

Box CC-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 (29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; 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).

[INSERT FIGURE CR-1 HERE

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al.*, 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al.*, 2008). C and D: three CO₂ seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO₂ 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 CO₂ sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; 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).]

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (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 6.3.1. for physiological details and 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; 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 1997–98 was unmatched in the period 1903 to 1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; 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*; 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 towards net dissolution (*medium confidence*; 5.4.2.4). Ocean warming and acidification have synergistic effects in several reef-builders (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*; 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 SE Asian regions (*very high confidence*, 1-2% per year for 1968-2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 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 RCP3-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.*, 2013). 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 Moreno, 2003). Over 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 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 (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 Domestic Product 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.*, 2012) 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*; 5.2.4.4, 30.5).

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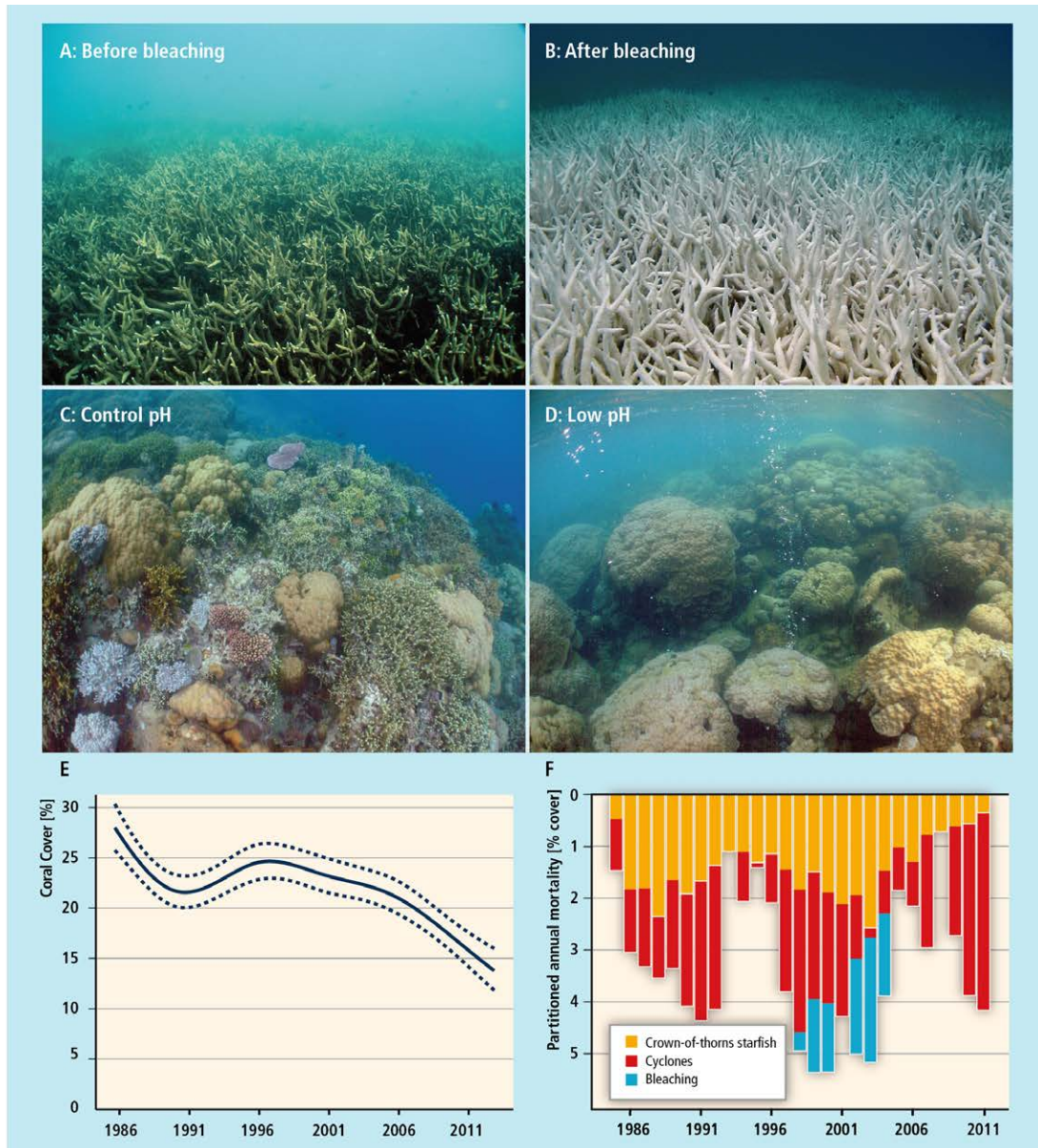


Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al.*, 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al.*, 2008). C and D: three CO₂ seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO₂ 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 CO₂ sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; 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).

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 24, 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 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. 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 services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Day et al., 2007; Midgley et al., 2012; Opperman et al., 2009)
- 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. 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 is 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.

[INSERT FIGURE EA-1 HERE]

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.]

Box CC-EA References

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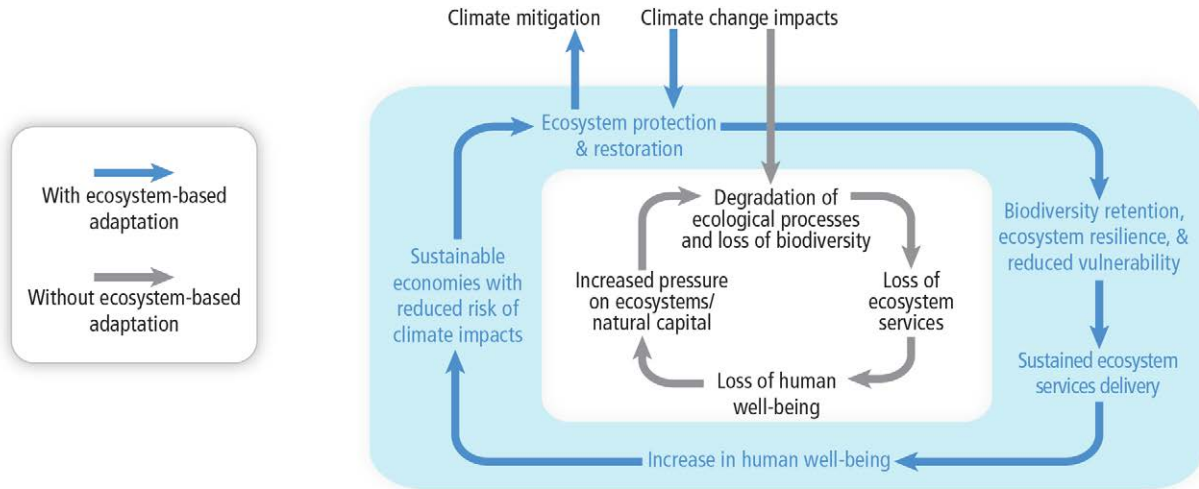


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Box CC-GC. Gender and Climate Change

[Jon Barnett (Australia), Marta G. Rivera Ferre (Spain), Petra Tschakert (U.S.A.), Katharine Vincent (South Africa), Alistair Woodward (New Zealand)]

Gender, along with socio-demographic 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; Nightingale, 2009; Buechler, 2009; Nelson and Stathers, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resurreccion, 2011; Omolo, 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 labour markets, making women in particular less able to cope with and adapt to climate change impacts (Rijkers and Costa, 2012; Djoudi and Brockhaus, 2011; Paavola, 2008). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whilst both men and women experience increases in productive roles, only women experience increased reproductive roles (Resurreccion, 2011; 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 since 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*) [11.3.3, Table 12-3]. Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981-2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007) [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). While 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 due to 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 U.S. and Australia (Jenkins and Phillips, 2008; Anastario *et al.*, 2009; Alston, 2011; Whittenbury, 2013; Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (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 Sao 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 (Figueiredo and Perkins, 2012; Arora-Jonsson, 2011; Vincent *et al.*, 2010). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women since cash generation is seen as a male activity in rural areas (Gladwin *et al.*, 2001;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 (Below *et al.*, 2012; Goulden *et al.*, 2009; Vincent *et al.*, 2010) 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, 2013; Bee *et al.*, 2013; Tschakert and Machado, 2012; see also 22.4.3 and Table 22-5).

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Box CC-HS. Heat Stress and Heat Waves

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Heat waves are periods of abnormally and uncomfortably hot weather during which the risk of heat stress on people and ecosystems is high. The number and intensity of hot days have increased markedly in the last three decades (Coumou et al., 2013) (*high confidence*). According to WG I, it is *likely* that the occurrence of heat waves has more than doubled in some locations due to human influence and it is *virtually certain* that there will be more frequent hot extremes over most land areas in the latter half of the 21st century. Coumou et al. (2013) predicted that, under a medium warming scenario, the number of monthly heat records will be over 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 +10C or more, the habitability of large 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 they may act as triggers for tipping points (Hughes et al., 2013). Consequently, heat waves play an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society [Ch 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). In LICs and MICs, 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 [Ch 11]

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro *et al.*, 2011; Rahmstorf and Coumou, 2011; Nitschke et al., 2011; Diboulo et al., 2012; Hansen et al., 2012). 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, Jan C et al., 2008). Increase in ozone concentrations due to high temperatures affects health (Smith et al., 2010), leading to premature mortality, e.g. cardiopulmonary mortality (Smith et al., 2010). High temperatures are also associated with an increase in air-borne allergens acting as a trigger for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems [Ch 4, 5, 6, 30]

Tree mortality is increasing globally (Williams et al., 2012) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult due 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 (Duguay et al., 2013), 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°C)

shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO₂ levels and associated acidification (Hoegh-Guldberg et al., 2007), Figure 6-5, (*medium confidence*) [Ch 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*). [Ch 5, 6, 30.4-30.5, CC-CR, CC-MB]

Agriculture [Ch 7]

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3C of local warming without adaptation, even with benefits of higher CO₂ and rainfall, are expected even in cool environments (Teixeira et al., 2011). 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 U.S., current economic losses due to heat stress of livestock are estimated at several billion USD annually (St-Pierre et al., 2003).

Box CC-HS References

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Box CC-KR. A Selection of the Hazards, Key Vulnerabilities, Key Risks, and Emergent Risks Identified in the WGII Contribution to the Fifth Assessment Report

The accompanying table provides a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapter 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 which 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.

