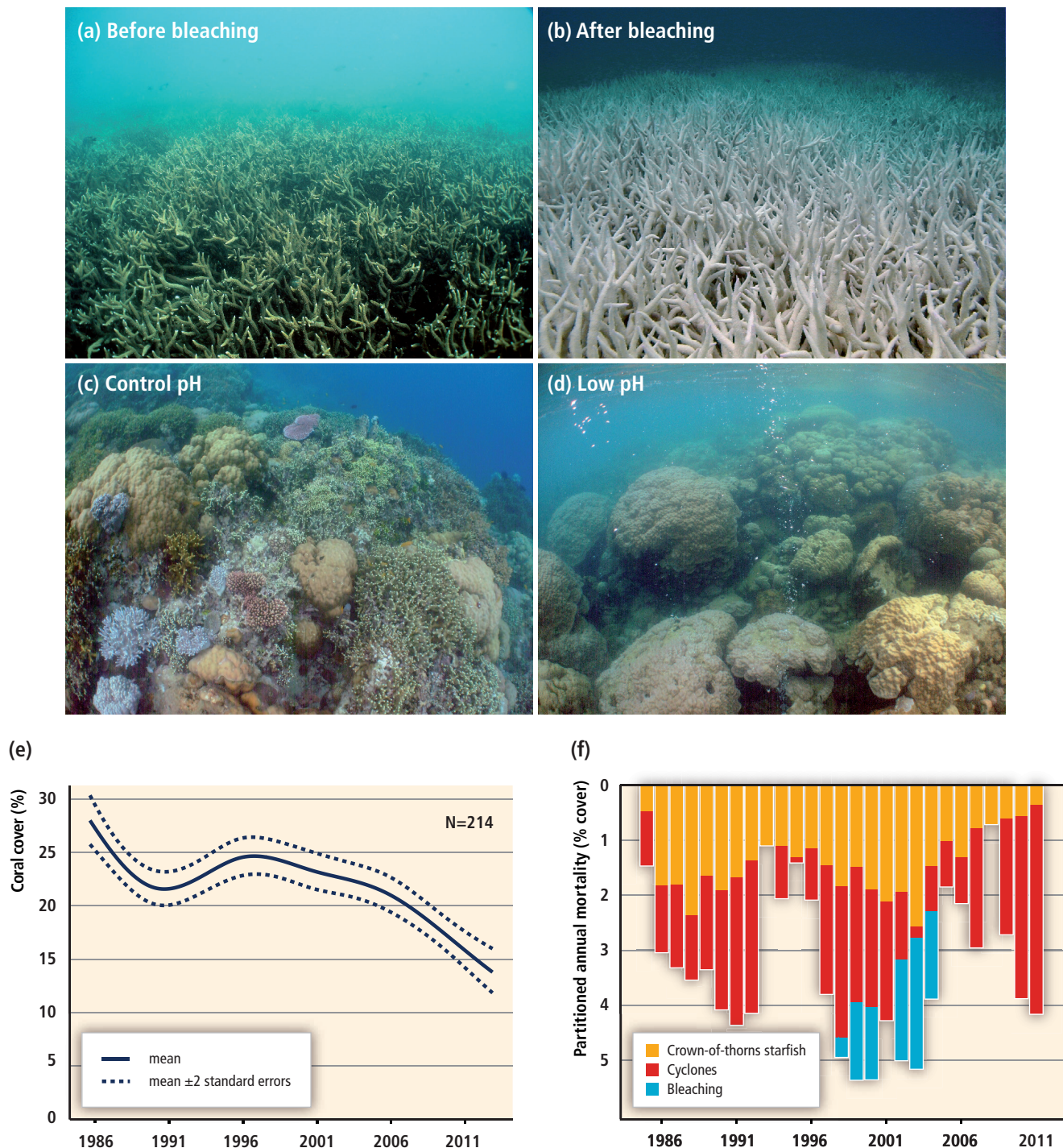
## Coral Reefs

Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection, and appealing environments for tourism (Wild et al., 2011). About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011), including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling), and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (Section 29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; Sections 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5), and more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment, and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (Sections 5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see Section 6.3.1. for physiological details and Section 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; Sections 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5, and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997–1998 was unmatched in the period 1903–1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; Sections 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; Section 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs toward net dissolution (*medium confidence*; Section 5.4.2.4).



**Figure CR-1** | (a, b) The same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Approximately 95% of the coral community was severely bleached in 2002 (Elvidge et al., 2004). Corals experience increasing mortality as the intensity of a heating event increases. A few coral species show the ability to shuffle symbiotic communities of dinoflagellates and appear to be more tolerant of warmer conditions (Berkelmans and van Oppen, 2006; Jones et al., 2008). (c, d) Three  $\text{CO}_2$  seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high  $\text{CO}_2$  is related to fundamental changes in the ecology of coral reefs (Fabricius et al., 2011), including reduced coral diversity (–39%), severely reduced structural complexity (–67%), lower density of young corals (–66%), and fewer crustose coralline algae (–85%). At high  $\text{CO}_2$  sites (d; median  $\text{pH}_t \sim 7.8$ , where  $\text{pH}_t$  is pH on the total scale), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (c; median  $\text{pH}_t \sim 8.0$ ). Reef development ceases at  $\text{pH}_t$  values below 7.7. (e) Temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N=number of reefs, De'ath et al., 2012). (f) Composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). (Photo credit: R. Berkelmans (a and b) and K. Fabricius (c and d).)

Ocean warming and acidification have synergistic effects in several reef-builders (Section 5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; Section 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg et al., 2007). The abundance of reef building corals is in rapid decline in many Pacific and Southeast Asian regions (*very high confidence*, 1 to 2% per year for 1968–2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by more than 80% on many Caribbean reefs (1977–2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators, and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones et al., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate-related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the Representative Concentration Pathway (RCP)3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present-day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high-frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan et al., 2014). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- **Resources:** Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and de Leiva Moreno, 2003). More than half (55%) of the 49 island countries considered by Newton et al. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the Special Report on Emission Scenarios (SRES) A2 emissions scenario (Bell et al., 2013).
- **Coastal protection:** Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification, and higher rates of dissolution and bioerosion due to ocean warming and acidification (Sections 5.4.2.4, 6.4.1, 30.5).
- **Tourism:** More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A\$5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the global gross domestic product (GDP) but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001–2011; Laurans et al., 2013). At the local scale, these two services provided in 2009–2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour et al., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig et al., 2012), suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012; Billé et al., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm et al., 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (McLeod et al., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2013) and coastal pollutants enriched with fertilizers can increase acidification (Kelly et al., 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; Section 5.2.4.4, 30.5).

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# Ecosystem-Based Approaches to Adaptation—Emerging Opportunities

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Ecosystem-based adaptation (EBA), defined as the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (CBD, 2009), integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see IPCC AR5 WGII Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even serve as a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls, and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches (CBD, 2009). In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012; Midgley et al., 2012; Roberts et al., 2012).

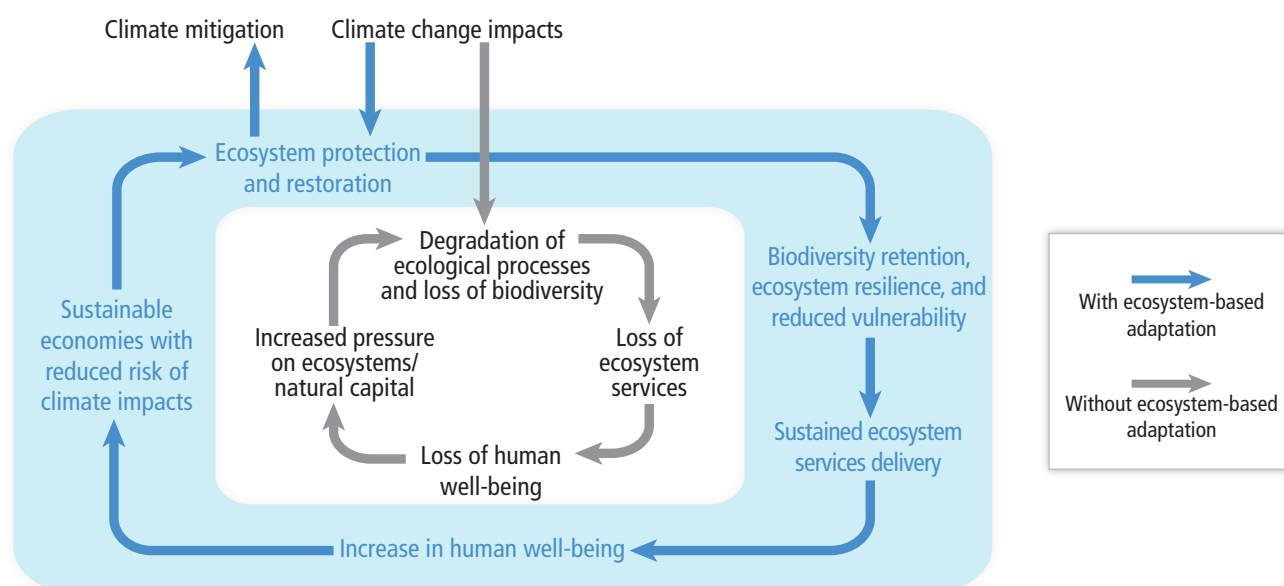
Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and

enhanced baseflows, flood regulation and protection services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Opperman et al., 2009; Midgley et al., 2012)

- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques.
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach (CBD, 2009). The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.



**Figure EA-1** | Adapted from Munang et al. (2013). Ecosystem-based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

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# Gender and Climate Change

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Gender, along with sociodemographic factors of age, wealth, and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation, and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger et al., 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer et al., 2007; Buechler, 2009; Nelson and Stathers, 2009; Nightingale, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Omolo, 2011; Resurreccion, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health, and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labor markets, making women in particular less able to cope with and adapt to climate change impacts (Paavola, 2008; Djoudi and Brockhaus, 2011; Rijkers and Costa, 2012). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whereas both men and women experience increases in productive roles, only women experience increased reproductive roles (Resurreccion, 2011; Section 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity because food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota et al., 2011).

AR4 assessed a body of literature that focused on women's relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger et al., 2007). Additional literature published since that time adds nuances by showing how socially constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*; Section 11.3.3, Table 12-3). Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981 and 2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007; see also Box 13-1). Reasons for gendered differences in mortality include various socially and culturally determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house,

even during floods and in risk-prone areas (Bradshaw, 2010). Although the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality (Box 13-1). In Hai Lang district, Vietnam, for example, more men died than women as a result of their involvement in search and rescue and protection of fields during flooding (Campbell et al., 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the USA and Australia (Jenkins and Phillips, 2008; Anastario et al., 2009; Alston, 2011; Whittenbury, 2013; see also Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (Section 11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and São Paulo (Bell et al., 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Vincent et al., 2010; Arora-Jonsson, 2011; Figueiredo and Perkins, 2012). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women because cash generation is seen as a male activity in rural areas (Gladwin et al., 2001; see also Section 13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor, which women cannot necessarily afford to provide (Baiphethi et al., 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Goulden et al., 2009; Vincent et al., 2010; Below et al., 2012) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert and Machado, 2012; Bee et al., 2013; Tschakert, 2013; see also Section 22.4.3 and Table 22-5).

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# HS

## Heat Stress and Heat Waves

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According to WGI, it is *very likely* that the number and intensity of hot days have increased markedly in the last three decades and *virtually certain* that this increase will continue into the late 21st century. In addition, it is *likely (medium confidence)* that the occurrence of heat waves (multiple days of hot weather in a row) has more than doubled in some locations, but *very likely* that there will be more frequent heat waves over most land areas after mid-century. Under a medium warming scenario, Coumou et al. (2013) predicted that the number of monthly heat records will be more than 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +7°C or more, the habitability of parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and may act as triggers of tipping points (Hughes et al., 2013). Consequently, heat stress plays an important role in several key risks noted in Chapter 19 and CC-KR.

### **Economy and Society (Chapters 10, 11, 12, 13)**

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present-day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012; see also Section 8.2.3.1). In low- and medium-income countries, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).



## Human Health (Chapter 11)

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro et al., 2011; Nitschke et al., 2011; Rahmstorf and Coumou, 2011; Diboulo et al., 2012; Hansen et al., 2012). Elderly people and people with circulatory and respiratory diseases are also vulnerable even in developed countries; they can become victims even inside their own houses (Honda et al., 2011). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, et al., 2008). High temperatures are also associated with an increase in air-borne allergens acting as triggers for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

## Ecosystems (Chapters 4, 5, 6, 30)

Tree mortality is increasing globally (Williams et al., 2013) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult owing to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013; see also Box 4.2).

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small ( $<0.5^{\circ}\text{C}$ ) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated  $\text{CO}_2$  levels and associated acidification (*medium confidence*; Hoegh-Guldberg et al., 2007; see also Figure 6-5; Sections 6.3.1, 6.3.5, 30.4, 30.5; CC-MB).

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*). Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*; Sections 5, 6, 30.4, 30.5, CC-CR, CC-MB).

## Agriculture (Chapter 7)

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past  $+3^{\circ}\text{C}$  of local warming without adaptation, even with benefits of higher  $\text{CO}_2$  and rainfall, are expected even in cool environments (Teixeira et al., 2013). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and suitability for crops (*medium evidence, medium agreement*; Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the USA, current economic losses due to heat stress of livestock are estimated at several billion US\$ annually (St-Pierre et al., 2003).

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# A Selection of the Hazards, Key Vulnerabilities, Key Risks, and Emergent Risks Identified in the WGII Contribution to the Fifth Assessment Report

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The accompanying table provides a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development context (e.g., in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. A representative set of lines of sight is provided from across WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries.

Table KR-1 | Examples of hazards/stressors, key vulnerabilities, key risks, and emergent risks.

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Terrestrial and Inland Water Systems (Chapter 4)	Rising air, soil, and water temperature (Sections 4.2.4, 4.3.2, 4.3.3)	Exceedance of eco-physiological climate tolerance limits of species (limited coping and adaptive capacities), increased viability of alien organisms	Risk of loss of native biodiversity, increase in non-native organism dominance	Cascades of native species loss due to interdependencies
		Health response to spread of temperature-sensitive vectors (insects)	Risk of novel and/or much more severe pest and pathogen outbreaks	Interactions among pests, drought, and fire can lead to new risks and large negative impacts on ecosystems.
	Change in seasonality of rain (Section 4.3.3)	Increasing susceptibility of plants and ecosystem services, due to mismatch between plant life strategy and growth opportunities	Changes in plant functional type mix leading to biome change with respective risks for ecosystems and ecosystem services	Fire-promoting grasses grow in winter-rainfall areas and provide fuel in dry summers.
Ocean Systems (Chapter 6)	Rising water temperature, increase of (thermal and haline) stratification, and marine acidification (Section 6.1.1)	Tolerance limits of endemic species surpassed (limited coping and adaptive capacities), increased abundance of invasive organisms, high susceptibility and sensitivity of warm water coral reefs and respective ecosystem services for coastal communities (Sections 6.3.1, 6.4.1)	Risk of loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms.  Increasing risk of loss of coral cover and associated ecosystem with reduction of biodiversity and ecosystem services (Section 6.3.1)	Enhancement of risk as a result of interactions, e.g., acidification and warming on calcareous organisms (Section 6.3.5)
		New vulnerabilities can emerge as a result of shifted productivity zones and species distribution ranges, largely from low to high latitudes (Sections 6.3.4, 6.5.1), shifting fishery catch potential with species migration (Sections 6.3.1, 6.5.2, 6.5.3)	Risks due to unknown productivity and services of new ecosystem types (Sections 6.4.1, 6.5.3)	Enhancement of risk due to interactions of warming, hypoxia, acidification, new biotic interactions (Sections 6.3.5, 6.3.6)
	Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication (Section 6.1.1)	Increasing susceptibility because hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates (Section 6.3.3)	Risk of loss of larger animals and plants, shifts to hypoxia-adapted, largely microbial communities with reduced biodiversity (Section 6.3.3)	Enhancement of risk due to expanding hypoxia in warming and acidifying oceans (Section 6.3.5)
	Enhanced harmful algal blooms in coastal areas due to rising water temperature (Section 6.4.2.3)	Increasing susceptibility and limited adaptive capacities of important ecosystems and valuable services due to already existing multiple stresses (Sections 6.3.5, 6.4.1)	Increasing risk due to enhanced frequency of dinoflagellate blooms and respective potential losses and degradations of coastal ecosystems and ecosystem services (Section 6.4.2)	Disproportionate enhancement of risk due to interactions of various stresses (Section 6.3.5)
Food Security and Food Production Systems (Chapter 7)	Rising average temperatures and more frequent extreme temperatures (Sections 7.1, 7.2, 7.4, 7.5)	Susceptibility of all elements of the food system from production to consumption, particularly for key grain crops	Risk of crop failures, breakdown of food distribution and storage processes	Increase in the global population to about 9 billion combined with rising temperatures and other trace gases such as ozone affecting food production and quality. Upper temperature limit to the ability of some food systems to adapt
	Extreme precipitation and droughts (Section 7.4)	Crops, pasture, and husbandry are susceptible and sensitive to drought and extreme precipitation.	Risk of crop failure, risk of limited food access and quality	Flood and droughts affect crop yields and quality, and directly affect food access in most developing countries. (Section 7.4)
Urban Areas (Chapter 8)	Inland flooding (Sections 8.2.3, 8.2.4)	Large numbers of people exposed in urban areas to flood events. Particularly susceptible are people in low-income informal settlements with inadequate infrastructure (and often on flood plains or along river banks). These bring serious environmental health consequences from overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and widespread impermeable surfaces. Local governments are often unable or unwilling to give attention to needed flood-related disaster risk reduction. Much of the urban population unable to get or afford housing that protects against flooding, or insurance. Certain groups are more sensitive to ill health from flood impacts, which may include increased mosquito- and water-borne diseases.	Risks of deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	In many urban areas, larger and more frequent flooding impacting much larger population. No insurance available or impacts reaching the limits of insurance. Shift in the burden of risk management from the state to those at risk, leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
	Coastal flooding (including sea level rise and storm surge) (Sections 8.1.4, 8.2.3, 8.2.4)	High concentrations of people, businesses, and physical assets including critical infrastructure exposed in low-lying and unprotected coastal zones. Particularly susceptible is the urban population that is unable to get or afford housing that protects against flooding or insurance. The local government is unable or unwilling to give needed attention to disaster risk reduction.	Risks from deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	Additional 2 billion or so urban dwellers expected over the next three decades  Sea level rise means increasing risks over time, yet with high and often increasing concentrations of population and economic activities on the coasts. No insurance available or reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Urban Areas (continued) (Chapter 8)	Heat and cold (including urban heat island effect) (Section 8.2.3)	Particularly susceptible is a large and often increasing urban population of infants, young children, older age groups, expectant mothers, people with chronic diseases or compromised immune system in settlements exposed to higher temperatures (especially in heat islands) and unexpected cold spells. Inability of local organizations for health, emergency, and social services to adapt to new risk levels and set up needed initiatives for vulnerable groups	Risk of mortality and morbidity increasing, including shifts in seasonal patterns and concentrations due to hot days with higher or more prolonged high temperatures or unexpected cold spells. Avoiding risks often most difficult for low-income groups	Duration and variability of heat waves increasing risks over time for most locations owing to interactions with multiple stressors such as air pollution
	Water shortages and drought in urban regions (Sections 8.2.3, 8.2.4)	Lack of piped water to homes of hundreds of millions of urban dwellers. Many urban areas subject to water shortages and irregular supplies, with constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural–urban linkages. Dependence on water resources in energy production systems	Risks from constraints on urban water provision services to people and industry with human and economic impacts. Risk of damage and loss to urban ecology and its services including urban and peri-urban agriculture.	Cities' viability may be threatened by loss or depletion of freshwater sources—including for cities dependent on distant glacier melt water or on depleting groundwater resources.
	Changes in urban meteorological regimes lead to enhanced air pollution. (Section 8.2.3)	Increases in exposure and in pollution levels with impacts most serious among physiologically susceptible populations. Limited coping and adaptive capacities, due to lacking implementation of pollution control legislation of urban governments	Increasing risk of mortality and morbidity, lowered quality of life. These risks can also undermine the competitiveness of global cities to attract key workers and investment.	Complex and compounding health crises
	Geo-hydrological hazards (salt water intrusion, mud/land slides, subsidence) (Sections 8.2.3, 8.2.4)	Local structures and networked infrastructure (piped water, sanitation, drainage, communications, transport, electricity, gas) particularly susceptible. Inability of many low-income households to move to housing on safer sites.	Risk of damage to networked infrastructure. Risk of loss of human life and property	Potential for large local and aggregate impacts Knock-on effects for urban activities and well-being
	Wind storms with higher intensity (Sections 8.1.4, 8.2.4)	Substandard buildings and physical infrastructure and the services and functions they support particularly susceptible. Old and difficult to retrofit buildings and infrastructure in cities  Local government unable or unwilling to give attention to disaster risk reduction (limited coping and adaptive capacities)	Risk of damage to dwellings, businesses, and public infrastructure. Risk of loss of function and services. Challenges to recovery, especially where insurance is absent	Challenges to individuals, businesses, and public agencies where the costs of retrofitting are high and other sectors or interests capture investment budgets; potential for tensions between development and risk reduction investments
	Changing hazard profile including novel hazards and new multi-hazard complexes (Sections 8.1.4, 8.2.4)	Newly exposed populations and infrastructure, especially those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks (e.g., geophysical rather than hydrometeorological)	Risks from failures within coupled systems, e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications. Potential of psychological shock from unanticipated risks	Loss of faith in risk management institutions. Potential for extreme impacts that are magnified by a lack of preparation and capacity in response
	Compound slow-onset hazards including rising temperatures and variability in temperature and water (Sections 8.2.2, 8.2.4)	Large sections of the urban population in low- and middle-income nations with livelihoods or food supplies dependent on urban and peri-urban agriculture are especially susceptible.	Risk of damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture, and other productive or protective ecosystem services. Risk of knock-on impacts for urban and peri-urban livelihoods and urban health	Collapsing of peri-urban economies and ecosystem services with wider implications for urban food security, service provision, and disaster risk reduction
	Climate change–induced or intensified hazard of more diseases and exposure to disease vectors (Sections 8.2.3, 8.2.4)	Large urban population that is exposed to food-borne and water-borne diseases and to malaria, dengue, and other vector-borne diseases that are influenced by climate change	Risk due to increases in exposure to these diseases	Lack of capacity of public health system to simultaneously address these health risks with other climate-related risks such as flooding
Rural Areas (Chapter 9)	Drought in pastoral areas (Sections 9.3.3.1, 9.3.5.2)	Increasing vulnerability due to encroachment on pastoral rangelands, inappropriate land policy, misperception and undermining of pastoral livelihoods, conflict over natural resources, all driven by remoteness and lack of voice	Risk of famine  Risk of loss of revenues from livestock trade	Increasing risks for rural livelihoods through animal disease in pastoral areas combined with direct impacts of drought
	Effects of climate change on artisanal fisheries (Sections 9.3.3.1, 9.3.5.2)	Artisanal fisheries affected by pollution and mangrove loss, competition from aquaculture, and the neglect of the sector by governments and researchers as well as complex property rights	Risk of economic losses for artisanal fisherfolk, due to declining catches and incomes and damage to fishing gear and infrastructure	Reduced dietary protein for those consuming artisanally caught fish, combined with other climate-related risks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Rural Areas (continued) (Chapter 9)	Water shortages and drought in rural areas (Section 9.3.5.1.1)	Rural people lacking access to drinking and irrigation water. High dependence of rural people on natural resource-related activities. Lack of capacity and resilience in water management regimes (institutionally driven). Increased water demand from population pressure	Risk of reduced agricultural productivity of rural people, including those dependent on rainfed or irrigated agriculture, or high-yield varieties, forestry, and inland fisheries. Risk of food insecurity and decrease in incomes. Decreases in household nutritional status (Section 9.3.5.1)	Impacts on livelihoods driven by interaction with other factors (water management institutions, water demand, water used by non-food crops), including potential conflicts for access to water. Water-related diseases
Human Health (Chapter 11)	Increasing frequency and intensity of extreme heat	Older people living in cities are most susceptible to hot days and heat waves, as well as people with preexisting health conditions. (Section 11.3)	Risk of increased mortality and morbidity during hot days and heat waves. (Section 11.4.1) Risk of mortality, morbidity, and productivity loss, particularly among manual workers in hot climates	The number of elderly people is projected to triple from 2010 to 2050. This can result in overloading of health and emergency services.
	Increasing temperatures, increased variability in precipitation	Poorer populations are particularly susceptible to climate-induced reductions in local crop yields. Food insecurity may lead to undernutrition. Children are particularly vulnerable. (Section 11.3)	Risk of a larger burden of disease and increased food insecurity for particular population groups. Increasing risk that progress in reducing mortality and morbidity from undernutrition may slow or reverse. (Section 11.6.1)	Combined effects of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequality, and ongoing food insecurity for the poor
	Increasing temperatures, changing patterns of precipitation	Non-immune populations who are exposed to water- and vector-borne diseases that are sensitive to meteorological conditions (Section 11.3)	Increasing health risks due to changing spatial and temporal distribution of diseases strains public health systems, especially if this occurs in combination with economic downturn. (Section 11.5.1)	Rapid climate and other environmental change may promote emergence of new pathogens.
	Increased variability in precipitation	People exposed to diarrhea aggravated by higher temperatures, and unusually high or low precipitation (Section 11.3)	Risk that the progress to date in reducing childhood deaths from diarrheal disease is compromised (Section 11.5.2)	Increased rate of failure of water and sanitation infrastructure due to climate change leading to higher diarrhea risk
Livelihoods and Poverty (Chapter 13)	Increasing frequency and severity of droughts, coupled with decreasing rainfall and/or increased unpredictability of rainfall (Sections 13.2.1.2, 13.2.1.4, 13.2.2.2)	Poorly endowed farmers (high and persistent poverty), particularly in drylands, are susceptible to these hazards, since they have a very limited ability to compensate for losses in water-dependent farming systems and/or livestock.	Risk of irreversible harm due to short time for recovery between droughts, approaching tipping point in rainfed farming system and/or pastoralism	Deteriorating livelihoods stuck in poverty traps, heightened food insecurity, decreased land productivity, outmigration, and new urban poor in LICs and MICs
	Floods and flash floods in informal urban settlements and mountain environments, destroying physical assets (e.g., homes, roads, terraces, irrigation canals) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4)	High exposure and susceptibility of people, particularly children and elderly, as well as disabled in flood-prone areas. Inadequate infrastructure, culturally imposed gender roles, and limited ability to cope and adapt due to political and institutional marginalization and high poverty adds to the susceptibility of these people in informal urban settlements; limited political interest in development and building adaptive capacity	Risk of high morbidity and mortality due to floods and flash floods. Factors that further increase risk may include a shift from transient to chronic poverty due to eroded human and economic assets (e.g., labor market) and economic losses due to infrastructure damage.	Exacerbated inequality between better-endowed households able to invest in flood-control measures and/or insurance and increasingly vulnerable populations prone to eviction, erosion of livelihoods, and outmigration
	Increased variability of precipitation; shifts in mean climate and extreme events (Sections 13.2.1.1, 13.2.1.4)	Limited ability to cope owing to exhaustion of social networks, especially among the elderly and female-headed households; mobilization of labor and food no longer possible	Hazard combines with vulnerability to shift populations from transient to chronic poverty due to persistent and irreversible socioeconomic and political marginalization. In addition, the lack of governmental support, as well as limited effectiveness of response options, increase the risk.	Increasing yet invisible multidimensional vulnerability and deprivation at the convergence of climatic hazards and socioeconomic stressors
	Successive and extreme events (floods, droughts) coupled with increasing temperatures and rising water demand (Sections 13.2.1.1, 13.2.1.5)	Rural communities are particularly susceptible, due to the marginalization of rural water users to the benefit of urban users, given political and economic priorities (e.g., Australia, Andes, Himalayas, Caribbean).	Risk of loss of rural livelihoods, severe economic losses in agriculture, and damage to cultural values and identity; mental health impacts (including increased rates of suicide)	Loss of rural livelihoods that have existed for generations, heightened outmigration to urban areas; emergence of new poverty in MICs and HICs
	Sea level rise (Sections 13.1.4, 13.2.1.1, 13.2.2.1, 13.2.2.3)	High number of people exposed in low-lying areas coupled with high susceptibility due to multidimensional poverty, limited alternative livelihood options among poor households, and exclusion from institutional decision-making structures	Risk of severe harm and loss of livelihoods. Potential loss of common-pool resources; of sense of place, belonging, and identity, especially among indigenous populations	Loss of livelihoods and mental health risks due to radical change in landscape, disappearance of natural resources, and potential relocation; increased migration
	Increasing temperatures and heat waves (Sections 13.2.1.5, 13.2.2.3, 13.2.2.4)	Agricultural wage laborers, small-scale farmers in areas with multidimensional poverty and economic marginalization, children in urban slums, and the elderly are particularly susceptible.	Risk of increased morbidity and mortality due to heat stress, among male and female workers, children, and the elderly, limited protection due to socioeconomic discrimination and inadequate governmental responses	Declining labor pool for agriculture coupled with new challenges for rural health care systems in LICs and MICs; aging and low-income populations without safety nets in HICs at risk

