Introduction

This Synthesis Report is based on the reports of the three Working Groups of the Intergovernmental Panel on Climate Change (IPCC), including relevant Special Reports. It provides an integrated view of climate change as the final part of the IPCC's Fifth Assessment Report (AR5).

This summary follows the structure of the longer report which addresses the following topics: Observed changes and their causes; Future climate change, risks and impacts; Future pathways for adaptation, mitigation and sustainable development; Adaptation and mitigation.

In the Synthesis Report, the certainty in key assessment findings is communicated as in the Working Group Reports and Special Reports. It is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from *very low* to *very high*) and, when possible, probabilistically with a quantified likelihood (from *exceptionally unlikely* to *virtually certain*)[1]. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

This report includes information relevant to Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).

SPM 1. Observed Changes and their Causes

Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems. *{1}*

SPM 1.1 Observed changes in the climate system

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. *{1.1}*

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was *likely* the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible (*medium confidence*). The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C[2] over the period 1880 to 2012, when multiple independently produced datasets exist (Figure SPM.1a). *{1.1.1, Figure 1.1}*

In addition to robust multi-decadal warming, the globally averaged surface temperature exhibits substantial decadal and interannual variability (Figure SPM.1a). Due to this natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over

[1] Each finding is grounded in an evaluation of underlying evidence and agreement. In many cases, a synthesis of evidence and agreement supports an assignment of confidence. The summary terms for evidence are: limited, medium or robust. For agreement, they are low, medium or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. See for more details: Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 4 pp.

[2] Ranges in square brackets or following '±' are expected to have a 90% likelihood of including the value that is being estimated, unless otherwise stated.

the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade). *{1.1.1, Box 1.1}*

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*), with only about 1% stored in the atmosphere. On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010. It is *virtually certain* that the upper ocean (0–700 m) warmed from 1971 to 2010, and it *likely* warmed between the 1870s and 1971. *{1.1.2, Figure 1.2}*

Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudes, area-averaged long-term positive or negative trends have *low confidence*. Observations of changes in ocean surface salinity also provide indirect evidence for changes in the global water cycle over the ocean (*medium confidence*). It is *very likely* that regions of high salinity, where evaporation dominates, have become more saline, while regions of low salinity, where precipitation dominates, have become fresher since the 1950s. *{1.1.1, 1.1.2}*

Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in acidification of the ocean; the pH of ocean surface water has decreased by 0.1 (*high confidence*), corresponding to a 26% increase in acidity, measured as hydrogen ion concentration. *{1.1.2}*

Over the period 1992 to 2011, the Greenland and Antarctic ice sheets have been losing mass (*high confidence*), *likely* at a larger rate over 2002 to 2011. Glaciers have continued to shrink almost worldwide (*high confidence*). Northern Hemisphere spring snow cover has continued to decrease in extent (*high confidence*). There is *high confidence* that permafrost temperatures have increased in most regions since the early 1980s in response to increased surface temperature and changing snow cover. *{1.1.3}*

The annual mean Arctic sea-ice extent decreased over the period 1979 to 2012, with a rate that was *very likely* in the range 3.5 to 4.1% per decade. Arctic sea-ice extent has decreased in every season and in every successive decade since 1979, with the most rapid decrease in decadal mean extent in summer (*high confidence*). It is *very likely* that the annual mean Antarctic sea-ice extent increased in the range of 1.2 to 1.8% per decade between 1979 and 2012. However, there is *high confidence* that there are strong regional differences in Antarctica, with extent increasing in some regions and decreasing in others. *{1.1.3, Figure 1.1}*

Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (Figure SPM.1b). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). *{1.1.4, Figure 1.1}*

SPM 1.2 Causes of climate change

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century. *{1.2, 1.3.1}*

Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Figure SPM.1c). Between 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 $GtCO_2$. About 40% of these emissions have remained in the atmosphere (880 ± 35 $GtCO_2$); the rest was removed from the atmosphere and stored on land (in plants and soils) and in the ocean. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification. About half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (*high confidence*) (Figure SPM.1d). *{1.2.1, 1.2.2}*

Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies. Anthropogenic GHG emissions in 2010 have reached 49 ± 4.5 $GtCO_2$-eq/yr [3]. Emissions of CO_2 from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010, with a similar percentage contribution for the increase during the period 2000 to 2010 (*high confidence*) (Figure SPM.2). Globally, economic and population growth continued to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply. Increased use of coal has reversed the long-standing trend of gradual decarbonization (i.e., reducing the carbon intensity of energy) of the world's energy supply (*high confidence*). *{1.2.2}*

The evidence for human influence on the climate system has grown since the IPCC Fourth Assessment Report (AR4). It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period (Figure SPM.3). Anthro-pogenic forcings have *likely* made a substantial contribution to surface temperature increases since the mid-20th century over every continental region except Antarctica[4]. Anthropogenic influences have *likely* affected the global water cycle since 1960 and contributed to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. Anthropogenic influences have *very likely* contributed to Arctic sea-ice loss since 1979 and have *very likely* made a substantial contribution to increases in global upper ocean heat content (0–700 m) and to global mean sea level rise observed since the 1970s. *{1.3, Figure 1.10}*

[3] Greenhouse gas emissions are quantified as CO_2-equivalent ($GtCO_2$-eq) emissions using weightings based on the 100-year Global Warming Potentials, using IPCC Second Assessment Report values unless otherwise stated. *{Box 3.2}*

[4] For Antarctica, large observational uncertainties result in *low confidence* that anthropogenic forcings have contributed to the observed warming averaged over available stations.

SPM 1.3 Impacts of climate change

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate. ***{1.3.2}***

Evidence of observed climate change impacts is strongest and most comprehensive for natural systems. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change (*high confidence*). Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences (Figure SPM.4). Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). Some impacts of ocean acidification on marine organisms have been attributed to human influence (*medium confidence*). *{1.3.2}*

SPM 1.4 Extreme events

Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions. *{1.4}*

It is *very likely* that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is *likely* that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. It is *very likely* that human influence has contributed to the observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century. It is *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations. There is *medium confidence* that the observed warming has increased heat-related human mortality and decreased cold-related human mortality in some regions. *{1.4}*

There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. Recent detection of increasing trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). It is *likely* that extreme sea levels (for example, as experienced in storm surges) have increased since 1970, being mainly a result of rising mean sea level. *{1.4}*

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). *{1.4}*

SPM 2. Future Climate Changes, Risks and Impacts

Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks. *{2}*

SPM 2.1 Key drivers of future climate

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Projections of greenhouse gas emissions vary over a wide range, depending on both socio-economic development and climate policy. *{2.1}*

Anthropogenic GHG emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5 (Figure SPM.5a). RCP2.6 is representative of a scenario that aims to keep global warming *likely* below 2°C above pre-industrial temperatures. The RCPs are consistent with the wide range of scenarios in the literature as assessed by WGIII[5]. *{2.1, Box 2.2, 4.3}*

Multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100 in both the RCPs and the wider set of mitigation scenarios analysed in WGIII (Figure SPM.5b). Any given level of warming is associated with a range of cumulative CO_2 emissions[6], and therefore, e.g., higher emissions in earlier decades imply lower emissions later. *{2.2.5, Table 2.2}*

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[5] Roughly 300 baseline scenarios and 900 mitigation scenarios are categorized by CO_2-equivalent concentration (CO_2-eq) by 2100. The CO_2-eq includes the forcing due to all GHGs (including halogenated gases and tropospheric ozone), aerosols and albedo change.

[6] Quantification of this range of CO_2 emissions requires taking into account non-CO_2 drivers.

Multi-model results show that limiting total human-induced warming to less than 2°C relative to the period 1861–1880 with a probability of >66%[7] would require cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain below about 2900 $GtCO_2$ (with a range of 2550 to 3150 $GtCO_2$ depending on non-CO_2 drivers). About 1900 $GtCO_2$[8] had already been emitted by 2011. For additional context see Table 2.2. *{2.2.5}*

SPM 2.2 Projected changes in the climate system

Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is *very likely* that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise. *{2.2}*

The projected changes in Section SPM 2.2 are for 2081–2100 relative to 1986–2005, unless otherwise indicated.

Future climate will depend on committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs and will *likely* be in the range 0.3°C to 0.7°C (*medium confidence*). This assumes that there will be no major volcanic eruptions or changes in some natural sources (e.g., CH_4 and N_2O), or unexpected changes in total solar irradiance. By mid-21st century, the magnitude of the projected climate change is substantially affected by the choice of emissions scenario. *{2.2.1, Table 2.1}*

Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to *likely* exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*). Warming is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), *more likely than not* to exceed 2°C for RCP4.5 (*medium confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). *{2.2.1}*

The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is *likely* to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5[9]. The Arctic region will continue to warm more rapidly than the global mean (Figure SPM.6a, Figure SPM.7a). *{2.2.1, Figure 2.1, Figure 2.2, Table 2.1}*

It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is *very likely* that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur. *{2.2.1}*

Changes in precipitation will not be uniform. The high latitudes and the equatorial Pacific are *likely* to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipi-tation will *likely* decrease, while in many mid-latitude wet regions, mean precipitation will *likely* increase under the RCP8.5 scenario (Figure SPM.7b). Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent. *{2.2.2, Figure 2.2}*

The global ocean will continue to warm during the 21st century, with the strongest warming projected for the surface in tropical and Northern Hemisphere subtropical regions (Figure SPM.7a). *{2.2.3, Figure 2.2}*

Earth System Models project a global increase in ocean acidification for all RCP scenarios by the end of the 21st century, with a slow recovery after mid-century under RCP2.6. The decrease in surface ocean pH is in the range of 0.06 to 0.07 (15 to 17% increase in acidity) for RCP2.6, 0.14 to 0.15 (38 to 41%) for RCP4.5, 0.20 to 0.21 (58 to 62%) for RCP6.0 and 0.30 to 0.32 (100 to 109%) for RCP8.5. *{2.2.4, Figure 2.1}*

Year-round reductions in Arctic sea ice are projected for all RCP scenarios. A nearly ice-free[11] Arctic Ocean in the summer sea-ice minimum in September before mid-century is *likely* for RCP8.5[12] (*medium confidence*). *{2.2.3, Figure 2.1}*

It is *virtually certain* that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases, with the area of permafrost near the surface (upper 3.5 m) projected to decrease by 37% (RCP2.6) to 81% (RCP8.5) for the multi-model average (*medium confidence*). *{2.2.3}*

The global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the Greenland and Antarctic ice sheets), is projected to decrease by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5 (*medium confidence*). *{2.2.3}*

There has been significant improvement in understanding and projection of sea level change since the AR4. Global mean sea level rise will continue during the 21st century, *very likely* at a faster rate than observed from 1971 to 2010. For the period 2081–2100 relative to 1986–2005, the rise will *likely* be in the ranges of 0.26 to 0.55 m for RCP2.6, and of 0.45 to 0.82 m for RCP8.5 (*medium confidence*)[10] (Figure SPM.6b). Sea level rise will not be uniform across regions. By the end of the 21st century, it is *very likely* that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience a sea level change within ±20% of the global mean. *{2.2.3}*

SPM 2.3 Future risks and impacts caused by a changing climate

Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. *{2.3}*

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive and in some cases irreversible detrimental impacts. Some risks are particularly relevant for individual regions (Figure SPM.8), while others are global. The overall risks of future climate change impacts can be reduced by limiting the rate and magnitude of climate change, including ocean acidification. The precise levels of climate change sufficient to trigger abrupt and irreversible change remain uncertain, but the risk associated with crossing such thresholds increases with rising temperature (*medium confidence*). For risk assessment, it is important to evaluate the widest possible range of impacts, including low-probability outcomes with large consequences. *{1.5, 2.3, 2.4, 3.3, Box Introduction.1, Box 2.3, Box 2.4}*

A large fraction of species faces increased extinction risk due to climate change during and beyond the 21st century, especially as climate change interacts with other stressors (*high confidence*). Most plant species cannot naturally shift their geographical ranges sufficiently fast to keep up with current and high projected rates of climate change in most landscapes; most small mammals and freshwater molluscs will not be able to keep up at the rates projected under RCP4.5 and above in flat landscapes in this century (*high confidence*). Future risk is indicated to be high by the observation that natural global climate change at rates lower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years. Marine organisms will face progressively lower oxygen levels and high rates and magnitudes of ocean acidification (*high confidence*), with associated risks exacerbated by rising ocean temperature extremes (*medium confidence*). Coral reefs and polar ecosystems are highly vulnerable. Coastal systems and low-lying areas are at risk from sea level rise, which will continue for centuries even if the global mean temperature is stabilized (*high confidence*). *{2.3, 2.4, Figure 2.5}*

Climate change is projected to undermine food security (Figure SPM.9). Due to projected climate change by the mid-21st century and beyond, global marine species redistribution and marine biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem services (*high confidence*). For wheat, rice and maize in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late 20th century levels, although individual locations may benefit (*medium confidence*). Global temperature increases of ~4°C or more[13] above late 20th century levels, combined with increasing food demand, would pose large risks to food security globally (*high confidence*). Climate change is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). *{2.3.1, 2.3.2}*

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). By 2100 for RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is expected to compromise common human activities, including growing food and working outdoors (*high confidence*). *{2.3.2}*