Examples of Hazards/Stressors, Key Vulnerabilities, Key Risks and Emergent Risks (using input from chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30)			
Hazard	Key vulnerabilities	Key risks	Emergent risks
Terrestrial and inland water systems (chapter 4)			
Rising air, soil, and water temperature [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 between pest, drought and fire can lead to new risks and large negative impacts on ecosystems.
Change in seasonality of rain [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 [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. [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. [6.3.1]	Enhancement of risk due to interactions, e.g., acidification and warming on calcareous organisms. [6.3.5]
	New vulnerabilities can emerge due to shifted productivity zones and	Risks due to unknown productivity and services of new ecosystem types. [6.4.1,	Enhancement of risk due to interactions of warming, hypoxia, acidification, new

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	species distribution ranges, largely from low to high latitudes [6.3.4, 6.5.1], shifting fishery catch potential with species migration. [6.3.1, 6.5.2, 6.5.3]	6.5.3]	biotic interactions. [6.3.5, 6.3.6]
Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication. [6.1.1]	Increasing susceptibility because hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates. [6.3.3]	Risk of loss of larger animals and plants, shifts to hypoxia adapted, largely microbial communities with reduced biodiversity. [6.3.3]	Enhancement of risk due to expanding hypoxia in warming and acidifying oceans. [6.3.5]
Enhanced harmful algal blooms in coastal areas due to rising water temperature. [6.4.2.3]	Increasing susceptibility and limited adaptive capacities of important ecosystems and valuable services due to already existing multiple stresses. [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. [6.4.2]	Disproportionate enhancement of risk due to interactions of various stresses. [6.3.5]
Food production systems and food security (chapter 7)			
Rising average temperatures and more frequent extreme temperatures [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 ca. 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 [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. [7.4]
Urban areas (chapter 8)			
Inland flooding [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	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.

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	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 more sensitive to ill health from flood impacts – that may include increased mosquito and water borne diseases.		
Coastal flooding (including sea level rise and storm surge) [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 urban population that is unable to get or afford housing that protects against flooding or insurance. Local government 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 3 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.
Heat and cold (including urban heat island effect) [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 services 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 due to interactions with multiple stressors such as air pollution.
Water shortages and drought in urban regions [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	Risks from constraints on urban water provision services to people and industry with human and economic impacts. Risk of damage and loss to urban	Cities' viability may be threatened by loss or depletion of freshwater sources – including for cities dependent on distant glacier melt water or on depleting

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	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.	ecology and its services including urban and peri-urban agriculture.	groundwater resources.
Changes in urban meteorological regimes lead to enhanced air pollution [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) [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 wellbeing.
Wind storms with higher intensity [8.1.4, 8.2.4]	Sub-standard buildings and physical infrastructure and the services and functions they support particularly susceptible. Old and difficult to retro-fit 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 [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 [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	Risk of damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture and other productive or	Collapsing of peri-urban economies and ecosystem services with wider implications for urban food security, service provision and disaster risk reduction.

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	especially susceptible.	protective ecosystem services. Risk of knock-on impacts for urban and peri-urban livelihoods and urban health.	
Climate change induced or intensified hazard of more diseases and exposure to disease vectors [8.2.3, 8.2.4]	Large urban population that is exposed to foodborne and waterborne 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 like flooding.
Rural areas (chapter 9)			
Drought in pastoral areas [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 [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.
Water shortages and drought in rural areas [9.3.5.1, 9.3.5.1]	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. [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 pre-existing health conditions. [11.3]	Risk of increased mortality and morbidity during hot days and heat waves. [11.4.1] Risk of mortality, morbidity and productivity loss, particularly amongst manual workers in hot climates.	The number of elderly people is projected to triple from 2010-2050. 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	Risk of a larger burden of disease and increased food insecurity for particular population groups. Increasing risk that progress in reducing mortality and	Combined impacts of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent

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	particularly vulnerable. [11.3]	morbidity from undernutrition may slow or reverse. [11.6.1]	inequality, and on-going food insecurity for the poor.
Increasing temperatures, changing patterns of precipitation	Non-immune populations that are exposed to water- and vector-borne disease which are sensitive to meteorological conditions. [11.3]	Increasing health risks due to changing spatial and temporal distribution strains public health systems, especially if this occurs in combination with economic downturn. [11.5.1]	Rapid climate and other environmental change may promote emergence of new pathogens.
Increased variability in precipitation	People exposed to diarrhoea aggravated by higher temperatures, and unusually high or low precipitation. [11.3]	Risk that the progress to date in reducing childhood deaths from diarrhoeal disease is compromised. [11.5.2]	Increased rate of failure of water and sanitation infrastructure due to climate change leading to higher diarrhoea risk.
Livelihood and poverty (chapter 13)			
Increasing frequency and severity of droughts, coupled with decreasing rainfall and/or increased unpredictability of rainfall [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 rain-fed 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) [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 a high morbidity and mortality 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); 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 [13.2.1.1; 13.2.1.4]	Limited ability to cope due 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 socio-economic 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 socio-economic stressors.
Successive and extreme events (floods, droughts) coupled with increasing temperatures and rising	Rural communities are particularly susceptible, due to the marginalization of rural water users to the	Risk of loss of rural livelihoods, severe economic losses in agriculture and damage to	Loss of rural livelihoods that have existed for generations, heightened outmigration to urban areas; emergence of

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water demand [13, 2.1.1; 13.2.1.5]	benefit of urban users, given political and economic priorities (e.g. Australia, Andes, Himalayas, Caribbean).	cultural values and identity; mental health impacts (including increased rates of suicide).	new poverty in MICs and HICs.
Sea level rise [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 [13.2.2.4; 13.2.1.5; 13.2.2.3]	Agricultural wage labourers, small-scale farmers in areas with multidimensional poverty and economic marginalization, children in urban slums, and the elderly 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 socio-economic 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.
Increased variability of rainfall and/or extreme events (floods, droughts, heat waves) [13.2.1.1; 13.2.1.3; 13.2.1.4; 13.2.1.5]	People highly dependent on rain-fed agriculture particularly at risk. Persistent poverty among subsistence farmers and urban wage labourers 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 rain-fed 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 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). For example if 1:20 year drought/flood becomes 1:5 year flood/drought.	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)			

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Warming and drying (precipitation changes of uncertain magnitude) [AR5 WGI TS.5.3, WGI SPM, WGI 11.3, WGI 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; socio-cultural constraints on some adaptation options. [19.2.2, 19.6.1.1, 19.3.2.2, 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. [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. [19.3.2.2, 19.6.3.4]
Changes in regional and seasonal temperature and precipitation over land [AR5 WGI TS.5.3, WGI SPM, WGI 11.3, WGI 12.4]	Communities highly dependent on ecosystem services [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±6% of widespread & common plants and 34±7% of widespread & common animals expected to lose ≥50% of their current climatic range by the 2080s leading to loss of services. [19.3.2.1]	Widespread loss of ecosystem services, including: <i>provisioning</i> , such as food and water; <i>regulating</i> , such as the control of climate and disease; <i>supporting</i> , such as nutrient cycles and crop pollination; and <i>cultural</i> , such as spiritual and recreational benefit. [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. [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. [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. [22.3.4.1, 22.3.4.2]	Range expansion of crop pests and diseases to high elevation agroecosystems. [22.3.4.3]
Extreme Events, e.g. floods and flash floods (& drought)	Population groups living in informal settlements in highly exposed urban areas; women and children often the most vulnerable to disaster risk. [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 diarrhoeal diseases (cholera).

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	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. [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. [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. [22.3.4.1, 22.3.4.2] Risk of increased incidence of food and waterborne diseases (e.g. cholera) and undernutrition. Risk of drinking water contamination due to heavy precipitation events and flooding. [22.3.5.2]	Compound effects of high temperature and changes in rainfall on human and natural systems. Increased incidence of stunting in children. [22.3.5.3].
Europe (chapter 23)			
Extreme weather events [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. [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. [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 system for key grain crops, particularly rice and other cereal crop farming systems are highly susceptible. [24.4.4.3]	Risk of crop failures and lower crop yield also can increase the risk of major losses for farmers and rural livelihoods. [24.4.4.3]	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. [24.4.4.3]	Risk of loss of arable areas due to submergence. [24.4.4.3]	Migration of farming communities to higher elevation areas entails risks for migrants and receiving

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			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 disruption of basic services such as water supply, sanitation, energy provision, and transportation system, 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 [25.2, Table 25-1, Figure 25-4, AR5 WGI 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, run-off, fishing, tourism, introduced predators and pests) are especially susceptible. [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. [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. [25.10.2, 25.10.3, Box 25-9]
Increased extreme rainfall related to flood risk in many locations [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. [25.3, Box 25-8, 25.10.2]	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand. [Box 25-8, 25.10.2]	
Continuing sea level rise, with projections spanning a particularly large range and continuing beyond 2100, even under mitigation scenarios [25.2, Box 25-1, AR5 WGI 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 towards the upper end of projected ranges. [Box 25-1, 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. [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. [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. [26.8.1]	Inability to reduce vulnerability in many areas results in increase in risk more so than change in physical hazard. [26.8.3]
Higher temperatures, decreases in runoff and	Vulnerability of small rural landholders, particularly in	Risk of increased losses and decreases in agricultural	Increasing risks of social instability and local

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lower soil moisture due to climate change [26.2, 26.3]	Mexican agriculture, and of the poor in rural settlements. [26.5, 26.8.2.2]	production. Risk of food and job insecurity for small landholders and social groups in regions exposed to these phenomena. [26.5, 26.8.2.2]	economic disruption due to internal migration. [26.2.1, 26.8.3]
Wildfires and drought conditions [Box 26-2]	Indigenous groups, low-income residents in peri-urban areas, and forest systems. [Box 26-2, 26.8.2]	Risk of loss of ecosystem integrity, property loss, human morbidity and mortality due to wildfires. [Box 26-2, 26.8.3]	
Extreme storm and heat events, air pollution, pollen, and infectious diseases [26.6.1]	Susceptibility of individuals is determined by factors such as economic status, pre-existing illness, age, and access to assets. [26.6.1]	Increasing risk of extreme temperature-, storm-, pollen, and infectious diseases-related human morbidity or mortality. [26.6.2]	
River and coastal floods, and sea level rise [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. [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. [26.4.2, 26.8.1]	Multiple risks from interacting hazards on populations' livelihoods, infrastructure and services. [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 [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 infections diseases. Economic impacts due to reallocation of populations.
Ocean acidification and warming [27.3.3, CC-OA]	Coral reef systems.	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 [27.2.1, 27.3.4]	Elevated CO ₂ 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	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