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Livelihoods and Poverty (continued) (Chapter 13)	Increased variability of rainfall and/or extreme events (floods, droughts, heat waves) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4, 13.2.1.5)	People highly dependent on rainfed agriculture are particularly at risk. Persistent poverty among subsistence farmers and urban wage laborers who are net buyers of food with limited coping mechanisms	Risk of crop failure, spikes in food prices, reduction in consumption to protect household assets, risk of food insecurity, shifts from transient to chronic poverty due to limited ability to reduce risks	Food riots, child food poverty, global food crises, limits of insurance and other risk-spreading strategies
	Changing rainfall patterns (temporally and spatially)	Households or people with a high dependence on rainfed agriculture and little access to alternative modes of income	Risks of crop failure, food shortage, severe famine	Coincidence of hazard with periods of high global food prices leads to risk of failure of coping strategies and adaptation mechanisms such as crop insurance (risk spreading).
	Stressor from soaring demand (and prices) for biofuel feedstocks due to climate policies	Farmers and groups that have unclear and/or insecure land tenure arrangements are exposed to the dispossession of land due to land grabbing in developing countries.	Risk of harm and loss of livelihoods for some rural residents due to soaring demand for biofuel feedstocks and insecure land tenure and land grabbing	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production
	Increasing frequency of extreme events (droughts, floods), e.g., if 1:20 year drought/flood becomes 1:5 year drought/flood	Pastoralists and small farmers subject to damage to their productive assets (e.g., herds of livestock; dykes, fences, terraces)	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.
Emergent Risks and Key Vulnerabilities (Chapter 19)	Warming and drying (precipitation changes of uncertain magnitude) (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; sociocultural constraints on some adaptation options (Sections 19.2.2, 19.3.2.2, 19.6.1.1, 19.6.3.4)	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition, limited coping and adaptation options increase the risk of harm and loss. (Sections 19.3.2.2, 19.6.3.4)	Competition for water from diverse sectors (e.g., energy, agriculture, industry) interacts with climate changes to produce locally severe shortages. (Sections 19.3.2.2, 19.6.3.4)
	Changes in regional and seasonal temperature and precipitation over land (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Communities highly dependent on ecosystem services (Sections 19.2.2.1, 19.3.2.1) which are negatively affected by changes in regional and seasonal temperature	Risk of large-scale species richness loss over most of the global land surface. $57 \pm 6\%$ of widespread and common plants and $34 \pm 7\%$ of widespread and common animals are expected to lose $\geq 50\%$ of their current climatic range by the 2080s leading to loss of services. (Section 19.3.2.1)	Widespread loss of ecosystem services, including: provisioning, such as food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefit (Sections 19.3.2.1, 19.6.3.4)
Africa (Chapter 22)	Increasing temperature	Children, pregnant women, and those with compromised health status are particularly at risk for temperature-related changes in diarrheal and vector-borne diseases, and for temperature-related reductions in crop yields. Outdoor workers, older adults, and young children are most susceptible to hot weather and heat waves. (Sections 22.3.5.2, 22.3.5.4)	Risk of changes in the geographic distribution, seasonality, and incidence of infectious diseases, leading to increases in the health burden. Risk of increased burdens of stunting in children. Risk of increase in morbidity and mortality during hot days and heat waves	Interactions among factors lead to emerging and re-emerging epidemics.
		Populations dependent on aquatic systems and aquatic ecosystem services that are sensitive to increased water temperatures	Loss of aquatic ecosystems and risks for people who might depend on these resources; reduction in freshwater fisheries production (Sections 22.3.2.2, 22.3.4.4)	Risk of loss of livelihoods due to interactions of loss of ecosystem services and other climate-related stressors on poor communities
		Rural and urban populations whose food and livelihood security is diminished	Risk of harm and loss due to increased heat stress on crops and livestock resulting in reduced productivity; increased food storage losses due to spoilage (Sections 22.3.4.1, 22.3.4.2)	Range expansion of crop pests and diseases to high-elevation agroecosystems (Section 22.3.4.3)
	Extreme events, e.g., floods and flash floods (and drought)	Population groups living in informal settlements in highly exposed urban areas; women and children often the most vulnerable to disaster risk (Sections 22.3.6, 22.4.3)	Increasing risk of mortality, harm and losses due to water logging triggered by heavy rainfall events	Compounded risk of epidemics including diarrheal diseases (e.g., cholera)
		Susceptible groups include those who experience diminished access to food resulting from reduced capacity to transport, store, and market food, such as the urban poor.	Risk of food shortages and of damages to the food system due to storms and flooding	Food price spikes due to convergence of climatic and non-climatic forces that reduce food access for the poor whose income is disproportionately spent on food (Section 22.3.4.5)
		Children, pregnant women, and those with compromised health status are particularly vulnerable to reduced access to safe water and improved sanitation and increasing food insecurity. (Sections 22.3.5.2, 22.3.5.3)	Risk of crop and livestock losses from drought  Risk of reduced water supply and quality for household use. (Sections 22.3.4.1, 22.3.4.2) Risk of increased incidence of food- and water-borne diseases (e.g., cholera) and undernutrition.  Risk of drinking water contamination due to heavy precipitation events and flooding (Section 22.3.5.2)	Compound effects of high temperature and changes in rainfall on human and natural systems. Increased incidence of stunting in children (Section 22.3.5.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Europe (Chapter 23)	Extreme weather events (Section 23.9)	Sectors with limited coping and adaptive capacity as well as high sensitivity to these extreme events, such as transport, energy, and health, are particularly susceptible.	Risk of new systemic threats due to stress on multiple and interconnected sectors. Risk of failure of service provision of one or more sectors	Disproportionate intensification of risk due to increasing interdependencies
	Climate change increases the spatial distribution and seasonality of pests and diseases. (Section 23.4.1, 23.4.3, 23.4.4)	High susceptibility of plants and animals that are exposed to pests and diseases	Risk of increases in crop losses and animal diseases or even fatalities of livestock	Increasing risks due to limited response options and various feedback processes in agriculture, e.g., use of pesticides or antibiotics to protect plants and livestock increases resistance of disease vectors
	Extreme weather events and reduced water availability due to climate change (Section 23.3.4)	Low adaptive capacity of power systems might lead to limited energy supply as well as higher supply costs during such extreme events and conditions.	Increasing risk of power shortages due to limited energy supply, e.g., of nuclear power plants due to limited cooling water during heat stress	Continued underinvestment in adaptive energy systems might increase the risk of mismatches between limited energy supply during these events and increased demands, e.g., during a heat wave.
Asia (Chapter 24)	Rising average temperatures and more frequent extreme temperatures, as well as changing rainfall patterns (temporally and spatially)	Food systems and food production systems for key grain crops, particularly rice and other cereal crop farming systems, are highly susceptible. (Section 24.4.3)	Risk of crop failures and lower crop yield also can increase the risk of major losses for farmers and rural livelihoods. (Section 24.4.3)	Increase in Asian population combined with rising temperatures affecting food production. Upper temperature limit to the ability of some food systems to adapt could be reached.
	Rising sea level	Paddy fields and farmers near the coasts are particularly susceptible. (Section 24.4.3)	Risk of loss of arable areas due to submergence (Section 24.4.3)	Migration of farming communities to higher elevation areas entails risks for migrants and receiving regions.
	Projected increase in frequency of various extreme events (heat wave, floods, and droughts) and sea level rise	Increasing exposure due to convergence of livelihood and properties into coastal megacities. People in areas that are not sufficiently protected against natural hazards are particularly susceptible.	Risk of loss of life and assets due to coastal floods accompanied by increasing vulnerabilities.	Projected increase in disruptions of basic services such as water supply, sanitation, energy provision, and transportation systems, which themselves could increase vulnerabilities
Australasia (Chapter 25)	Rising air and sea surface temperatures, drying trends, reduced snow cover, increased intensity of severe cyclones, ocean acidification (Section 25.2; Table 25-1; Figure 25-4; WGI AR5 Chapter 14 and Atlas)	Species that live in a limited climatic range and that suffer from habitat fragmentation as well as from external stressors (pollution, runoff, fishing, tourism, introduced predators, and pests) are especially susceptible. (Sections 25.6.1, 25.6.2)	Risk of significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia (Sections 25.6.1, 25.6.2, 25.10.2)	Increasing risk from compound extreme events across time and space, and cumulative adaptation needs, with recovery and risk reduction measures hampered further by impacts and responses reaching across different levels of government (Sections 25.10.2, 25.10.3; Box 25-9)
	Increased extreme rainfall related to flood risk in many locations (Section 25.2; Table 25-1)	Adaptation deficit of existing infrastructure and settlements to current flood risk; expansion and densification of urban areas; effective adaptation includes transformative changes such as land-use controls and retreat. (Sections 25.3, 25.10.2; Box 25-8)	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (Box 25-8; Section 25.10.2)	
	Continuing sea level rise, with projections spanning a particularly large range and continuing beyond 2100, even under mitigation scenarios (Section 25.2; Box 25-1; WGI AR5 Chapter 13)	Long-lived and high asset value coastal infrastructure and low-lying ecosystems are highly susceptible. Expansion of coastal populations and assets into coastal zones increases the exposure. Conflicting priorities constrain adaptation options and limit effective response strategies. (25.3, Box 25-1)	Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damages toward the upper end of projected ranges (Box 25-1; Sections 25.6.1, 25.6.2, 25.10.2)	
North America (Chapter 26)	Increases in frequency and/or intensity of extreme events, such as heavy precipitation, river and coastal floods, heat waves, and droughts (Sections 26.2.2, 26.3.1, 26.8.1)	Physical infrastructure in a declining state in urban areas particularly susceptible. Also increases in income disparities and limited institutional capacities might result in larger proportions of people susceptible to these stressors due to limited economic resources. (Sections 26.7, 26.8.2)	Risk of harm and loss in urban areas, particularly in coastal and dry environments due to enhanced vulnerabilities of social groups, physical systems, and institutional settings combined with the increases of extreme weather events (Section 26.8.1)	Inability to reduce vulnerability in many areas results in an increase in risk more so than change in physical hazard. (Section 26.8.3)
	Higher temperatures, decreases in runoff, and lower soil moisture due to climate change (Sections 26.2, 26.3)	Vulnerability of small rural landholders, particularly in Mexican agriculture, and of the poor in rural settlements (Sections 26.5, 26.8.2.2)	Risk of increased losses and decreases in agricultural production. Risk of food and job insecurity for small landholders and social groups in regions exposed to these phenomena (Sections 26.5, 26.8.2.2)	Increasing risks of social instability and local economic disruption due to internal migration (Sections 26.2.1, 26.8.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
North America (continued) (Chapter 26)	Wildfires and drought conditions (Box 26-2)	Indigenous groups, low-income residents in peri-urban areas, and forest systems (Box 26-2; Section 26.8.2)	Risk of loss of ecosystem integrity, property loss, human morbidity, and mortality due to wildfires (Box 26-2; Section 26.8.3)	
	Extreme storm and heat events, air pollution, pollen, and infectious diseases (Section 26.6.1)	Susceptibility of individuals is determined by factors such as economic status, preexisting illness, age, and access to assets. (Section 26.6.1)	Increasing risk of extreme temperature-, storm-, pollen-, and infectious diseases-related human morbidity or mortality (Section 26.6.2)	
	River and coastal floods, and sea level rise (Sections 26.2.2, 26.4.2, 26.8.1)	Increasing exposure of populations, property, as well as ecosystems, partly resulting from overwhelmed drainage networks. Groups and economic sectors that highly depend on the functioning of different supply chains, public health institutions that can be disrupted, and groups that have limited coping capacities to deal with supply chain interruptions and disruptions to their livelihoods are particularly susceptible. (Sections 26.7, 26.8.1)	Risk of property damage, supply chain disruption, public health, water quality impairment, ecosystem disruption, infrastructure damage, and social system disruption from urban flooding due to river and coastal floods and floods of drainage networks (Sections 26.4.2, 26.8.1)	Multiple risks from interacting hazards on populations' livelihoods, infrastructure, and services (Sections 26.7, 26.8.3)
Central and South America (Chapter 27)	Reduced water availability in semi-arid regions and regions dependent on glacier meltwater; flooding in urban areas due to extreme precipitation (Sections 27.2.1, 27.3.3)	Groups that cannot keep agricultural livelihoods and are forced to migrate are especially vulnerable. Limited infrastructure and planning capacity can further increase the lack of coping and adaptive capacities to rapid changes expected (precipitation), especially in large cities.	Risk of loss of human lives, livelihood, and property	Increase in infectious diseases. Economic impacts due to reallocation of populations
	Ocean acidification and warming (Section 27.3.3; Box CC-OA)	Sensitivity of coral reef systems to ocean acidification and warming	Risk of loss of biodiversity (species) and risk of a reduced fishing capacity with respective impacts for coastal livelihoods	Economic losses and impact on food (fishery) production in certain regions
	Extremes of drought/precipitation (Sections 27.2.1, 27.3.4)	Elevated CO <sub>2</sub> decreases nutrient contents in plants, especially nitrogen in relation to carbon in food products.	Risk of loss of (food) production and productivity in some regions where extreme events may occur. Need to adjust diet due to decrease in food quality (e.g., less protein due to lower nitrogen assimilation). Decrease in bioenergy production	Strong economic impacts related to the need to move crops to more suitable regions. Teleconnections (related to food quality) related to the intense exportation of food by the region. Impacts on energy system and carbon emissions with consequent increase in fossil fuel demand.
	Higher temperatures and humidity lead to a spread of vector-borne diseases in altitude and latitude. (Section 27.3.7)	People exposed and vulnerable to vector-borne diseases and an increase in mosquito biting rates that increase the probability of human infections	Risk of increase in morbidity and in disability-adjusted life years (DALYs); risk of loss of human lives; risk of decrease in school and labor productivity	High economic impacts owing to the necessity to increase the financing of health programs, as well as the costs of DALYs, increase in hospitals and medical infrastructure adequate to cope with increasing disease incidence rates, and the spread of diseases to newer regions
Polar Regions (Chapter 28)	Loss of multi-year ice and reductions in the spatial extent of summer sea ice (Sections 28.2.5, 28.3.2, 28.4.1)	Indigenous communities that depend on sea ice for traditional livelihoods are vulnerable to this hazard, particularly due to loss of breeding and foraging platforms for marine mammals.	Risk of loss of traditional livelihoods and food sources.	Top-down shifts in food webs
		Ecosystems are vulnerable owing to the shifts in the distribution and timing of ice algal and ocean phytoplankton blooms.	Risk of disruption of synchronized timing of zooplankton ontogeny and availability of prey. Increased variability in secondary production while zooplankton adapt to shifts in timing. Risks also to local marine food webs.	Bottom up shifts in food webs. Potential changes in pelagic and benthic coupling
	Ocean acidification (Sections 28.2.2, 28.3.2)	Tolerance limits of endemic species surpassed. Impacts on exoskeleton formation for some species and alteration of physiological and behavioral properties during larval development	Localized loss of endemic species, local impacts on marine food webs	Localized declines in commercial fisheries. Local declines in fish, shellfish, seabirds, and marine mammals
	Shifts in boundaries of marine eco-regions due to rising water temperature, shifts in mixed layer depth, changes in the distribution and intensity of ocean currents (Sections 28.2.2, 28.3.2)	Marine organisms that are susceptible to spatial shifts are particularly vulnerable.	Risk of changes in the structure and function of marine systems and potentially species invasions	Disputes over international fisheries and shared stocks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Polar Regions (continued) (Chapter 28)	Declining sea ice, changes in snow and ice timing and state, decreasing predictability of weather (Sections 28.1, 28.4.1)	Many traditional subsistence food sources—especially for indigenous peoples—such as Arctic marine and land mammals, fish, and waterfowl. Various traditional livelihoods are susceptible to these hazards.	Risk of loss of habitats and changes in migration patterns of marine species	Enhancement of risk to food security and basic nutrition—especially for indigenous peoples—from loss of subsistence foods and increased risk to subsistence hunters', herders', and fishers' health and safety in changing ice conditions
	Increased river and coastal flooding and erosion and thawing of permafrost (Sections 28.2.4, 28.3.1, 28.3.4)	Rural and remote communities as well as urban communities in low-lying Arctic areas are exposed. Susceptibility and limited coping capacity of community water supplies due to potential damages to infrastructure.	Community and public health infrastructure damaged resulting in disease from contamination and sea water intrusion	Reduced water quality and quantity may result in increased rates of infection, other medical problems, and hospitalizations.
	Extreme and rapidly changing weather, intense weather and precipitation events, rapid snow and ice melt, changing river and sea ice conditions, permafrost thaw (Section 28.2.4)	People living from subsistence travel and hunting, herding, and fishing, for example indigenous peoples in remote and isolated communities, are particularly susceptible.	Accidents, physical/mental injuries, death, and cold-related exposure, injuries, and diseases	Enhanced risks to safe travel or subsistence hunting, herding, fishing activities affect livelihoods and well-being.
	Diminished sea ice; earlier sea ice melt-out; faster sea ice retreat; thinner, less predictable ice in general; greater variability in snow melt/freeze; ice, weather, winds, temperatures, precipitation (Sections 28.2.5, 28.2.6, 28.4.1)	Livelihoods of many indigenous peoples (e.g., Inuit and Saami) depend upon subsistence hunting and access to and favorable conditions for animals. These livelihoods are susceptible. Also marine ecosystems are susceptible (e.g., marine mammals).	Risk of loss of livelihoods and damage due to, e.g., more difficult access to marine mammals associated with diminishing sea ice (a risk to the Inuit), and loss of access by reindeer to their forage under snow due to ice layers formed by warming winter temperatures and "rain on snow" (a risk to the Saami).	Enhanced risk of loss of livelihoods and culture of increasing numbers of indigenous peoples, exacerbated by increasing loss of lands and sea ice for hunting, herding, fishing due to enhanced petroleum and mineral exploration, and increased maritime traffic
Small Islands (Chapter 29)	Increases in intensity of tropical cyclones (WGI AR5 Sections 14.6, 14.8.4)	Various countries and communities are vulnerable to these hazards because of their high dependence on natural and ecological systems for security of settlements and tourism (Section 29.3.3.1), human health (Section 29.3.3.2), and water resources (Section 29.3.2).	Risk of loss of ecosystems, settlements, and infrastructure, as well as negative impacts on human health and island economies (Figure 29-4)	Increased risk of interactions of damages to ecosystems, settlements, island economies, and risks to human life (Section 29.6; Figure 29-4)
	Ocean warming and acidification leading to coral bleaching (Sections 29.3.1.2, 30.5.4.2, 30.5.6.1.1, 30.5.6.2)	Tropical island communities are highly dependent on coral reef ecosystems for subsistence life styles, food security, coastal protection and beach, and reef-based tourist economic activity, and hence are highly susceptible to the hazard of coral bleaching. (Sections 29.3.1.2, 30.6.2.1.2)	Risk of decline and possible loss of coral reef ecosystems through thermal stress. Risk of serious harm and loss of subsistence lifestyles. Risk of loss of coastal protection and beaches, risk of loss of tourist revenue (Sections 29.3.1.1, 29.3.1.2)	Impacts on human health and loss of subsistence lifestyles. Potential increase in internal migration/urbanization (Section 29.3.3.3; Chapter 9)
	Sea level rise (Sections 29.3.1.1, 30.3.1.2; WGI AR5 Section 3.7.1)	Many small island communities and associated settlements and infrastructure are in low-lying coastal zones (high exposure) and are also vulnerable to increasing inundation, erosion and wave incursion. (Sections 5.3.2, 29.3.1.1; Figure 29-2)	Risk of loss and harm due to sea level rise in small island communities. Global mean sea level is likely to increase by 0.35 to 0.70 m for Representative Concentration Pathway (RCP) 4.5 during the 21st century, threatening low-lying coastal areas and atoll islands. (Section 29.4.3, Table 29-1; WGI AR5 Section 13.5.1, Table 13.5)	Incremental upwards shift in sea-level baselines results in increased frequency and extent of marine flooding during high tides and episodic storm surges. These events could render soils and fresh groundwater resources unfit for human use before permanent inundation of low-lying areas. (Sections 29.3.1.1, 29.3.2, 29.3.3.1, 29.5.1)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
The Ocean (Chapter 30)	Increasing ocean temperatures. Increased frequency of thermal extremes	Corals and other organisms whose tolerance limits are exceeded are particularly susceptible (especially CBS, STG, SES, and EUS ocean regions). (Sections 6.2.2.1, 6.2.2.2, 30.5.2, 30.5.4, 30.5.5; Boxes CC-CR, 30.5.6, CC-OA)	Risk of increased mass coral bleaching and mortality (loss of coral cover) with severe risks for coastal fisheries, tourism, and coastal protection (Sections 6.3.2, 6.3.5, 5.4.2.4, 7.2.1.2, 6.4.1.4, 29.3.1.2, 30.5.2, 30.5.3, 30.5.4, 30.5.5; Box CC-CR)	Loss of coastal reef systems, risk of decreased food security and reduced livelihoods, and reduced coastal protection (Sections 7.2.1.2, 30.6.2.1, 30.6.5)
		Marine species and ecosystems as well as fisheries and coastal livelihoods and tourism that cannot cope or adapt to changing temperatures and changes in the distribution are particularly vulnerable, especially for HLSBS, CBS, STG, and EBUE. (Sections 6.3.2, 6.3.4, 7.3.2.6, 30.5; Box CC-BIO)	Risk for fishery and coastal livelihoods. Fishery opportunity changes as stock abundance may rise or fall; increased risk of disease and invading species impacting ecosystems and fisheries (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.6, 7.4.2, 29.5.3, 29.5.4)	Significant risk of fishery collapse may develop as the capacity of fisheries to resist the following is exceeded: a) fundamental change to fishery composition, and b) the increased migration of disease and other organisms. (Sections 6.5.3, 7.5.1.1.3)
		Coastal ecosystems and communities that might be exposed to phenomena of elevated rates of microbial respiration leading to reduced oxygen at depth and increased spread of dead zones are particularly vulnerable (particularly for EBUE, SES, EUS).	Risk of loss of habitats and fishery resources as well as losses of key fisheries species. Oxygen levels decrease, leading to impacts on ecosystems (e.g., loss of habitat) and organisms (e.g., physiological performance of fish) resulting in reduced capture of key fisheries species.	Increasing risk of loss of livelihoods
		Deep sea life is sensitive to hazards and to change given the very constant conditions under which it has evolved. (30.1.3.1.3, 30.5.2, 30.5.5)	Risk of fundamental changes in conditions associated with deep sea (e.g., oxygen, pH, carbonate, CO <sub>2</sub> , temperature) drive fundamental changes that result in broad-scale changes throughout the ocean. (Sections 30.1.3.1.3, 30.5.2, 30.5.5; Boxes CC-UP, CC-NPP)	Changes in the deep ocean may be a prelude to ocean wide changes with planetary implications.
	Rising ocean acidification	Reef systems, corals, and coastal ecosystems that are exposed to a reduced rate of calcification and greater decalcification leading to potential loss of carbonate reef systems, corals, molluscs, and other calcifiers in key regions, such as the CBS, STG (Section 6.2.2.2)	Risk of the alteration of ecosystem services including risks to food provisioning with impacts on fisheries and aquaculture (Sections 6.2.5.3, 7.2.1.2, 7.3.2, 7.4.2.)	Income and livelihoods for communities are reduced as productivity of fisheries and aquaculture diminish. (Sections 7.5.1.1.3, 30.6)
		Marine organisms that are susceptible to changes in pH and carbonate chemistry imply a large number of changes to the physiology and ecology of marine organisms (particularly in CBS, STG, SES regions). (Sections 6.2.5, 6.3.4, 30.3.2.2)	Risk of fundamental shifts in ecosystems composition as well as organism function occur, leading to broad scale and fundamental change. Income and livelihoods from dependent communities are affected as ecosystem goods and services decline, with the prospect that recovery may take tens of thousands of years. (Section 6.1.1.2)	Risk to ecosystems and livelihoods is increased by the potential for interaction among ocean warming and acidification to create unknown impacts. (Section CC-OA)
		Coastal systems are increasingly exposed to upwelling in some areas, which results in periods of high CO <sub>2</sub> , low O <sub>2</sub> and pH. (Box CC-UP; Sections 6.2.2.2, 6.2.5.3)	Risk of loss and harm to fishery and aquaculture operations and respective livelihoods (e.g., oyster cultivation), especially those exposed periodically to harmful conditions during elevated upwelling, which trigger adaptation responses. (Section 30.6.2.1.4)	Background pH and carbonate chemistry are also such that harmful conditions are always present (avoiding impacts via adaptation not possible any more). (Section 30.6.2.1.4)
	Increased stratification as a result of ocean warming; reduced ventilation	Ocean ecosystems are vulnerable due to the reduced regeneration of nutrients as mixing between the ocean and its surface is reduced (EUS, STG, and EBUE). (Sections 6.2, 6.3, 6.5, 30.5.2, 30.5.4, 30.5.5)	Risk of productivity losses of oceans and respective negative impacts on fisheries. The concentration of inorganic nutrients in the upper layers of the ocean is reduced, leading to lower rates of primary productivity. (Box CC-NPP)	Reduced primary productivity of the ocean impacts fisheries productivity leading to lower catch rates and effects on livelihoods (Section 6.4.1.1; Box CC-NPP)
		Ecosystems and organisms that are sensitive to decreasing oxygen levels (Sections 30.5.2, 30.5.3, 30.5.5, 30.5.6, 30.5.7)	Increased risk of dead (hypoxic) zones reducing key ecosystems and fisheries habitat (Sections 6.1.1.3, 30.3.2.3)	
	Changes to wind, wave height, and storm intensity	Shipping and industrial infrastructure is vulnerable to wave and storm intensity. (Section 30.6.2)	Risk of increasing losses and damages to shipping and industrial infrastructure	Risk of accidents increases for enterprises such as shipping, as well as deep sea oil gas and mineral extraction.