In urban areas climate change is projected to increase risks for people, assets, economies and ecosystems, including risks from heat stress, storms and extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scar-city, sea level rise and storm surges (*very high confidence*). These risks are amplified for those lacking essential infrastructure and services or living in exposed areas. *{2.3.2}*

Rural areas are expected to experience major impacts on water availability and supply, food security, infrastructure and agricultural incomes, including shifts in the production areas of food and non-food crops around the world (*high confidence*). *{2.3.2}*

Aggregate economic losses accelerate with increasing temperature (*limited evidence, high agreement*), but global economic impacts from climate change are currently difficult to estimate. From a poverty perspective, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales. *{2.3.2}*

Climate change is projected to increase displacement of people (*medium evidence, high agreement*). Populations that lack the resources for planned migration experience higher exposure to extreme weather events, particularly in developing countries with low income. Climate change can indirectly increase risks of violent conflicts by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). *{2.3.2}*

SPM 2.4 Climate change beyond 2100, irreversibility and abrupt changes

Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases. *{2.4}*

Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial timescale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. *{2.4, Figure 2.8}*

Stabilization of global average surface temperature does not imply stabilization for all aspects of the climate system. Shifting biomes, soil carbon, ice sheets, ocean temperatures and associated sea level rise all have their own intrinsic long timescales which will result in changes lasting hundreds to thousands of years after global surface temperature is stabilized. *{2.1, 2.4}*

There is *high confidence* that ocean acidification will increase for centuries if CO_2 emissions continue, and will strongly affect marine ecosystems. *{2.4}*

It is *virtually certain* that global mean sea level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions. The threshold for the loss of the Greenland ice sheet over a millennium or more, and an associated sea level rise of up to 7 m, is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures. Abrupt and irreversible ice loss from the Antarctic ice sheet is possible, but current evidence and understanding is insufficient to make a quantitative assessment. *{2.4}*

Magnitudes and rates of climate change associated with medium- to high-emission scenarios pose an increased risk of abrupt and irreversible regional-scale change in the composition, structure and function of marine, terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). A reduction in permafrost extent is *virtually certain* with continued rise in global temperatures. *{2.4}*

SPM 3. Future Pathways for Adaptation, Mitigation and Sustainable Development

Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development. *{3.2, 3.3, 3.4}*

SPM 3.1 Foundations of decision-making about climate change

Effective decision-making to limit climate change and its effects can be informed by a wide range of analytical approaches for evaluating expected risks and benefits, recognizing the importance of governance, ethical dimensions, equity, value judgments, economic assessments and diverse perceptions and responses to risk and uncertainty. *{3.1}*

Sustainable development and equity provide a basis for assessing climate policies. Limiting the effects of climate change is necessary to achieve sustainable development and equity, including poverty eradication. Countries' past and future contributions to the accumulation of GHGs in the atmosphere are different, and countries also face varying challenges and circumstances and have different capacities to address mitigation and adaptation. Mitigation and adaptation raise issues of equity, justice and fairness. Many of those most vulnerable to climate change have contributed and contribute little to GHG emissions. Delaying mitigation shifts burdens from the present to the future, and insufficient adaptation responses to emerging impacts are already eroding the basis for sustainable development. Comprehensive strategies in response to climate change that are consistent with sustainable development take into account the co-benefits, adverse side effects and risks that may arise from both adaptation and mitigation options. *{3.1, 3.5, Box 3.4}*

The design of climate policy is influenced by how individuals and organizations perceive risks and uncertainties and take them into account. Methods of valuation from economic, social and ethical analysis are available to assist decision-making. These methods can take account of a wide range of possible impacts, including low-probability outcomes with large consequences. But they cannot identify a single best balance between mitigation, adaptation and residual climate impacts. *{3.1}*

Climate change has the characteristics of a collective action problem at the global scale, because most GHGs accumulate over time and mix globally, and emissions by any agent (e.g., individual, community, company, country) affect other agents. Effective mitigation will not be achieved if individual agents advance their own interests independently. Cooperative responses, including international cooperation, are therefore required to effectively mitigate GHG emissions and address other climate change issues. The effectiveness of adaptation can be enhanced through complementary actions across levels, including international cooperation. The evidence suggests that outcomes seen as equitable can lead to more effective cooperation. *{3.1}*

SPM 3.2 Climate change risks reduced by mitigation and adaptation

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*). Mitigation involves some level of co-benefits and of risks due to adverse side effects, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change, increasing the benefits from near-term mitigation efforts. *{3.2, 3.4}*

Mitigation and adaptation are complementary approaches for reducing risks of climate change impacts over different timescales (*high confidence*). Mitigation, in the near term and through the century, can substantially reduce climate change impacts in the latter decades of the 21st century and beyond. Benefits from adaptation can already be realized in addressing current risks, and can be realized in the future for addressing emerging risks. *{3.2, 4.5}*

Five Reasons For Concern (RFCs) aggregate climate change risks and illustrate the implications of warming and of adaptation limits for people, economies and ecosystems across sectors and regions. The five RFCs are associated with: (1) Unique and threatened systems, (2) Extreme weather events, (3) Distribution of impacts, (4) Global aggregate impacts, and (5) Large-scale singular events. In this report, the RFCs provide information relevant to Article 2 of UNFCCC. *{Box 2.4}*

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*) (Figure SPM.10). In most scenarios without additional mitigation efforts (those with 2100 atmospheric concentrations

>1000 ppm CO_2-eq), warming is *more likely than not* to exceed 4°C above pre-industrial levels by 2100 (Table SPM.1). The risks associated with temperatures at or above 4°C include substantial species extinction, global and regional food insecurity, consequential constraints on common human activities and limited potential for adaptation in some cases (*high confidence*). Some risks of climate change, such as risks to unique and threatened systems and risks associated with extreme weather events, are moderate to high at temperatures 1°C to 2°C above pre-industrial levels. *{2.3, Figure 2.5, 3.2, 3.4, Box 2.4, Table SPM.1}*

Substantial cuts in GHG emissions over the next few decades can substantially reduce risks of climate change by limiting warming in the second half of the 21st century and beyond. Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Limiting risks across RFCs would imply a limit for cumulative emissions of CO_2. Such a limit would require that global net emissions of CO_2 eventually decrease to zero and would constrain annual emissions over the next few decades (Figure SPM.10) (*high confidence*). But some risks from climate damages are unavoidable, even with mitigation and adaptation. *{2.2.5, 3.2, 3.4}*

Mitigation involves some level of co-benefits and risks, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change. Inertia in the economic and climate system and the possibility of irreversible impacts from climate change increase the benefits from near-term mitigation efforts (*high confidence*). Delays in additional mitigation or constraints on technological options increase the longer-term mitigation costs to hold climate change risks at a given level (Table SPM.2). *{3.2, 3.4}*

SPM 3.3 Characteristics of adaptation pathways

Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change. Taking a longer-term perspective, in the context of sustainable development, increases the likelihood that more immediate adaptation actions will also enhance future options and preparedness. *{3.3}*

Adaptation can contribute to the well-being of populations, the security of assets and the maintenance of ecosystem goods, functions and services now and in the future. Adaptation is place- and context-specific (*high confidence*). A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*). Integration of adaptation into planning, including policy design, and decision-making can promote synergies with development and disaster risk reduction. Building adaptive capacity is crucial for effective selection and implementation of adaptation options (*robust evidence, high agreement*). *{3.3}*

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and sub-national governments, for example by protecting vulnerable groups, by supporting economic diversification and by providing information, policy and legal frameworks and financial support (*robust evidence*, *high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence*, *high agreement*). *{3.3}*

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts and expectations can benefit decision-making processes. Indigenous, local and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation. *{3.3}*

Constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Another constraint includes insufficient research, monitoring, and observation and the finance to maintain them. *{3.3}*

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). Limits to adaptation emerge from the interaction among climate change and biophysical and/or socio-economic constraints. Further, poor planning or implementation, overemphasizing short-term outcomes or failing to sufficiently anticipate consequences can result in maladaptation, increasing the vulnerability or exposure of the target group in the future or the vulnerability of other people, places or sectors (*medium evidence, high agreement*). Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes. *{3.3}*

Significant co-benefits, synergies and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use and biodiversity, but tools to understand and manage these interactions remain limited. Examples of actions with co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging, climate-altering air pollutants; (ii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iii) sustainable agriculture and forestry; and (iv) protection of ecosystems for carbon storage and other ecosystem services. *{3.3}*

Transformations in economic, social, technological and political decisions and actions can enhance adaptation and promote sustainable development (*high confidence*). At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. Restricting adaptation responses to incremental changes to existing systems and structures, without considering transformational change, may increase costs and losses and miss opportunities. Planning and implementation of transformational adaptation could reflect strengthened, altered or aligned paradigms and may place new and increased demands on governance structures to reconcile different goals and visions for the future and to address possible equity and ethical implications. Adaptation pathways are enhanced by iterative learning, deliberative processes and innovation. *{3.3}*

SPM 3.4 Characteristics of mitigation pathways

There are multiple mitigation pathways that are *likely* to limit warming to below 2°C relative to pre-industrial levels. These pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges but on different timescales. *{3.4}*

Without additional efforts to reduce GHG emissions beyond those in place today, global emissions growth is expected to persist, driven by growth in global population and economic activities. Global mean surface temperature increases in 2100 in baseline scenarios—those without additional mitigation—range from 3.7°C to 4.8°C above the average for 1850–1900 for a median climate response. They range from 2.5°C to 7.8°C when including climate uncertainty (5th to 95th percentile range) (*high confidence*). *{3.4}*

Emissions scenarios leading to CO_2-equivalent concentrations in 2100 of about 450 ppm or lower are *likely* to maintain warming below 2°C over the 21st century relative to pre-industrial levels[15]. These scenarios are characterized by 40 to 70% global anthropogenic GHG emissions reductions by 2050 compared to 2010[16], and emissions levels near zero or below in 2100. Mitigation scenarios reaching concentration levels of about 500 ppm CO_2-eq by 2100 are *more likely than not* to limit temperature change to less than 2°C, unless they temporarily overshoot concentration levels of roughly 530 ppm CO_2-eq

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[15] For comparison, the CO_2-eq concentration in 2011 is estimated to be 430 ppm (uncertainty range 340 to 520 ppm)

[16] This range differs from the range provided for a similar concentration category in the AR4 (50 to 85% lower than 2000 for CO_2 only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in the AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include Carbon Dioxide Removal (CDR) technologies (see below). Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010.

before 2100, in which case they are *about as likely as not* to achieve that goal. In these 500 ppm CO_2-eq scenarios, global 2050 emissions levels are 25 to 55% lower than in 2010. Scenarios with higher emissions in 2050 are characterized by a greater reliance on Carbon Dioxide Removal (CDR) technologies beyond mid-century (and vice versa). Trajectories that are *likely* to limit warming to 3°C relative to pre-industrial levels reduce emissions less rapidly than those limiting warming to 2°C. A limited number of studies provide scenarios that are *more likely than not* to limit warming to 1.5°C by 2100; these scenarios are characterized by concentrations below 430 ppm CO_2-eq by 2100 and 2050 emission reduction between 70% and 95% below 2010. For a comprehensive overview of the characteristics of emissions scenarios, their CO_2-equivalent concentrations and their likelihood to keep warming to below a range of temperature levels, see Figure SPM.11 and Table SPM.1. *{3.4}*

Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a *likely* chance to keep warming below 2° C relative to pre-industrial levels) typically involve temporary overshoot[17] of atmospheric concentrations, as do many scenarios
reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq in 2100 (Table SPM.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture
and storage (BECCS) and afforestation in the second half of the century. The availability and scale of these and other CDR technologies and methods are uncertain and CDR technologies are, to varying degrees, associated with challenges and risks[18]. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive (*high confidence*). *{3.4, Box 3.3}*

Reducing emissions of non-CO_2 agents can be an important element of mitigation strategies. All current GHG emissions and other forcing agents affect the rate and magnitude of climate change over the next few decades, although long-term
warming is mainly driven by CO_2 emissions. Emissions of non-CO_2 forcers are often expressed as 'CO_2-equivalent emissions', but the choice of metric to calculate these emissions, and the implications for the emphasis and timing of abatement of the
various climate forcers, depends on application and policy context and contains value judgments. *{3.4, Box 3.2}*

Delaying additional mitigation to 2030 will substantially increase the challenges associated with limiting warming over the 21st century to below 2°C relative to pre-industrial levels. It will require substantially higher rates of emissions reductions from 2030 to 2050; a much more rapid scale-up of low-carbon energy over this period; a larger reliance on CDR in the long term; and higher transitional and long-term economic impacts. Estimated global emissions levels in 2020 based on the Cancún Pledges are not consistent with cost-effective mitigation trajectories that are at least *about as likely as not* to limit warming to below 2°C relative to pre-industrial levels, but they do not preclude the option to meet this goal (*high confidence*) (Figure SPM.12, Table SPM.2). *{3.4}*

Estimates of the aggregate economic costs of mitigation vary widely depending on methodologies and assumptions, but increase with the stringency of mitigation. Scenarios in which all countries of the world begin mitigation immediately, in which there is a single global carbon price, and in which all key technologies are available have been used as a cost-effective benchmark for estimating macro-economic mitigation costs (Figure SPM.13). Under these assumptions mitigation scenarios that are *likely* to limit warming to below 2°C through the 21st century relative to pre-industrial levels entail losses in global consumption—not including benefits of reduced climate change as well as co-benefits and adverse side effects of mitiga-tion—of 1 to 4% (median: 1.7%) in 2030, 2 to 6% (median: 3.4%) in 2050 and 3 to 11% (median: 4.8%) in 2100 relative to consumption in baseline scenarios that grows anywhere from 300% to more than 900% over the century (Figure SPM.13). These numbers correspond to an annualized reduction of consumption growth by 0.04 to 0.14 (median: 0.06) percentage points over the century relative to annualized consumption growth in the baseline that is between 1.6 and 3% per year (*high confidence*). *{3.4}*

In the absence or under limited availability of mitigation technologies (such as bioenergy, CCS and their combination BECCS, nuclear, wind/solar), mitigation costs can increase substantially depending on the technology considered. Delaying additional mitigation increases mitigation costs in the medium to long term. Many models could not limit *likely* warming to below 2°C over the 21st century relative to pre-industrial levels if additional mitigation is considerably delayed. Many models could not limit *likely* warming to below 2°C if bioenergy, CCS and their combination (BECCS) are limited (*high confidence*) (Table SPM.2). *{3.4}*

Notes:

[a] Delayed mitigation scenarios are associated with greenhouse gas emission of more than 55 $GtCO_2$-eq in 2030, and the increase in mitigation costs is measured relative to cost-effective mitigation scenarios for the same long-term concentration level.