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		lower nitrogen assimilation). Decrease in bioenergy production.	region. Impacts on energy system and carbon emissions with consequent increase in fossil fuel demand.
Higher temperatures and humidity leads to a spread of vector-borne diseases in altitude and latitude [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 labour 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 enough to cope with increasing disease incidence rates, and the spread of diseases to newer regions.
Polar Systems (chapter 28)			
Loss of multi-year ice and reductions in the spatial extent of summer sea ice [28.2.5, 28.3.2, 28.4.1]	Indigenous communities that dependent 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 foodwebs.
	Ecosystems are vulnerable due 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 foodwebs.	Bottom up shifts in food webs. Potential changes in pelagic and benthic coupling.
Ocean acidification [28.2.2, 28.3.2]	Tolerance limits of endemic species surpassed. Impacts on exoskeleton formation for some species and alteration of physiological and behavioural properties during larval development.	Localized loss of endemic species, local impacts on marine foodwebs.	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. [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
Declining sea ice, changes in snow and ice timing and state, decreasing predictability of weather. [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	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

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	susceptible to these hazards.		fishers' health and safety in changing ice conditions.
Increased river and coastal flooding and erosion and thawing of permafrost [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. [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 wellbeing.
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. [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 favourable 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., Inuit: more difficult access to marine mammals associated with diminishing sea ice) and (e.g., Saami: loss of access by reindeer to their forage under snow due to ice layers formed by warming winter temperatures and "rain on snow").	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 [AR5 WGI 14.6, 14.8.4]	Various countries and communities are vulnerable to these hazards due to their high dependence on natural and ecological systems for security of settlements and tourism [29.3.3.1], human health [29.3.3.2] and water resources [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. [29.6, Figure 29-4].
Ocean warming and acidification leading to coral bleaching [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. [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. [29.3.1.1, 29.3.1.2]	Impacts on human health and loss of subsistence lifestyles. Potential increase in internal migration / urbanisation. [29.3.3.3, Chapter 9]
Sea level rise [29.3.1.1, 30.3.1.2; AR5 WGI 3.7.1]	Many small island communities and associated settlements and infrastructure are in low-lying coastal zones (high exposure) and are also	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 RCP 4.5 during the 21st	Incremental upwards shift in sea-level baselines results in increased frequency and extent of marine flooding during high tides and episodic storm surges These

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	vulnerable to increasing inundation, erosion and wave incursion. [5.3.2, 29.3.1.1, Figure 29-2]	century, threatening low-lying coastal areas and atoll islands. [29.4.3, Table 29-1; AR5 WGI 13.5.1, Table 13.5]	events could render soils and fresh groundwater resources unfit for human use before permanent inundation of low-lying areas. [29.3.1.1, 29.3.2, 29.3.3.1, 29.5.1].
Regional Oceans (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). [30.5.2, 30.5.4, 30.5.5, CC-CR, 30.5.6, CC-OA, 6.2.2.1, 6.2.2.2]	Risk of increased mass coral bleaching and mortality (loss of coral cover) with severe risks for coastal fisheries, tourism and coastal protection. [30.5.2, 30.5.3, 30.5.4, 30.5.5, Box CC-CR, 6.3.2, 6.3.5, 5.4.2.4, 7.2.1.2, 6.4.1.4, 29.3.1.2]	Loss of coastal reef systems, risk of decreased food security and reduced livelihoods, and reduced coastal protection. [30.6.2.1, 30.6.5, 7.2.1.2]
	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. [30.5, CC-BIO, 6.3.2, 6.3.4, 7.3.2.6]	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. [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 fisheries collapse may develop as the capacity for fisheries to resist fundamental change to fishery composition as well as the increased migration of disease and other organisms is accelerated. [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) results 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 ₂ , temperature) drive fundamental changes that result in broad scale changes throughout the ocean. [30.1.3.1.3, 30.5.2, 30.5.5, 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	Risk of the alteration of ecosystem services including risks to food provisioning with impacts on fisheries and aquaculture. [7.2.1.2, 7.3.2, 7.4.2, 6.2.5.3]	Income and livelihoods for communities are reduced as productivity of fisheries and aquaculture diminish. [7.5.1.1.3, 30.6]

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	in key regions, such as the CBS, STG [6.2.2.2]		
	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). [30.3.2.2, .2 .2, 6.3.4, 6.2.5]	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. [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. [CC-OA]
	Coastal systems are increasingly exposed to upwelling in upwelling systems which results in periods of high CO ₂ , low O ₂ and pH. [CC-UP, 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. [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. [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). [30.5.2, 30.5.4, 30.5.5; 6.2, 6.3, 6.5]	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. [CC-NPP]	Reduced primary productivity of the ocean impacts fisheries productivity leading to lower catch rates and effects on livelihoods. [6.4.1.1, CC-NPP]
	Ecosystems and organisms that are sensitive to decreasing oxygen levels. [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. [30.3.2.3, .1 .1 .3]	
Changes to wind, wave height and storm intensity.	Shipping and industrial infrastructure is vulnerable to wave and storm intensity. [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.

Box CC-MB. Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

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

WGII AR4 presented detection and attribution of a global climate change fingerprint on natural systems (AR4, Ch 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 changes within the Ocean to climate change (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 (6.2, Table 6.7, 30.5) (*robust evidence, high agreement, high confidence*).

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 occurrence change in a biological parameter (including distribution, phenology, abundance, demography or community composition) and, if change occurs, 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) included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term-climate variability.

[INSERT FIGURE MB-1 HERE

Figure MB-1: 1735 observed responses to climate change from 208 single- and multi-species studies. Changes attributed to climate change (blue), inconsistent with climate change (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite or equivocal) observations within each region. Note: 57% of the studies included were published since AR4 (from Poloczanska *et al.*, 2013).]

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 (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 ± 0.7 days decade⁻¹ (mean \pm SE) and summer events by 4.4 ± 1.1 days decade⁻¹ (*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 (6.3.2, 30.5).

The distributions of benthic, pelagic and demersal species and communities have shifted by 10s to 1000s of km, although the range shifts have not been uniform across taxonomic groups or ocean regions (6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at 72.0 ± 13.5 km decade⁻¹ and trailing edges contracted in a poleward direction at 15.8 ± 8.7 km decade⁻¹ (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 (WG1 3.2).

[INSERT FIGURE MB-2 HERE

Figure MB-2. Rates of change in distribution (km decade⁻¹) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range

location, are in black. Distribution rates 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 (from Poloczanska *et al.*, 2013).]

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) (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, 30.5). Observed changes in species composition of catches from 1970–2006 that is partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in sub-tropical and higher latitude regions, and reduction in abundance of sub-tropical species in equatorial waters (Cheung *et al.*, 2013), with implications for fisheries (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 (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 to 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 1950s, have generally been able to track observed velocities (Fig MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities, but with considerable variability within and among taxonomic groups (Poloczanska *et al.* 2013).

Biogeographic shifts are also be influenced by other factors such as nutrient and stratification changes, species’ interactions, habitat availability and fishing (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 warming rates, hence climate velocities, increase (Fig 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 (4.3.2.5, Figure 4.6) For marine species, the observed rates of shift are generally much faster than those land 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 North-east Atlantic (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 species-specific thermal window widths 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. Changes in local and regional species richness, abundance, community composition, productivity, energy flows and invasion resistance result. Even among Antarctic stenotherms such differences related to mode of life, phylogeny and associated metabolic capacities exist (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 and facilitate adaptive management strategies effective in mitigating these impacts (6.3, 6.4).

[INSERT FIGURE MB-3 HERE

Figure MB-3. A. Rate of climate change for the Ocean (sea surface temperature (SST) °C); B. corresponding climate velocities for the Ocean and median velocity from land (adapted from Burrows et al., 2011); and C. observed rates of displacement of marine taxonomic groups over several decades until 2010. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.008 °C yr^{-1} correspond to ca. 2.4 km yr^{-1} median climate velocity in the Ocean. When compared to observed rates of displacement, many marine taxonomic groups have been able to track these velocities, except phyto- and zooplankton where rates of displacement greatly exceed climate velocity. 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 (Black dotted line) are derived from HadISST1.1 data set, all other rates are calculated based on the average of the CMIP5 climate model ensembles (Table S30-3) for the historical period and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window. (B) Median climate velocity calculated from HadISST1.1 dataset over 1960–2010 using the methods of Burrows et al., 2011. The three axes represent estimated median climate velocities are representative of areas of slow velocities such as Pacific subtropical gyre (STG) system (Purple line), the global Ocean surface (excluding polar seas, Blue line), and areas of high velocities such as the Coral Triangle and North Sea (Orange line). Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2010. The Red line corresponds to the median rate over global land surface calculated using historical surface temperatures from the CMIP5 model ensemble (Table S30-3). (C) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. 2013 using published studies (Figure MB-2 Black data set). Note the displacement rates for phytoplankton exceed the axis, so values are given.]

Box CC-MB References

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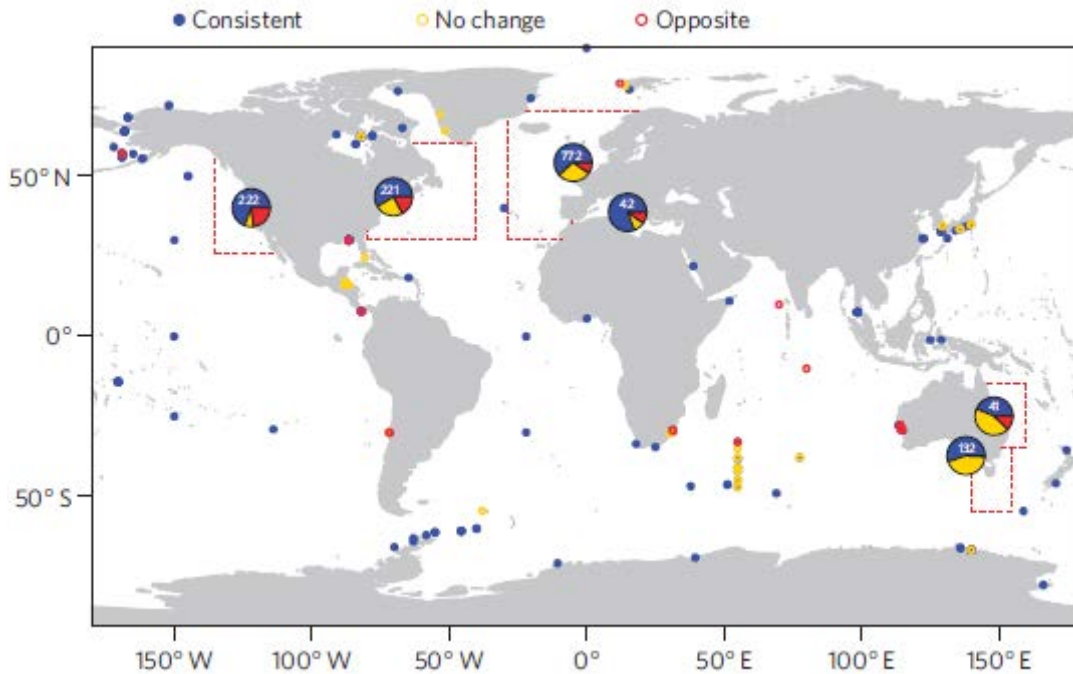


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[Illustration to be redrawn to conform to IPCC publication specifications.]