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwelling Ecosystems; EUS = Equatorial Upwelling Systems; HIC, LIC, MIC = high-, low-, and medium-income countries; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Sub-Tropical Gyres.

#### This cross-chapter box should be cited as:

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# Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

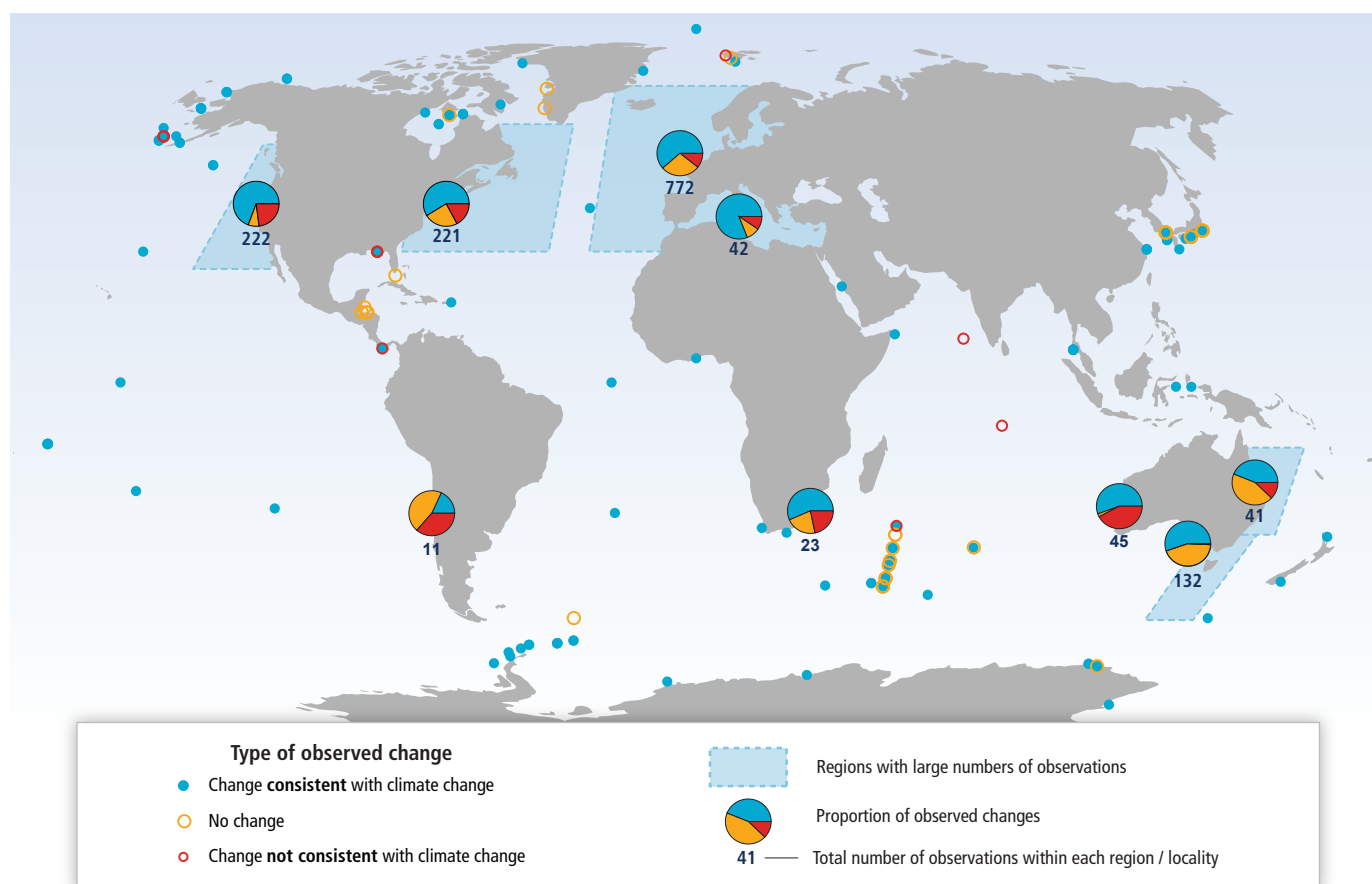
Elvira Poloczanska (Australia), Ove Hoegh-Guldberg (Australia), William Cheung (Canada), Hans-Otto Pörtner (Germany), Michael T. Burrows (UK)

IPCC WGII AR4 presented the detection of a global fingerprint on natural systems and its attribution to climate change (AR4, Chapter 1, SPM Figure 1), but studies from marine systems were mostly absent. Since AR4, there has been a rapid increase in studies that focus on climate change impacts on marine species, which represents an opportunity to move from more anecdotal evidence to examining and potentially attributing detected biological changes within the ocean to climate change (Section 6.3; Figure MB-1). Recent changes in populations of marine species and the associated shifts in diversity patterns are resulting, at least partly, from climate change-mediated biological responses across ocean regions (*robust evidence, high agreement, high confidence*; Sections 6.2, 30.5; Table 6-7).

Poloczanska et al. (2013) assess a potential pattern in responses of ocean life to recent climate change using a global database of 208 peer-reviewed papers. Observed responses ( $n = 1735$ ) were recorded from 857 species or assemblages across regions and taxonomic groups, from phytoplankton to marine reptiles and mammals (Figure MB-1). Observations were defined as those where the authors of a particular paper assessed the change in a biological parameter (including distribution, phenology, abundance, demography, or community composition) and, if change occurred, the consistency of the change with that expected under climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) authors included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term climate variability.

The results of this meta-analysis show that climate change has already had widespread impacts on species' distribution, abundance, phenology, and subsequently, species richness and community composition across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, changes in phenology, distribution and abundance were overwhelmingly (81%) in a direction that was consistent with theoretical responses to climate change (Section 6.2). Knowledge gaps exist, especially in equatorial sub-regions and the Southern Hemisphere (Figure MB-1).

The timing of many biological events (phenology) had an earlier onset. For example, over the last 50 years, spring events shifted earlier for many species with an average advancement of  $4.4 \pm 0.7$  days per decade (mean  $\pm$  SE) and summer events by  $4.4 \pm 1.1$  days per decade (*robust evidence, high agreement, high confidence*) (Figure MB-2). Phenological observations included in the study range from shifts in peak abundance of phytoplankton and zooplankton, to reproduction and migration of invertebrates, fishes, and seabirds (Sections 6.3.2, 30.5).



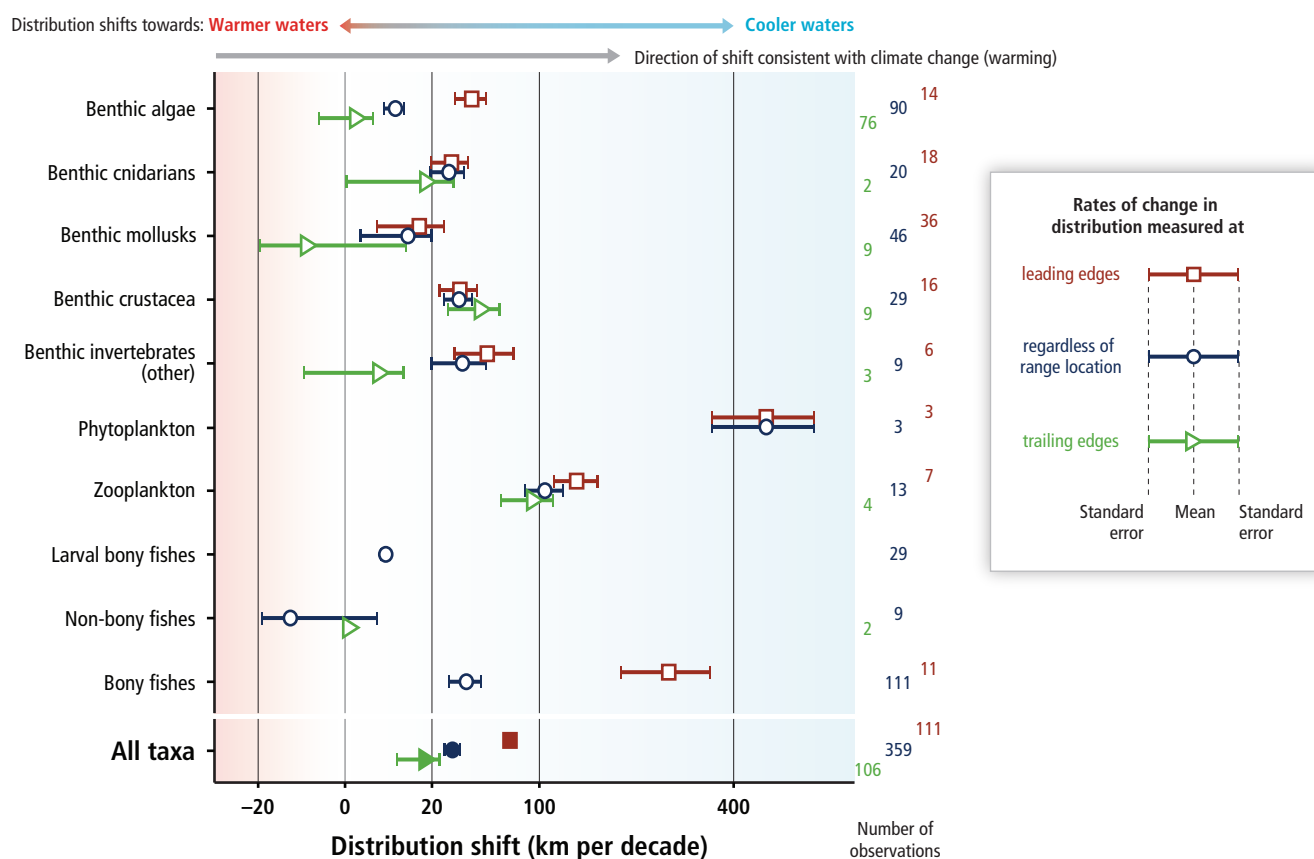
**Figure MB-1** | 1735 observed responses to climate change from 208 single- and multi-species studies. Data shown include changes that are attributed (at least partly) to climate change (blue), changes that are inconsistent with climate change (red), and no change (orange). Each circle represents the center of a study area. Where points fall on land, it is because they are centroids of distributions that surround an island or peninsula. Studies encompass areas from single sites (e.g., seabird breeding colony) to large ocean regions (e.g., continuous plankton recorder surveys in north-east Atlantic). For regions (indicated by blue shading) and localities with large numbers of observations, pie charts summarize the relative proportions of the three types of observed changes (consistent with climate change, inconsistent with climate change, and no change) in those regions or localities. The numbers indicate the total observations within each region or locality. Note: 57% of the studies included were published since AR4. (From Poloczanska et al., 2013).

The distributions of benthic, pelagic, and demersal species and communities have shifted by up to a thousand kilometers, although the range shifts have not been uniform across taxonomic groups or ocean regions (Sections 6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at  $72.0 \pm 13.5$  km per decade and trailing edges contracted in a poleward direction at  $15.8 \pm 8.7$  km per decade (Figure MB-2), revealing much higher current rates of migration than the potential maximum rates reported for terrestrial species (Figure 4-6) despite slower warming of the ocean than land surface (WGI Section 3.2).

Poleward distribution shifts have resulted in increased species richness in mid- to high-latitude regions (Hiddink and ter Hofstede, 2008) and changing community structure (Simpson et al., 2011; see also Section 28.2.2). Increases in warm-water components of communities concurrent with regional warming have been observed in mid- to high-latitude ocean regions including the Bering Sea, Barents Sea, Nordic Sea, North Sea, and Tasman Sea (Box 6.1; Section 30.5). Observed changes in species composition of catches from 1970–2006 that are partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in subtropical and higher latitude regions, and reduction in abundance of subtropical species in equatorial waters (Cheung et al., 2013), with implications for fisheries (Sections 6.5, 7.4.2, 30.6.2.1).

The magnitude and direction of distribution shifts can be related to temperature velocities (i.e., the speed and direction at which isotherms propagate across the ocean's surface (Section 30.3.1.1; Burrows et al., 2011). Pinsky et al. (2013) showed that shifts in both latitude and depth of benthic fish and crustaceans could be explained by climate velocity with remarkable accuracy, using a database of 128 million individuals across 360 marine taxa from surveys of North American coastal waters conducted over 1968–2011. Poloczanska et al. (2013) found that faster distribution shifts generally occur in regions of highest surface temperature velocity, such as the North Sea and sub-Arctic Pacific Ocean. Observed marine species shifts, since approximately the 1950s, have generally been able to track observed velocities (Figure MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities observed over most of the ocean surface, but with considerable variability within and among taxonomic groups (Poloczanska et al., 2013).





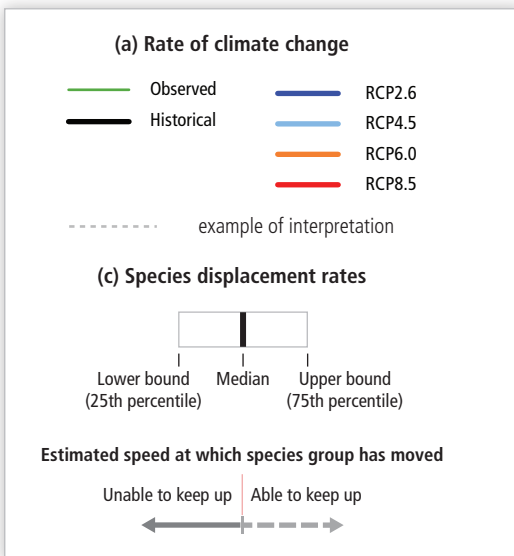
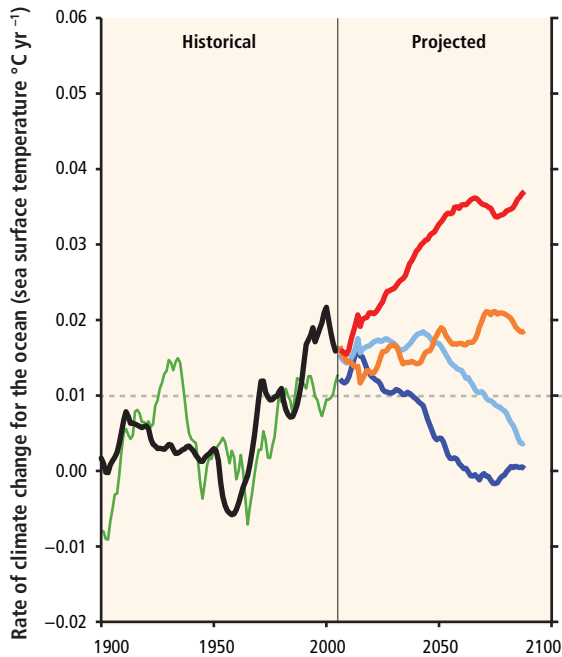
**Figure MB-2** | Rates of change in distribution (kilometers per decade) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (green). Average distribution shifts were calculated using all data, regardless of range location, and are in dark blue. Distribution shifts have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means  $\pm$  standard error are shown, along with number of observations. Non-bony fishes include sharks, rays, lampreys, and hagfish. (From Poloczanska et al., 2013).

Biogeographic shifts are also influenced by other factors such as currents, nutrient and stratification changes, light levels, sea ice, species' interactions, habitat availability and fishing, some of which can be independently influenced by climate change (Section 6.3). Rate and pattern of biogeographic shifts in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g., of the Mediterranean (Bianchi, 2007), coastal upwelling e.g., (Lima et al., 2007)). Geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram et al., 2010), with associated niches filled by alien species, either naturally migrating or artificially introduced (Philippart et al., 2011).

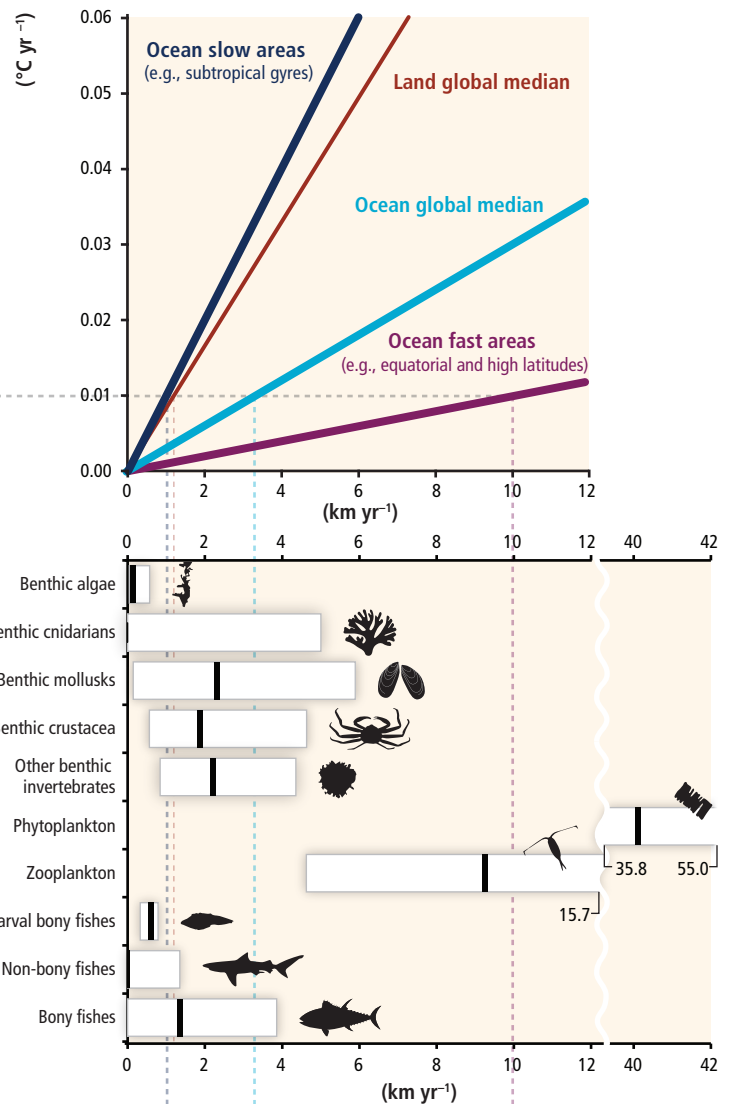
Whether marine species can continue to keep pace as rates of warming, hence climate velocities, increase (Figure MB-3b) is a key uncertainty. Climate velocities on land are expected to outpace the ability of many terrestrial species to track climate velocities this century (Section 4.3.2.5; Figure 4-6). For marine species, the observed rates of shift are generally much faster than those for land species, particularly for primary producers and lower trophic levels (Poloczanska et al., 2013). Phyto- and zooplankton communities (excluding larval fish) have extended distributions at remarkable rates (Figure MB-3b), such as in the Northeast Atlantic (Section 30.5.1) with implications for marine food webs.