[b] Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and impose no additional limitations on technology relative to the models' default technology assumptions.

[c] The range is determined by the central scenarios encompassing the 16th to 84th percentile range of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm CO_2-eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm CO_2-eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation.

[d] No CCS: carbon dioxide capture and storage is not included in these scenarios. Nuclear phase out: no addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20% global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations and industry was around 18 EJ/yr in 2008). EJ = Exajoule = 10^{18} Joule.

[e] Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline gross domestic product (GDP, for scenarios from partial equilibrium models) for the period 2015–2100, discounted at 5% per year.

Mitigation scenarios reaching about 450 or 500 ppm CO_2-eq by 2100 show reduced costs for achieving air quality and energy security objectives, with significant co-benefits for human health, ecosystem impacts and sufficiency of resources and resilience of the energy system. *{4.4.2.2}*

Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters (*high confidence*). The availability of CCS would reduce the adverse effects of mitigation on the value of fossil fuel assets (*medium confidence*). *{4.4.2.2}*

Solar Radiation Management (SRM) involves large-scale methods that seek to reduce the amount of absorbed solar energy in the climate system. SRM is untested and is not included in any of the mitigation scenarios. If it were deployed, SRM would entail numerous uncertainties, side effects, risks and shortcomings and has particular governance and ethical implications. SRM would not reduce ocean acidification. If it were terminated, there is *high confidence* that surface temperatures would rise very rapidly impacting ecosystems susceptible to rapid rates of change. *{Box 3.3}*

SPM 4. Adaptation and Mitigation

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself. Effective implementation depends on policies and cooperation at all scales and can be enhanced through integrated responses that link adaptation and mitigation with other societal objectives. *{4}*

SPM 4.1 Common enabling factors and constraints for adaptation and mitigation responses

Adaptation and mitigation responses are underpinned by common enabling factors. These include effective institutions and governance, innovation and investments in environmentally sound technologies and infrastructure, sustainable livelihoods and behavioural and lifestyle choices. *{4.1}*

Inertia in many aspects of the socio-economic system constrains adaptation and mitigation options (*medium evidence, high agreement*). Innovation and investments in environmentally sound infrastructure and technologies can reduce GHG emissions and enhance resilience to climate change (*very high confidence*). *{4.1}*

Vulnerability to climate change, GHG emissions and the capacity for adaptation and mitigation are strongly influenced by livelihoods, lifestyles, behaviour and culture (*medium evidence, medium agreement*). Also, the social acceptability and/or effectiveness of climate policies are influenced by the extent to which they incentivize or depend on regionally appropriate changes in lifestyles or behaviours. *{4.1}*

For many regions and sectors, enhanced capacities to mitigate and adapt are part of the foundation essential for managing climate change risks (*high confidence*). Improving institutions as well as coordination and cooperation in governance can help overcome regional constraints associated with mitigation, adaptation and disaster risk reduction (*very high confidence*). *{4.1}*

SPM 4.2 Response options for adaptation

Adaptation options exist in all sectors, but their context for implementation and potential to reduce climate-related risks differs across sectors and regions. Some adaptation responses involve significant co-benefits, synergies and trade-offs. Increasing climate change will increase challenges for many adaptation options. *{4.2}*

Adaptation experience is accumulating across regions in the public and private sectors and within communities. There is increasing recognition of the value of social (including local and indigenous), institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). *{1.6, 4.2, 4.4.2.1}*

The need for adaptation along with associated challenges is expected to increase with climate change (*very high confidence*). Adaptation options exist in all sectors and regions, with diverse potential and approaches depending on their context in vulnerability reduction, disaster risk management or proactive adaptation planning (Table SPM.3). Effective strategies and actions consider the potential for co-benefits and opportunities within wider strategic goals and development plans. *{4.2}*

SPM 4.3 Response options for mitigation

Mitigation options are available in every major sector. Mitigation can be more cost-effective if using an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize energy supply, reduce net emissions and enhance carbon sinks in land-based sectors. *{4.3}*

Well-designed systemic and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors, with efforts in one sector affecting the need for mitigation in others (*medium confidence*). Mitigation measures intersect with other societal goals, creating the possibility of co-benefits or adverse side effects. These intersections, if well-managed, can strengthen the basis for undertaking climate action. *{4.3}*

Emissions ranges for baseline scenarios and mitigation scenarios that limit CO_2-equivalent concentrations to low levels (about 450 ppm CO_2-eq, *likely* to limit warming to 2°C above pre-industrial levels) are shown for different sectors and gases in Figure SPM.14. Key measures to achieve such mitigation goals include decarbonizing (i.e., reducing the carbon intensity of) electricity generation (*medium evidence, high agreement*) as well as efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development (*robust evidence, high agreement*). In scenarios reaching 450 ppm CO_2-eq concentrations by 2100, global CO_2 emissions from the energy supply sector are projected to decline over the next decade and are characterized by reductions of 90% or more below 2010 levels between 2040 and 2070. In the majority of low-concentration stabilization scenarios (about 450 to about 500 ppm CO_2-eq, at least *about as likely as not* to limit warming to 2°C above pre-industrial levels), the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and carbon dioxide capture and storage (CCS) including bioenergy with carbon dioxide capture and storage (BECCS)) increases from the current share of approximately 30% to more than 80% by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100. *{4.3}*

Near-term reductions in energy demand are an important element of cost-effective mitigation strategies, provide more flexibility for reducing carbon intensity in the energy supply sector, hedge against related supply-side risks, avoid lock-in to carbon-intensive infrastructures, and are associated with important co-benefits. The most cost-effective mitigation options in forestry are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions; and in agriculture, cropland management, grazing land management and restoration of organic soils (*medium evidence, high agreement*). *{4.3, Figures 4.1, 4.2, Table 4.3}*

Behaviour, lifestyle and culture have a considerable influence on energy use and associated emissions, with high mitigation potential in some sectors, in particular when complementing technological and structural change (*medium evidence, medium agreement*). Emissions can be substantially lowered through changes in consumption patterns, adoption of energy savings measures, dietary change and reduction in food wastes. *{4.1, 4.3}*

SPM 4.4 Policy approaches for adaptation and mitigation, technology and finance

Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national. Policies across all scales supporting technology development, diffusion and transfer, as well as finance for responses to climate change, can complement and enhance the effectiveness of policies that directly promote adaptation and mitigation. *{4.4}*

International cooperation is critical for effective mitigation, even though mitigation can also have local co-benefits. Adaptation focuses primarily on local to national scale outcomes, but its effectiveness can be enhanced through coordination across governance scales, including international cooperation: *{3.1, 4.4.1}*

- The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum focused on addressing climate change, with nearly universal participation. Other institutions organized at different levels of governance have resulted in diversifying international climate change cooperation. *{4.4.1}*

- The Kyoto Protocol offers lessons towards achieving the ultimate objective of the UNFCCC, particularly with respect to participation, implementation, flexibility mechanisms and environmental effectiveness (*medium evidence, low agreement*). *{4.4.1}*

- Policy linkages among regional, national and sub-national climate policies offer potential climate change mitigation benefits (*medium evidence, medium agreement*). Potential advantages include lower mitigation costs, decreased emission leakage and increased market liquidity. *{4.4.1}*

- International cooperation for supporting adaptation planning and implementation has received less attention historically than mitigation but is increasing and has assisted in the creation of adaptation strategies, plans and actions at the national, sub-national and local level (*high confidence*). *{4.4.1}*

There has been a considerable increase in national and sub-national plans and strategies on both adaptation and mitigation since the AR4, with an increased focus on policies designed to integrate multiple objectives, increase co-benefits and reduce adverse side effects (*high confidence*): *{4.4.2.1, 4.4.2.2}*

- National governments play key roles in adaptation planning and implementation (*robust evidence, high agreement*) through coordinating actions and providing frameworks and support. While local government and the private sector have different functions, which vary regionally, they are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence, high agreement*). *{4.4.2.1}*

- Institutional dimensions of adaptation governance, including the integration of adaptation into planning and decision-making, play a key role in promoting the transition from planning to implementation of adaptation (*robust evidence,* *high agreement*). Examples of institutional approaches to adaptation involving multiple actors include economic options (e.g., insurance, public-private partnerships), laws and regulations (e.g., land-zoning laws) and national and government policies and programmes (e.g., economic diversification). *{4.2, 4.4.2.1, Table SPM.3}*

- In principle, mechanisms that set a carbon price, including cap and trade systems and carbon taxes, can achieve mitigation in a cost-effective way but have been implemented with diverse effects due in part to national circumstances as well as policy design. The short-run effects of cap and trade systems have been limited as a result of loose caps or caps that have not proved to be constraining (*limited evidence, medium agreement*). In some countries, tax-based policies specifically aimed at reducing GHG emissions—alongside technology and other policies—have helped to weaken the link between GHG emissions and GDP (*high confidence*). In addition, in a large group of countries, fuel taxes (although not necessarily designed for the purpose of mitigation) have had effects that are akin to sectoral carbon taxes. *{4.4.2.2}*

- Regulatory approaches and information measures are widely used and are often environmentally effective (*medium evidence, medium agreement*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. *{4.4.2.2}*

- Sector-specific mitigation policies have been more widely used than economy-wide policies (*medium evidence, high agreement*). Sector-specific policies may be better suited to address sector-specific barriers or market failures and may be bundled in packages of complementary policies. Although theoretically more cost-effective, administrative and political barriers may make economy-wide policies harder to implement. Interactions between or among mitigation policies may be synergistic or may have no additive effect on reducing emissions. *{4.4.2.2}*

- Economic instruments in the form of subsidies may be applied across sectors, and include a variety of policy designs, such as tax rebates or exemptions, grants, loans and credit lines. An increasing number and variety of renewable energy (RE) policies including subsidies—motivated by many factors—have driven escalated growth of RE technologies in recent years. At the same time, reducing subsidies for GHG-related activities in various sectors can achieve emission reductions, depending on the social and economic context (*high confidence*). *{4.4.2.2}*

Co-benefits and adverse side effects of mitigation could affect achievement of other objectives such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development. The potential for co-benefits for energy end-use measures outweighs the potential for adverse side effects whereas the evidence suggests this may not be the case for all energy supply and agriculture, forestry and other land use (AFOLU) measures. Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations (*low confidence*). These potential adverse side effects on energy access can be avoided with the adoption of complementary policies such as income tax rebates or other benefit transfer mechanisms (*medium confidence*). Whether or not side effects materialize, and to what extent side effects materialize, will be case- and site-specific, and depend on local circumstances and the scale, scope and pace of implementation. Many co-benefits and adverse side effects have not been well-quantified. *{4.3, 4.4.2.2, Box 3.4}*

Technology policy (development, diffusion and transfer) complements other mitigation policies across all scales, from international to sub-national; many adaptation efforts also critically rely on diffusion and transfer of technologies and management practices (*high confidence*). Policies exist to address market failures in R&D, but the effective use of technologies can also depend on capacities to adopt technologies appropriate to local circumstances. *{4.4.3}*

Substantial reductions in emissions would require large changes in investment patterns (*high confidence*). For mitigation scenarios that stabilize concentrations (without overshoot) in the range of 430 to 530 ppm CO_2-eq by 2100[19], annual investments in low carbon electricity supply and energy efficiency in key sectors (transport, industry and buildings) are projected in the scenarios to rise by several hundred billion dollars per year before 2030. Within appropriate enabling environments, the private sector, along with the public sector, can play important roles in financing mitigation and adaptation (*medium evidence, high agreement*). *{4.4.4}*

Financial resources for adaptation have become available more slowly than for mitigation in both developed and developing countries. Limited evidence indicates that there is a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). There is a need for better assessment of global adaptation costs, funding and investment. Potential synergies between international finance for disaster risk management and adaptation have not yet been fully realized (*high confidence*). *{4.4.4}*

SPM 4.5 Trade-offs, synergies and interactions with sustainable development

Climate change is a threat to sustainable development. Nonetheless, there are many opportunities to link mitigation, adaptation and the pursuit of other societal objectives through integrated responses (*high confidence*). Successful implementation relies on relevant tools, suitable governance structures and enhanced capacity to respond (*medium confidence*). *{3.5, 4.5}*

Climate change exacerbates other threats to social and natural systems, placing additional burdens particularly on the poor (*high confidence*). Aligning climate policy with sustainable development requires attention to both adaptation and mitigation (*high confidence*). Delaying global mitigation actions may reduce options for climate-resilient pathways and adaptation in the future. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, encompassing connections among human health, water, energy, land use and biodiversity (*medium evidence, high agreement*). *{3.1, 3.5, 4.5}*

Strategies and actions can be pursued now which will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being and effective environmental management. In some cases, economic diversification can be an important element of such strategies. The effectiveness of integrated responses can be enhanced by relevant tools, suitable governance structures and adequate institutional and human capacity (*medium confidence*). Integrated responses are especially relevant to energy planning and implementation; interactions among water, food, energy and biological carbon sequestration; and urban planning, which provides substantial opportunities for enhanced resilience, reduced emissions and more sustainable development (*medium confidence*). *{3.5, 4.4, 4.5}*

Introduction

The Synthesis Report (SYR) of the IPCC Fifth Assessment Report (AR5) provides an overview of the state of knowledge concerning the science of climate change, emphasizing new results since the publication of the IPCC Fourth Assessment Report (AR4) in 2007. The SYR synthesizes the main findings of the AR5 based on contributions from Working Group I (*The Physical Science Basis*), Working Group II (*Impacts, Adaptation and Vulnerability*) and Working Group III (*Mitigation of Climate Change*), plus two additional IPCC reports (*Special Report on Renewable Energy Sources and Climate Change Mitigation* and *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*).