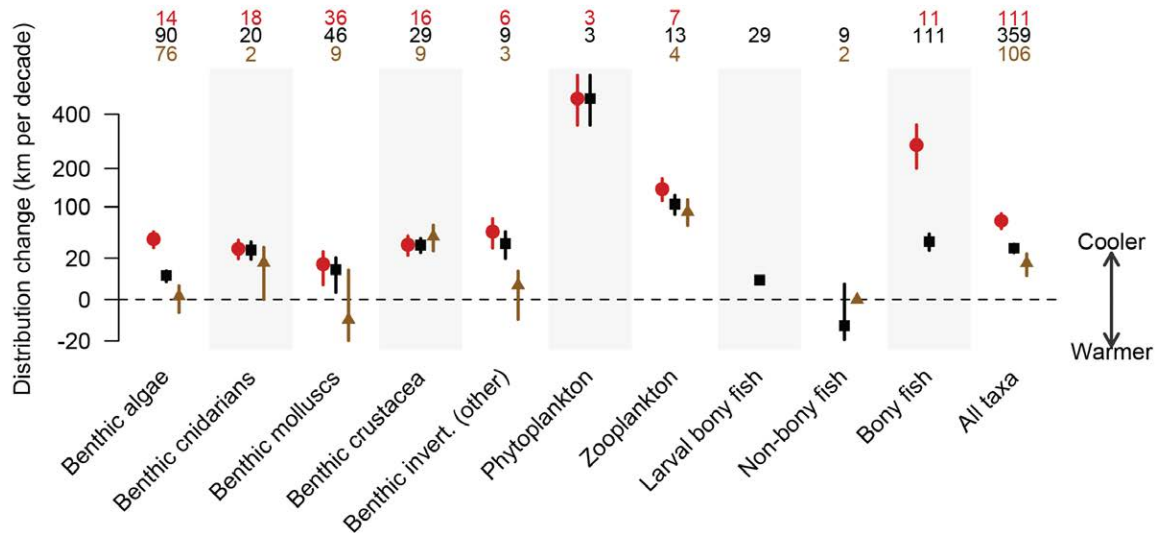


Figure MB-2. Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; 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 (from Poloczanska *et al.*, 2013).

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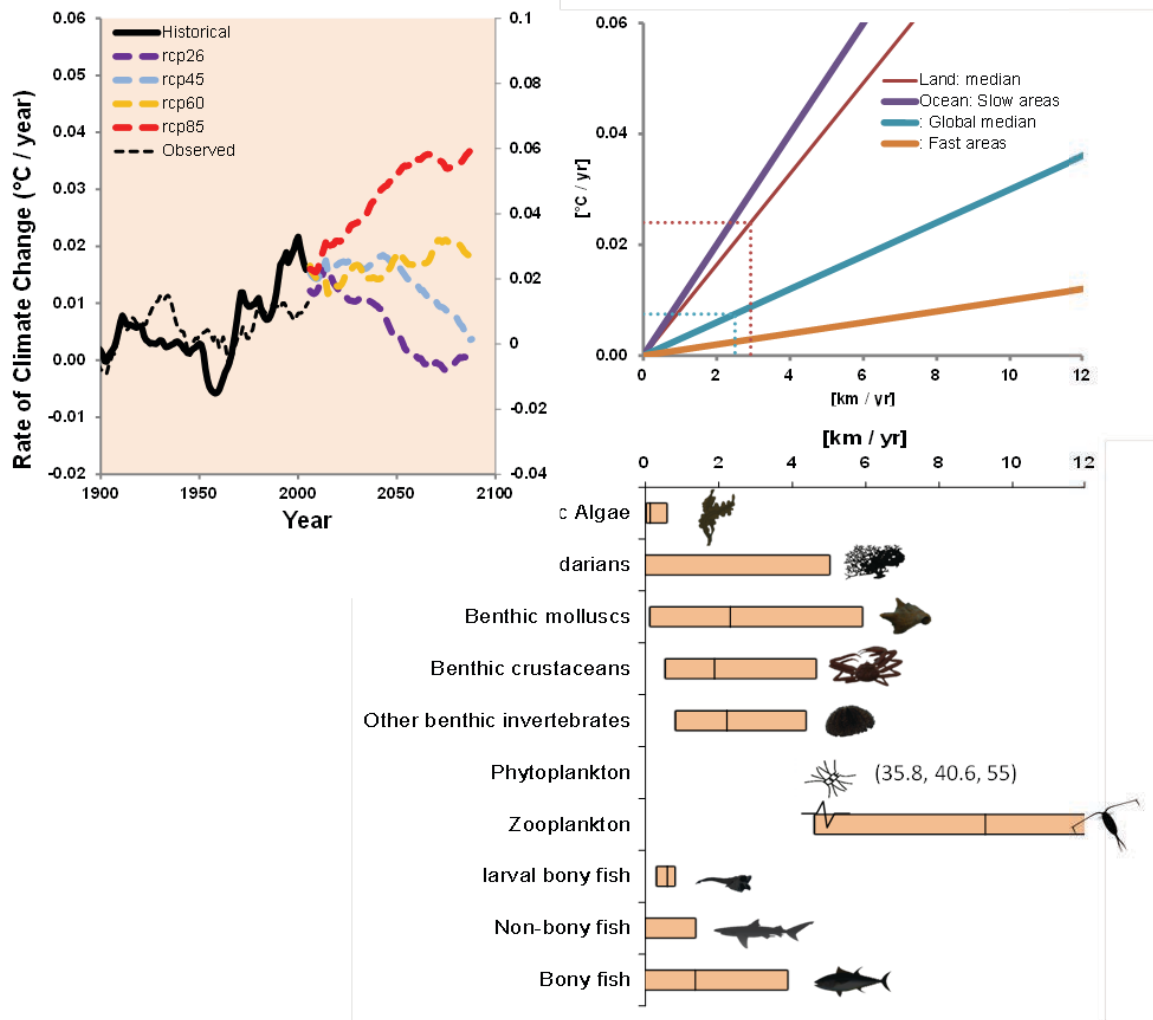


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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO₂ (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE

Figure OA-1: A: Overview of the chemical, biological, 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 CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled 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 CO₂ concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) 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. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO₂ result in an increased flux of CO₂ 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 CO₂ levels (Fig. CC-OA-1B). Observations of changing upper ocean CO₂ 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 year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO₂, +1 °C, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO₂, +3.7 °C, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 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 metaanalyses (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*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. 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*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 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 (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, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 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*; 6.1.2).

Projections of ocean acidification effects at 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 (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO₂ vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 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 (5.4.2.2).

Due 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 (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, 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, 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 due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (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 mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD 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 (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global 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 (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 CO₂), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO₂ is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could

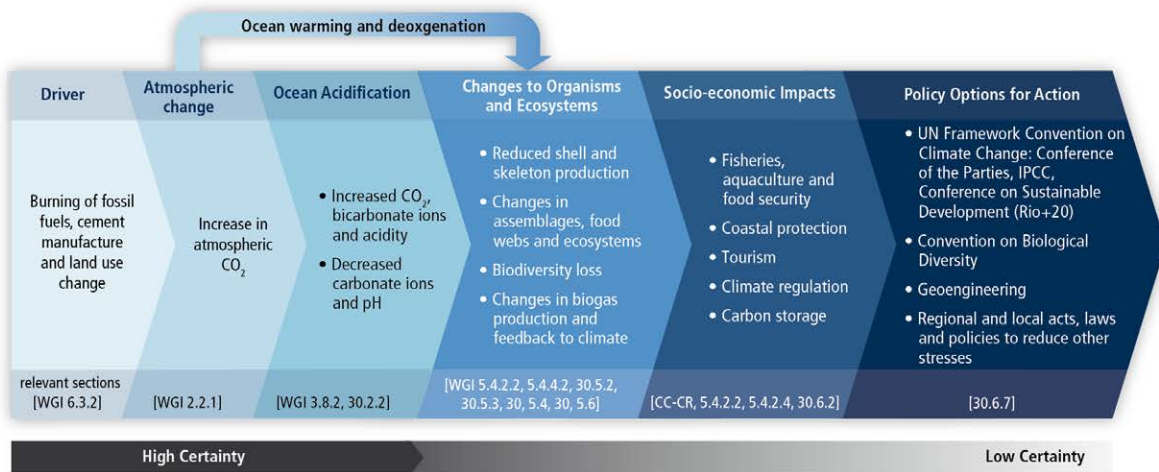
increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO₂ storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO₂, such as nutrient pollution (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 (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 (6.4.2.1).

Box CC-OA References

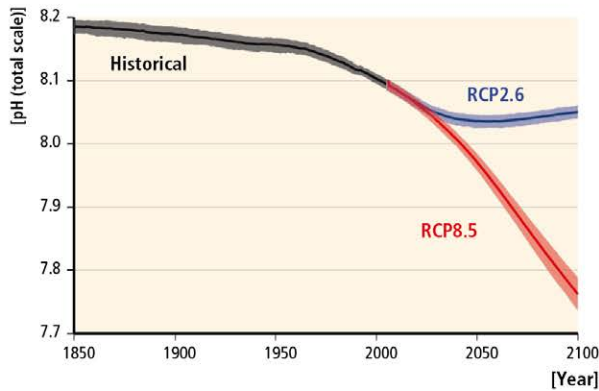
Kroeker K., R.C. Kordas, A. Ryan, I. Hendriks, L.Ramajo, G. Singh, C. Duarte and J.-P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology* **19**, 1884-1896.

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A.



B.



C.

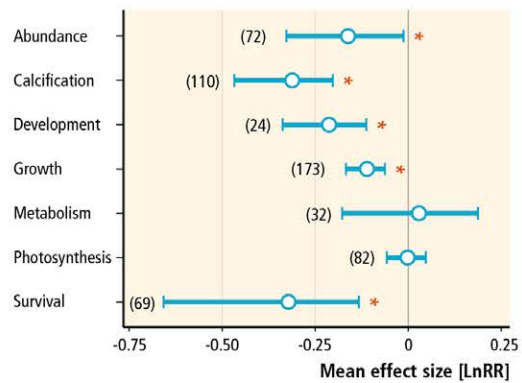


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled 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 CO₂ concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) 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. * denotes a statistically significant effect.