Geographical range shifts and depth distribution vary between coexisting marine species (Genner et al., 2004; Perry et al., 2005; Simpson et al., 2011) as a consequence of the width of species-specific thermal windows and associated vulnerabilities (Figure 6-5). Warming therefore causes differential changes in growth, reproductive success, larval output, early juvenile survival, and recruitment, implying shifts in the relative performance of animal species and, thus, their competitiveness (Pörtner and Farrell, 2008; Figure 6-7A). Such effects may underlie abundance losses or local extinctions, "regime shifts" between coexisting species, or critical mismatches between predator and prey organisms, resulting in changes in local and regional species richness, abundance, community composition, productivity, energy flows, and invasion resistance. Even among Antarctic stenotherms, differences in biological responses related to mode of life, phylogeny and associated metabolic capacities exist (Section 6.3.1.4). As a consequence, marine ecosystem functions may be substantially reorganized at the regional scale, potentially triggering a range of cascading effects (Hoegh-Guldberg and Bruno, 2010). A focus on understanding the mechanisms underpinning the nature and magnitude of responses of marine organisms to climate change can help forecast impacts and the associated costs to society as well as facilitate adaptive management strategies for mitigating these impacts (Sections 6.3, 6.4).

## (a) Climate change scenarios



## (b) Estimate of climate velocity to determine rate of displacement



## (c) Species displacement rates (required to track climate velocity)

**Figure MB-3** | (a) Rate of climate change for the ocean (sea surface temperature (SST)  $^{\circ}\text{C yr}^{-1}$ ). (b) Corresponding climate velocities for the ocean and median velocity from land (adapted from Burrows et al., 2011). (c) Observed rates of displacement of marine taxonomic groups based on observations over 1900–2010. The dotted bands give an example of interpretation. Rates of climate change of  $0.01^{\circ}\text{C yr}^{-1}$  correspond to approximately  $3.3 \text{ km yr}^{-1}$  median climate velocity in the ocean. When compared to observed rates of displacement (c), many marine taxonomic groups have been able to track these velocities. For phytoplankton and zooplankton the rates of displacement greatly exceed median climate velocity for the ocean and, for phytoplankton exceed velocities in fast areas of the ocean approximately  $10.0 \text{ km yr}^{-1}$ . All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (a) Observed rates of climate change for ocean SST (green line) are derived from the Hadley Centre Interpolated SST 1.1 (HadISST1.1) data set, and all other rates are calculated based on the average of the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles (Table SM30-3) for the historical period and for the future based on the four Representative Concentration Pathway (RCP) scenarios. Data were smoothed using a 20-year sliding window. (b) Median climate velocity over the global ocean surface (light blue line; excluding polar seas) calculated from HadISST1.1 data set over 1960–2009 using the methods of Burrows et al. (2011). Median velocities representative of ocean regions of slow velocities such as the Pacific subtropical gyre (dark blue line) and of high velocities such as the Coral Triangle or the North Sea (purple line) shown. Median rates over global land surface (red line) over 1960–2009 calculated using Climate Research Unit data set CRU TS3.1. Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2009. (d) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. (2013) using published studies. Note the displacement rates for phytoplankton exceed the axis, so values are given.

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# OA

## Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO<sub>2</sub> (Figure OA-1A; WGI, Section 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulfur all exacerbate ocean acidification locally (Sections 5.3.3.6, 6.1.1, 30.3.2.2).

### Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO<sub>2</sub> result in an increased flux of CO<sub>2</sub> into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO<sub>2</sub> levels (Figure CC-OA-1B). Observations of changing upper ocean CO<sub>2</sub> chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30-8, 30-9). Projected changes in open ocean, surface water chemistry for the year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to pre-industrial values range from a pH change of −0.14 units with Representative Concentration Pathway (RCP)2.6 (421 ppm CO<sub>2</sub>, +1°C, 22% reduction of carbonate ion concentration) to a pH change of −0.43 units with RCP8.5 (936 ppm CO<sub>2</sub>, +3.7°C, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (Sections 5.3.3.5, 30.3.2.2), in polar regions (WGI Section 6.4.4), and at depth are more difficult but generally follow similar trends.

### Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several meta-analyses (Sections 6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; Sections 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Figure OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories, and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; Sections 5.4.2.4, 6.3.5).

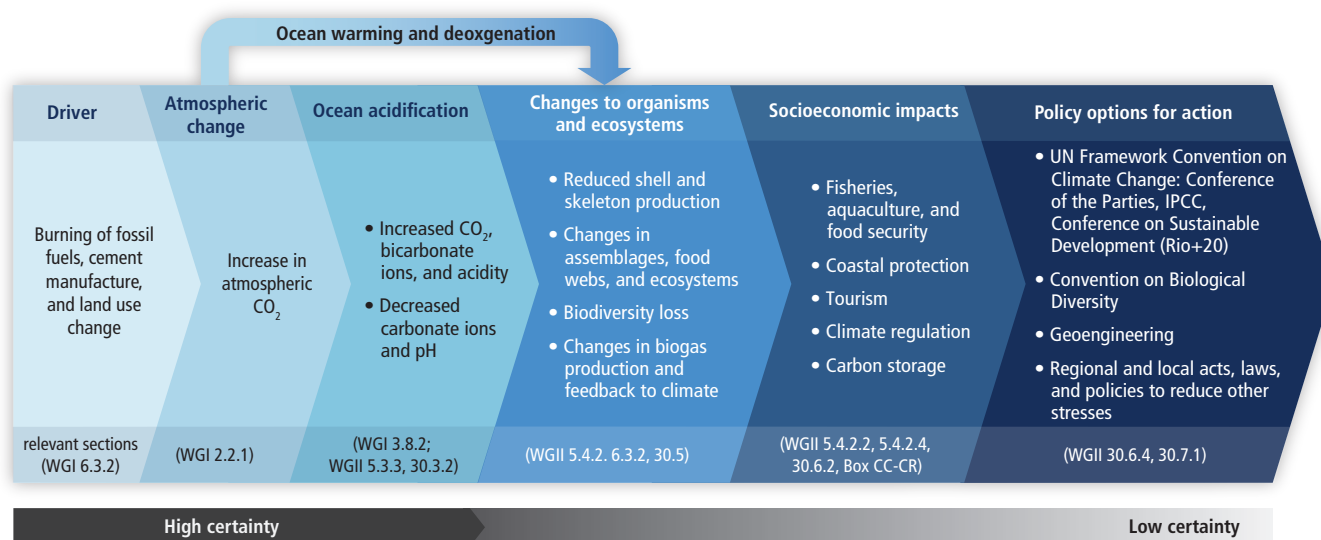
Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; Sections 5.4.2.3, 6.3.2.2, 6.3.2.3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not

all, sea floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves, and gastropods, reducing the competitiveness with non-calcifiers (Sections 5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4). Some corals and temperate fishes experience disturbances to behavior, navigation, and their ability to tell conspecifics from predators (Section 6.3.2.4). However, there is no evidence for these effects to persist on evolutionary time scales in the few groups analyzed (Section 6.3.2).

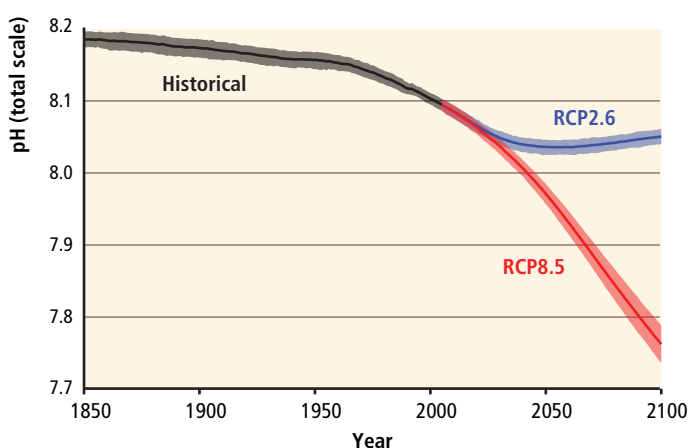
Some phytoplankton and molluscs displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; Section 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; Section 6.1.2).

Projections of ocean acidification effects at the ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator–prey relationships and competitive interactions (Sections

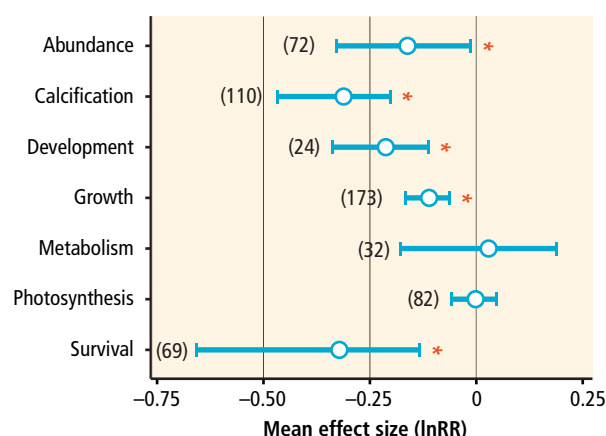
(a)



(b)



(c)



**Figure OA-1** | (a) Overview of the chemical, biological, and socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). (b) Multi-model simulated time series of global mean ocean surface pH (on the total scale) from Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations from 1850 to 2100. Projections are shown for emission scenarios Representative Concentration Pathway (RCP)2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (gray shading) is the modeled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO<sub>2</sub> concentrations (WGI AR5 Figures SPM.7 and TS.20). (c) Effect of near-future acidification (seawater pH reduction of  $\leq 0.5$  units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The \* denotes a statistically significant effect.



6.3.2.5, 6.3.5, 6.3.6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO<sub>2</sub> vents indicate decreased species diversity, biomass, and trophic complexity of communities (Box CC-CR; Sections 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (Section 5.4.2.2).

Owing to an incomplete understanding of species-specific responses and trophic interactions, the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic, or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

### Risks, Socioeconomic Impacts, and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (Section 6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, Section 5.4.2.4) and the goods and services that they provide such as fisheries, tourism, and coastal protection (*limited evidence, high agreement*; Box CC-CR; Sections 6.4.1.1, 19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed because of the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (Section 19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially exploited shelled molluscs (Section 6.4.1.1) would result in a reduction of USA production of 3 to 13% according to the Special Report on Emission Scenarios (SRES) A1FI emission scenario (*low confidence*). The global cost of production loss of molluscs could be more than US\$100 billion by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic, and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Section 6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2012, to be US\$870 and 528 billion, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; Section 6.4.1). Although this number is small compared to global gross domestic product (GDP), it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (Sections 25.7.5, 29.3.1.2).

### Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e., reduce anthropogenic emissions of CO<sub>2</sub>) and/or adaptation by reducing the consequences of past and future ocean acidification (Section 6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO<sub>2</sub> is the most effective and the least risky method to limit ocean acidification and its impacts (Section 6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (Section 6.4.2.2). Geoengineering techniques to remove CO<sub>2</sub> from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO<sub>2</sub> storage capacity (Section 6.4.2.2). In addition, some ocean-based approaches, such as iron fertilization, would only relocate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Sections 6.4.2.2, 30.3.2.3, 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO<sub>2</sub>, such as nutrient pollution (Section 6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (Section 5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (Section 6.4.2.1).

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# PP

## Net Primary Production in the Ocean

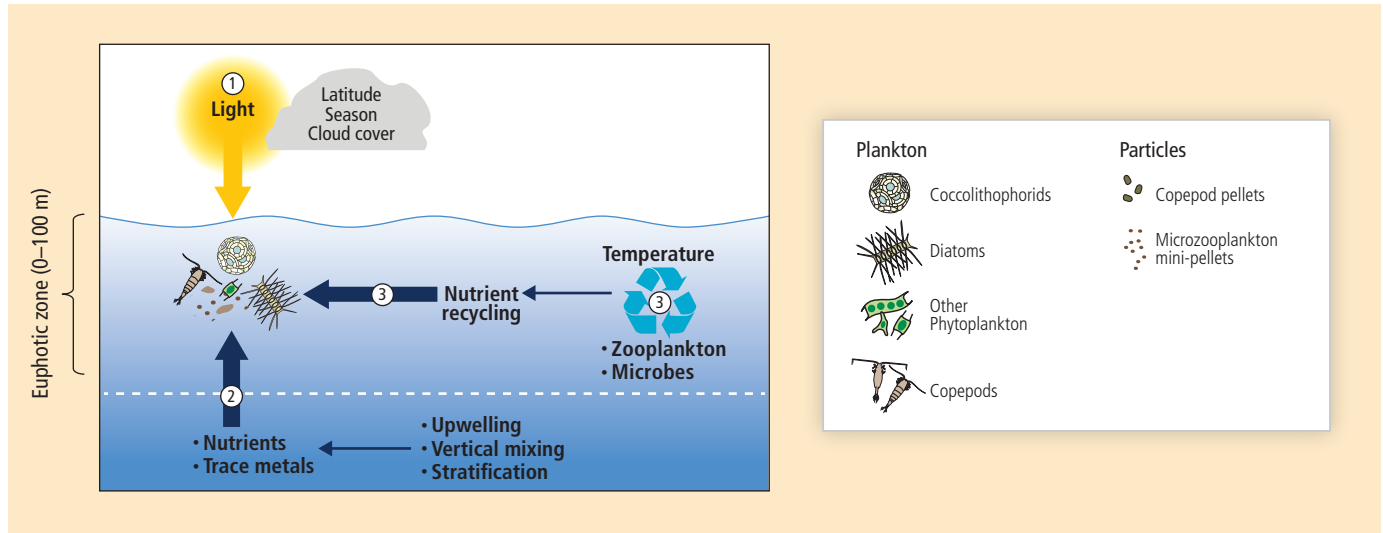
Philip W. Boyd (New Zealand), Svein Sundby (Norway), Hans-Otto Pörtner (Germany)

Net Primary Production (NPP) is the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for cellular respiration and maintenance by autotrophic planktonic microbes and benthic plants (Sections 6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, CO<sub>2</sub>, and temperature (Figure PP-1a). These drivers, in turn, are influenced by oceanic and atmospheric processes, including cloud cover; sea ice extent; mixing by winds, waves, and currents; convection; density stratification; and various forms of upwelling induced by eddies, frontal activity, and boundary currents. Temperature has multiple roles as it influences rates of phytoplankton physiology and heterotrophic bacterial recycling of nutrients, in addition to stratification of the water column and sea ice extent (Figure PP-1a). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI AR5, Chapter 3), and on ecosystem structure and functioning (*medium confidence*; Sections 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity with nutrient-poor subtropical waters and light-limited Arctic waters at the lower range and productive upwelling regions and highly eutrophic coastal regions at the upper range (Figure PP-1b).

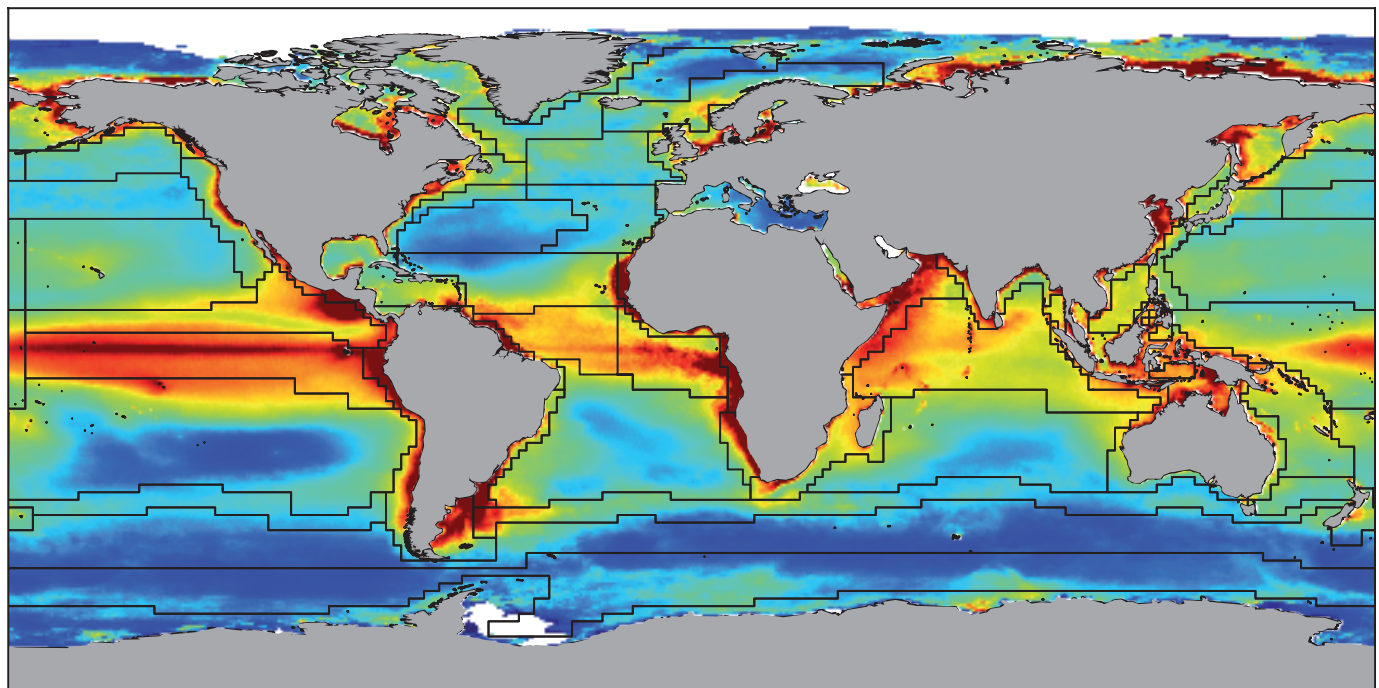
The oceans currently provide  $\sim 50 \times 10^{15}$  g C yr<sup>-1</sup>, or about half of global NPP (Field et al., 1998). Global estimates of NPP are obtained mainly from satellite remote sensing (Section 6.1.2), which provides unprecedented spatial and temporal coverage, and may be validated regionally against oceanic measurements. Observations reveal significant changes in rates of NPP when environmental controls are altered by episodic natural perturbations, such as volcanic eruptions enhancing iron supply, as observed in high-nitrate low-chlorophyll waters of the Northeast Pacific (Hamme et al., 2010). Climate variability can drive pronounced changes in NPP (Chavez et al., 2011), such as from El Niño to La Niña transitions in Equatorial Pacific, when vertical nutrient and trace element supply are enhanced (Chavez et al., 1999).

Multi-year time series records of NPP have been used to assess spatial trends in NPP in recent decades. Behrenfeld et al. (2006), using satellite data, reported a prolonged and sustained global NPP decrease of  $190 \times 10^{12}$  g C yr<sup>-1</sup>, for the period 1999–2005—an annual reduction of 0.57% of global NPP. In contrast, a time series of directly measured NPP between 1988 and 2007 by Saba et al. (2010) (i.e., *in situ* incubations using the radiotracer <sup>14</sup>C-bicarbonate) revealed an increase (2% yr<sup>-1</sup>) in NPP for two low-latitude open ocean sites. This discrepancy between *in situ* and remotely sensed NPP trends points to uncertainties in either the methodology used and/or the extent to which discrete sites are representative of oceanic provinces (Saba et al., 2010, 2011). Modeling studies have subsequently revealed that the <15-year archive of satellite-

(a)



(b)

NPP ( $\text{g C m}^{-2} \text{ y}^{-1}$ )

0 50 100 150 200 250 300

**Figure PP-1** | (a) Environmental factors controlling Net Primary Production (NPP). NPP is controlled mainly by three basic processes: (1) light conditions in the surface ocean, that is, the photic zone where photosynthesis occurs; (2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, and (3) regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical, and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. (b) Annual composite map of global areal NPP rates (derived from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite climatology from 2003–2012; NPP was calculated with the Carbon-based Productivity Model (CbPM; Westberry et al., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. White areas = no data. (Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.)

derived NPP is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson et al., 2010; Beaulieu et al., 2013). Although multi-decadal, the available time series of oceanic NPP measurements are also not of sufficient duration relative to the time scales of longer-term climate variability modes as for example Atlantic Multi-decadal Oscillation (AMO), with periodicity of 60-70 years, Figure 6-1). Recent attempts to synthesize longer (i.e., centennial) records of chlorophyll as a proxy for phytoplankton stocks (e.g., Boyce et al., 2010) have been criticized for relying on questionable linkages between different proxies for chlorophyll over a century of records (e.g., Rykaczewski and Dunne, 2011).

Models in which projected climate change alters the environmental drivers of NPP provide estimates of spatial changes and of the rate of change of NPP. For example, four global coupled climate–ocean biogeochemical Earth System Models (WG1 AR5 Chapter 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP, particularly in the high-latitude biomes (Steinacher et al., 2010). However, this regional increase in NPP was more than offset by decreases in NPP at lower latitudes and at mid-latitudes due to the reduced input of macronutrients into the photic zone. The reduced mixed-layer depth and reduced rate of circulation may cause a decrease in the flux of macronutrients to the euphotic zone (Figure 6-2). These changes to oceanic conditions result in a reduction in global mean NPP by 2 to 13% by 2100 relative to 2000 under a high emission scenario (Polovina et al., 2011; SRES (Special Report on Emission Scenarios) A2, between RCP6.0 and RCP8.5). This is consistent with a more recent analysis based on 10 Earth System Models (Bopp et al., 2013), which project decreases in global NPP by 8.6 ( $\pm 7.9$ ), 3.9 ( $\pm 5.7$ ), 3.6 ( $\pm 5.7$ ), and 2.0 ( $\pm 4.1$ ) % in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5, and RCP2.6, respectively. However, the magnitude of projected changes varies widely between models (e.g., from 0 to 20% decrease in NPP globally under RCP 8.5). The various models show very large differences in NPP at regional scales (i.e., provinces, see Figure PP-1b).

Model projections had predicted a range of changes in global NPP from an increase (relative to preindustrial rates) of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0; Sarmiento et al., 2004; Schmittner et al., 2008) to a decrease of 2-20% under the SRES A2 emission scenario (Steinacher et al., 2010). These projections did not consider the potential contribution of primary production derived from atmospheric nitrogen fixation in tropical and subtropical regions, favoured by increasing stratification and reduced nutrient inputs from mixing. This mechanism is potentially important, although such episodic increases in nitrogen fixation are not sustainable without the presence of excess phosphate (e.g., Moore et al., 2009; Boyd et al., 2010). This may lead to an underestimation of NPP (Mohr et al., 2010; Mulholland et al., 2012; Wilson et al., 2012), however, the extent of such underestimation is unknown (Luo et al., 2012).

Care must be taken when comparing global, provincial (e.g., low-latitude waters, e.g., Behrenfeld et al., 2006) and regional trends in NPP derived from observations, as some regions have additional local environmental influences such as enhanced density stratification of the upper ocean from melting sea ice. For example, a longer phytoplankton growing season, due to more sea ice-free days, may have increased NPP (based on a regionally validated time-series of satellite NPP) in Arctic waters (Arrigo and van Dijken, 2011) by an average of  $8.1 \times 10^{12}$  g C yr<sup>-1</sup> between 1998 and 2009. Other regional trends in NPP are reported in Sections 30.5.1 to 30.5.6. In addition, although future model projections of global NPP from different models (Steinacher et al., 2010; Bopp et al., 2013) are comparable, regional projections from each of the models differ substantially. This raises concerns as to which aspect(s) of the different model NPP parameterizations are responsible for driving regional differences in NPP, and moreover, how accurate model projections are of global NPP.

From a global perspective, open ocean NPP will decrease moderately by 2100 under both low- (SRES B1 or RCP4.5) and high-emission scenarios (*medium confidence*; SRES A2 or RCPs 6.0, 8.5, Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*).

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# Regional Climate Summary Figures

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Information about the likelihood of regional climate change, assessed by Working Group I (WGI), is foundational for the Working Group II assessment of climate-related risks. To help communicate this assessment, the regional chapters of WGII present a coordinated set of regional climate figures, which summarize observed and projected change in annual average temperature and precipitation during the near term and the longer term for RCP2.6 and RCP8.5. These WGII regional climate summary figures use the same temperature and precipitation fields that are assessed in WGI Chapter 2 and WGI Chapter 12, with spatial boundaries, uncertainty metrics, and data classes tuned to support the WGII assessment of climate-related risks and options for risk management. Additional details on regional climate and regional climate processes can be found in WGI Chapter 14 and WGI Annex 1.