The AR5 SYR longer report is divided into four topics. Topic 1 (Observed Changes and their Causes) focuses on observational evidence for a changing climate, the impacts caused by this change and the human contributions to it. Topic 2 (Future Climate Changes, Risks and Impacts) assesses projections of future climate change and the resultant projected impacts and risks. Topic 3 (Future Pathways for Adaptation, Mitigation and Sustainable Development) considers adaptation and mitigation as complementary strategies for reducing and managing the risks of climate change. Topic 4 (Adaptation and Mitigation) describes individual adaptation and mitigation options and policy approaches. It also addresses integrated responses that link mitigation and adaptation with other societal objectives.

The challenges of understanding and managing risks and uncertainties are important themes in this report. See Box 1 (Risk and the Management of an Uncertain Future) and Box 2 (Communicating the Degree of Certainty in Assessment Findings).

This report includes information relevant to Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).

Box Introduction.1 | Risk and the Management of an Uncertain Future

Climate change exposes people, societies, economic sectors and ecosystems to risk. Risk is the potential for consequences when something of value is at stake and the outcome is uncertain, recognizing the diversity of values. *{WGII SPM Background Box SPM.2, WGIII 2.1, SYR Glossary}*

Risks from climate change impacts arise from the interaction between hazard (triggered by an event or trend related to climate change), vulnerability (susceptibility to harm) and exposure (people, assets or ecosystems at risk). Hazards include processes that range from brief events, such as severe storms, to slow trends, such as multi-decade droughts or multi-century sea level rise. Vulnerability and exposure are both sensitive to a wide range of social and economic processes, with possible increases or decreases depending on development pathways. Risks and co-benefits also arise from policies that aim to mitigate climate change or to adapt to it. (1.5)

Risk is often represented as the probability of occurrence of hazardous events or trends multiplied by the magnitude of the consequences if these events occur. Therefore, high risk can result not only from high probability outcomes but also from low probability outcomes with very severe consequences. This makes it important to assess the full range of possible outcomes, from low probability tail outcomes to very likely outcomes. For example, it is unlikely that global mean sea level will rise by more than one meter in this century, but the consequence of a greater rise could be so severe that this possibility becomes a significant part of risk assessment. Similarly, low confidence but high consequence outcomes are also policy relevant; for instance the possibility that the response of Amazon forest could substantially amplify climate change merits consideration despite our currently imperfect ability to project the outcome. (2.4, Table 2.3) *{WGI Table 13.5, WGII SPM A-3, 4.4, Box 4-3, WGIII Box 3-9, SYR Glossary}*

Risk can be understood either qualitatively or quantitatively. It can be reduced and managed using a wide range of formal or informal tools and approaches that are often iterative. Useful approaches for managing risk do not necessarily require that risk levels can be accurately quantified. Approaches recognizing diverse qualitative values, goals and priorities, based on ethical, psychological, cultural or social factors, could increase the effectiveness of risk management. *{WGII 1.1.2, 2.4, 2.5, 19.3, WGIII 2.4, 2.5, 3.4}*

Box Introduction.2 | Communicating the Degree of Certainty in Assessment Findings

An integral feature of IPCC reports is the communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Uncertainty can result from a wide range of sources. Uncertainties in the past and present are the result of limitations of available measurements, especially for rare events, and the challenges of evaluating causation in complex or multi-component processes that can span physical, biological and human systems. For the future, climate change involves changing likelihoods of diverse outcomes. Many processes and mechanisms are well understood, but others are not. Complex interactions among multiple climatic and non-climatic influences changing over time lead to persistent uncertainties, which in turn lead to the possibility of surprises. Compared to past IPCC reports, the AR5 assesses a substantially larger knowledge base of scientific, technical and socio-economic literature. *{WGI 1.4, WGII SPM A-3, 1.1.2, WGIII 2.3}*

The IPCC Guidance Note on Uncertainty[a] defines a common approach to evaluating and communicating the degree of certainty in findings of the assessment process. Each finding is grounded in an evaluation of underlying evidence and agreement. In many cases, a synthesis of evidence and agreement supports an assignment of confidence, especially for findings with stronger agreement and multiple independent lines of evidence. The degree of certainty in each key finding of the assessment is based on the type, amount, quality and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. The summary terms for evidence are: limited, medium or robust. For agreement, they are low, medium or high. Levels of confidence include five qualifiers: very low, low, medium, high and very high, and are typeset in italics, e.g., *medium confidence*. The likelihood, or probability, of some well-defined outcome having occurred or occurring in the future can be described quantitatively through the following terms: virtually certain, 99–100% probability; extremely likely, 95–100%; very likely, 90–100%; likely, 66–100%; more likely than not, >50–100%; about as likely as not, 33–66%; unlikely, 0–33%; very unlikely, 0–10%; extremely unlikely, 0–5%; and exceptionally unlikely, 0–1%. Additional terms (extremely likely, 95–100%; more likely than not, >50–100%; more unlikely than likely, 0–<50%; and extremely unlikely, 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high confidence*. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. *{WGI SPM B, WGII Background Box SPM.3, WGIII 2.1}*

Topic 1: Observed Changes and their Causes

Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.

Topic 1 focuses on observational evidence of a changing climate, the impacts caused by this change and the human contributions to it. It discusses observed changes in climate (1.1) and external influences on climate (forcings), differentiating those forcings that are of anthropogenic origin, and their contributions by economic sectors and greenhouse gases (GHGs) (1.2). Section 1.3 attributes observed climate change to its causes and attributes impacts on human and natural systems to climate change, determining the degree to which those impacts can be attributed to climate change. The changing probability of extreme events and their causes are discussed in Section 1.4, followed by an account of exposure and vulnerability within a risk context (1.5) and a section on adaptation and mitigation experience (1.6).

1.1 Observed changes in the climate system

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.

1.1.1 Atmosphere

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was *very likely* the warmest 30-year period of the last 800 years in the Northern Hemisphere, where such assessment is possible (*high confidence*) and *likely* the warmest 30-year period of the last 1400 years (*medium confidence*). *{WGI 2.4.3, 5.3.5}*

The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C[20] over the period 1880 to 2012, for which multiple independently produced datasets exist. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C, based on the single longest dataset available. For the longest period when calculation of regional trends is sufficiently complete (1901 to 2012), almost the entire globe has experienced surface warming (Figure 1.1). *{WGI SPM B.1, 2.4.3}*

In addition to robust multi-decadal warming, the globally averaged surface temperature exhibits substantial decadal and interannual variability (Figure 1.1). Due to this natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade; see Box 1.1). *{WGI SPM B.1, 2.4.3}*

Based on multiple independent analyses of measurements, it is *virtually certain* that globally the troposphere has warmed and the lower stratosphere has cooled since the mid-20th century. There is *medium confidence* in the rate of change and its vertical structure in the Northern Hemisphere extratropical troposphere. *{WGI SPM B.1, 2.4.4}*

Confidence in precipitation change averaged over global land areas since 1901 is *low* prior to 1951 and *medium* afterwards. Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has *likely* increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudes area-averaged long-term positive or negative trends have *low confidence* (Figure 1.1). *{WGI SPM B.1, Figure SPM.2, 2.5.1}*

1.1.2 Ocean

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*) with only about 1% stored in the atmosphere (Figure 1.2). On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010. It is *virtually certain* that the upper ocean (0–700 m) warmed from 1971 to 2010, and it *likely* warmed between the 1870s and 1971. It is *likely* that the ocean warmed from 700 to 2000 m from 1957 to 2009 and from 3000 m to the bottom for the period 1992 to 2005 (Figure 1.2). *{WGI SPM B.2, 3.2, Box 3.1}*

It is *very likely* that regions of high surface salinity, where evaporation dominates, have become more saline, while regions of low salinity, where precipitation dominates, have become fresher since the 1950s. These regional trends in ocean salinity provide indirect evidence for changes in evaporation and precipitation over the oceans and thus for changes in the global water cycle (*medium confidence*). There is no observational evidence of a long-term trend in the Atlantic Meridional Overturning Circulation (AMOC). *{WGI SPM B.2, 2.5, 3.3, 3.4.3, 3.5, 3.6.3}*

1.1.3 Cryosphere

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass (*high confidence*). Glaciers have continued to shrink almost worldwide (*high confidence*). North-ern Hemisphere spring snow cover has continued to decrease in extent (*high confidence*). There is *high confidence* that there are strong regional differences in the trend in Antarctic sea ice extent, with a *very likely* increase in total extent. *{WGI SPM B.3, 4.2–4.7}*

Glaciers have lost mass and contributed to sea level rise throughout the 20th century. The rate of ice mass loss from the Greenland ice sheet has *very likely* substantially increased over the period 1992 to 2011, resulting in a larger mass loss over 2002 to 2011 than over 1992 to 2011. The rate of ice mass loss from the Antarctic ice sheet, mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica, is also *likely* larger over 2002 to 2011. *{WGI SPM B.3, SPM B.4, 4.3.3, 4.4.2, 4.4.3}*

The annual mean Arctic sea ice extent decreased over the period 1979 (when satellite observations commenced) to 2012. The rate of decrease was *very likely* in the range 3.5 to 4.1% per decade. Arctic sea ice extent has decreased in every season and in every successive decade since 1979, with the most rapid decrease in decadal mean extent in summer (*high confidence*). For the summer sea ice minimum, the decrease was *very likely* in the range of 9.4 to 13.6% per decade (range of 0.73 to 1.07 million km^2 per decade) (see Figure 1.1). It is *very likely* that the annual mean Antarctic sea ice extent increased in the range of 1.2 to 1.8% per decade (range of 0.13 to 0.20 million km^2 per decade) between 1979 and 2012. However, there is *high confidence* that there are strong regional differences in Antarctica, with extent increasing in some regions and decreasing in others. *{WGI SPM B.5, 4.2.2, 4.2.3}*

There is *very high confidence* that the extent of Northern Hemisphere snow cover has decreased since the mid-20th century by 1.6 [0.8 to 2.4] % per decade for March and April, and 11.7% per decade for June, over the 1967 to 2012 period. There is *high confidence* that permafrost temperatures have increased in most regions of the Northern Hemisphere since the early 1980s, with reductions in thickness and areal extent in some regions. The increase in permafrost temperatures has occurred in response to increased surface temperature and changing snow cover. *{WGI SPM B.3, 4.5, 4.7.2}*

1.1.4 Sea level

Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (Figure 1.1). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). *{WGI SPM B.4, 3.7.2, 5.6.3, 13.2}*

It is *very likely* that the mean rate of global averaged sea level rise was 1.7 [1.5 to 1.9] mm/yr between 1901 and 2010 and 3.2 [2.8 to 3.6] mm/yr between 1993 and 2010. Tide gauge and satellite altimeter data are consistent regarding the higher rate during the latter period. It is *likely* that similarly high rates occurred between 1920 and 1950. *{WGI SPM B.4, 3.7, 13.2}*

Since the early 1970s, glacier mass loss and ocean thermal expansion from warming together explain about 75% of the observed global mean sea level rise (*high confidence*). Over the period 1993–2010, global mean sea level rise is, with *high confidence*, consistent with the sum of the observed contributions from ocean thermal expansion, due to warming, from changes in glaciers, the Greenland ice sheet, the Antarctic ice sheet and land water storage. *{WGI SPM B.4, 13.3.6}*