Box CC-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 (6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, carbon dioxide, and temperature (Panel A). 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 (Panel A). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI, Ch. 3), and on ecosystem structure and functioning (*medium confidence*, 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity: from $<50 \text{ g C m}^{-2} \text{ year}^{-1}$ in nutrient-poor subtropical waters and light-limited Arctic waters to $\gg 300 \text{ g C m}^{-2} \text{ year}^{-1}$ in productive upwelling regions and highly eutrophic coastal regions (Panel B).

The oceans currently provide $\sim 50 \times 10^{15} \text{ g C year}^{-1}$, or about half of global NPP (Field *et al.* 1998). Global estimates of NPP are mainly obtained from satellite remote-sensing (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 NE Pacific (Hamme *et al.*, 2010). Climate variability can drive pronounced changes in NPP (Chavez *et al.*, 2011), such as during 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 $190 \times 10^{12} \text{ g C year}^{-1}$, for the period 1999 to 2005 - an annual reduction of $\sim 0.4 \%$ of global NPP. In contrast, a time-series of directly measured NPP between 1988 to 2007 by Saba *et al.* (2010) (i.e. *in situ* incubations using the radiotracer ^{14}C -bicarbonate) revealed an increase (2% year^{-1}) 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-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 multidecadal, the available time-series of oceanic NPP measurements are also not of sufficient duration relative to the timescales of climate variability modes (up to 60-70 years for AMO, for example, 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 (WGI Ch. 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP particularly in Northern and Southern Hemisphere 'subpolar gyre' 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 macro-nutrients 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 photic 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 1860 under a high emission scenario (Polovina *et al.*, 2011; SRES 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 (± 7.9), 3.9 (± 5.7), 3.6 (± 5.7), 2.0 (± 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 (i.e. provinces, see panel B) scales.

Earlier model projections had predicted changes in global NPP from a decrease of > 10% (Field *et al.*, 1998; Boyd and Doney, 2002) to an increase of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0) (Sarmiento *et al.*, 2004; Schmittner *et al.*, 2008). 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, for example 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 Tg C year⁻¹ between 1998 and 2009. Other regional trends in NPP are reported in 30.5.1-6. 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 (A2 or RCP6.0 - 8.5, 6.3.4, 6.5.1, *medium confidence*), 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*).

[INSERT FIGURE PP-1 HERE]

Figure PP-1: A) Environmental factors controlling Net Primary Production (NPP). NPP is mainly controlled by three basic processes: 1) Light conditions in the surface ocean, i.e. the photic zone where photosynthesis occurs, 2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, 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 MODIS Aqua satellite climatology from 2003–2012; NPP was calculated with the Carbon-based Production 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. Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.]

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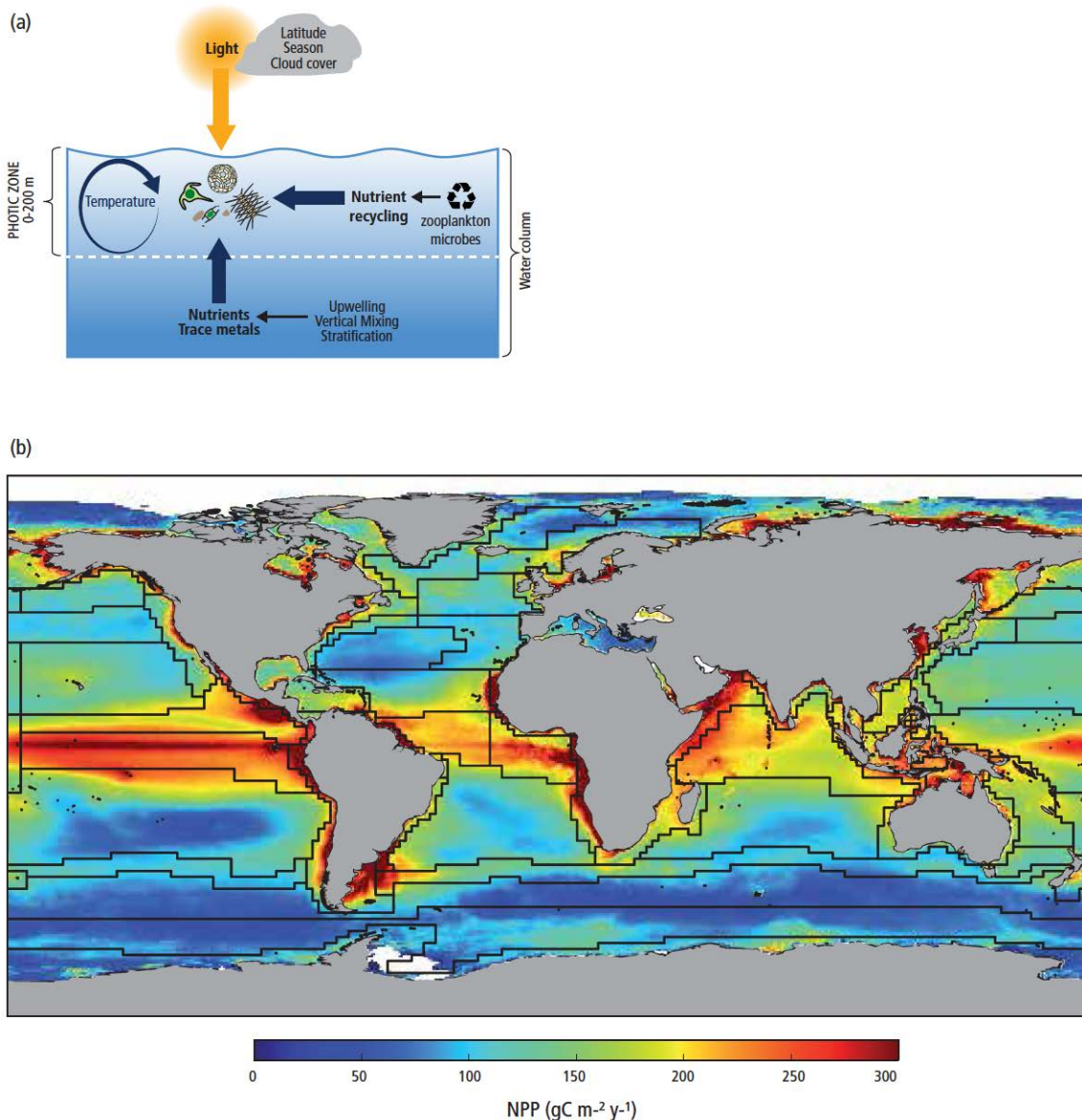


Figure PP-1: A) Environmental factors controlling Net Primary Production (NPP). NPP is mainly controlled by three basic processes: 1) Light conditions in the surface ocean, i.e. the photic zone where photosynthesis occurs, 2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, 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 MODIS Aqua satellite climatology from 2003-2012; NPP was calculated with the Carbon-based Production 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. Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.

[Illustration to be redrawn to conform to IPCC publication specifications.]

Box CC-RC. Regional Climate Summary Figures

[Noah Diffenbaugh (USA), Dáithí Stone (Canada / South Africa / USA), Peter Thorne (USA / Norway / UK), Filippo Giorgi (Italy), Bruce Hewitson (South Africa), Richard Jones (UK), Geert Jan van Oldenborgh (Netherlands)]

Information about the likelihood of regional climate change, assessed by 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 MLOST for annual temperature, and over the 1951-2010 period of 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 (i) 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 (ii) 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 Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012), which also form the basis for the figures presented in WGI (including WGI Chapter 12, Chapter 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, varies 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 1.

In contrast to Phase 3 of the Coupled Model Intercomparison Project (CMIP3) (Meehl et al., 2007), which used the IPCC 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 Fig. 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 Fig. 12.5). For this longer-term era of climate options, near-term and ongoing 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 timeframes, and present-day choices thus affect the risks of climate change throughout the 21st century.

[INSERT FIGURE RC-1 HERE]

Figure RC-1: Observed and projected changes in global annual average temperature. Values are expressed relative to 1986-2005. Black lines show the GISTEMP, NCDC-MLOST, and HadCRUT4.2 estimates from observational measurements. Colored shading denotes the ± 1.64 standard deviation range based on simulations from 32 models for RCP2.6 (blue) and 39 models for RCP8.5 (red). Blue and red lines denote the scenario mean for RCP2.6 and RCP8.5, respectively.]

The projection maps plot differences in annual average temperature and precipitation between the future and reference periods (Figure RC-2 and Figure 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 66-100% and “very likely” defined as 90-100%.

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, and >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% of models show change greater than the baseline variability, and >66% of models agree on sign of change.
- 3) Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change.
- 4) Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less 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 timescales.

[INSERT FIGURE RC-2 HERE]

Figure RC-2: Observed and projected changes in annual average temperature. (A) Observed temperature trends from 1901-2012 are determined by linear regression. Trends have been calculated 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 change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.1 and 2.21. The range of grid-point values is -0.53 to $+2.50^{\circ}\text{C}$ over period. (B) CMIP5 multi-model mean projections of annual average temperature changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, 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 and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less 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.]