The WGII maps of observed annual temperature and precipitation use the same source data, calculations of data sufficiency, and calculations of trend significance as WGI Chapter 2 and WGI Figures SPM.1 and SPM.2. (A full description of the observational data selection and significance testing can be found in WGI Box 2.2.) Observed trends are determined by linear regression over the 1901–2012 period of Merged Land–Ocean Surface Temperature (MLOST) for annual temperature, and over the 1951–2010 period of Global Precipitation Climatology Centre (GPCC) for annual precipitation. Data points on the maps are classified into three categories, reflecting the categories used in WGI Figures SPM.1 and SPM.2:

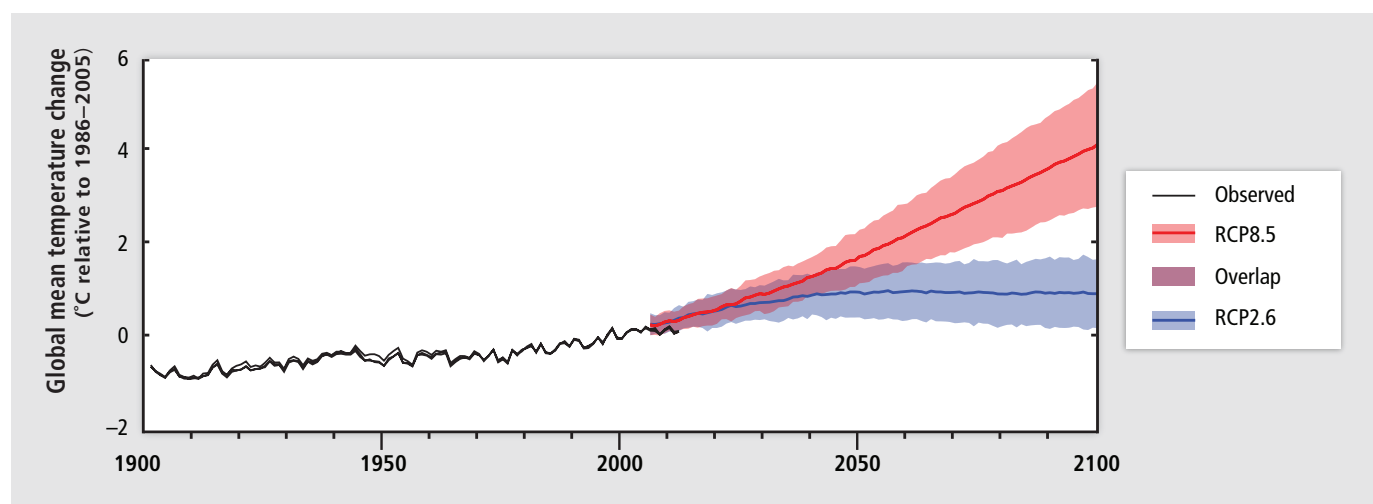
- 1) Solid colors indicate areas where (a) sufficient data exist to permit a robust estimate of the trend (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period), and (b) the trend is significant at the 10% level (after accounting for autocorrelation effects on significance testing).
- 2) Diagonal lines indicate areas where sufficient data exist to permit a robust estimate of the trend, but the trend is not significant at the 10% level.
- 3) White indicates areas where there are not sufficient data to permit a robust estimate of the trend.

The WGII maps of projected annual temperature and precipitation are based on the climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), which also form the basis for the figures presented in WGI (including WGI Chapters 12, 14, and Annex I). The CMIP5 archive includes output from Atmosphere–Ocean General Circulation Models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, vary between the different CMIP5 experiments. The WGII regional climate maps use the same source data as WGI Chapter 12 (e.g., Box 12.1 Figure

1), including the WGI multi-model mean values; the WGI individual model values; the WGI measure of baseline (“internal”) variability; and the WGI time periods for the reference (1986–2005), mid-21st century (2046–2065), and late-21st century (2081–2100) periods. The full description of the selection of models, the selection of realizations, the definition of internal variability, and the interpolation to a common grid can be found in WGI Chapter 12 and Annex I.

In contrast to the Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al., 2007), which used the IPCC Special Report on Emission Scenarios (SRES) emission scenarios (IPCC, 2000), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) to characterize possible trajectories of climate forcing over the 21st century. The WGII regional climate projection maps include RCP2.6 and RCP8.5, which represent the high and low end of the RCP range at the end of the 21st century. Projected changes in global mean temperature are similar across the RCPs over the next few decades (Figure RC-1; WGI Figure 12.5). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. In addition, societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, the magnitude of global temperature increase diverges across the RCPs (Figure RC-1; WGI Figure 12.5). For this longer-term era of climate options, near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change. The benefits of mitigation and adaptation thereby occur over different but overlapping time frames, and present-day choices thus affect the risks of climate change throughout the 21st century.

The projection maps plot differences in annual average temperature and precipitation between the future and reference periods (Figures RC-2 and RC-3), categorized into four classes. The classes are constructed based on the IPCC uncertainty guidance, providing a quantitative basis for assigning likelihood (Mastrandrea et al., 2010), with *likely* defined as 66 to 100% and *very likely* defined as 90 to 100%.

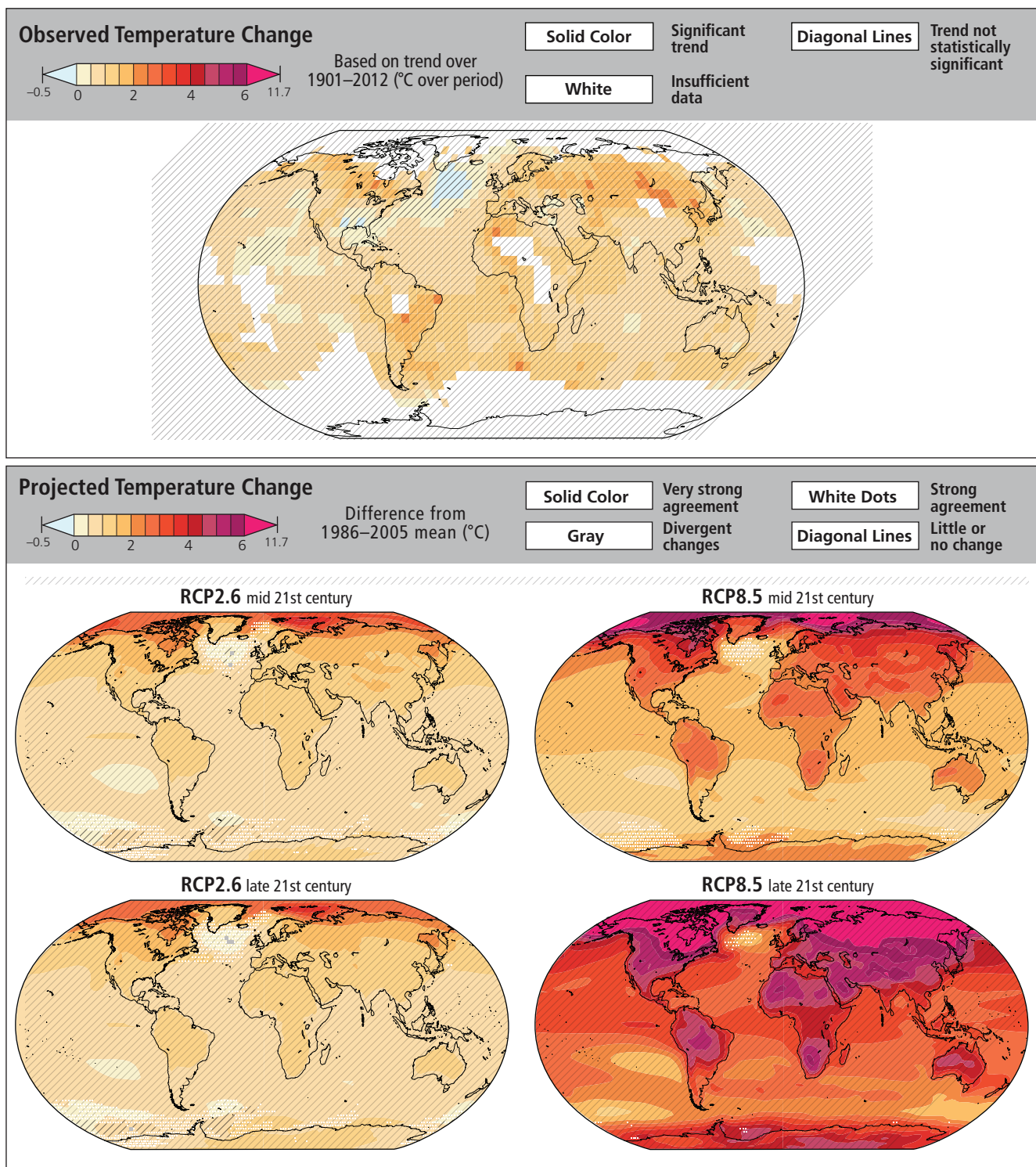


**Figure RC-1** | Observed and projected changes in global annual average temperature. Values are expressed relative to 1986–2005. Black lines show the Goddard Institute for Space Studies Surface Temperature Analysis (GIStEMP), National Climate Data Center Merged Land–Ocean Surface Temperature (NCDC-MLOST), and Hadley Centre/Climatic Research Unit gridded surface temperature data set 4.2 (HadCRUT4.2) estimates from observational measurements. Blue and red lines and shading denote the ensemble mean and  $\pm 1.64$  standard deviation range, based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations from 32 models for Representative Concentration Pathway (RCP) 2.6 and 39 models for RCP8.5.

The classifications in the WGII regional climate projection figures are based on two aspects of likelihood (e.g., WGI Box 12.1 and Knutti et al., 2010). The first is the likelihood that projected changes exceed differences arising from internal climate variability (e.g., Tebaldi et al., 2011). The second is agreement among models on the sign of change (e.g., Christensen et al., 2007; and IPCC, 2012).

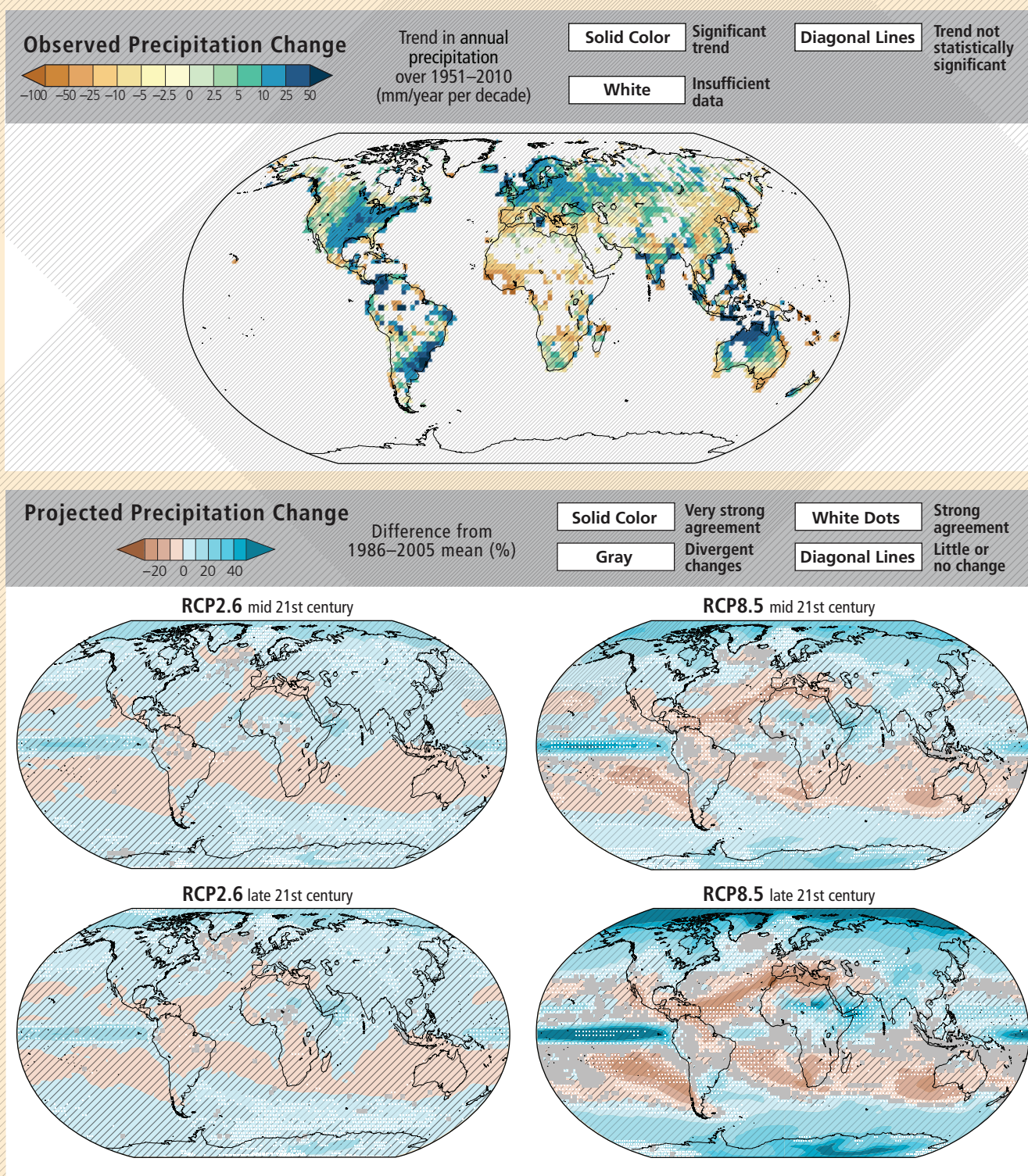
The four classifications of projected change depicted in the WGII regional climate maps are:

- 1) Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means), and greater than or equal to 90% of models agree on sign of change. These criteria (and the areas that fall into this category) are identical to the highest confidence category in WGI Box 12.1. This category supersedes other categories in the WGII regional climate maps.
- 2) Colors with white dots indicate areas with strong agreement, where 66% or more of models show change greater than the baseline variability, and 66% or more of models agree on sign of change.
- 3) Gray indicates areas with divergent changes, where 66% or more of models show change greater than the baseline variability, but fewer than 66% agree on sign of change.
- 4) Colors with diagonal lines indicate areas with little or no change, where fewer than 66% of models show change greater than the baseline variability. It should be noted that areas that fall in this category for the annual average could still exhibit significant change at seasonal, monthly, and/or daily time scales.



RC

**Figure RC-2 |** Observed and projected changes in annual average surface temperature. (A) Map of observed annual average temperature change from 1901 to 2012, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values:  $-0.53$  to  $+2.50^{\circ}\text{C}$  over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections of annual average temperature changes for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means) and  $\geq 90\%$  of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where  $\geq 66\%$  of models show change greater than the baseline variability and  $\geq 66\%$  of models agree on sign of change. Gray indicates areas with divergent changes, where  $\geq 66\%$  of models show change greater than the baseline variability, but  $< 66\%$  agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where  $< 66\%$  of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is:  $+0.19$  to  $+4.08^{\circ}\text{C}$  for mid 21st century of RCP2.6;  $+0.06$  to  $+3.85^{\circ}\text{C}$  for late 21st century of RCP2.6;  $+0.70$  to  $+7.04^{\circ}\text{C}$  for mid 21st century of RCP8.5; and  $+1.38$  to  $+11.71^{\circ}\text{C}$  for late 21st century of RCP8.5.



**Figure RC-3** | Observed and projected changes in annual average precipitation. (A) Map of observed annual precipitation change from 1951–2010, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: -185 to +111 mm/year per decade) are from WGI AR5 Figures SPM.2 and 2.29. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and  $\geq 90\%$  of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where  $\geq 66\%$  of models show change greater than the baseline variability and  $\geq 66\%$  of models agree on sign of change. Gray indicates areas with divergent changes, where  $\geq 66\%$  of models show change greater than the baseline variability, but  $< 66\%$  agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where  $< 66\%$  of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: -10 to +24% for mid 21st century of RCP2.6; -9 to +22% for late 21st century of RCP2.6; -19 to +57% for mid 21st century of RCP8.5; and -34 to +112% for late 21st century of RCP8.5.



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# Impact of Climate Change on Freshwater Ecosystems due to Altered River Flow Regimes

Petra Döll (Germany), Stuart E. Bunn (Australia)

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff et al., 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e., changes to the frequency, magnitude, duration, and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino et al., 2009).

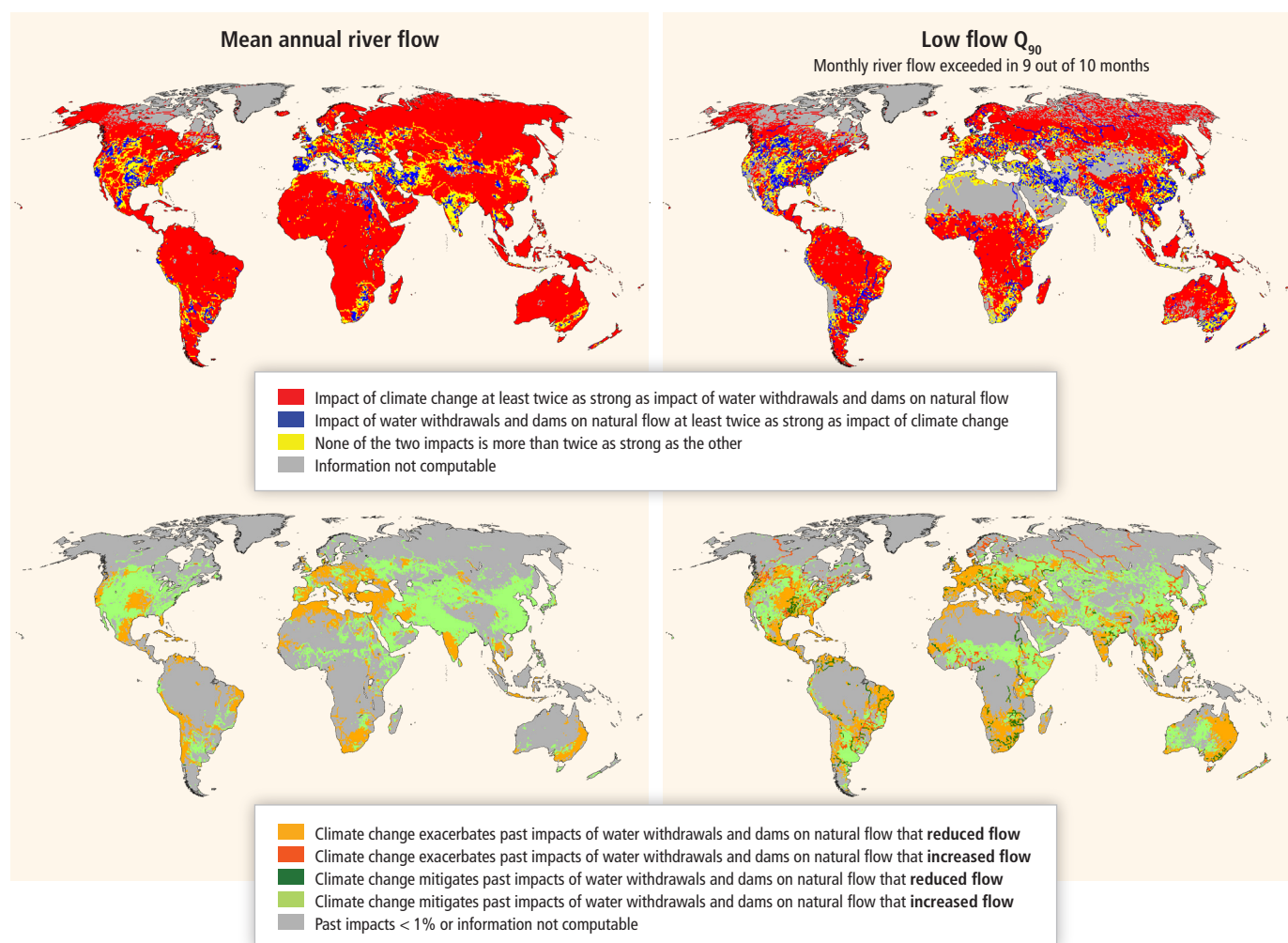
There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*medium confidence*; Xenopoulos et al., 2005; Aldous et al., 2011). By the 2050s, climate change is projected to impact river flow characteristics such as long-term average discharge, seasonality, and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (Special Report on Emission Scenarios (SRES) A2 emissions, Met Office Hadley Centre climate prediction model 3 (HadCM3)), 15% of the global land area may be negatively affected, by the 2050s, by a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, that is, with a lower spring flood and increased runoff during winter months (Renofalt et al., 2010).

Because biota are often adapted to a certain level of river flow variability, the projected larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke et al., 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah et al., 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5 to 7% of the global land area, mainly in semiarid areas (Döll and Müller Schmied, 2012; see Table 3-2 in Chapter 3).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme et al., 2010). Eco-regions containing more than 80% of Africa's freshwater fish species and several

outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme et al., 2010).

As a result of increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows, and possibly reduced summer low flows (Section 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20 to 40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin et al., 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart et al., 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer et al., 2009).

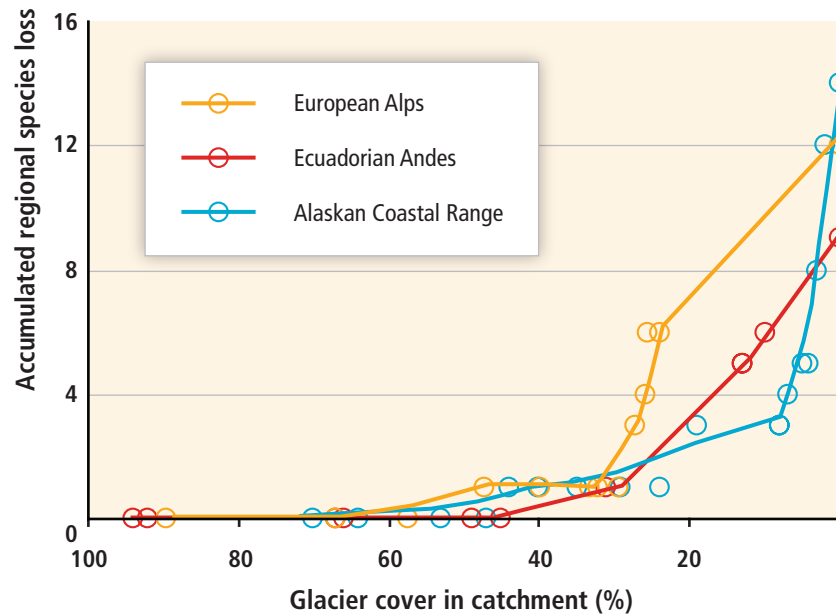


**Figure RF-1** | Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow  $Q_{90}$ ), computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961–1990 and 2041–2070 according to the emissions scenario A2 as implemented by the global climate model Met Office Hadley Centre Coupled Model, version 3 (HadCM3). Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett et al., 2005; Vuille et al., 2008; Jacobsen et al., 2012). In the first phase, when river discharge is increased as a result of intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream flow may have negative impacts on narrow range endemics (Jacobsen et al., 2012). In the second phase, when snowfields melt early and glaciers have shrunk to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C, and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C, and 3.8°C, respectively (van Vliet

et al., 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet et al., 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.



**Figure RF-2** | Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9 to 14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16, and 38% of the total species richness in the three study regions in Ecuador, Europe, and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site (Europe or Ecuador) or date (Alaska), and lines are Lowess fits. (Adapted by permission from Jacobsen et al., 2012.)

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# TC

## Building Long-Term Resilience from Tropical Cyclone Disasters

Yoshiki Saito (Japan), Kathleen McInnes (Australia)

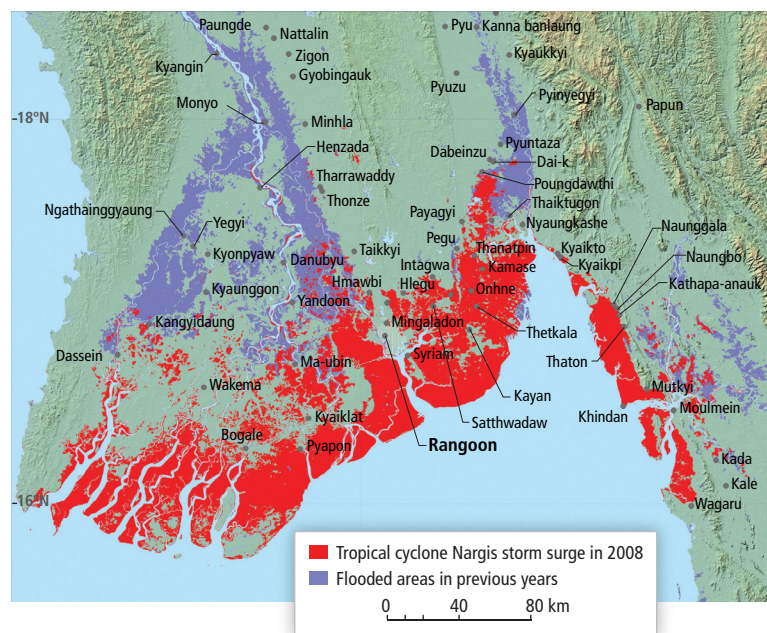
Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves, and storm surge, all of which can have major impacts on society and ecosystems. Bangladesh and India suffer 86% of mortality from tropical cyclones (Murray et al., 2012), which occurs mainly during the rarest and most severe storm categories (i.e., Categories 3, 4, and 5 on the Saffir–Simpson scale).