Rates of sea level rise over broad regions can be several times larger or smaller than the global mean sea level rise for periods of several decades, due to fluctuations in ocean circulation. Since 1993, the regional rates for the Western Pacific are up to three times larger than the global mean, while those for much of the Eastern Pacific are near zero or negative. *{WGI 3.7.3, FAQ 13.1}*

There is *very high confidence* that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 m higher than present and

Box 1.1 | Recent Temperature Trends and their Implications

The observed reduction in surface warming trend over the period 1998 to 2012 as compared to the period 1951 to 2012, is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from natural internal variability, which includes a possible redistribution of heat within the ocean (*medium confidence*). The rate of warming of the observed global mean surface temperature over the period from 1998 to 2012 is estimated to be around one-third to one-half of the trend over the period from 1951 to 2012 (Box 1.1, Figures 1a and 1c). Even with this reduction in surface warming trend, the climate system has *very likely* continued to accumulate heat since 1998 (Figure 1.2) and sea level has continued to rise (Figure 1.1). *{WGI SPM D.1, Box 9.2}*

The radiative forcing of the climate system has continued to increase during the 2000s, as has its largest contributor, the atmospheric concentration of CO_2. However, the radiative forcing has been increasing at a lower rate over the period from 1998 to 2011, compared to 1984 to 1998 or 1951 to 2011, due to cooling effects from volcanic eruptions and the cooling phase of the solar cycle over the period from 2000 to 2009. There is, however, *low confidence* in quantifying the role of the forcing trend in causing the reduction in the rate of surface warming. *{WGI 8.5.2, Box 9.2}*

For the period from 1998 to 2012, 111 of the 114 available climate-model simulations show a surface warming trend larger than the observations (Box 1.1, Figure 1a). There is *medium confidence* that this difference between models and observations is to a substantial degree caused by natural internal climate variability, which sometimes enhances and sometimes counteracts the long-term externally forced warming trend (compare Box 1.1, Figures 1a and 1b; during the period from 1984 to 1998, most model simulations show a smaller warming trend than observed). Natural internal variability thus diminishes the relevance of short trends for long-term climate change. The difference between models and observations may also contain contributions from inadequacies in the solar, volcanic and aerosol forcings used by the models and, in some models, from an overestimate of the response to increasing greenhouse gas and other anthropogenic forcing (the latter dominated by the effects of aerosols). *{WGI 2.4.3, Box 9.2, 9.4.1, 10.3.1.1}*

For the longer period from 1951 to 2012, simulated surface warming trends are consistent with the observed trend (*very high confidence*) (Box 1.1, Figure 1c). Furthermore, the independent estimates of radiative forcing, of surface warming and of observed heat storage (the latter available since 1970) combine to give a heat budget for the Earth that is consistent with the assessed *likely* range of equilibrium climate sensitivity (1.5–4.5 °C)[21]. The record of observed climate change has thus allowed characterization of the basic properties of the climate system that have implications for future warming, including the equilibrium climate sensitivity and the transient climate response (see Topic 2). *{WGI Box 9.2, 10.8.1, 10.8.2, Box 12.2, Box 13.1}* *high confidence* that it did not exceed 10 m above present. During the last interglacial period, the Greenland ice sheet *very likely* contributed between 1.4 and 4.3 m to the higher global mean sea level, implying with *medium confidence* an additional contribution from the Antarctic ice sheet. This change in sea level occurred in the context of different orbital forcing and with high-latitude surface temperature, averaged over several thousand years, at least 2°C warmer than present (*high confidence*). *{WGI SPM B.4, 5.3.4, 5.6.2, 13.2.1}*

1.2 Past and recent drivers of climate change

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era driven largely by economic and population growth. From 2000 to 2010 emissions were the highest in history. Historical emissions have driven atmospheric concentrations of carbon dioxide, methane and nitrous oxide to levels that are unprecedented in at least the last 800,000 years, leading to an uptake of energy by the climate system.

Natural and anthropogenic substances and processes that alter the Earth's energy budget are physical drivers of climate change. Radiative forcing quantifies the perturbation of energy into the Earth system caused by these drivers. Radiative forcings larger than zero lead to a near-surface warming, and radiative forcings smaller than zero lead to a cooling. Radiative forcing is estimated based on in-situ and remote observations, properties of GHGs and aerosols, and calculations using numerical models. The radiative forcing over the 1750–2011 period is shown in Figure 1.4 in major groupings. The 'Other Anthropogenic' group is principally comprised of cooling effects from aerosol changes, with smaller contributions from ozone changes, land use reflectance changes and other minor terms. *{WGI SPM C, 8.1, 8.5.1}*

1.2.1 Natural and anthropogenic radiative forcings

Atmospheric concentrations of GHGs are at levels that are unprecedented in at least 800,000 years. **Concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have all shown large increases since 1750 (40%, 150% and 20%, respectively) (Figure 1.3).** CO_2 concentrations are increasing at the fastest observed decadal rate of change (2.0 ± 0.1 ppm/yr) for 2002–2011. After almost one decade of stable CH_4 concentrations since the late 1990s, atmospheric measurements have shown renewed increases since 2007. N_2O concentrations have steadily increased at a rate of 0.73 ± 0.03 ppb/yr over the last three decades. *{WGI SPM B5, 2.2.1, 6.1.2, 6.1.3, 6.3}*

The total anthropogenic radiative forcing over 1750–2011 is calculated to be a warming effect of 2.3 [1.1 to 3.3] W/m^2 (Figure 1.4), and it has increased more rapidly since 1970 than during prior decades. Carbon dioxide is the largest single contributor to radiative forcing over 1750–2011 and its trend since 1970. The total anthropogenic radiative forcing estimate for 2011 is substantially higher (43%) than the estimate reported in the IPCC Fourth Assessment Report (AR4) for the year 2005. This is caused by a combination of continued growth in most GHG concentrations and an improved estimate of radiative forcing from aerosols. *{WGI SPM C, 8.5.1}*

The radiative forcing from aerosols, which includes cloud adjustments, is better understood and indicates a weaker cooling effect than in AR4. The aerosol radiative forcing over 1750–2011 is estimated as –0.9 [–1.9 to –0.1] W/m^2 (*medium confidence*). Radiative forcing from aerosols has two competing components: a dominant cooling effect from most aerosols and their cloud adjustments and a partially offsetting warming con-tribution from black carbon absorption of solar radiation. There is *high confidence* that the global mean total aerosol radiative forcing has counteracted a substantial portion of radiative forcing from well-mixed GHGs. Aerosols continue to contribute the largest uncertainty to the total radiative forcing estimate. *{WGI SPM C, 7.5, 8.3, 8.5.1}*

Changes in solar irradiance and volcanic aerosols cause natural radiative forcing (Figure 1.4). The radiative forcing from strato-spheric volcanic aerosols can have a large cooling effect on the climate system for some years after major volcanic eruptions. Changes in total solar irradiance are calculated to have contributed only around 2% of the total radiative forcing in 2011, relative to 1750. *{WGI SPM C, Figure SPM.5, 8.4}*

1.2.2 Human activities affecting emission drivers

About half of the cumulative anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (*high confidence*). Cumulative anthropogenic CO_2 emissions of 2040 ± 310 $GtCO_2$ were added to the atmosphere between 1750 and 2011. Since 1970, cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring have tripled, and cumulative CO_2 emissions from forestry and other land use (FOLU)[22] have increased by about 40% (Figure 1.5)[23]. In 2011, annual CO_2 emissions from fossil fuel combustion, cement production and flaring were 34.8 ± 2.9 $GtCO_2$/yr. For 2002–2011, average annual emissions from FOLU were 3.3 ± 2.9 $GtCO_2$/yr. *{WGI 6.3.1, 6.3.2, WGIII SPM.3}*

About 40% of these anthropogenic CO_2 emissions have remained in the atmosphere (880 ± 35 $GtCO_2$) since 1750. The rest was removed from the atmosphere by sinks, and stored in natural carbon cycle reservoirs. Sinks from ocean uptake and vegetation with soils account, in roughly equal measures, for the remainder of the cumulative CO_2 emissions. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification. *{WGI 3.8.1, 6.3.1}*

Total annual anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010 (*high confidence*). Despite a growing number of climate change mitigation policies, annual GHG emissions grew on average by 1.0 $GtCO_2$-eq (2.2%) per year, from 2000 to 2010, compared to 0.4 $GtCO_2$-eq (1.3%) per year, from 1970 to 2000 (Figure 1.6)[24]. Total anthropogenic GHG emissions from 2000 to 2010 were the highest in human history and reached 49 (±4.5) $GtCO_2$-eq/yr in 2010. The global economic crisis of 2007/2008 reduced emissions only temporarily. *{WGIII SPM.3, 1.3, 5.2, 13.3, 15.2.2, Box TS.5, Figure 15.1}*

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% to the total GHG emission increase between 1970 and 2010, with a contribution of similar percentage over the 2000–2010 period (*high confidence*). Fossil-fuel-related CO_2 emissions reached 32 (±2.7) $GtCO_2$/yr, in 2010, and grew further by about 3% between 2010 and 2011, and by about 1 to 2% between 2011 and 2012. CO_2 remains the major anthropogenic GHG, accounting for 76% of total anthropogenic GHG emissions in 2010. Of the total, 16% comes from CH_4, 6.2% from N_2O, and 2.0% from fluorinated gases (F-gases) (Figure 1.6)[25]. Annually, since 1970, about 25% of anthropogenic GHG emissions have been in the form of non-CO_2 gases[26]. *{WGIII SPM.3, 1.2, 5.2}*

Total annual anthropogenic GHG emissions have increased by about 10 $GtCO_2$-eq between 2000 and 2010. This increase directly came from the energy (47%), industry (30%), transport (11%) and building (3%) sectors (*medium confidence*). Accounting for indirect emissions raises the contributions by the building and industry sectors (*high confidence*). Since 2000, GHG emissions have been growing in all sectors, except in agriculture, forestry and other land use (AFOLU)[22]. In 2010, 35% of GHG emissions were released by the energy sector, 24% (net emissions) from AFOLU, 21% by industry, 14% by transport and 6.4% by the building sector. When emissions from electricity and heat production are attributed to the sectors that use the final energy (i.e., indirect emissions), the shares of the industry and building sectors in global GHG emissions are increased to 31% and 19%, respectively (Figure 1.7). *{WGIII SPM.3, 7.3, 8.1, 9.2, 10.3, 11.2}* See also Box 3.2 for contributions from various sectors, based on metrics other than 100-year Global Warming Potential (GWP_{100}).

Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to that of the previous three decades, while the contribution of economic growth has risen sharply (*high confidence*). Between 2000 and

1.3 Attribution of climate changes and impacts

The evidence for human influence on the climate system has grown since AR4. Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, and in global mean sea level rise; and it is *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century. In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate.

The causes of observed changes in the climate system, as well as in any natural or human system impacted by climate, are established following a consistent set of methods. Detection addresses the question of whether climate or a natural or human system affected by climate has actually changed in a statistical sense, while attribution evaluates the relative contributions of multiple causal factors to an observed change or event with an assignment of statistical confidence[27]. Attribution of climate change to causes quantifies the links between observed climate change and human activity, as well as other, natural, climate drivers. In contrast, attribution of observed impacts to climate change considers the links between observed changes in natural or human systems and observed climate change, regardless of its cause. Results from studies attributing climate change to causes provide estimates of the magnitude of warming in response to changes in radiative forcing and hence support projections of future climate change (Topic 2). Results from studies attributing impacts to climate change provide strong indications for the sensitivity of natural or human systems to future climate change. *{WGI 10.8, WGII SPM A-1, WGI/II/III/SYR Glossaries}*

1.3.1 Attribution of climate changes to human and natural influences on the climate system

It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together (Figure 1.9). The best estimate of the human induced contribution to warming is similar to the observed warming over this period. GHGs contributed a global mean surface warming *likely* to be in the range of 0.5°C to 1.3°C over the period 1951 to 2010, with further contributions from other anthropogenic forcings, including the cooling effect of aerosols, from natural forcings, and from natural internal variability (see Figure 1.9). Together these assessed contributions are consistent with the observed warming of approximately 0.6°C to 0.7°C over this period. *{WGI SPM D.3, 10.3.1}*

It is *very likely* that anthropogenic influence, particularly GHGs and stratospheric ozone depletion, has led to a detectable observed pattern of tropospheric warming and a corresponding cooling in the lower stratosphere since 1961. *{WGI SPM D.3, 2.4.4, 9.4.1, 10.3.1}*

Over every continental region except Antarctica, anthropogenic forcings have *likely* made a substantial contribution to surface temperature increases since the mid-20th century (Figure 1.10). For Antarctica, large observational uncertainties result in *low confidence* that anthropogenic forcings have contributed to the observed warming averaged over available stations. In contrast, it is *likely* that there has been an anthropogenic contribution to the very substantial Arctic warming since the mid-20th century. Human influence has *likely* contributed to temperature increases in many sub-continental regions. *{WGI SPM D.3, TS.4.8, 10.3.1}*

Anthropogenic influences have *very likely* contributed to Arctic sea ice loss since 1979 (Figure 1.10). There is *low confidence* in the scientific understanding of the small observed increase in Antarctic sea ice extent due to the incomplete and competing scientific explanations for the causes of change and *low confidence* in estimates of natural internal variability in that region. *{WGI SPM D.3, 10.5.1, Figure 10.16}*