[INSERT FIGURE RC-3 HERE]

Figure RC-3: Observed and projected changes in annual average precipitation. (A) Observed precipitation trends from 1951-2010 are determined by linear regression. Trends have been calculated 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 change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.2. The range of grid-point values is -185 to +111 mm/year/decade. (B) CMIP5 multi-model mean projections of annual average precipitation changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, 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 and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less 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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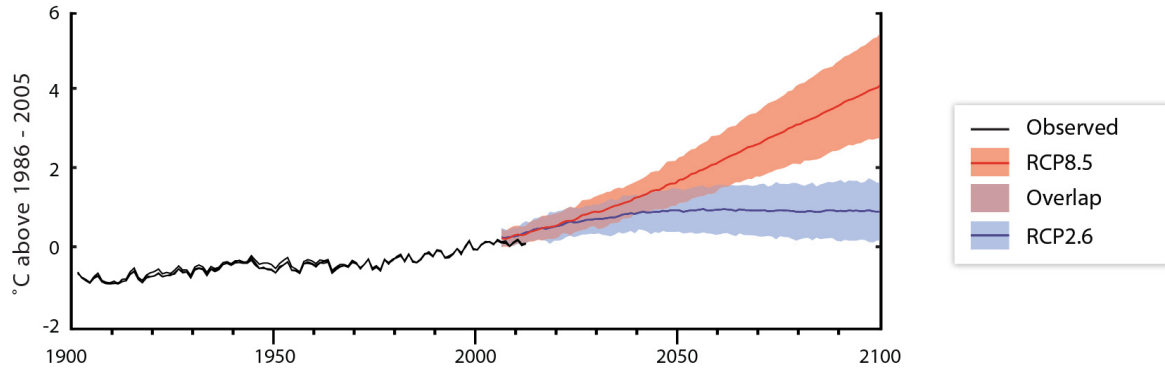


Figure RC-1: Observed and projected changes in global annual average temperature. Values are expressed relative to 1986-2005. Black lines show the GISTEMP, NCDC-MLOST, and HadCRUT4.2 estimates from observational measurements. Colored shading denotes the ± 1.64 standard deviation range based on simulations from 32 models for RCP2.6 (blue) and 39 models for RCP8.5 (red). Blue and red lines denote the scenario mean for RCP2.6 and RCP8.5, respectively. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

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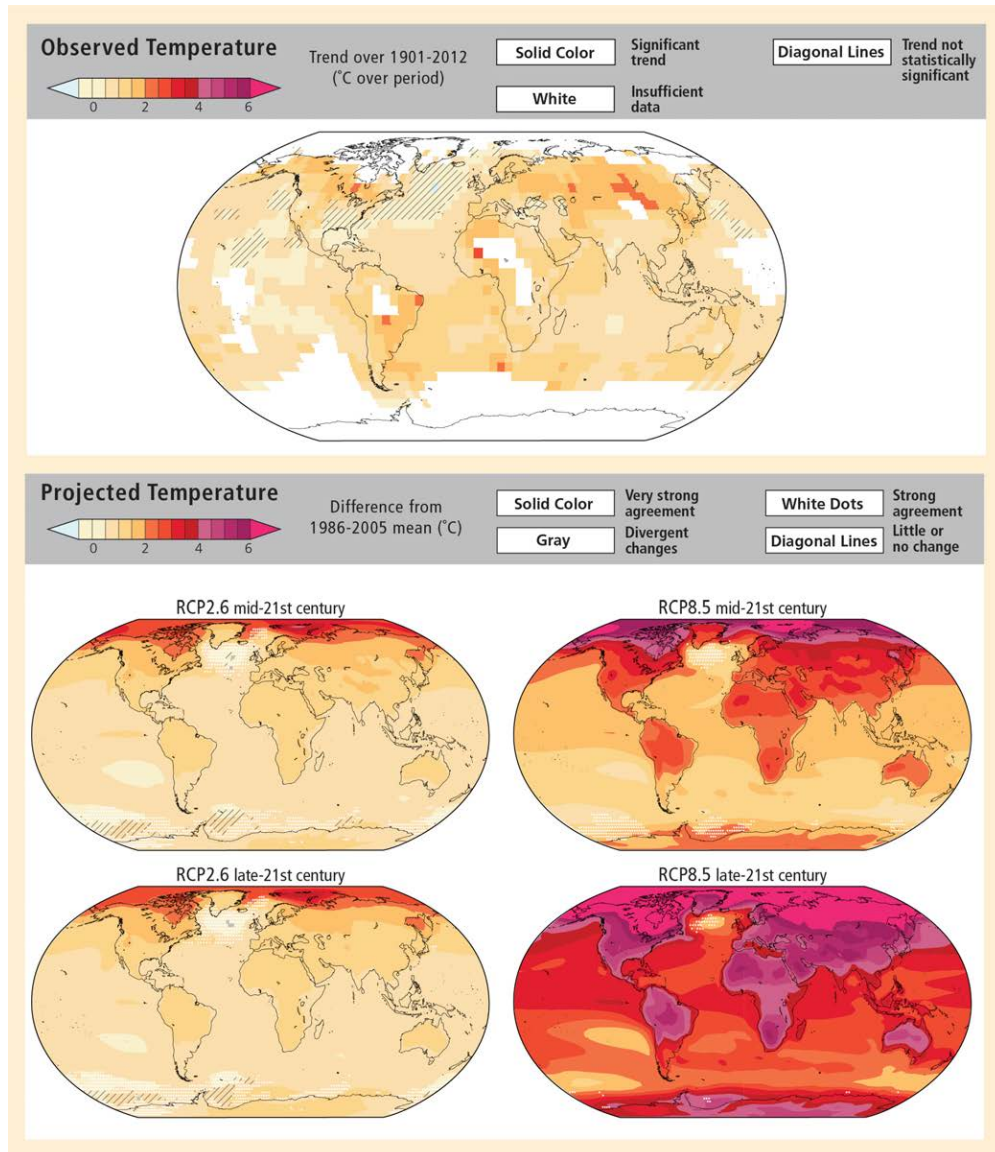


Figure RC-2: Observed and projected changes in annual average temperature. (A) Observed temperature trends from 1901-2012 are determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.1 and 2.21. The range of grid-point values is -0.53 to $+2.50^{\circ}\text{C}$ over period. (B) CMIP5 multi-model mean projections of annual average temperature changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, 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 and $>90\%$ of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where $>66\%$ of models show change greater than the baseline variability and $>66\%$ of models agree on the sign of change. Gray indicates areas with divergent changes, where $>66\%$ of models show change greater than the baseline variability, but $<66\%$ agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where $>66\%$ of models show change less 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.

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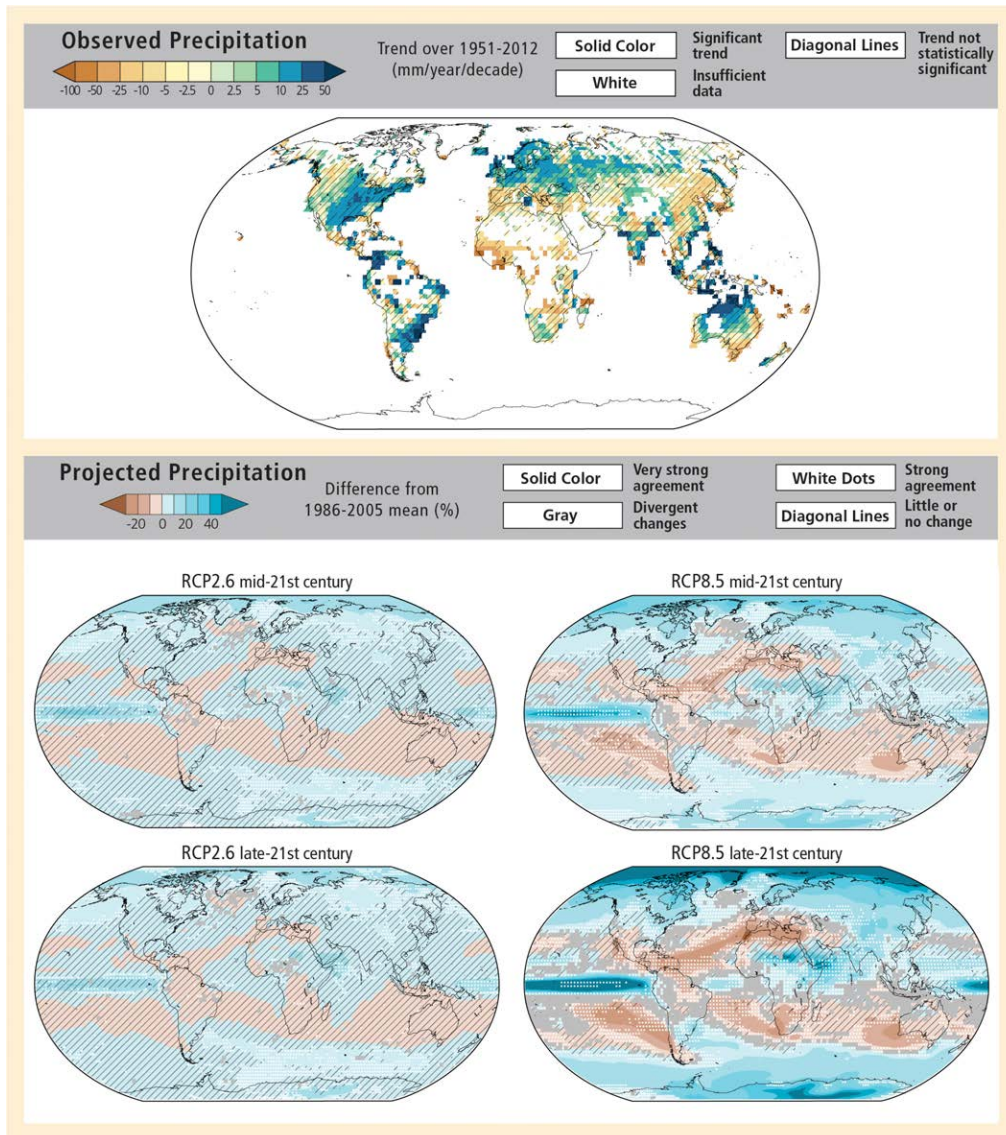


Figure RC-3: Observed and projected changes in annual average precipitation. (A) Observed precipitation trends from 1951-2010 are determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records 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 change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.2. The range of grid-point values is -185 to +111 mm/year/decade. (B) CMIP5 multi-model mean projections of annual average precipitation changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, 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 and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less 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.

Box CC-RF. 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*) (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like 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 (SRES A2 emissions, HadCM3 climate model), 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, i.e. 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 5-7% of the global land area, mainly in semi-arid 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 over 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).

Due to 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 in Chapter 3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% 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).

[INSERT FIGURE RF-1 HERE]

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). Monthly Q_{90} was defined as the flow that is exceeded in 9 out of 10 months. 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 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 due to 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.