About 90 tropical cyclones occur globally each year (Seneviratne et al., 2012) although interannual variability is large. Changes in observing techniques, particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities, which leads to *low confidence* that any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne et al., 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e., maximum wind speed and rainfall rates) is *likely* to increase (WGI AR5 Section 14.6). Regionally specific projections have *lower confidence* (see WGI AR5 Box 14.2).

Longer-term impacts from tropical cyclones include salinization of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer-term changes associated with climate change.

Asian deltas are particularly vulnerable to tropical cyclones owing to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused more than 0.5 million fatalities (Murray et al., 2012), for example, cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on May 2, 2008 and caused more than 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga et al., 2003; Brakenridge et al., 2013). The flooded areas were captured by a NASA Moderate Resolution Imaging Spectrometer (MODIS) image on May 5, 2008 (see Figure TC-1).





**Figure TC-1** | The intersection of inland and storm surge flooding. Red shows May 5, 2008 Moderate Resolution Imaging Spectrometer (MODIS) mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The purple areas to the north were flooded by the river in prior years. (Source: Brakenridge et al., 2013.)

Murray et al. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargis in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation. Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3400 compared to more than 138,000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multistoried cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. Disaster risk management strategies for tropical cyclones in coastal areas create protective measures, anticipate and plan for extreme events, and increase the resilience of potentially exposed communities. The integration of activities relating to education, training, and awareness-raising into relevant ongoing processes and practices is important for the long-term success of disaster risk reduction and management (Murray et al., 2012). However, Birkmann and Teichman (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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# UP

## Uncertain Trends in Major Upwelling Ecosystems

Salvador E. Lluch-Cota (Mexico), Ove Hoegh-Guldberg (Australia), David Karl (USA), Hans O. Pörtner (Germany), Svein Sundby (Norway), Jean-Pierre Gattuso (France)

Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These conditions trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the planet, the Equatorial Upwelling System (EUS; Section 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE; Section 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25% to global fish production (Figure 30.1B, Table SM30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of “bottom-up” trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds, and marine mammals.

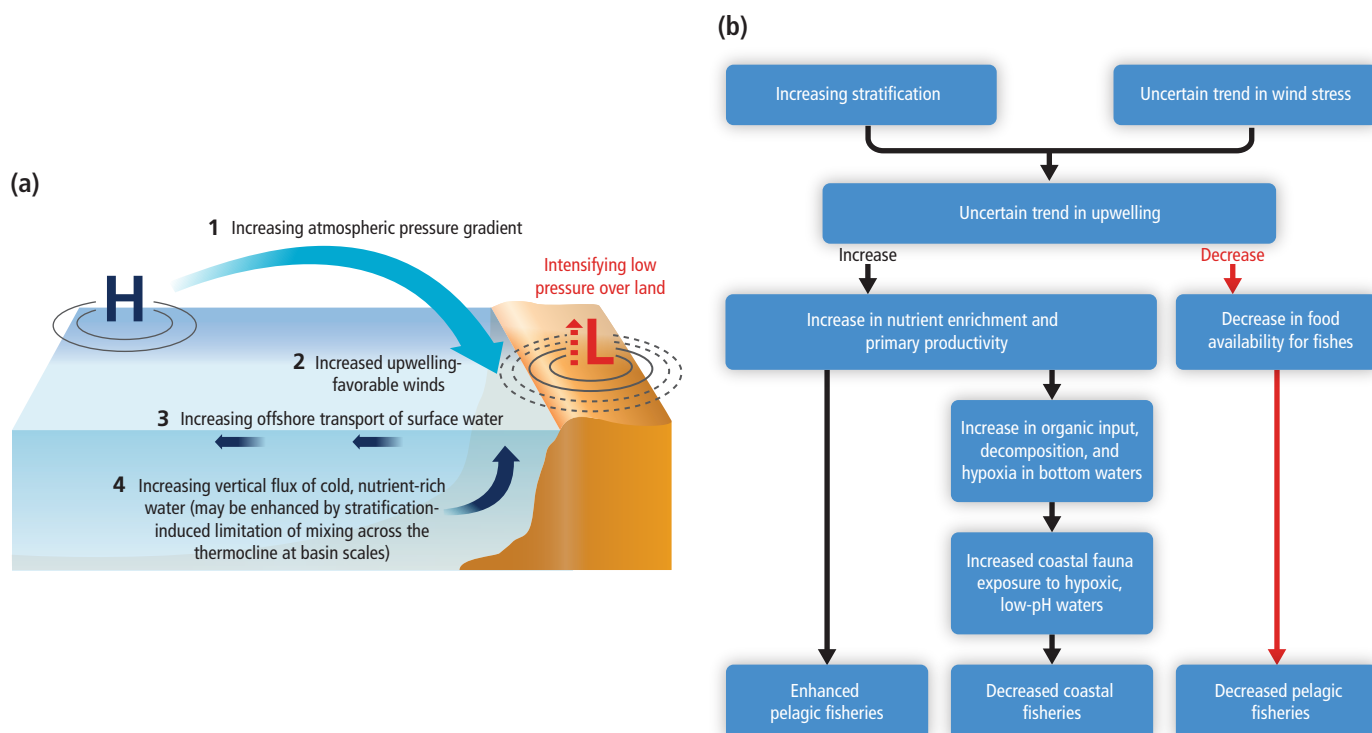
There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI Sections 3.2, 3.3, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, owing to the uncertainty in wind speed trends (WGI Section 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the late 1990s (WGI Section 3.4.4). Observations and modeling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the difference in rates of heat gain between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping and the upwelling of nutrient-rich, cold waters (Figure CC-UP). Some regional records support this hypothesis; others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems, making it difficult to predict changes in the intensity of all Eastern EBUEs (Section 30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic, or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts

are highly relevant because these systems provide a significant portion of global primary productivity and fishery catch (Figure 30.1 A, B; Table SM30.1). Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO<sub>2</sub> enrichment in deeper water layers. Once this water returns to the surface through upwelling, benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (*high confidence*; Sections 6.3.2, 6.3.3, 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller et al., 2010), reduce fisheries' catch potential, and impact aquaculture in coastal areas (Barton et al., 2012; see also Sections 5.4.3.3, 6.3.3, 6.4.1, 30.5.1.1.2, 30.5.5.1.3). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulfide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor. This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004; Bakun et al., 2010), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia's most valuable fishery (Hamukuaya et al., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (Section 6.4.1, Chapter 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean, upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N<sub>2</sub>-fixing microorganisms (Deutsch et al., 2007; Deutsch and Weber, 2012), but field observations of N<sub>2</sub> fixation in these regions have not supported these predictions (Fernandez et al., 2011; Franz et al., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O<sub>2</sub> and CO<sub>2</sub> inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO<sub>2</sub> concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending on pCO<sub>2</sub> of the upwelled water, and potentially increasingly impact the biota of EBUEs.



**Figure UP-1** | (a) Hypothetic mechanism of increasing coastal wind-driven upwelling at Equatorial and Eastern Boundary upwelling systems (EUS, EBUE, Figure 30-1), where differential warming rates between land and ocean results in increased land-ocean (1) pressure gradients that produce (2) stronger alongshore winds and (3) offshore movement of surface water through Ekman transport, and (4) increased upwelling of deep cold nutrient rich waters to replace it. (b) Potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decrease coastal fisheries due to an increased exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.

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# Urban–Rural Interactions – Context for Climate Change Vulnerability, Impacts, and Adaptation

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Rural areas and urban areas have always been interconnected and interdependent, but recent decades have seen new forms of these interconnections: a tendency for rural–urban boundaries to become less well defined, and new types of land use and economic activity on those boundaries. These conditions have important implications for understanding climate change impacts, vulnerabilities, and opportunities for adaptation. This box examines three critical implications of these interactions:

- 1) Climate extremes in rural areas resulting in urban impacts—teleconnections of resources and migration streams mean that climate extremes in non-urban locations with associated shifts in water supply, rural agricultural potential, and the habitability of rural areas will have downstream impacts in cities.
- 2) Events specific to the rural–urban interface—given the highly integrated nature of rural–urban interface areas and overarching demand to accommodate both rural and urban demands in these settings, there is a set of impacts, vulnerabilities, and opportunities for adaptation specific to these locations. These impacts include loss of local agricultural production, economic marginalization resulting from being neither rural or urban, and stress on human health.
- 3) Integrated infrastructure and service disruption—as urban demands often take preference, interdependent rural and urban resource systems place nearby rural areas at risk, because during conditions of climate stress, rural areas more often suffer resource shortages or other disruptions to sustain resources to cities. For example, under conditions of resource stress associated with climate risk (e.g., droughts) urban areas are at an advantage because of political, social, and economic requirements to maintain service supply to cities to the detriment of relatively marginal rural sites and settlements.

Urban areas historically have been dependent on the lands just beyond their boundaries for most of their critical resources including water, food, and energy. Although in many contexts, the connections between urban settlements and surrounding rural areas are still present, long distance, teleconnected, large-scale supply chains have been developed particularly with respect to energy resources and food supply (Güneralp et al., 2013). Extreme event disruptions in distant resource areas or to the supply chain and relevant infrastructure can negatively impact the urban areas dependent on these materials (Wilbanks et al., 2012). During the summer of 2012, for instance, an extended drought period in the central United States led to significantly reduced river levels on the Mississippi River that led to interruptions of barge traffic and delay of commodity flows to cities throughout the country. Urban water supply is also vulnerable to droughts in predominantly rural areas. In the case of Bulawayo, Zimbabwe, periodic urban water shortages over the last few decades have been triggered by rural droughts (Mkandla et al., 2005).

A further teleconnection between rural and urban areas is rural–urban migration. There have been cases where migration and urbanization patterns have been attributed to climate change or its proxies such as in parts of Africa (Morton, 1989; Barrios et al., 2006). However, as recognized by Black et al. (2011), life in rural areas across the world typically involves complex patterns of rural–urban and rural–rural migration, subject to economic, political, social, and demographic drivers, patterns that are modified or exacerbated by climate events and trends rather than solely caused by them.

Globally, an increased blending of urban and rural qualities has occurred. Simon et al. (2006, p. 4) assert that the simple dichotomy between “rural” and “urban” has “long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South.” One approach to reconciling this is through the increasing application of the concept of “peri-urban areas” (Simon et al., 2006; Simon, 2008). These areas can be seen as rural locations that have “become more urban in character” (Webster, 2002, p. 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be “largely rural landscapes” (Learner and Eakin, 2010, p. 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). The inhabitants of “core” urban areas within cities have also increasingly turned to agriculture, with production of staple foods, higher value crops and livestock (Bryld, 2003; Devendra et al., 2005; Lerner and Eakin, 2010; Lerner et al., 2013). Bryld (2003) sees this as driven by rural–urban migration and by structural adjustment (e.g., withdrawal of food price controls and food subsidies). Lerner and Eakin (2011; also Lerner et al., 2013) explored reasons why people produce food in urban environments, despite high opportunity costs of land and labor: buffering of risk from insecure urban labor markets; response to consumer demand; and the meeting of cultural needs.

Livelihoods and areas on the rural–urban interface suffer highly specific forms of vulnerability to disasters, including climate-related disasters. These may be summarized as specifically combining urban vulnerabilities of population concentration, dependence on infrastructure, and social diversity limiting social support with rural traits of distance, isolation, and invisibility to policymakers (Pelling and Mustafa, 2010). Increased connectivity can also encourage land expropriation to enable commercial land development (Pelling and Mustafa, 2010). Vulnerability may arise from the coexistence of rural and urban perspectives, which may give rise to conflicts between different social/interest groups and economic activities (Masuda and Garvin, 2008; Solona-Solona 2010; Darly and Torre, 2013).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Iaquinta and Drescher, 2000). Rapid declines in traditional informal institutions and forms of collective action, and their imperfect replacement with formal state and market institutions, may also increase vulnerability (Pelling and Mustafa, 2010).

Peri-urban areas and livelihoods have low visibility to policymakers at both local and national levels, and may suffer from a lack of necessary services and inappropriate and uncoordinated policies. In Tanzania and Malawi, national policies of agricultural extension to farmer groups, for example, do not reach peri-urban farmers (Liwenga et al., 2012). In peri-urban areas around Mexico City (Eakin et al., 2013), management of the substantial risk of flooding is led *de facto* by agricultural and water agencies, in the absence of capacity within peri-urban municipalities and despite clear evidence that urban encroachment is a key driver of flood risk. In developed country contexts, suburban–exurban fringe areas often are overlooked in the policy arena that traditionally focuses on rural development and agricultural production, or urban growth and services (Hanlon et al., 2010). The environmental function of urban agriculture, in particular, in protection against flooding, will increase in the context of climate change (Aubry et al., 2012).

However, peri-urban areas and mixed livelihoods more generally on rural–urban interfaces, also exhibit specific factors that increase their resilience to climate shocks (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education. The expansion of local labor markets and wage labor in these areas can strengthen adaptive capacity through providing new livelihood opportunities (Pelling and Mustafa, 2010). Maintaining mixed portfolios of agricultural and non-agricultural livelihoods also spreads risk (Lerner et al., 2013).

In high-income countries, practices attempting to enhance the ecosystem services and localized agriculture more typically associated with lower density areas have been encouraged. In many situations these practices are focused increasingly on climate adaptation and mitigating the impacts of climate extremes such as those associated with heating and the urban heat island effect, or wetland restoration efforts to limit the impact of storm surge wave action (Verburg et al., 2012).

The dramatic growth of urban areas also implies that rural areas and communities are increasingly politically and economically marginalized within national contexts, resulting in potential infrastructure and service disruptions for such sites. Existing rural–urban conflicts for the management of natural resources (Castro and Nielsen, 2003) such as water (Celio et al., 2011) or land use conversion in rural areas, for example, wind farms in rural Catalonia (Zografos and Martínez-Alier, 2009); industrial coastal areas in Sweden (Stepanova and Bruckmeier, 2013); or conversion of rice land into industrial, residential, and recreational uses in the Philippines (Kelly, 1998) have been documented, and it is expected that stress from climate change impacts on land and natural resources will exacerbate these tensions. For instance, climate-induced reductions in water availability may be more of a concern than population growth or increased per capita use for securing continued supplies of water to large cities (Jenerette and Larsen, 2006), which requires an innovative approach to address such conflicts (Pearson et al., 2010).



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# Active Role of Vegetation in Altering Water Flows under Climate Change

Dieter Gerten (Germany), Richard Betts (UK), Petra Döll (Germany)

Climate, vegetation, and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and  $\text{CO}_2$  uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e., by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric  $\text{CO}_2$  concentrations. In addition, effects of climate change (e.g., higher temperature or altered precipitation) on vegetation structure, biomass production, and plant distribution have an indirect influence on water flows. Rising  $\text{CO}_2$  concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air  $\text{CO}_2$  Enrichment (FACE), laboratory and modeling experiments (e.g., Leakey et al., 2009; Reddy et al., 2010; de Boer et al., 2011). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, that is, lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of  $\text{C}_3$  plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and  $\text{CO}_2$ -induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of  $\text{CO}_2$  is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas et al., 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and in a temperate semi-natural grassland (Koehler et al., 2010), although in one boreal tree species WUE ceased to increase after 1970 (Gagen et al., 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan et al., 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modeling study by Gedney et al., 2006) or has increased in some regions due to the structural  $\text{CO}_2$  effect (as assumed in models by Piao et al., 2007; Gerten et al., 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and  $\text{CO}_2$  change (Andreu-Hayles et al.,

2011; Peñuelas et al., 2011). However, basal area measurements at more than 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis et al., 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO<sub>2</sub> effects (McMahon et al., 2010). Satellite observations analyzed in Donohue et al. (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO<sub>2</sub> fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO<sub>2</sub> increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modeling studies, can suppress the CO<sub>2</sub> fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO<sub>2</sub> effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney et al. (2006) that suggested that the physiological CO<sub>2</sub> effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat et al. (2004). However, a more recent analysis based on a more complete data set (Dai et al., 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland et al., 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO<sub>2</sub> increase and land use change have contributed less (Piao et al., 2007; Gerten et al., 2008; Alkama et al., 2011; Sterling et al., 2013). Oliveira et al. (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

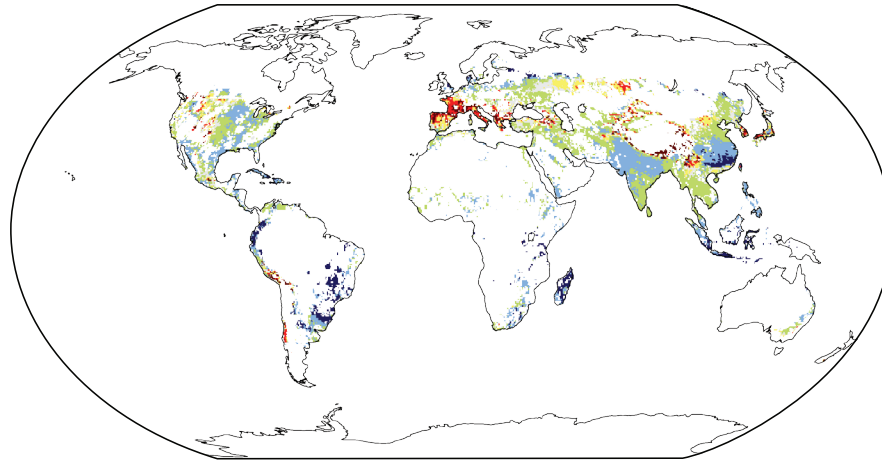
It is uncertain how vegetation responses to future increases in CO<sub>2</sub> and to climate change will modulate the impacts of climate change on freshwater flows. Twenty-first century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO<sub>2</sub> effect is included in addition to climate change effects (Betts et al., 2007; Murray et al., 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten et al., 2011; Wiltshire et al., 2013). In absolute terms, the isolated effect of CO<sub>2</sub> has been modeled to increase future global runoff by 4 to 5% (Gerten et al., 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO<sub>2</sub> trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were in Nugent and Matthews, 2012). In a global model intercomparison study (Davie et al., 2013), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO<sub>2</sub> effects compared to simulations with constant CO<sub>2</sub> concentration (consistent with the above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO<sub>2</sub>, stomatal closure, and plant growth is a source of uncertainty, as also suggested by Cao et al. (2009). Lower transpiration due to rising CO<sub>2</sub> concentration may also affect future regional climate change itself (Boucher et al., 2009) and enhance the contrast between land and ocean surface warming (Joshi et al., 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama et al., 2010).

An application of a soil–vegetation–atmosphere–transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum et al., 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO<sub>2</sub> rise, that is, increasing WUE and either increasing or decreasing leaf area (Crosbie et al., 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green et al., 2007). For a site in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma et al., 2010).

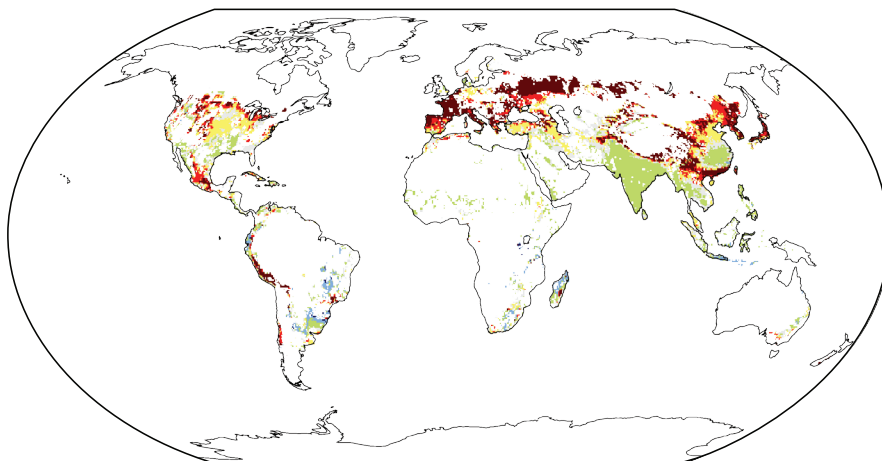
Using a large ensemble of climate change projections, Konzmann et al. (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO<sub>2</sub> effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader et al., 2010). However, substantial CO<sub>2</sub>-driven improvements will be realized only if proper management abates limitation of plant growth by nutrient availability or other factors.

Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg et al., 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the atmosphere such as in the Amazon region (Port et al., 2012; Saatchi et al., 2013). One model in the study by Davie et al. (2013) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO<sub>2</sub> effects. As water, carbon, and vegetation dynamics evolve synchronously and interactively under climate change (Heyder et al., 2011; Gerten et al., 2013), it remains a challenge to disentangle the individual effects of climate, CO<sub>2</sub>, and land cover change on the water cycle.

(a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO<sub>2</sub>



(b) Impact of climate change only



Percentage change in net irrigation requirements

■ <-40	■ -20 to -40	■ -5 to 20	■ -5 to 5	■ 5 to 20	■ 20 to 40	■ >40	□ No irrigation
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**Figure VW-1** | Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. (a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO<sub>2</sub> concentration (co-limitation by nutrients not considered). (b) Impact of climate change only. Shown is the median change derived from climate change projections by 19 General Circulation Models (GCMs; based on the Special Report on Emission Scenarios (SRES) A2 emissions scenario) used to force a vegetation and hydrology model. (Modified after Konzmann et al., 2013.)

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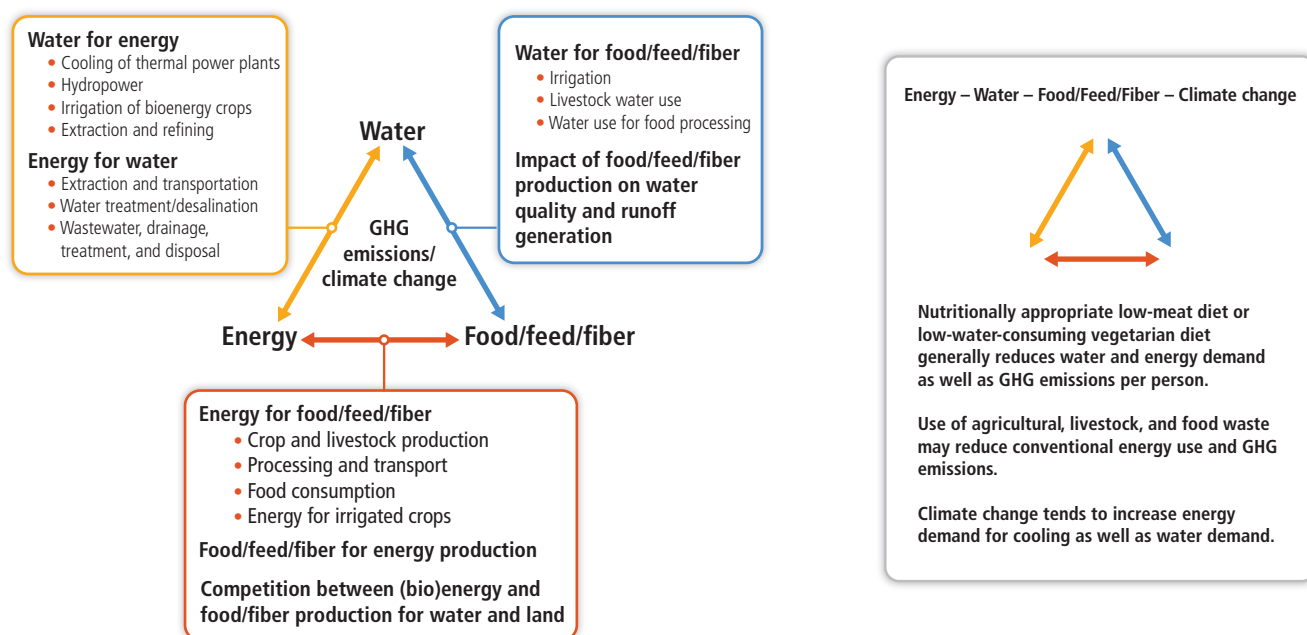


# The Water–Energy–Food/ Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Energy technologies (e.g., biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber, 2008; McMahon and Price, 2011; Macknick et al., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice, and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Metcalf & Eddy, Inc. et al., 2007; Khan and Hanjra, 2009; EPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport, and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (*robust evidence, high agreement*; Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012). Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional nonrenewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Oh et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane byproducts are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale, 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence, high agreement*; Sections 10.2.2, 10.3.4, 25.7.4; and van Vliet et al., 2012; Davies et al., 2013). Water for biofuels, for example, under the International Energy Agency (IEA) Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (*medium evidence, high agreement*; WEC, 2010; Sattler et al.,



**Figure WE-1** | The water–energy–food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, and energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

2012). Future water availability for energy production will change due to climate change (*robust evidence, high agreement*; Sections 3.4, 3.5.1, 3.5.2.2).