Anthropogenic influences *likely* contributed to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. Due to a low level of scientific understanding, however, there is *low confidence* in attributing the causes of the observed loss of mass from the Antarctic ice sheet over the past two decades. It is *likely* that there has been an anthropogenic contribution to observed reductions in Northern Hemisphere spring snow cover since 1970. *{WGI 4.3.3, 10.5.2, 10.5.3}*

It is *likely* that anthropogenic influences have affected the global water cycle since 1960. Anthropogenic influences have contributed to observed increases in atmospheric moisture content (*medium confidence*), to global-scale changes in precipitation patterns over land (*medium confidence*), to intensification of heavy precipitation over land regions where data are sufficient (*medium confidence*) (see 1.4) and to changes in surface and subsurface ocean salinity (*very likely*). *{WGI SPM D.3, 2.5.1, 2.6.2, 3.3.2, 3.3.3, 7.6.2, 10.3.2, 10.4.2, 10.6}*

It is *very likely* that anthropogenic forcings have made a substantial contribution to increases in global upper ocean heat content (0–700 m) observed since the 1970s (Figure 1.10). There is evidence for human influence in some individual ocean basins**.** It is *very likely* that there is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s. This is based on the *high confidence* in an anthropogenic influence on the two largest contributions to sea level rise: thermal expansion and glacier mass loss. Oceanic uptake of anthropogenic CO_2 has resulted in gradual acidification of ocean surface waters (*high confidence*). *{WGI SPM D.3, 3.2.3, 3.8.2, 10.4.1, 10.4.3, 10.4.4, 10.5.2, 13.3, Box 3.2, TS.4.4, WGII 6.1.1.2, Box CC-OA}*

1.3.2 Observed impacts attributed to climate change

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate. Evidence of observed climate change impacts is strongest and most comprehensive for natural systems. Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences (Figure 1.11). Impacts on human systems are often geographically heterogeneous because they depend not only on changes in climate variables but also on social and economic factors. Hence, the changes are more easily observed at local levels, while attribution can remain difficult. *{WGII SPM A-1, SPM A-3, 18.1, 18.3–18.6}*

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Glaciers continue to shrink almost worldwide due to climate change (*high confidence*), affecting runoff and water resources downstream (*medium confidence*). Climate change is causing permafrost warming and thawing in high-latitude regions and in high-elevation regions (*high confidence*). *{WGII SPM A-1}*

Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change (*high confidence*). While only a few recent species extinctions have been attributed as yet to climate change (*high confidence*), natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years (*high confidence*). Increased tree mortality, observed in many places worldwide, has been attributed to climate change in some regions. Increases in the frequency or intensity of ecosystem disturbances such as droughts, windstorms, fires and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Numerous observations over the last decades in all ocean basins show changes in abundance, distribution shifts poleward and/or to deeper, cooler waters for marine fishes, invertebrates and phytoplankton (*very high confidence*), and altered ecosystem composition (*high confidence*), tracking climate trends. Some warm-water corals and their reefs have responded to warming with species replacement, bleaching, and decreased coral cover causing habitat loss (*high confidence*). Some impacts of ocean acidification on marine organisms have been attributed to human influence, from the thinning of pteropod and foraminiferan shells (*medium confidence*) to the declining growth rates of corals (*low confidence*). Oxygen minimum zones are progressively expanding in the tropical Pacific, Atlantic and Indian Oceans, due to reduced ventilation and O_2 solubility in warmer, more stratified oceans, and are constraining fish habitat (*medium confidence*). *{WGII SPM A-1, Table SPM.A1, TS A-1, 6.3.2.5, 6.3.3, 18.3–18.4, 30.5.1.1, Box CC-OA, Box CC-CR}*

Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). The smaller number of studies showing positive impacts relate mainly to high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions (*high confidence*). Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (*medium confidence*). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data which are fewer for soy compared to the other crops (see Figure 1.11c). Observed impacts relate mainly to production aspects of food security rather than access or other components of food security. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (*medium confidence*). *{WGII SPM A-1}*

At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered the distribution of some water-borne illnesses and disease vectors (*medium confidence*). *{WGII SPM A-1}*

'Cascading' impacts of climate change can now be attributed along chains of evidence from physical climate through to intermediate systems and then to people (Figure 1.12). The changes in climate feeding into the cascade, in some cases, are linked to human drivers (e.g., a decreasing amount of water in spring snowpack in western North America), while, in other cases, assessments of the causes of observed climate change leading into the cascade are not available. In all cases, confidence in detection and attribution to observed climate change decreases for effects further down each impact chain. *{WGII 18.6.3}*

1.4 Extreme events

Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions.

It is *very likely* that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is *likely* that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. It is *very likely* that human influence has contributed to the observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century. It is *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations. *{WGI SPM B.1, SPM D.3, Table SPM.1, FAQ 2.2, 2.6.1, 10.6}*

There is *medium confidence* that the observed warming has increased heat-related human mortality and decreased cold-related human mortality in some regions. Extreme heat events currently result in increases in mortality and morbidity in North America (*very high confidence*), and in Europe with impacts that vary according to people's age, location and socio-economic factors (*high confidence*). *{WGII SPM A-1, 11.4.1, Table 23-1, 26.6.1.2}*

There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency and intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, *confidence* in trends is at most *medium.* It is *very likely* that global near-surface and tropospheric air specific humidity has increased since the 1970s. In land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. *{WGI SPM B-1, 2.5.1, 2.5.4–2.5.5, 2.6.2, 10.6, Table SPM.1, FAQ 2.2, SREX Table 3-1, 3.2}*

There is *low confidence* that anthropogenic climate change has affected the frequency and magnitude of fluvial floods on a global scale. The strength of the evidence is limited mainly by a lack of long-term records from unmanaged catchments. Moreover, floods are strongly influenced by many human activities impacting catchments, making the attribution of detected changes to climate change difficult. However, recent detection of increasing trends in extreme precipitation and discharges in some catchments implies greater risks of flooding on a regional scale (*medium confidence*). Costs related to flood damage, worldwide, have been increasing since the 1970s, although this is partly due to the increasing exposure of people and assets. *{WGI 2.6.2, WGII 3.2.7, SREX SPM B}*

There is *low confidence* in observed global-scale trends in droughts, due to lack of direct observations, dependencies of inferred trends on the choice of the definition for drought, and due to geographical inconsistencies in drought trends. There is also *low confidence* in the attribution of changes in drought over global land areas since the mid-20th century, due to the same observational uncertainties and difficulties in distinguishing decadal scale variability in drought from long-term trends. *{WGI Table SPM.1, 2.6.2.3, 10.6, Figure 2.33, WGII 3.ES, 3.2.7}*

There is *low confidence* that long-term changes in tropical cyclone activity are robust, and there is *low confidence* in the attribution of global changes to any particular cause. However, it is *virtually certain* that intense tropical cyclone activity has increased in the North Atlantic since 1970. *{WGI Table SPM.1, 2.6.3, 10.6}*

It is *likely* that extreme sea levels (for example, as experienced in storm surges) have increased since 1970, being mainly the result of mean sea level rise. Due to a shortage of studies and the difficulty of distinguishing any such impacts from other modifications to coastal systems, limited evidence is available on the impacts of sea level rise. *{WGI 3.7.4–3.7.6, Figure 3.15, WGII 5.3.3.2, 18.3}*

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, human morbidity and mortality and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors. *{WGII SPM A-1, 3.2, 4.2-3, 8.1, 9.3, 10.7, 11.3, 11.7, 13.2, 14.1, 18.6, 22.2.3, 22.3, 23.3.1.2, 24.4.1, 25.6-8, 26.6-7, 30.5,Table 18-3, Table 23-1, Figure 26-2, Box 4-3, Box 4-4, Box 25-5, Box 25-6, Box 25-8, Box CC-CR}*

Direct and insured losses from weather-related disasters have increased substantially in recent decades, both globally and regionally. Increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters (*high confidence*). *{WGII 10.7.3, SREX SPM B, 4.5.3.3}*

1.5 Exposure and vulnerability

The character and severity of impacts from climate change and extreme events emerge from risk that depends not only on climate-related hazards but also on exposure (people and assets at risk) and vulnerability (susceptibility to harm) of human and natural systems.

Exposure and vulnerability are influenced by a wide range of social, economic and cultural factors and processes that have been incompletely considered to date and that make quantitative assessments of their future trends difficult (*high confidence*). These factors include wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures and institutions to resolve conflict. *{WGII SPM A-3, SREX SPM B}*

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes (*very high confidence*). These differences shape differential risks from climate change. People who are socially, economically, culturally, politically, institutionally or otherwise marginalized are especially vulnerable to climate change and also to some adaptation and mitigation responses (*medium evidence, high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socio-economic status and income, as well as in exposure. Such social processes include, for example, discrimination on the basis of gender, class, ethnicity, age and (dis)ability. *{WGII SPM A-1, Figure SPM.1, 8.1–8.2, 9.3–9.4, 10.9, 11.1, 11.3–11.5, 12.2–12.5, 13.1–13.3, 14.1–14.3, 18.4, 19.6, 23.5, 25.8, 26.6, 26.8, 28.4, Box CC-GC}*

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reductions in crop yields or the destruction of homes, and indirectly through, for example, increased food prices and food insecurity. Observed positive effects for poor and marginalized people, which are limited and often indirect, include examples such as diversification of social networks and of agricultural practices. *{WGII SPM A-1, 8.2–8.3, 9.3, 11.3, 13.1–13.3, 22.3, 24.4, 26.8}*

Violent conflict increases vulnerability to climate change (*medium evidence, high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural resources, social capital and livelihood opportunities. *{WGII SPM A-1, 12.5, 19.2, 19.6}*

1.6 Human responses to climate change: adaptation and mitigation

Adaptation and mitigation experience is accumulating across regions and scales, even while global anthropogenic greenhouse gas emissions have continued to increase.

Throughout history, people and societies have adjusted to and coped with climate, climate variability and extremes, with varying degrees of success. In today's changing climate, accumulating experience with adaptation and mitigation efforts can provide opportunities for learning and refinement (3, 4). *{WGII SPM A-2}*

Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programmes, such as disaster risk management and water management. There is increasing recognition of the value of social, institutional and ecosystem-based measures and of the extent of constraints to adaptation. *{WGII SPM A-2, 4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3–14.4, 15.2–15.5, 17.2–17.3, 21.3, 21.5, 22.4, 23.7, 25.4, 26.8–26.9, 30.6, Box 25-1, Box 25-2, Box 25-9, Box CC-EA}*

Governments at various levels have begun to develop adaptation plans and policies and integrate climate change considerations into broader development plans. Examples of adaptation are now available from all regions of the world (see Topic 4 for details on adaptation options and policies to support their implementation). *{WGII SPM A-2, 22.4, 23.7, 24.4–24.6, 24.9, 25.4, 25.10, 26.7–26.9, 27.3, 28.2, 28.4, 29.3, 29.6, 30.6, Table 25-2, Table 29-3, Figure 29-1, Box 5-1, Box 23-3, Box 25-1, Box 25-2, Box 25-9, Box CC-TC}*

Global increases in anthropogenic emissions and climate impacts have occurred, even while mitigation activities have taken place in many parts of the world. Though various mitigation initiatives between the sub-national and global scales have been developed or implemented, a full assessment of their impact may be premature. *{WGIII SPM.3, SPM.5}*

Topic 2: Future Climate Changes, Risk and Impacts

Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.

Topic 2 assesses projections of future climate change and the resulting risks and impacts. Factors that determine future climate change, including scenarios for future greenhouse gas (GHG) emissions, are outlined in Section 2.1. Descriptions of the methods and tools used to make projections of climate, impacts and risks, and their development since the IPCC Fourth Assessment Report (AR4), are provided in Boxes 2.1 to 2.3. Details of projected changes in the climate system, including the associated uncertainty and the degree of expert confidence in the projections are provided in Section 2.2. The future impacts of climate change on natural and human systems and associated risks are assessed in Section 2.3. Topic 2 concludes with an assessment of irreversible changes, abrupt changes and changes beyond 2100 in Section 2.4.

2.1 Key drivers of future climate and the basis on which projections are made

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Projections of greenhouse gas emissions vary over a wide range, depending on both socio-economic development and climate policy.