[INSERT FIGURE RF-2 HERE

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 9-14 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 or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

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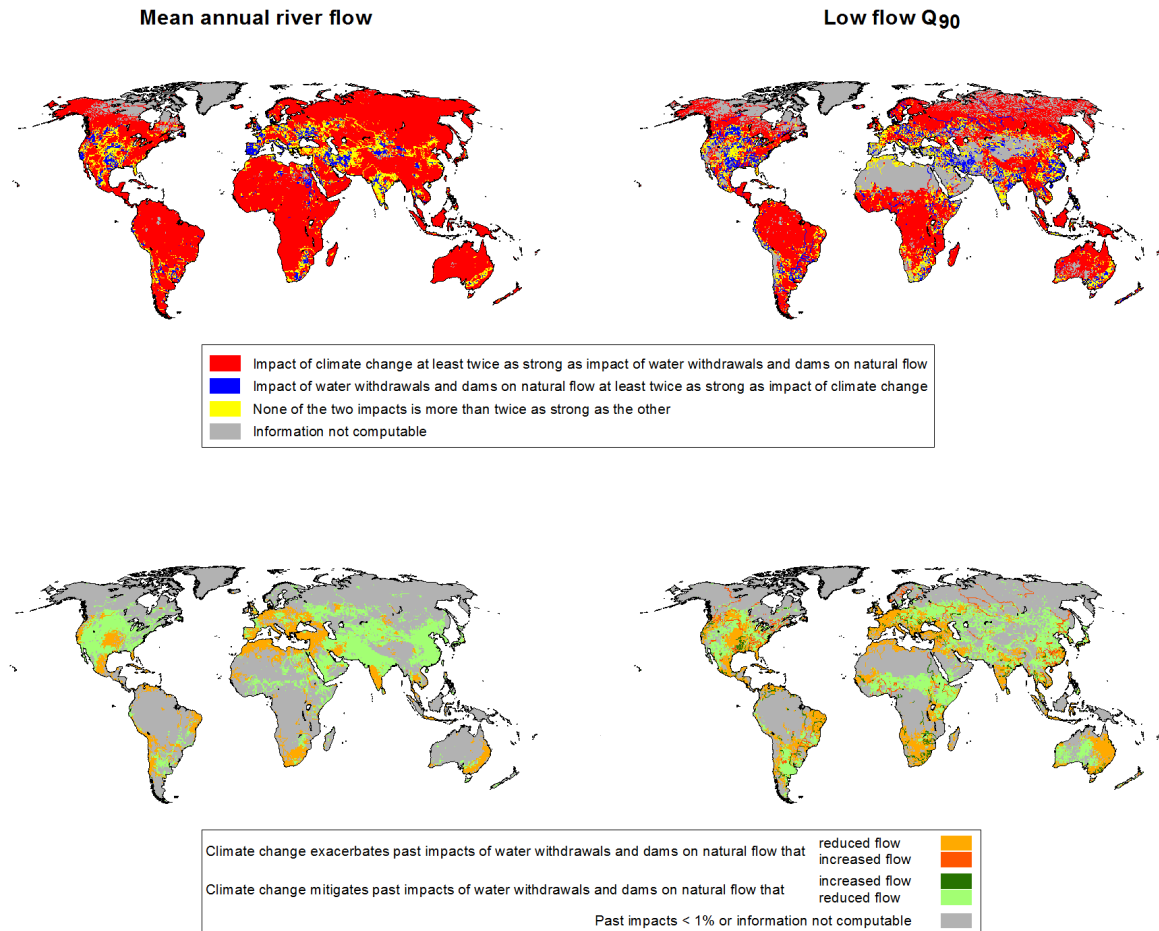


Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out of 10 months. 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 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.

[Illustration to be redrawn to conform to IPCC publication specifications.]

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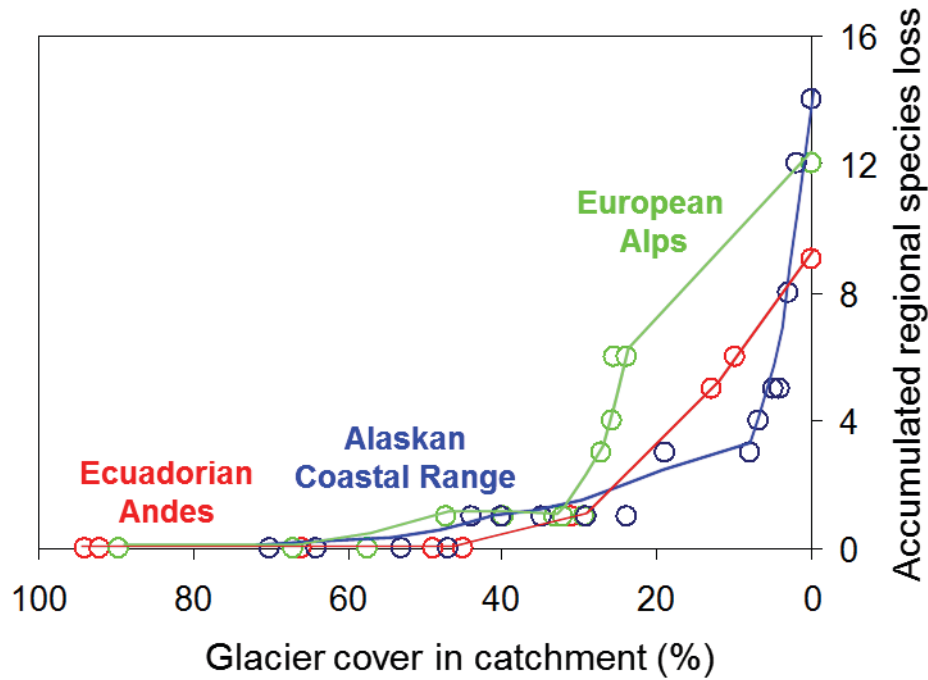


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species 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 or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

[Illustration to be redrawn to conform to IPCC publication specifications.]

Box CC-TC. Building Long-Term Resilience from Tropical Cyclone Disasters

[Yoshiaki Saito (Japan), Kathleen McInnes (Australia)]

Tropical cyclones (also referred to as hurricanes and typhoons in some regions or strength) cause powerful winds, torrential rains, high waves and storm surge, all of which can have major impacts on society and ecosystems. Bangladesh and India account for 86% of mortality from tropical cyclones (Murray et al., 2012), which is mainly due to 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. Therefore, IPCC (2012) “Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)” concluded that there is *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 (AR5 WG1 Ch 14.6). Regionally specific projections have *lower confidence* (see AR5 WG1 Box 14.2).

Longer-term impacts from tropical cyclones include salinisation 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.

Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray et al., 2012) e.g., 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 2 May 2008 and caused over 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 MODIS image on 5 May 2008 (see Figure TC-1).

[INSERT FIGURE TC-1 HERE

Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue 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 (3,400 compared to over 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. The strategies of disaster risk management for tropical cyclones in coastal areas, that create protective measures, anticipate and plan for extreme events, 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). 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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Box CC-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 waters 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, 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE, 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 S30.1).

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 3.2, 3.4.4, 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, due to the uncertainty in wind speed trends (WGI, 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the early 1990s (WGI, 9.4.1.3.4). Observations and modelling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the the difference in heat gaining rates 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 Boundary Upwelling Ecosystems (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 since these are the most biologically active systems in the ocean. 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 CO₂ 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, 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 the fisheries catch potential and impact aquaculture in coastal areas (5.4.3.3, 6.3.7, 30.5.1.1.2, 30.5.5.1.3, Barton *et al.*, 2012). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulphide 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), 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 (6.4.1, Chp 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 N₂-fixing microorganisms (Deutsch *et al.*, 2007; Deutsch and Weber, 2012), but field observations of N₂ 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 O₂ and CO₂ inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO₂ concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending upon pCO₂ of the upwelled water, and potentially increasingly impact the biota of Eastern Boundary Upwelling Ecosystems.

[INSERT FIGURE UP-1 HERE]

Figure UP-1: Upper panel: Schematic hypothetical mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: 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 decreased coastal fisheries due to an augmented 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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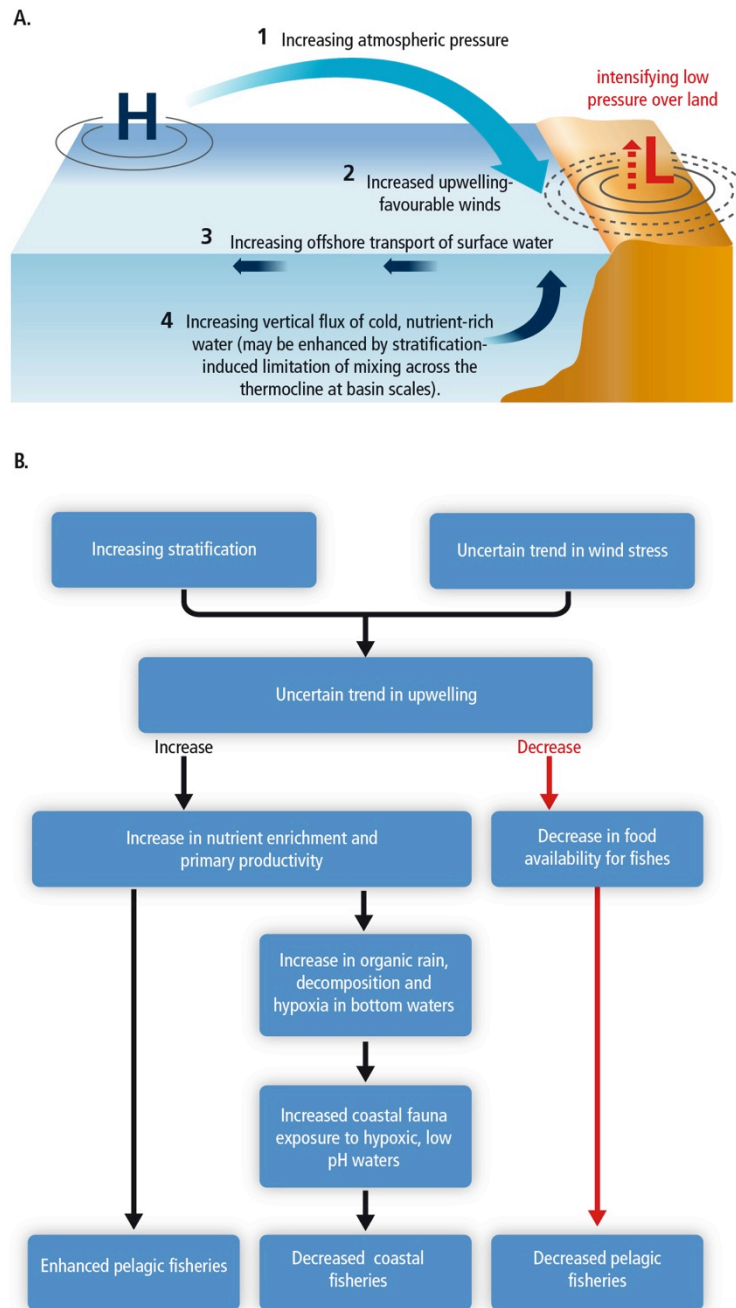


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**Box CC-UR. Urban-Rural Interactions –
Context for Climate Change Vulnerability, Impacts, and Adaptation**

[John Morton (UK), William Solecki (USA), Purnamita Dasgupta (India), David Dodman (Jamaica), Marta G. Rivera-Ferre (Spain)]

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; and,
- 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 in order 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, 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. While 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 which 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 which 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.* (2006:4) 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: 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be “largely rural landscapes” (Lerner and Eakin 2010: 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 labour: buffering of risk from insecure urban labour 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 summarised 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 policy-makers (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 co-existence of rural and urban perspectives, which may give rise to conflicts between different social /interest groups and economic activities (Darly and Torre 2013, Masuda and Garvin 2008, Solona-Solona 2010).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Jaquinta 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 policy-makers 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 (Liwenda 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 areas, 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., 2011). 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 labour markets and wage labour 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 (e.g. 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) or Spain 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 (Darrel Jenerette and Larsen, 2006), both of which requires an innovative approach to address such conflicts (Pearson et al., 2010).