Water may require significant amounts of energy for lifting, transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m<sup>3</sup> of water vary by about a factor of 10 between different sources, for example, locally produced potable water from ground/surface water sources versus desalinated seawater (Box 25-2, Tables 25-6, 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly—electricity use (kWh m<sup>-3</sup> of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (*medium confidence*; Smit and Nasr, 1992; Jiménez-Cisneros, 1996; Qadir et al., 2007; Raschid-Sally and Jayakody, 2008). More energy efficient treatment methods enable poor quality (“black”) wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional freshwater and associated energy demands (Kerai et al., 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (*high confidence*; Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jiménez-Cisneros, 2009).

Linkages among water, energy, food/feed/fiber, and climate are also strongly related to land use and management (*robust evidence, high agreement*; Section 4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food, or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (*medium evidence, high agreement*; Sections 25.4.3, 25.6.2, Box 25-10). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity, and other factors (see Figure CC-WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; and air pollution reduction, as well as the implications for health and economic impacts as described throughout this Assessment Report.

The interconnectivity of food/fiber, water, land use, energy, and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel–food–land use–water–greenhouse gas (GHG) mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type, and use requirements, energy requirements, and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300 EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water, and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change is increasingly recognized as critical to effective climate resilient pathway decision making (*medium evidence, high agreement*), although tools to support local- and regional-scale assessments and decision support remain very limited.

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# Glossary



# Glossary

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**Abrupt climate change**

A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

**Access to food**

One of the three components underpinning food security, the other two being availability and utilization. Access to food is dependent on (1) the affordability of food (i.e., people have income or other resources to exchange for food); (2) satisfactory allocation within the household or society; and (3) preference (i.e., it is what people want to eat, influenced by socio-cultural norms). See also Food security.

**Acclimatization**

A change in functional or morphological traits occurring once or repeatedly (e.g., seasonally) during the lifetime of an individual organism in its natural environment. Through acclimatization the individual maintains performance across a range of environmental conditions. For a clear differentiation between findings in laboratory and field studies, the term *acclimation* is used in ecophysiology for the respective phenomena when observed in well-defined experimental settings. The term (*adaptive*) *plasticity* characterizes the generally limited scope of changes in phenotype that an individual can reach through the process of acclimatization.

**Adaptability**

See Adaptive capacity.

**Adaptation<sup>1</sup>**

The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

**Incremental adaptation** Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.<sup>2</sup>

**Transformational adaptation** Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

See also Autonomous adaptation, Evolutionary adaptation, and Transformation.

**Adaptation assessment**

The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.

**Adaptation constraint**

Factors that make it harder to plan and implement adaptation actions or that restrict options.

**Adaptation deficit**

The gap between the current state of a system and a state that minimizes adverse impacts from existing climate conditions and variability.

**Adaptation limit**

The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

**Hard adaptation limit** No adaptive actions are possible to avoid intolerable risks.

**Soft adaptation limit** Options are currently not available to avoid intolerable risks through adaptive action.

**Adaptation needs**

The circumstances requiring action to ensure safety of populations and security of assets in response to climate impacts.

**Adaptation opportunity**

Factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.

**Adaptation options**

The array of strategies and measures that are available and appropriate for addressing adaptation needs. They include a wide range of actions that can be categorized as structural, institutional, or social.

**Adaptive capacity**

The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.<sup>3</sup>

**Adaptive management**

A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables.

**Aggregate impacts**

Total impacts integrated across sectors and/or regions. The aggregation of impacts requires knowledge of (or assumptions about) the relative importance of different impacts. Measures of aggregate impacts include, for example, the total number of people affected, or the total economic costs, and are usually bound by time, place, and/or sector.

**Ancillary benefits**

See Co-benefits.

**Anomaly**

The deviation of a variable from its value averaged over a reference period.

<sup>1</sup> Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

<sup>2</sup> This definition builds from the definition used in Park et al. (2012).

<sup>3</sup> This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005).

**Anthropogenic**

Resulting from or produced by human activities.

**Anthropogenic emissions**

Emissions of greenhouse gases, greenhouse gas precursors, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management, and industrial processes.

**Arid zone**

Areas where vegetation growth is severely constrained due to limited water availability. For the most part, the native vegetation of arid zones is sparse. There is high rainfall variability, with annual averages below 300 mm. Crop farming in arid zones requires irrigation.

**Atlantic Multi-decadal Oscillation/Variability (AMO/AMV)**

A multi-decadal (65- to 75-year) fluctuation in the North Atlantic, in which sea surface temperatures showed warm phases during roughly 1860 to 1880 and 1930 to 1960 and cool phases during 1905 to 1925 and 1970 to 1990 with a range of approximately 0.4°C. See AMO Index in WGI AR5 Box 2.5.

**Atmosphere-Ocean General Circulation Model (AOGCM)**

See Climate model.

**Attribution**

See Detection and attribution.

**Autonomous adaptation**

Adaptation in response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change. Also referred to as spontaneous adaptation.

**Baseline/reference**

The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed. The baseline concentration of a trace gas is that measured at a location not influenced by local anthropogenic emissions.

**Biodiversity**

The variability among living organisms from terrestrial, marine, and other ecosystems. Biodiversity includes variability at the genetic, species, and ecosystem levels.<sup>4</sup>

**Bioenergy**

Energy derived from any form of biomass such as recently living organisms or their metabolic by-products.

**Biofuel**

A fuel, generally in liquid form, developed from organic matter or combustible oils produced by living or recently living plants. Examples of biofuel include alcohol (bioethanol), black liquor from the paper-manufacturing process, and soybean oil.

**First-generation manufactured biofuel** First-generation manufactured biofuel is derived from grains, oilseeds, animal fats, and waste vegetable oils with mature conversion technologies.

**Second-generation biofuel** Second-generation biofuel uses non-traditional biochemical and thermochemical conversion processes and feedstock mostly derived from the lignocellulosic fractions of, for example, agricultural and forestry residues, municipal solid waste, etc.

**Third-generation biofuel** Third-generation biofuel would be derived from feedstocks such as algae and energy crops by advanced processes still under development.

These second- and third-generation biofuels produced through new processes are also referred to as next-generation or advanced biofuels, or advanced biofuel technologies.

**Biomass**

The total mass of living organisms in a given area or volume; dead plant material can be included as dead biomass. Biomass burning is the burning of living and dead vegetation.

**Biome**

A biome is a major and distinct regional element of the biosphere, typically consisting of several ecosystems (e.g., forests, rivers, ponds, swamps within a region). Biomes are characterized by typical communities of plants and animals.

**Biosphere**

The part of the Earth system comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere), or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter, and oceanic detritus.

**Boundary organization**

A bridging institution, social arrangement, or network that acts as an intermediary between science and policy.

**Business As Usual (BAU)**

Business as usual projections are based on the assumption that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g., a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place. See also Baseline/reference, Climate scenario, Emission scenario, Representative Concentration Pathways, Scenario, Socioeconomic scenario, and SRES scenarios.

**Capacity building**

The practice of enhancing the strengths and attributes of, and resources available to, an individual, community, society, or organization to respond to change.

<sup>4</sup> This glossary entry builds from definitions used in the Global Biodiversity Assessment (Heywood, 1995) and the Millennium Ecosystem Assessment (MEA, 2005).

### Carbon cycle

The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide) through the atmosphere, ocean, terrestrial and marine biosphere, and lithosphere. In this report, the reference unit for the global carbon cycle is GtC or equivalently PgC ( $10^{15}$ g).

### Carbon dioxide (CO<sub>2</sub>)

A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas, and coal, of burning biomass, of land use changes, and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.

### Carbon dioxide (CO<sub>2</sub>) fertilization

The enhancement of the growth of plants as a result of increased atmospheric carbon dioxide (CO<sub>2</sub>) concentration.

### Carbon sequestration

See Uptake.

### Clean Development Mechanism (CDM)

A mechanism defined under Article 12 of the Kyoto Protocol through which investors (governments or companies) from developed (Annex B) countries may finance greenhouse gas emission reduction or removal projects in developing (Non-Annex B) countries, and receive Certified Emission Reduction Units for doing so, which can be credited towards the commitments of the respective developed countries. The CDM is intended to facilitate the two objectives of promoting sustainable development in developing countries and of helping industrialized countries to reach their emissions commitments in a cost-effective way.

### Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

### Climate-altering pollutants (CAPs)

Gases and particles released from human activities that affect the climate either directly, through mechanisms such as radiative forcing from changes in greenhouse gas concentrations, or indirectly, by, for example, affecting cloud formation or the lifetime of greenhouse gases in the atmosphere. CAPs include both those pollutants that have a warming effect on the atmosphere, such as CO<sub>2</sub>, and those with cooling effects, such as sulfates.

### Climate change

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of

the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also Climate change commitment and Detection and Attribution.

### Climate change commitment

Due to the thermal inertia of the ocean and slow processes in the cryosphere and land surfaces, the climate would continue to change even if the atmospheric composition were held fixed at today's values. Past change in atmospheric composition leads to a committed climate change, which continues for as long as a radiative imbalance persists and until all components of the climate system have adjusted to a new state. The further change in temperature after the composition of the atmosphere is held constant is referred to as the constant composition temperature commitment or simply committed warming or warming commitment. Climate change commitment includes other future changes, for example, in the hydrological cycle, in extreme weather events, in extreme climate events, and in sea level change. The constant emission commitment is the committed climate change that would result from keeping anthropogenic emissions constant and the zero emission commitment is the climate change commitment when emissions are set to zero. See also Climate change.

### Climate extreme (Extreme weather or climate event)

See Extreme weather event.

### Climate feedback

An interaction in which a perturbation in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. In this Assessment Report, a somewhat narrower definition is often used in which the climate quantity that is perturbed is the global mean surface temperature, which in turn causes changes in the global radiation budget. In either case, the initial perturbation can either be externally forced or arise as part of internal variability.

### Climate governance

Purposeful mechanisms and measures aimed at steering social systems towards preventing, mitigating, or adapting to the risks posed by climate change (Jagers and Striiple, 2003).

### Climate model (spectrum or hierarchy)

A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such



aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal, and interannual climate predictions. See also Earth System Model.

### Climate prediction

A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual, or decadal time scales. Because the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. See also Climate projection, Climate scenario, and Predictability.

### Climate projection

A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative-forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized. See also Climate scenario.

### Climate-resilient pathways

Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change.

### Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. See also Emission scenario and Scenario.

### Climate sensitivity

In IPCC reports, equilibrium climate sensitivity (units: °C) refers to the equilibrium (steady state) change in the annual global mean surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. Owing to computational constraints, the equilibrium climate sensitivity in a climate model is sometimes estimated by running an atmospheric general circulation model coupled to a mixed-layer ocean model, because equilibrium climate sensitivity is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The climate sensitivity parameter (units: °C (W m<sup>-2</sup>)<sup>-1</sup>) refers to the equilibrium change in the annual

global mean surface temperature following a unit change in radiative forcing.

The effective climate sensitivity (units: °C) is an estimate of the global mean surface temperature response to doubled carbon dioxide concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state, and therefore may differ from equilibrium climate sensitivity.

The transient climate response (units: °C) is the change in the global mean surface temperature, averaged over a 20-year period, centered at the time of atmospheric carbon dioxide doubling, in a climate model simulation in which CO<sub>2</sub> increases at 1% yr<sup>-1</sup>. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing.

### Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere, and the interactions among them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and anthropogenic forcings such as the changing composition of the atmosphere and land use change.

### Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also Climate change.

### Climate velocity

The speed at which isolines of a specified climate variable travel across landscapes or seascapes due to changing climate. For example, climate velocity for temperature is the speed at which isotherms move due to changing climate (km yr<sup>-1</sup>) and is calculated as the temporal change in temperature (°C yr<sup>-1</sup>) divided by the current spatial gradient in temperature (°C km<sup>-1</sup>). It can be calculated using additional climate variables such as precipitation or can be based on the climatic niche of organisms.

### Climatic driver (Climate driver)

A changing aspect of the climate system that influences a component of a human or natural system.

### CMIP3 and CMIP5

Phases three and five of the Coupled Model Intercomparison Project (CMIP3 and CMIP5), coordinating and archiving climate model simulations based on shared model inputs by modeling groups from around the world. The CMIP3 multi-model data set includes projections using SRES scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways.

### Coastal squeeze

A narrowing of coastal ecosystems and amenities (e.g., beaches, salt marshes, mangroves, and mud and sand flats) confined between landward-retreating shorelines (from sea level rise and/or erosion) and naturally or artificially fixed shorelines including engineering defenses (e.g., seawalls), potentially making the ecosystems or amenities vanish.

### Co-benefits

The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.

### Community-based adaptation

Local, community-driven adaptation. Community-based adaptation focuses attention on empowering and promoting the adaptive capacity of communities. It is an approach that takes context, culture, knowledge, agency, and preferences of communities as strengths.

### Confidence

The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively (Mastrandrea et al., 2010). See Box 1-1. See also Uncertainty.

### Contextual vulnerability (Starting-point vulnerability)

A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes (O'Brien et al., 2007).

### Convection

Vertical motion driven by buoyancy forces arising from static instability, usually caused by near-surface cooling or increases in salinity in the case of the ocean and near-surface warming or cloud-top radiative cooling in the case of the atmosphere. In the atmosphere, convection gives rise to cumulus clouds and precipitation and is effective at both scavenging and vertically transporting chemical species. In the ocean, convection can carry surface waters to deep within the ocean.

### Coping

The use of available skills, resources, and opportunities to address, manage, and overcome adverse conditions, with the aim of achieving basic functioning of people, institutions, organizations, and systems in the short to medium term.<sup>5</sup>

### Coping capacity

The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term.<sup>6</sup>

### Coral bleaching

Loss of coral pigmentation through the loss of intracellular symbiotic algae (known as zooxanthellae) and/or loss of their pigments.

### Cryosphere

All regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers and ice sheets, and frozen ground (which includes permafrost).

### Cultural impacts

Impacts on material and ecological aspects of culture and the lived experience of culture, including dimensions such as identity, community cohesion and belonging, sense of place, worldview, values, perceptions, and tradition. Cultural impacts are closely related to ecological impacts, especially for iconic and representational dimensions of species and landscapes. Culture and cultural practices frame the importance and value of the impacts of change, shape the feasibility and acceptability of adaptation options, and provide the skills and practices that enable adaptation.

### Dead zones

Extremely hypoxic (i.e., low-oxygen) areas in oceans and lakes, caused by excessive nutrient input from human activities coupled with other factors that deplete the oxygen required to support many marine organisms in bottom and near-bottom water. See also Eutrophication and Hypoxic events.

### Decarbonization

The process by which countries or other entities aim to achieve a low-carbon economy, or by which individuals aim to reduce their consumption of carbon.

### Deforestation

Conversion of forest to non-forest. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and *deforestation* see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). See also the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

### Desertification

Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Land degradation in arid, semi-arid, and dry sub-humid areas is reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as (1) soil erosion caused by wind and/or water; (2) deterioration of the physical, chemical, biological, or economic properties of soil; and (3) long-term loss of natural vegetation (UNCCD, 1994).

<sup>5</sup> This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).

<sup>6</sup> This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).

### Detection and attribution

Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence (Hegerl et al., 2010).

### Detection of impacts of climate change

For a natural, human, or managed system, identification of a change from a specified baseline. The baseline characterizes behavior in the absence of climate change and may be stationary or non-stationary (e.g., due to land use change).

### Disadvantaged populations

Sectors of a society that are marginalized, often because of low socioeconomic status, low income, lack of access to basic services such as health or education, lack of power, race, gender, religion, or poor access to communication technologies.

### Disaster

Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

### Disaster management

Social processes for designing, implementing, and evaluating strategies, policies, and measures that promote and improve disaster preparedness, response, and recovery practices at different organizational and societal levels.

### Disaster risk

The likelihood within a specific time period of disaster. See Disaster.

### Disaster Risk Management (DRM)

Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.

### Disaster Risk Reduction (DRR)

Denotes both a policy goal or objective, and the strategic and instrumental measures employed for anticipating future disaster risk; reducing existing exposure, hazard, or vulnerability; and improving resilience.

### Discounting

A mathematical operation making monetary (or other) amounts received or expended at different times (years) comparable across time. The

discount rate uses a fixed or possibly time-varying discount rate ( $>0$ ) from year to year that makes future value worth less today.

### Disturbance regime

Frequency, intensity, and types of disturbances of ecological systems, such as fires, insect or pest outbreaks, floods, and droughts.

### Diurnal temperature range

The difference between the maximum and minimum temperature during a 24-hour period.

### Downscaling

Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information.

### Drought

A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more. For the corresponding indices, see WGI AR5 Box 2.4.

### Dynamic Global Vegetation Model (DGVM)

A model that simulates vegetation development and dynamics through space and time, as driven by climate and other environmental changes.

### Early warning system

The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organizations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss.<sup>7</sup>

### Earth System Model (ESM)

A coupled atmosphere-ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO<sub>2</sub> or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included. See also Climate model.

<sup>7</sup> This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).

### Ecophysiological process

Processes in which individual organisms respond continuously to environmental variability or change, such as climate change, generally at a microscopic or sub-organ scale. Ecophysiological mechanisms underpin individual organisms' tolerance to environmental stress, and comprise a broad range of responses defining the absolute tolerances by individuals of environmental conditions. Ecophysiological responses may scale up to control species' geographic ranges.

### Ecosystem

A functional unit consisting of living organisms, their non-living environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment.

### Ecosystem approach

A strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way. An ecosystem approach is based on the application of scientific methodologies focused on levels of biological organization, which encompass the essential structure, processes, functions, and interactions of organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral component of many ecosystems. The ecosystem approach requires adaptive management to deal with the complex and dynamic nature of ecosystems and the absence of complete knowledge or understanding of their functioning. Priority targets are conservation of biodiversity and of the ecosystem structure and functioning, in order to maintain ecosystem services.<sup>8</sup>

### Ecosystem-based adaptation

The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. Ecosystem-based adaptation uses the range of opportunities for the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. It aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change. Ecosystem-based adaptation is most appropriately integrated into broader adaptation and development strategies (CBD, 2009).

### Ecosystem services

Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food, fiber, or fish, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation.

### El Niño-Southern Oscillation (ENSO)

The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere-ocean phenomenon, with preferred time scales of 2 to about 7 years, is known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Tahiti and Darwin or the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña. For the corresponding indices, see WGI AR5 Box 2.5.

### Emergent risk

A risk that arises from the interaction of phenomena in a complex system, for example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region.

### Emission scenario

A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented, which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emissions Scenarios (Nakićenović and Swart, 2000) emission scenarios, the so-called SRES scenarios, were published, some of which were used, among others, as a basis for the climate projections presented in Chapters 9 to 11 of IPCC (2001) and Chapters 10 and 11 of IPCC (2007). New emission scenarios for climate change, the four Representative Concentration Pathways, were developed for, but independently of, the present IPCC assessment. See also Climate scenario and Scenario.

### Ensemble

A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modeled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.

<sup>8</sup> This glossary entry builds from definitions used in CBD (2000), MEA (2005), and the Fourth Assessment Report.

**Environmental migration**

Human migration involves movement over a significant distance and duration. Environmental migration refers to human migration where environmental risks or environmental change plays a significant role in influencing the migration decision and destination. Migration may involve distinct categories such as direct, involuntary, and temporary displacement due to weather-related disasters; voluntary relocation as settlements and economies become less viable; or planned resettlement encouraged by government actions or incentives. All migration decisions are multi-causal, and hence it is not meaningful to describe any migrant flow as being solely for environmental reasons.

**Environmental services**

See Ecosystem services.

**Eutrophication**

Over-enrichment of water by nutrients such as nitrogen and phosphorus. It is one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms. See also Dead zones.

**Evolutionary adaptation**

For a population or species, change in functional characteristics as a result of selection acting on heritable traits. The rate of evolutionary adaptation depends on factors such as strength of selection, generation turnover time, and degree of outcrossing (as opposed to inbreeding). See also Adaptation.

**Exposure**

The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

**External forcing**

External forcing refers to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations, and anthropogenic changes in the composition of the atmosphere and land use change are external forcings. Orbital forcing is also an external forcing as the insolation changes with orbital parameters eccentricity, tilt, and precession of the equinox.

**Externalities/external costs/external benefits**

Externalities arise from a human activity when agents responsible for the activity do not take full account of the activity's impacts on others' production and consumption possibilities, and no compensation exists for such impacts. When the impacts are negative, they are external costs. When the impacts are positive, they are external benefits.

**Extratropical cyclone**

A large-scale (of order 1000 km) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy precipitation especially in wintertime.

**Extreme climate event**

See Extreme weather event.

**Extreme sea level**

See Storm surge.

**Extreme weather event**

An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

**Famine**

Scarcity of food over an extended period and over a large geographical area, such as a country, or lack of access to food for socioeconomic, political, or cultural reasons. Famines may be caused by climate-related extreme events such as droughts or floods and by disease, war, or other factors.

**Feedback**

See Climate feedback.

**Fire weather**

Weather conditions conducive to triggering and sustaining wild fires, usually based on a set of indicators and combinations of indicators including temperature, soil moisture, humidity, and wind. Fire weather does not include the presence or absence of fuel load.

**Fitness (Darwinian)**

Fitness is the relative capacity of an individual or genotype to both survive and reproduce, quantified as the average contribution of the genotype to the gene pool of the next generations. During evolution, natural selection favors functions providing greater fitness such that the functions become more common over generations.

**Flood**

The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

**Food security**

A state that prevails when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development, and an active and healthy life.<sup>9</sup> See also Access to food.

**Food system**

A food system includes the suite of activities and actors in the food chain (i.e., producing, processing and packaging, storing and transporting, trading and retailing, and preparing and consuming food); and the outcome of these activities relating to the three components underpinning food security (i.e., access to food, utilization of food, and food availability), all of which need to be stable over time. Food security is therefore

<sup>9</sup> This glossary entry builds from definitions used in FAO (2000) and previous IPCC reports.



underpinned by food systems, and is an emergent property of the behavior of the whole food system. Food insecurity arises when any aspect of the food system is stressed.

### Forecast

See Climate prediction and Climate projection.

### General Circulation Model (GCM)

See Climate model.

### Geoengineering

Geoengineering refers to a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most, but not all, methods seek to either (1) reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management) or (2) increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate (Carbon Dioxide Removal). Scale and intent are of central importance. Two key characteristics of geoengineering methods of particular concern are that they use or affect the climate system (e.g., atmosphere, land, or ocean) globally or regionally and/or could have substantive unintended effects that cross national boundaries. Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy (IPCC, 2012b, p. 2).

### Global change

A generic term to describe global scale changes in systems, including the climate system, ecosystems, and social-ecological systems.

### Global Climate Model (also referred to as General Circulation Model, both abbreviated as GCM)

See Climate model.

### Global mean surface temperature

An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.

### Greenhouse effect

The infrared radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.

### Greenhouse gas (GHG)

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and clouds. This property causes the greenhouse effect. Water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>), and ozone (O<sub>3</sub>) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>, the Kyoto Protocol deals with the greenhouse gases sulfur hexafluoride (SF<sub>6</sub>), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). For a list of well-mixed greenhouse gases, see WGI AR5 Table 2.SM.1.

### Ground-level ozone

Atmospheric ozone formed naturally or from human-emitted precursors near Earth's surface, thus affecting human health, agriculture, and ecosystems. Ozone is a greenhouse gas, but ground-level ozone, unlike stratospheric ozone, also directly affects organisms at the surface. Ground-level ozone is sometimes referred to as tropospheric ozone, although much of the troposphere is well above the surface and thus does not directly expose organisms at the surface. See also Ozone.

### Groundwater recharge

The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.

### Hazard

The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.

### Heat wave

A period of abnormally and uncomfortably hot weather.

### Hotspot

A geographical area characterized by high vulnerability and exposure to climate change.

### Human security

A condition that is met when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In the context of climate change, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests and to live with dignity.

### Human system

Any system in which human organizations and institutions play a major role. Often, but not always, the term is synonymous with society or



social system. Systems such as agricultural systems, political systems, technological systems, and economic systems are all human systems in the sense applied in this report.