Climate models are mathematical representations of processes important in the Earth's climate system. Results from a hierarchy of climate models are considered in this report; ranging from simple idealized models, to models of intermediate complexity, to comprehensive General Circulation Models (GCMs), including Earth System Models (ESMs) that also simulate the carbon cycle. The GCMs simulate many climate aspects, including the temperature of the atmosphere and the oceans, precipitation, winds, clouds, ocean currents and sea-ice extent. The models are extensively tested against historical observations (Box 2.1). *{WGI 1.5.2, 9.1.2, 9.2, 9.8.1}*

In order to obtain climate change projections, the climate models use information described in scenarios of GHG and air pollutant emissions and land use patterns. Scenarios are generated by a range of approaches, from simple idealised experiments to Integrated Assessment Models (IAMs, see Glossary). Key factors driving changes in anthropogenic GHG emissions are economic and population growth, lifestyle and behavioural changes, associated changes in energy use and land use, technology and climate policy, which are fundamentally uncertain. *{WGI 11.3, 12.4, WGIII 5, 6, 6.1}*

The standard set of scenarios used in the AR5 is called Representative Concentration Pathways (RCPs, Box 2.2). *{WGI Box SPM.1}*

Box 2.1 | Advances, Confidence and Uncertainty in Modelling the Earth's Climate System

Improvements in climate models since the IPCC Fourth Assessment Report (AR4) are evident in simulations of continental-scale surface temperature, large-scale precipitation, the monsoon, Arctic sea ice, ocean heat content, some extreme events, the carbon cycle, atmospheric chemistry and aerosols, the effects of stratospheric ozone and the El Niño-Southern Oscillation. Climate models reproduce the observed continental-scale surface temperature patterns and multi-decadal trends, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*). The simulation of large-scale patterns of precipitation has improved somewhat since the AR4, although models continue to perform less well for precipitation than for surface temperature. *Confidence* in the representation of processes involving clouds and aerosols remains *low*. *{WGI SPM D.1, 7.2.3,* 7.3.3, *7.6.2, 9.4, 9.5, 9.8, 10.3.1}*

The ability to simulate ocean thermal expansion, glaciers and ice sheets, and thus sea level, has improved since the AR4, but significant challenges remain in representing the dynamics of the Greenland and Antarctic ice sheets. This, together with advances in scientific understanding and capability, has resulted in improved sea level projections in this report, compared with the AR4. *{WGI SPM E.6, 9.1.3, 9.2, 9.4.2, 9.6, 9.8, 13.1, 13.4, 13.5}*

There is overall consistency between the projections from climate models in AR4 and AR5 for large-scale patterns of change and the magnitude of the uncertainty has not changed significantly, but new experiments and studies have led to a more complete and rigorous characterization of the uncertainty in long-term projections. *{WGI 12.4}*

Box 2.2 | The Representative Concentration Pathways

The Representative Concentration Pathways (RCPs) describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs have been developed using Integrated Assessment Models (IAMs) as input to a wide range of climate model simulations to project their consequences for the climate system. These climate projections, in turn, are used for impacts and adaptation assessment. The RCPs are consistent with the wide range of scenarios in the mitigation literature assessed by WGIII[28]. The scenarios are used to assess the costs associated with emission reductions consistent with particular concentration pathways. The RCPs represent the range of GHG emissions in the wider literature well (Box 2.2, Figure 1); they include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5. RCP2.6 is representative of a scenario that aims to keep global warming *likely* below 2°C above pre-industrial temperatures. The majority of models indicate that scenarios meeting forcing levels similar to RCP2.6 are characterized by substantial net negative emissions[29] by 2100, on average around 2 $GtCO_2$/yr. The land use scenarios of RCPs, together, show a wide range of possible futures, ranging from a net reforestation to further deforestation, consistent with projections in the full scenario literature. For air pollutants such as sulfur dioxide (SO_2), the RCP scenarios assume a consistent decrease in emissions as a consequence of assumed air pollution control and GHG mitigation policy (Box 2.2, Figure 1). Importantly, these future scenarios do not account for possible changes in natural forcings (e.g., volcanic eruptions) (see Box 1.1). *{WGI Box SPM.1, 6.4, 8.5.3, 12.3, Annex II, WGII 19, 21, WGIII 6.3.2, 6.3.6}*

The RCPs cover a wider range than the scenarios from the Special Report on Emissions Scenarios (SRES) used in previous assessments, as they also represent scenarios with climate policy. In terms of overall forcing, RCP8.5 is broadly comparable to the SRES A2/A1FI scenario, RCP6.0 to B2 and RCP4.5 to B1. For RCP2.6, there is no equivalent scenario in SRES. As a result, the differences in the magnitude of AR4 and AR5 climate projections are largely due to the inclusion of the wider range of emissions assessed. *{WGI TS Box TS.6, 12.4.9}*

The methods used to estimate future impacts and risks resulting from climate change are described in Box 2.3. Modelled future impacts assessed in this report are generally based on climate-model projections using the RCPs, and in some cases, the older Special Report on Emissions Scenarios (SRES). *{WGI Box SPM.1, WGII 1.1, 1.3, 2.2–2.3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC}*

Risk of climate-related impacts results from the interaction between climate-related hazards (including hazardous events and trends) and the vulnerability and exposure of human and natural systems. Alternative development paths influence risk by changing the likelihood of climatic events and trends, through their effects on GHGs, pollutants and land use, and by altering vulnerability and exposure. *{WGII SPM, 19.2.4, Figure 19-1, Box 19-2}*

Experiments, observations and models used to estimate future impacts and risks have improved since the AR4, with increasing understanding across sectors and regions. For example, an improved knowledge base has enabled expanded assessment of risks for human security and livelihoods and for the oceans. For some aspects of climate change and climate change impacts, uncertainty about future outcomes has narrowed. For others, uncertainty will persist. Some of the persistent uncertainties are grounded in the mechanisms that control the magnitude and pace of climate change. Others emerge from potentially complex interactions between the changing climate and the underlying vulnerability and exposure of people, societies and ecosystems. The combination of persistent uncertainty in key mechanisms plus the prospect of complex interactions motivates a focus on risk in this report. Because risk involves both probability and consequence, it is important to consider the full range of possible outcomes, including low-probability, high-consequence impacts that are difficult to simulate. *{WGII 2.1–2.4, 3.6, 4.3, 11.3, 12.6, 19.2, 19.6, 21.3–21.5, 22.4, 25.3–25.4, 25.11, 26.2}*

2.2 Projected changes in the climate system

Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is *very likely* that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise.

The projected changes in Section 2.2 are for 2081–2100 relative to 1986–2005, unless otherwise indicated.

2.2.1 Air temperature

The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs, and will *likely* be in the range 0.3°C to 0.7°C (*medium confidence*)[30]. This range assumes no major volcanic eruptions or changes in some natural sources (e.g., methane (CH_4) and nitrous oxide (N_2O)), or unexpected changes in total solar irradiance. Future climate will depend on

Box 2.3 | Models and Methods for Estimating Climate Change Risks, Vulnerability and Impacts

Future climate-related risks, vulnerabilities and impacts are estimated in the AR5 through experiments, analogies and models, as in previous assessments. 'Experiments' involve deliberately changing one or more climate-system factors affecting a subject of interest to reflect anticipated future conditions, while holding the other factors affecting the subject constant. 'Analogies' make use of existing variations and are used when controlled experiments are impractical due to ethical constraints, the large area or long time required or high system complexity. Two types of analogies are used in projections of climate and impacts. Spatial analogies identify another part of the world currently experiencing similar conditions to those anticipated to be experienced in the future. Temporal analogies use changes in the past, sometimes inferred from paleo-ecological data, to make inferences about changes in the future. 'Models' are typically numerical simulations of real-world systems, calibrated and validated using observations from experiments or analogies, and then run using input data representing future climate. Models can also include largely descriptive narratives of possible futures, such as those used in scenario construction. Quantitative and descriptive models are often used together. Impacts are modelled, among other things, for water resources, biodiversity and ecosystem services on land, inland waters, the oceans and ice bodies, as well as for urban infrastructure, agricultural productivity, health, economic growth and poverty. *{WGII 2.2.1, 2.4.2, 3.4.1, 4.2.2, 5.4.1, 6.5, 7.3.1, 11.3.6, 13.2.2}*

Risks are evaluated based on the interaction of projected changes in the Earth system with the many dimensions of vulnerability in societies and ecosystems. The data are seldom sufficient to allow direct estimation of probabilities of a given outcome; therefore, expert judgment using specific criteria (large magnitude, high probability or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation) is used to integrate the diverse information sources relating to the severity of consequences and the likelihood of occurrence into a risk evaluation, considering exposure and vulnerability in the context of specific hazards. *{WGII 11.3, 19.2, 21.1, 21.3–21.5, 25.3–25.4, 25.11, 26.2}* committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. By the mid-21st century, the magnitude of the projected climate change is substantially affected by the choice of emissions scenarios. Climate change continues to diverge among the scenarios through to 2100 and beyond (Table 2.1, Figure 2.1). The ranges provided for particular RCPs (Table 2.1), and those given below in Section 2.2, primarily arise from differences in the sensitivity of climate models to the imposed forcing. *{WGI SPM E.1, 11.3.2, 12.4.1}*

Notes:

[a] Based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble; changes calculated with respect to the 1986–2005 period. Using Hadley Centre Climatic Research Unit Gridded Surface Temperature Data Set 4 (HadCRUT4) and its uncertainty estimate (5 to 95% confidence interval), the observed warming from 1850–1900 to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period. *{WGI 2.4.3, 11.2.2, 12.4.1, Table 12.2, Table 12.3}*

[b] Based on 21 CMIP5 models; changes calculated with respect to the 1986–2005 period. Based on current understanding (from observations, physical understanding and modelling), only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5 to 95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065, *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for the 2081–2100 period. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near term (2016–2035) change in global mean surface temperature that is lower than the 5 to 95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. *{WGI 11.3.1}*

[d] Calculated from projections as 5 to 95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to *likely* exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*). Warming is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), *more likely than not* to exceed 2°C for RCP4.5 (*medium confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). *{WGI SPM E.1, 12.4.1, Table 12.3}*

The Arctic region will continue to warm more rapidly than the global mean (Figure 2.2) (*very high confidence*). The mean warming over land will be larger than over the ocean (*very high confidence*) and larger than global average warming (Figure 2.2). *{WGI SPM E.1, 11.3.2, 12.4.3, 14.8.2}*

It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is *very likely* that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur. *{WGI SPM E.1, 12.4.3}*

2.2.2 Water cycle

Changes in precipitation in a warming world will not be uniform. The high latitudes and the equatorial Pacific are *likely* to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will *likely* decrease, while in many mid-latitude wet regions, mean precipitation will *likely* increase under the RCP8.5 scenario (Figure 2.2). *{WGI SPM E.2, 7.6.2, 12.4.5, 14.3.1, 14.3.5}*

Extreme precipitation events over most mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent as global mean surface temperature increases. *{WGI SPM E.2, 7.6.2, 12.4.5}*

Globally, in all RCPs, it is *likely* that the area encompassed by monsoon systems will increase and monsoon precipitation is *likely* to intensify and El Niño-Southern Oscillation (ENSO) related precipitation variability on regional scales will *likely* intensify. *{WGI SPM E.2, 14.2, 14.4}*

2.2.3 Ocean, cryosphere and sea level

The global ocean will continue to warm during the 21st century. The strongest ocean warming is projected for the surface in tropical and Northern Hemisphere subtropical regions. At greater depth the warming will be most pronounced in the Southern Ocean (*high confidence*). *{WGI SPM E.4, 6.4.5, 12.4.7}*

It is *very likely* that the Atlantic Meridional Overturning Circulation (AMOC) will weaken over the 21st century, with best estimates and model ranges for the reduction of 11% (1 to 24%) for the RCP2.6 scenario, 34% (12 to 54%) for the RCP8.5. Nevertheless, it is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century. *{WGI SPM E.4, 12.4.7.2}*

Year-round reductions in Arctic sea ice are projected for all RCP scenarios. The subset of models that most closely reproduce the observations[31] project that a nearly ice-free Arctic Ocean[32] in September is *likely* for RCP8.5 before mid-century (*medium confidence*) (Figure 2.1). In the Antarctic, a decrease in sea ice extent and volume is projected with *low confidence*. *{WGI SPM E.5, 12.4.6.1}*

The area of Northern Hemisphere spring snow cover is *likely* to decrease by 7% for RCP2.6 and by 25% in RCP8.5 by the end of the 21st century for the multi-model average (*medium confidence*). *{WGI SPM E.5, 12.4.6}*

It is *virtually certain* that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. The area of permafrost near the surface (upper 3.5 m) is *likely* to decrease by 37% (RCP2.6) to 81% (RCP8.5) for the multi-model average (*medium confidence*). *{WGI SPM E.5, 12.4.6}*

The global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the Greenland and Antarctic ice sheets), is projected to decrease by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5 (*medium confidence*). *{WGI SPM E.5, 13.4.2, 13.5.1}*

Global mean sea level will continue to rise during the 21st century (Table 2.1, Figure 2.1). There has been significant improvement in understanding and projection of sea level change since the AR4. Under all RCP scenarios, the rate of sea level rise will *very likely* exceed the observed rate of 2.0 [1.7–2.3] mm/yr during 1971–2010, with the rate of rise for RCP8.5 during 2081–2100 of 8 to 16 mm/yr (*medium confidence*). *{WGI SPM B4, SPM E.6, 13.5.1}*

Sea level rise will not be uniform across regions. By the end of the 21st century, it is *very likely* that sea level will rise in more than about 95% of the ocean area. Sea level rise depends on the pathway of CO_2 emissions, not only on the cumulative total; reducing emissions earlier rather than later, for the same cumulative total, leads to a larger mitigation of sea level rise. About 70% of the coastlines worldwide are projected to experience sea level change within ±20% of the global mean (Figure 2.2). It is *very likely* that there will be a significant increase in the occurrence of future sea level extremes in some regions by 2100. *{WGI SPM E.6, TS 5.7.1, 12.4.1, 13.4.1, 13.5.1, 13.6.5, 13.7.2, Table 13.5}*