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Box CC-VW. 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 CO₂ 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 CO₂ 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 CO₂ concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO₂ Enrichment (FACE), laboratory and modelling experiments (e.g. Leakey *et al.*, 2009; de Boer *et al.*, 2011; Reddy *et al.*, 2010). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, i.e. lower leaf-level transpiration. On the other hand, a *structural* effect (“fertilization effect”) stimulates photosynthesis and biomass production of C3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO₂-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO₂ 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 modelling study by Gedney *et al.*, 2006) or has increased in some regions due to the structural CO₂ 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 CO₂ change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 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 CO₂ effects (McMahon *et al.*, 2010). Satellite observations analysed in Donohue *et al.* (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO₂ fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO₂ increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modelling studies, can suppress the CO₂ fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO₂ effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.* (2006) which suggested that the physiological CO₂ 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 dataset (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 CO₂ 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 CO₂ and to climate change will modulate the impacts of climate change on freshwater flows. 21st century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO₂ 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.*, in press). In absolute terms, the isolated effect of CO₂ has been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO₂ trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were not in Nugent and Matthews, 2012). In a global model intercomparison study (Davie *et al.*, in press), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO₂ effects compared to simulations with constant CO₂ concentration (consistent with 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 CO₂, stomatal closure and plant growth is a source of uncertainty, as also suggested by Cao *et al.* (2009). Lower transpiration due to rising CO₂ 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 CO₂ rise, i.e. 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 CO₂ 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 CO₂-driven improvements will only be realized if proper management abates limitation of plant growth by nutrient availability or other factors.

[INSERT FIGURE VW-1 HERE

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. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO₂ concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).]

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.* (in press) 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 CO₂ effects. As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011; Gerten *et al.*, in press), it remains a challenge to disentangle the individual effects of climate, CO₂ and land cover change on the water cycle.

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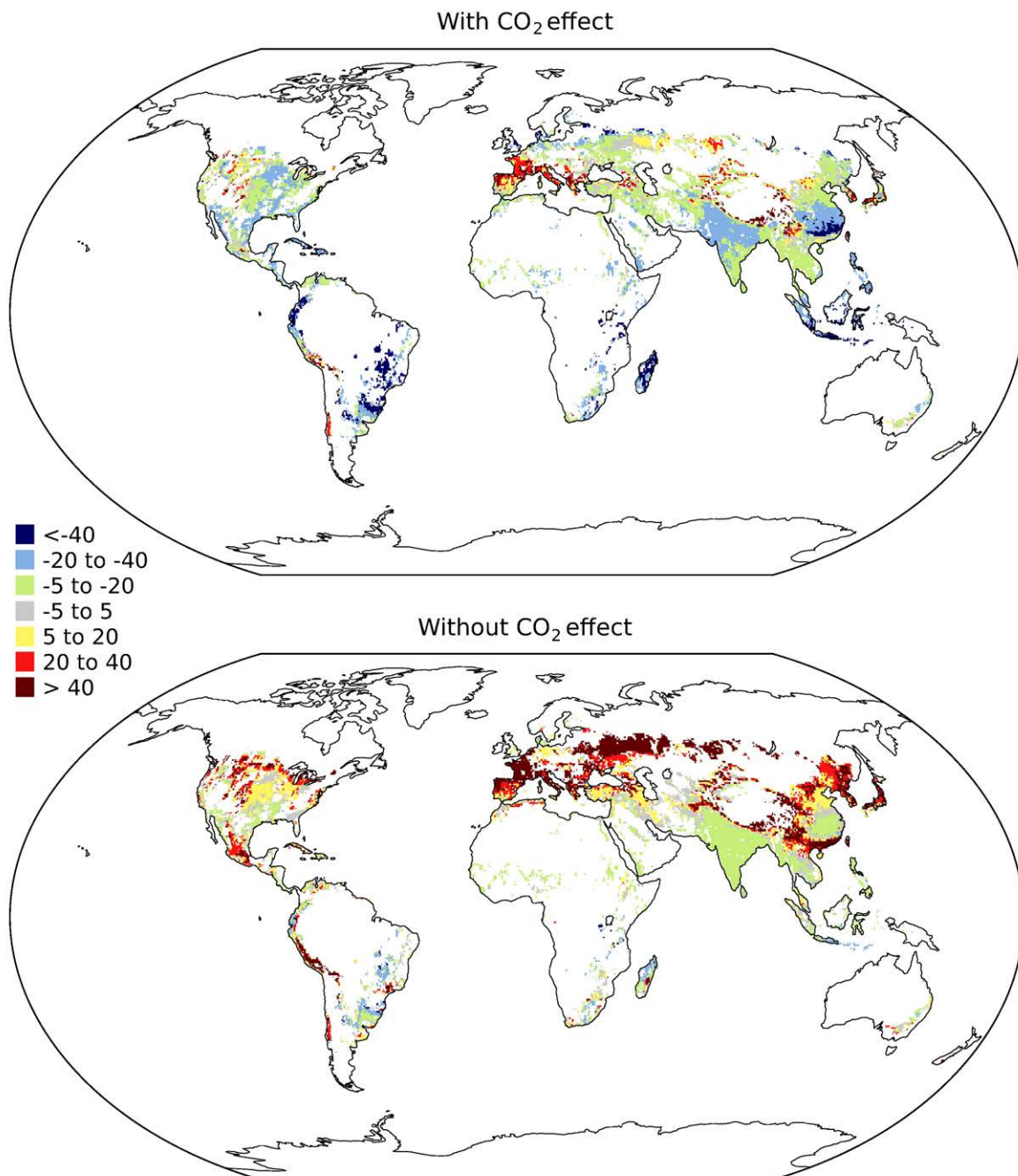


Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO₂ concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).

[Illustration to be redrawn to conform to IPCC publication specifications.]

Box CC-WE: The Water-Energy-Food/Feed/Fiber Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Kenneth M. Strzepek (UNU / USA), Blanca Elena Jimenez Cisneros (Mexico), Andy Reisinger (New Zealand), Ferenc Toth (IAEA / Hungary), Taikan Oki (Japan)]

Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between 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 (Asano *et al.*, 2006; Khan and Hanjra, 2009; USEPA, 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 (Section 7.3.2, Box 25-10; Diffenbaugh *et al.*, 2012; Skaggs *et al.*, 2012) (*robust evidence, high agreement*). Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable 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; Sung *et al.*, 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products 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.

[INSERT FIGURE WE-1 HERE

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

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) (Sections 10.2.2, 10.3.4, 25.7.4; van Vliet *et al.*, 2012; Davies *et al.*, 2013) (*robust evidence, high agreement*). Water for biofuels, for example, under the 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 (WEC, 2010; Sattler *et al.*, 2012) (*medium evidence, high agreement*). Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) (*robust evidence, high agreement*).

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 m³ of water vary by about a factor of 10 between different sources, e.g. locally produced potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 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 (kWhr/m³ 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 (Smit and Nasr, 1992; Jimenez, 1996; Wichelns *et al.*,

2007; Raschid-Sally and Jayakody, 2008) (*medium confidence*). More energy efficient treatment methods enable poor quality (“black”) wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita 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 (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) (*high confidence*).

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) (*robust evidence, high agreement*). 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 (Sections 25.4.3 and 25.6.2, Box 25-10) (*medium evidence, high agreement*). 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 WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this 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-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 300EJ 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.

Box CC-WE References

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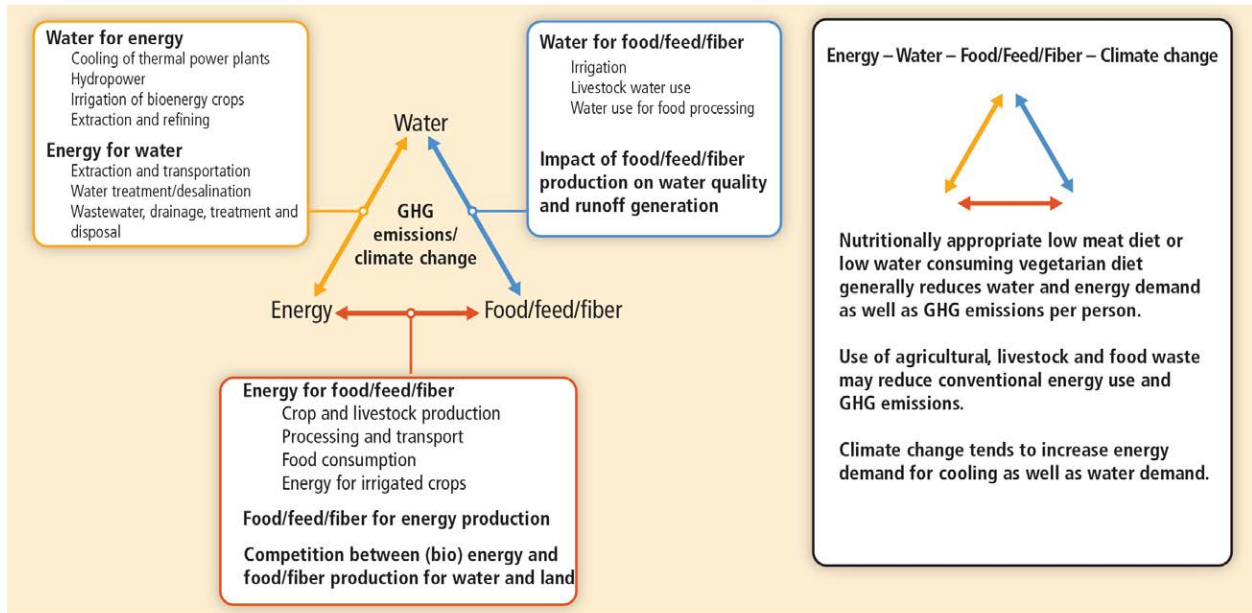


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