### Hydrological cycle

The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapor, condenses to form clouds, precipitates over ocean and land as rain or snow, which on land can be intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans, from which it will eventually evaporate again. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

### Hypoxic events

Events that lead to deficiencies of oxygen in water bodies. See also Dead zones and Eutrophication.

### Ice cap

A dome-shaped ice mass that is considerably smaller in extent than an ice sheet.

### Ice sheet

A mass of land ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are only two ice sheets in the modern world, one on Greenland and one on Antarctica. During glacial periods there were others.

### Ice shelf

A floating slab of ice of considerable thickness extending from the coast (usually of great horizontal extent with a very gently sloping surface), often filling embayments in the coastline of an ice sheet. Nearly all ice shelves are in Antarctica, where most of the ice discharged into the ocean flows via ice shelves.

### (climate change) Impact assessment

The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems.

### Impacts (Consequences, Outcomes)<sup>10</sup>

Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the

interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

### Income

The maximum amount that a household, or other unit, can consume without reducing its real net worth. Total income is the broadest measure of income and refers to regular receipts such as wages and salaries, income from self-employment, interest and dividends from invested funds, pensions or other benefits from social insurance, and other current transfers receivable.<sup>11</sup>

### Indian Ocean Dipole (IOD)

Large-scale mode of interannual variability of sea surface temperature in the Indian Ocean. This pattern manifests through a zonal gradient of tropical sea surface temperature, which in one extreme phase in boreal autumn shows cooling off Sumatra and warming off Somalia in the west, combined with anomalous easterlies along the equator.

### Indigenous peoples

Indigenous peoples and nations are those that, having a historical continuity with pre-invasion and pre-colonial societies that developed on their territories, consider themselves distinct from other sectors of the societies now prevailing on those territories, or parts of them. They form at present principally non-dominant sectors of society and are often determined to preserve, develop, and transmit to future generations their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples, in accordance with their own cultural patterns, social institutions, and common law system.<sup>12</sup>

### Industrial Revolution

A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide. In this report the terms *preindustrial* and *industrial* refer, somewhat arbitrarily, to the periods before and after 1750, respectively.

### Industrialized/developed/developing countries

There are a diversity of approaches for categorizing countries on the basis of their level of development, and for defining terms such as industrialized, developed, or developing. Several categorizations are used in this report. In the United Nations system, there is no established convention for the designation of developed and developing countries or areas. The United Nations Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as least developed countries, landlocked

<sup>10</sup> Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

<sup>11</sup> This glossary entry builds from the definition used in OECD (2003).

<sup>12</sup> This glossary entry builds from the definitions used in Cobo (1987) and previous IPCC reports.

developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle, and high income. The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite human development index (HDI) to classify countries as low, medium, high, or very high human development. See Box 1-2.

### **Informal sector**

Commercial enterprises (mostly small) that are not registered or that otherwise fall outside official rules and regulations. Among the businesses that make up the informal sector, there is great diversity in the value of the goods or services produced, the numbers employed, the extent of illegality, and the connection to the formal sector. Many informal enterprises have some characteristics of formal-sector enterprises, and some people are in informal employment in the formal sector as they lack legal protection or employment benefits.

### **Informal settlement**

A term given to settlements or residential areas that by at least one criterion fall outside official rules and regulations. Most informal settlements have poor housing (with widespread use of temporary materials) and are developed on land that is occupied illegally with high levels of overcrowding. In most such settlements, provision for safe water, sanitation, drainage, paved roads, and basic services is inadequate or lacking. The term *slum* is often used for informal settlements, although it is misleading as many informal settlements develop into good quality residential areas, especially where governments support such development.

### **Institutions**

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction. Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations—such as parliaments, regulatory agencies, private firms, and community bodies—develop and act in response to institutional frameworks and the incentives they frame. Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization.

### **Insurance/reinsurance**

A family of financial instruments for sharing and transferring risk among a pool of at-risk households, businesses, and/or governments. See also Risk transfer.

### **Integrated assessment**

A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions among these components, in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

### **Integrated Coastal Zone Management (ICZM)**

An integrated approach for sustainably managing coastal areas, taking into account all coastal habitats and uses.

### **Invasive species/Invasive Alien Species (IAS)**

A species introduced outside its natural past or present distribution (i.e., an alien species) that becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity (IUCN, 2000; CBD, 2002).

### **Key vulnerability, Key risk, Key impact**

A vulnerability, risk, or impact relevant to the definition and elaboration of “dangerous anthropogenic interference (DAI) with the climate system,” in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policy makers in that context.

Key risks are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered “key” due to high hazard or high vulnerability of societies and systems exposed, or both.

Vulnerabilities are considered “key” if they have the potential to combine with hazardous events or trends to result in key risks. Vulnerabilities that have little influence on climate-related risk, for instance, due to lack of exposure to hazards, would not be considered key.

Key impacts are severe consequences for humans and social-ecological systems.

### **Land grabbing**

Large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities.

### **Land surface air temperature**

The surface air temperature as measured in well-ventilated screens over land at 1.5 m above the ground.

### **Land use and Land use change**

Land use refers to the total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term *land use* is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus give rise to radiative forcing and/or other impacts on climate, locally or globally. See also the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

### **La Niña**

See El Niño-Southern Oscillation.

### **Last Glacial Maximum (LGM)**

The period during the last ice age when the glaciers and ice sheets reached their maximum extent, approximately 21 ka ago. This period

has been widely studied because the radiative forcings and boundary conditions are relatively well known.

### **Likelihood**

The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al., 2010), defined in Box 1-1. See also Confidence and Uncertainty.

### **Livelihood**

The resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorized as human, social, natural, physical, or financial.

### **Low regrets policy**

A policy that would generate net social and/or economic benefits under current climate and a range of future climate change scenarios.

### **Maladaptive actions (Maladaptation)**

Actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future.

### **Mean sea level**

The surface level of the ocean at a particular point averaged over an extended period of time such as a month or year. Mean sea level is often used as a national datum to which heights on land are referred.

### **Meridional Overturning Circulation (MOC)**

Meridional (north-south) overturning circulation in the ocean quantified by zonal (east-west) sums of mass transports in depth or density layers. In the North Atlantic, away from the subpolar regions, the MOC (which is in principle an observable quantity) is often identified with the thermohaline circulation (THC), which is a conceptual and incomplete interpretation. It must be borne in mind that the MOC is also driven by wind, and can also include shallower overturning cells such as occur in the upper ocean in the tropics and subtropics, in which warm (light) waters moving poleward are transformed to slightly denser waters and subducted equatorward at deeper levels. See also Thermohaline circulation.

### **Microclimate**

Local climate at or near the Earth's surface. See also Climate.

### **Mitigation (of climate change)**

A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

### **Mitigation (of disaster risk and disaster)**

The lessening of the potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability.

### **Mode of climate variability**

Underlying space-time structure with preferred spatial pattern and temporal variation that helps account for the gross features in variance

and for teleconnections. A mode of variability is often considered to be the product of a spatial climate pattern and an associated climate index time series.

### **Monsoon**

A monsoon is a tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer.

### **Non-climatic driver (Non-climate driver)**

An agent or process outside the climate system that influences a human or natural system.

### **Nonlinearity**

A process is called nonlinear when there is no simple proportional relation between cause and effect. The climate system contains many such nonlinear processes, resulting in a system with potentially very complex behavior. Such complexity may lead to abrupt climate change. See also Predictability.

### **North Atlantic Oscillation (NAO)**

The North Atlantic Oscillation consists of opposing variations of surface pressure near Iceland and near the Azores. It therefore corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded extratropical cyclones with their associated frontal systems. See NAO Index in WGI AR5 Box 2.5.

### **Ocean acidification**

Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011, p. 37).

### **Opportunity costs**

The benefits of an activity forgone through the choice of another activity.

### **Outcome vulnerability (End-point vulnerability)**

Vulnerability as the end point of a sequence of analyses beginning with projections of future emission trends, moving on to the development of climate scenarios, and concluding with biophysical impact studies and the identification of adaptive options. Any residual consequences that remain after adaptation has taken place define the levels of vulnerability (Kelly and Adger, 2000; O'Brien et al., 2007).

### **Oxygen Minimum Zone (OMZ)**

The midwater layer (200 to 1000 m) in the open ocean in which oxygen saturation is the lowest in the ocean. The degree of oxygen depletion depends on the largely bacterial consumption of organic matter, and the distribution of the OMZs is influenced by large-scale ocean circulation. In coastal oceans, OMZs extend to the shelves and may also affect benthic ecosystems.

### Ozone

Ozone, the triatomic form of oxygen (O<sub>3</sub>), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O<sub>2</sub>). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

### Pacific Decadal Oscillation (PDO)

The pattern and time series of the first empirical orthogonal function of sea surface temperature over the North Pacific north of 20°N. The PDO broadened to cover the whole Pacific Basin is known as the Inter-decadal Pacific Oscillation (IPO). The PDO and IPO exhibit similar temporal evolution.

### Parameterization

In climate models, this term refers to the technique of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes) by relationships between model-resolved larger-scale variables and the area- or time-averaged effect of such sub-grid scale processes.

### Particulates

Very small solid particles emitted during the combustion of fossil and biomass fuels. Particulates may consist of a wide variety of substances. Of greatest concern for health are particulates of diameter less than or equal to 10 nm, usually designated as PM<sub>10</sub>.

### Pastoralism

A livelihood strategy based on moving livestock to seasonal pastures primarily in order to convert grasses, forbs, tree leaves, or crop residues into human food. The search for feed is however not the only reason for mobility; people and livestock may move to avoid various natural and/or social hazards, to avoid competition with others, or to seek more favorable conditions. Pastoralism can also be thought of as a strategy that is shaped by both social and ecological factors concerning uncertainty and variability of precipitation, and low and unpredictable productivity of terrestrial ecosystems.

### Path dependence

The generic situation where decisions, events, or outcomes at one point in time constrain adaptation, mitigation, or other actions or options at a later point in time.

### Permafrost

Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least 2 consecutive years.

### Persistent Organic Pollutants (POPs)

Toxic organic chemical substances that persist in the environment for long periods of time, are transported and deposited in locations distant from their sources of release, bioaccumulate, and can have adverse effects on human health and ecosystems.<sup>13</sup>

### Phenology

The relationship between biological phenomena that recur periodically (e.g., development stages, migration) and climate and seasonal changes.

### Photochemical smog

A mix of oxidizing air pollutants produced by the reaction of sunlight with primary air pollutants, especially hydrocarbons.

### Poverty

Poverty is a complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation, or limited resources), economic conditions (such as standard of living, inequality, or economic position), and/or social relationships (such as social class, dependency, exclusion, lack of basic security, or lack of entitlement).

### Poverty trap

Poverty trap is understood differently across disciplines. In the social sciences, the concept, primarily employed at the individual, household, or community level, describes a situation in which escaping poverty becomes impossible due to unproductive or inflexible resources. A poverty trap can also be seen as a critical minimum asset threshold, below which families are unable to successfully educate their children, build up their productive assets, and get out of poverty. Extreme poverty is itself a poverty trap, since poor persons lack the means to participate meaningfully in society. In economics, the term *poverty trap* is often used at national scales, referring to a self-perpetuating condition where an economy, caught in a vicious cycle, suffers from persistent underdevelopment (Matsuyama, 2008). Many proposed models of poverty traps are found in the literature.

### Predictability

The extent to which future states of a system may be predicted based on knowledge of current and past states of the system. Because knowledge of the climate system's past and current states is generally imperfect, as are the models that utilize this knowledge to produce a climate prediction, and because the climate system is inherently nonlinear and chaotic, predictability of the climate system is inherently limited. Even with arbitrarily accurate models and observations, there may still be limits to the predictability of such a nonlinear system (AMS, 2000).

### Preindustrial

See Industrial Revolution.

### Probability Density Function (PDF)

A probability density function is a function that indicates the relative chances of occurrence of different outcomes of a variable. The function integrates to unity over the domain for which it is defined and has the property that the integral over a sub-domain equals the probability that the outcome of the variable lies within that sub-domain. For example, the probability that a temperature anomaly defined in a particular way is greater than zero is obtained from its PDF by integrating the PDF over all possible temperature anomalies greater than zero. Probability density functions that describe two or more variables simultaneously are similarly defined.

<sup>13</sup> This glossary entry builds from the definition in the Stockholm Convention on Persistent Organic Pollutants (Secretariat of the Stockholm Convention, 2001).

### Projection

A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized. See also Climate prediction and Climate projection.

### Proxy

A proxy climate indicator is a record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies include pollen analysis, tree ring records, speleothems, characteristics of corals, and various data derived from marine sediments and ice cores. Proxy data can be calibrated to provide quantitative climate information.

### Public good

A good that is both non-excludable and non-rivalrous in that individuals cannot be effectively excluded from use and where use by one individual does not reduce availability to others.

### Radiative forcing

Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in  $\text{W m}^{-2}$ ) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or the output of the Sun. Sometimes internal drivers are still treated as forcings even though they result from the alteration in climate, for example aerosol or greenhouse gas changes in paleoclimates. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere.

### Reanalysis

Reanalyses are estimates of historical atmospheric temperature and wind or oceanographic temperature and current, and other quantities, created by processing past meteorological or oceanographic data using fixed state-of-the-art weather forecasting or ocean circulation models with data assimilation techniques. Using fixed data assimilation avoids effects from the changing analysis system that occur in operational analyses. Although continuity is improved, global reanalyses still suffer from changing coverage and biases in the observing systems.

### Reasons for concern

Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be “dangerous” (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

### Reference scenario

See Baseline/reference.

### Reflexivity

A system attribute where cause and effect form a feedback loop, in which the effect changes the system itself. Self-adapting systems such as societies are inherently reflexive, as are planned changes in complex systems. Reflexive decision making in a social system has the potential to change the underpinning values that led to those decisions. Reflexivity is also an important aspect of adaptive management.

### Reforestation

Planting of forests on lands that have previously contained forests but that have been converted to some other use. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). See also the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

### Relative sea level

Sea level measured by a tide gauge with respect to the land upon which it is situated. See also Mean sea level and Sea level change.

### Representative Concentration Pathways (RCPs)

Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word *representative* signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term *pathway* emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al., 2010).

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding emission scenarios. Extended Concentration Pathways (ECPs) describe extensions of the RCPs from 2100 to 2500 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent scenarios.

Four RCPs produced from Integrated Assessment Models were selected from the published literature and are used in the present IPCC Assessment as a basis for the climate predictions and projections in WGI AR5 Chapters 11 to 14:

**RCP2.6** One pathway where radiative forcing peaks at approximately  $3 \text{ W m}^{-2}$  before 2100 and then declines (the corresponding ECP assuming constant emissions after 2100).

**RCP4.5 and RCP6.0** Two intermediate stabilization pathways in which radiative forcing is stabilized at approximately  $4.5 \text{ W m}^{-2}$  and  $6.0 \text{ W m}^{-2}$  after 2100 (the corresponding ECPs assuming constant concentrations after 2150).



**RCP8.5** One high pathway for which radiative forcing reaches greater than  $8.5 \text{ W m}^{-2}$  by 2100 and continues to rise for some amount of time (the corresponding ECP assuming constant emissions after 2100 and constant concentrations after 2250).

For further description of future scenarios, see WGI AR5 Box 1.1.

### Resilience

The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.<sup>14</sup>

### Return period

An estimate of the average time interval between occurrences of an event (e.g., flood or extreme rainfall) of (or below/above) a defined size or intensity. See also Return value.

### Return value

The highest (or, alternatively, lowest) value of a given variable, on average occurring once in a given period of time (e.g., in 10 years). See also Return period.

### Risk

The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values.<sup>15</sup> Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

### Risk assessment

The qualitative and/or quantitative scientific estimation of risks.

### Risk management

Plans, actions, or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.

### Risk perception

The subjective judgment that people make about the characteristics and severity of a risk.

### Risk transfer

The practice of formally or informally shifting the risk of financial consequences for particular negative events from one party to another.

### Runoff

That part of precipitation that does not evaporate and is not transpired, but flows through the ground or over the ground surface and returns to bodies of water. See also Hydrological cycle.

### Salt-water intrusion/encroachment

Displacement of fresh surface water or groundwater by the advance of salt water due to its greater density. This usually occurs in coastal and estuarine areas due to decreasing land-based influence (e.g., from reduced runoff or groundwater recharge, or from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative sea level rise).

### Scenario

A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions. See also Climate scenario, Emission scenario, Representative Concentration Pathways, and SRES scenarios.

### Sea level change

Sea level can change, both globally and locally due to (1) changes in the shape of the ocean basins, (2) a change in ocean volume as a result of a change in the mass of water in the ocean, and (3) changes in ocean volume as a result of changes in ocean water density. Global mean sea level change resulting from change in the mass of the ocean is called *barystatic*. The amount of *barystatic* sea level change due to the addition or removal of a mass of water is called its *sea level equivalent* (SLE). Sea level changes, both globally and locally, resulting from changes in water density are called *steric*. Density changes induced by temperature changes only are called *thermosteric*, while density changes induced by salinity changes are called *halosteric*. *Barystatic* and *steric* sea level changes do not include the effect of changes in the shape of ocean basins induced by the change in the ocean mass and its distribution. See also Relative sea level and Thermal expansion.

### Sea Surface Temperature (SST)

The sea surface temperature is the subsurface bulk temperature in the top few meters of the ocean, measured by ships, buoys, and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimeter thick) in the infrared or the top centimeter or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

### Semi-arid zone

Areas where vegetation growth is constrained by limited water availability, often with short growing seasons and high interannual variation in primary production. Annual precipitation ranges from 300 to 800 mm, depending on the occurrence of summer and winter rains.

### Sensitivity

The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range,

<sup>14</sup> This definition builds from the definition used in Arctic Council (2013).

<sup>15</sup> This definition builds from the definitions used in Rosa (1998) and Rosa (2003).



or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

### Significant wave height

The average trough-to-crest height of the highest one-third of the wave heights (sea and swell) occurring in a particular time period.

### Sink

Any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol from the atmosphere.

### Social Cost of Carbon (SCC)

The net present value of climate damages (with harmful damages expressed as a positive number) from one more tonne of carbon in the form of CO<sub>2</sub>, conditional on a global emissions trajectory over time.

### Social protection

In the context of development aid and climate policy, social protection usually describes public and private initiatives that provide income or consumption transfers to the poor, protect the vulnerable against livelihood risks, and enhance the social status and rights of the marginalized, with the overall objective of reducing the economic and social vulnerability of poor, vulnerable, and marginalized groups (Devereux and Sabates-Wheeler, 2004). In other contexts, social protection may be used synonymously with social policy and can be described as all public and private initiatives that provide access to services, such as health, education, or housing, or income and consumption transfers to people. Social protection policies protect the poor and vulnerable against livelihood risks and enhance the social status and rights of the marginalized, as well as prevent vulnerable people from falling into poverty.

### Socioeconomic scenario

A scenario that describes a possible future in terms of population, gross domestic product, and other socioeconomic factors relevant to understanding the implications of climate change.

### Southern Annular Mode (SAM)

The leading mode of variability of Southern Hemisphere geopotential height, which is associated with shifts in the latitude of the midlatitude jet. See SAM Index in WGI AR5 Box 2.5.

### Species distribution modeling

Simulation of ecological effects of climate change. Species distribution modeling uses statistically or theoretically derived response surfaces to relate observations of species occurrence or known tolerance limits to environmental predictor variables, thereby predicting a species' range as the manifestation of habitat characteristics that limit or support its presence at a particular location. Species distribution models are also referred to as environmental niche models. Bioclimate envelope models can be considered as a subset of species distribution models that predict species occurrence or habitat suitability based on climatic variables only.

### SRES scenarios

SRES scenarios are emission scenarios developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the climate projections shown in Chapters 9 to 11 of IPCC (2001) and Chapters 10

and 11 of IPCC (2007). The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

**Scenario family** Scenarios that have a similar demographic, societal, economic, and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1, and B2.

**Illustrative scenario** A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised marker scenarios for the scenario groups A1B, A2, B1, and B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.

**Marker scenario** A scenario that was originally posted in draft form on the SRES web site to represent a given scenario family. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakićenović and Swart (2000). These scenarios received the closest scrutiny of the entire writing team and via the SRES open process. Scenarios were also selected to illustrate the other two scenario groups.

**Storyline** A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of their evolution.

### Storm surge

The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.

### Storm tracks

Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the main regions where the tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems.

### Stratosphere

The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

### Stressors

Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate-related risk.

### Subsistence agriculture

Farming and associated activities that together form a livelihood strategy in which most output is consumed directly but some may be sold at market. Subsistence agriculture can be one of several livelihood activities.

**Surface temperature**

See Global mean surface temperature, Land surface air temperature, and Sea Surface Temperature.

**Sustainability**

A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

**Sustainable development**

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

**Thermal expansion**

In connection with sea level, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level. See also Sea level change.

**Thermocline**

The layer of maximum vertical temperature gradient in the ocean, lying between the surface ocean and the abyssal ocean. In subtropical regions, its source waters are typically surface waters at higher latitudes that have subducted and moved equatorward. At high latitudes, it is sometimes absent, replaced by a halocline, which is a layer of maximum vertical salinity gradient.

**Thermohaline circulation (THC)**

Large-scale circulation in the ocean that transforms low-density upper ocean waters to higher-density intermediate and deep waters and returns those waters back to the upper ocean. The circulation is asymmetric, with conversion to dense waters in restricted regions at high latitudes and the return to the surface involving slow upwelling and diffusive processes over much larger geographic regions. The THC is driven by high densities at or near the surface, caused by cold temperatures and/or high salinities, but despite its suggestive though common name, is also driven by mechanical forces such as wind and tides. Frequently, the name THC has been used synonymously with Meridional Overturning Circulation. See also Meridional Overturning Circulation.

**Tipping point**

A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated.<sup>16</sup>

**Traditional knowledge**

The knowledge, innovations, and practices of both indigenous and local communities around the world that are deeply grounded in history and experience. Traditional knowledge is dynamic and adapts to cultural and environmental change, and also incorporates other forms of knowledge and viewpoints. Traditional knowledge is generally transmitted orally from generation to generation. It is often used as a synonym for indigenous knowledge, local knowledge, or traditional ecological knowledge.

**Transformation**

A change in the fundamental attributes of natural and human systems.

**Tree line**

The upper limit of tree growth in mountains or at high latitudes. It is more elevated or more poleward than the forest line.

**Tropical cyclone**

A strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with 1-minute average surface winds between 18 and 32 m s<sup>-1</sup>. Beyond 32 m s<sup>-1</sup>, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.

**Troposphere**

The lowest part of the atmosphere, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height. See also Stratosphere.

**Tsunami**

A wave, or train of waves, produced by a disturbance such as a submarine earthquake displacing the sea floor, a landslide, a volcanic eruption, or an asteroid impact.

**Tundra**

A treeless biome characteristic of polar and alpine regions.

**Uncertainty**

A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see Moss and Schneider, 2000; Manning et al., 2004; Mastrandrea et al., 2010). See also Confidence and Likelihood.

**United Nations Framework Convention on Climate Change (UNFCCC)**

The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD countries and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The convention entered in force in March 1994. In 1997, the UNFCCC adopted the Kyoto Protocol.

<sup>16</sup> The glossary for the Working Group I contribution to the Fifth Assessment Report defines tipping point in the context of climate: “In climate, a hypothesized critical threshold when global or regional climate changes from one stable state to another stable state. The tipping point event may be irreversible.”

## Uptake

The addition of a substance of concern to a reservoir. The uptake of carbon containing substances, in particular carbon dioxide, is often called (carbon) sequestration.

## Upwelling region

A region of an ocean where cold, typically nutrient-rich waters well up from the deep ocean.

## Urban heat island

The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, effects on heat retention, and changes in surface albedo.

## Volatile Organic Compounds (VOCs)

Important class of organic chemical air pollutants that are volatile at ambient air conditions. Other terms used to represent VOCs are *hydrocarbons* (HCs), *reactive organic gases* (ROGs), and *non-methane volatile organic compounds* (NMVOCs). NMVOCs are major contributors (together with NO<sub>x</sub> and CO) to the formation of photochemical oxidants such as ozone.

## Vulnerability<sup>17</sup>

The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. See also Contextual vulnerability and Outcome vulnerability.

## Vulnerability index

A metric characterizing the vulnerability of a system. A climate vulnerability index is typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability.

## Water cycle

See Hydrological cycle.

## Water-use efficiency

Carbon gain by photosynthesis per unit of water lost by evapotranspiration. It can be expressed on a short-term basis as the ratio of photosynthetic carbon gain per unit transpirational water loss, or on a seasonal basis as the ratio of net primary production or agricultural yield to the amount of water used.

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