2.2.4 Carbon cycle and biogeochemistry

Ocean uptake of anthropogenic CO_2 will continue under all four RCPs through to 2100, with higher uptake for higher concentration pathways (*very high confidence*). The future evolution of the land carbon uptake is less certain. A majority of models projects a continued land carbon uptake under all RCPs, but some models simulate a land carbon loss due to the combined effect of climate change and land use change. *{WGI SPM E.7, 6.4.2, 6.4.3}*

Based on Earth System Models, there is *high confidence* that the feedback between climate change and the carbon cycle will amplify global warming. Climate change will partially offset increases in land and ocean carbon sinks caused by rising atmospheric CO_2. As a result more of the emitted anthropogenic CO_2 will remain in the atmosphere, reinforcing the warming. *{WGI SPM E.7, 6.4.2, 6.4.3}*

Earth System Models project a global increase in ocean acidification for all RCP scenarios by the end of the 21st century, with a slow recovery after mid-century under RCP2.6. The decrease in surface ocean pH is in the range of 0.06 to 0.07 (15 to 17% increase in acidity) for RCP2.6, 0.14 to 0.15 (38 to 41%) for RCP4.5, 0.20 to 0.21 (58 to 62%) for RCP6.0, and 0.30 to 0.32 (100 to 109%) for RCP8.5 (Figure 2.1). *{WGI SPM E.7, 6.4.4}*

It is *very likely* that the dissolved oxygen content of the ocean will decrease by a few percent during the 21st century in response to surface warming, predominantly in the subsurface mid-latitude oceans. There is no consensus on the future volume of low oxygen waters in the open ocean because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics. *{WGI TS 5.6, 6.4.5, WGII TS B-2, 6.1}*

2.2.5 Climate system responses

Climate system properties that determine the response to external forcing have been estimated both from climate models and from analysis of past and recent climate change. The equilibrium climate sensitivity (ECS)[33] is *likely* in the range 1.5°C to 4.5°C, *extremely unlikely* less than 1°C, and *very unlikely* greater than 6°C. *{WGI SPM D.2, TS TFE.6, 10.8.1, 10.8.2, 12.5.4, Box 12.2}*

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Multiple lines of evidence indicate a strong and consistent near-linear relationship across all scenarios considered between net cumulative CO_2 emissions (including the impact of CO_2 removal) and projected global temperature change to the year 2100 (Figure 2.3). Past emissions and observed warming support this relationship within uncertainties. Any given level of warming is associated with a range of cumulative CO_2 emissions (depending on non-CO_2 drivers), and therefore, for example, higher emissions in earlier decades imply lower emissions later. *{WGI SPM E.8, TS TFE.8, 12.5.4}*

The global mean peak surface temperature change per trillion tonnes of carbon (1000 GtC) emitted as CO_2 is *likely* in the range of 0.8°C to 2.5°C. This quantity, called the transient climate response to cumulative carbon emissions (TCRE), is supported by both modelling and observational evidence and applies to cumulative emissions up to about 2000 GtC. *{WGI SPM D.2, TS TFE.6, 12.5.4, Box 12.2}*

Figure 2.3 | Global mean surface temperature increase as a function of cumulative total global carbon dioxide (CO_2) emissions from various lines of evidence. Multi-model results from a hierarchy of climate carbon-cycle models for each Representative Concentration Pathway (RCP) until 2100 are shown (coloured lines). Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. Dots indicate decadal averages, with selected decades labelled. Ellipses show total anthropogenic warming in 2100 versus cumulative CO_2 emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in WGIII. Temperature values are always given relative to the 1861–1880 period, and emissions are cumulative since 1870. Black filled ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties. *{WGI SPM E.8, TS TFE.8, Figure 1, TS.SM.10, 12.5.4, Figure 12.45, WGIII Table SPM.1, Table 6.3}*

Warming caused by CO_2 emissions is effectively irreversible over multi-century timescales unless measures are taken to remove CO_2 from the atmosphere. Ensuring CO_2-induced warming remains *likely* less than 2°C requires cumulative CO_2 emissions from all anthropogenic sources to remain below about 3650 $GtCO_2$ (1000 GtC), over half of which were already emitted by 2011. *{WGI SPM E.8, TS TFE.8, 12.5.2, 12.5.3, 12.5.4}*

Multi-model results show that limiting total human-induced warming (accounting for both CO_2 and other human influences on climate) to less than 2°C relative to the period 1861–1880 with a probability of >66% would require total CO_2 emissions from all anthropogenic sources since 1870 to be limited to about 2900 $GtCO_2$ when accounting for non-CO_2 forcing as in the RCP2.6 scenario, with a range of 2550 to 3150 $GtCO_2$ arising from variations in non-CO_2 climate drivers across the scenarios considered by WGIII (Table 2.2). About 1900 [1650 to 2150] $GtCO_2$ were emitted by 2011, leaving about 1000 $GtCO_2$ to be consistent with this temperature goal. Estimated total fossil carbon reserves exceed this remaining amount by a factor of 4 to 7, with resources much larger still. *{WGI SPM E.8, TS TFE.8, Figure 1, TS.SM.10, 12.5.4, Figure 12.45, WGIII Table SPM.1, Table 6.3, Table 7.2}*

Notes:

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 base period.

[b] Note that the 66% range in this table should not be equated to the likelihood statements in Table SPM.1 and Table 3.1 and WGIII Table SPM.1. The assessment in these latter tables is not only based on the probabilities calculated for the full ensemble of scenarios in WGIII using a single climate model, but also the assessment in WGI of the uncertainty of the temperature projections not covered by climate models.

[c] Cumulative CO_2 emissions at the time the temperature threshold is exceeded that are required for 66%, 50% or 33% of the Coupled Model Intercomparison Project Phase 5 (CMIP5) complex models Earth System Model (ESM) and Earth System Models of Intermediate Complexity (EMIC) simulations, assuming non-CO_2 forcing follows the RCP8.5 scenario. Similar cumulative emissions are implied by other RCP scenarios. For most scenario–threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of CO_2 emissions, these figures provide an indication of the cumulative CO_2 emissions implied by the CMIP5 model simulations under RCP-like scenarios. Values are rounded to the nearest 50.

[d] Cumulative CO_2 emissions at the time of peak warming from WGIII scenarios for which a fraction of greater than 66% (66 to 100%), greater than 50% (50 to 66%) or greater than 33% (33 to 50%) of climate simulations keep global mean temperature increase to below the stated threshold. Ranges indicate the variation in cumulative CO_2 emissions arising from differences in non-CO_2 drivers across the WGIII scenarios. The fraction of climate simulations for each scenario is derived from a 600-member parameter ensemble of a simple carbon-cycle climate model, Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), in a probabilistic mode. Parameter and scenario uncertainty are explored in this ensemble. Structural uncertainties cannot be explored with a single model set-up. Ranges show the impact of scenario uncertainty, with 80% of scenarios giving cumulative CO_2 emissions within the stated range for the given fraction of simulations. Simple model estimates are constrained by observed changes over the past century, do not account for uncertainty in model structure and may omit some feedback processes: they are hence slightly higher than the CMIP5 complex models estimates. Values are rounded to the nearest 50.

[e] The numerical results for the cumulative CO_2 emissions for staying below 3°C with greater than 66% (66 to 100%) is greatly influenced by a large number of scenarios that would also meet the 2°C objective and therefore not comparable with numbers provided for the other temperature threshold.

[f] Reserves are quantities able to be recovered under existing economic and operating conditions; resources are those where economic extraction is potentially feasible. *{WGIII Table 7.2}*

2.3 Future risks and impacts caused by a changing climate

Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Increasing magnitudes of warming increase the likelihood of severe, pervasive and irreversible impacts for people, species and ecosystems. Continued high emissions would lead to mostly negative impacts for biodiversity, ecosystem services and economic development and amplify risks for livelihoods and for food and human security.

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive, and in some cases, irreversible detrimental impacts. Future climate change will amplify existing climate-related risks and create new risks. *{WGII SPM B, Figure SPM.1}*

Key risks are potentially severe impacts relevant to understanding dangerous anthropogenic interference with the climate system. Risks are considered key due to high hazard or high vulnerability of societies and systems exposed, or both. Their identification is based on large magnitude or high probability of impacts; irreversibility or timing of impacts; persistent vulnerability or exposure; or limited potential to reduce risks. Some risks are particularly relevant for individual regions (Figure 2.4), while others are global (Table 2.3). For risk assessment it is important to evaluate the widest possible range of impacts, including low-probability outcomes with large consequences. Risk levels often increase with temperature (Box 2.4) and are sometimes more directly linked to other dimensions of climate change, such as the rate of warming, as well as the magnitudes and rates of ocean acidification and sea level rise (Figure 2.5). *{WGII SPM A-3, SPM B-1}*

Key risks that span sectors and regions include the following (*high confidence*) *{WGII SPM B-1}*:

1. Risk of severe ill-health and disrupted livelihoods resulting from storm surges, sea level rise and coastal flooding; inland flooding in some urban regions; and periods of extreme heat.

2. Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services.

3. Risk of food and water insecurity and loss of rural livelihoods and income, particularly for poorer populations.

4. Risk of loss of ecosystems, biodiversity and ecosystem goods, functions and services.

The overall risks of future climate change impacts can be reduced by limiting the rate and magnitude of climate change, including ocean acidification. Some risks are considerable even at 1°C global mean temperature increase above pre-industrial levels. Many global risks are high to very high for global temperature increases of 4°C or more (see Box 2.4). These risks include severe and widespread impacts on unique and threatened systems, the extinction of many species, large risks to food security and compromised normal human activities, including growing food or working outdoors in some areas for parts of the year, due to the combination of high temperature and humidity (*high confidence*). The precise levels of climate change sufficient to trigger abrupt and irreversible change remain uncertain, but the risk associated with crossing such thresholds in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*). *{WGII SPM B-1}*

Adaptation can substantially reduce the risks of climate change impacts, but greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). The potential for adaptation, as well as constraints and limits to adaptation, varies among sectors, regions, communities and ecosystems. The scope for adaptation changes over time and is closely linked to socio-economic development pathways and circumstances. See Figure 2.4 and Table 2.3, along with Topics 3 and 4. *{WGII SPM B, SPM C, TS B, TS C}*

2.3.1 Ecosystems and their services in the oceans, along coasts, on land and in freshwater

Risks of harmful impacts on ecosystems and human systems increase with the rates and magnitudes of warming, ocean acidification, sea level rise and other dimensions of climate change (*high confidence*). Future risk is indicated to be high by the observation that natural global climate change at rates lower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years on land and in the oceans (*high confidence*). Many plant and animal species will be unable to adapt locally or move fast enough during the 21st century to track suitable climates under mid- and high range rates of climate change (RCP4.5, RCP6.0 and RCP8.5) (*medium confidence*) (Figure 2.5a). Coral reefs and polar ecosystems are highly vulnerable. *{WGII SPM A-1, SPM B-2, 4.3–4, 5.4, 6.1, 6.3, 6.5, 25.6, 26.4, 29.4, Box CC-CR, Box CC-MB, Box CC-RF}*

A large fraction of terrestrial, freshwater and marine species faces increased extinction risk due to climate change during and beyond the 21st century, especially as climate change interacts with other stressors (*high confidence*). Extinction risk is increased relative to pre-industrial and present periods, under all RCP scenarios, as a result of both the magnitude and rate of climate change (*high confidence*). Extinctions will be driven by several climate-associated drivers (warming, sea-ice loss, variations in precipitation, reduced river flows, ocean acidification and lowered ocean oxygen levels) and the interactions among these drivers and their interaction with simultaneous habitat modification, over-exploitation of stocks, pollution, eutrophication and invasive species (*high confidence*). *{WGII SPM B-2, 4.3–4.4, 6.1, 6.3, 6.5, 25.6, 26.4, Box CC-RF, Box CC-MB}*

Global marine species redistribution and marine biodiversity reduction in sensitive regions, under climate change, will challenge the sustained provision of fisheries productivity and other ecosystem services, especially at low latitudes (*high confidence*). By the mid-21st century, under 2°C global warming relative to pre-industrial temperatures, shifts in the geographical range of marine species will cause species richness and fisheries catch potential to increase, on average, at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes and in semi-enclosed seas (Figure 2.6a) (*medium confidence*). The progressive expansion of Oxygen Minimum Zones and anoxic 'dead zones' in the oceans will further constrain fish habitats (*medium confidence*). Open-ocean net primary production is projected to redistribute and to decrease globally, by 2100, under all RCP scenarios (*medium confidence*). Climate change adds to the threats of over-fishing and other non-climatic stressors (*high confidence*). *{WGII SPM B-2, 6.3–6.5, 7.4, 25.6, 28.3, 29.3, 30.6–30.7, Box CC-MB, Box CC-PP}*

Marine ecosystems, especially coral reefs and polar ecosystems, are at risk from ocean acidification (*medium* to *high confidence*). Ocean acidification has impacts on the physiology, behaviour and population dynamics of organisms. The impacts on individual species and the number of species affected in species groups increase from RCP4.5 to RCP8.5. Highly calcified molluscs, echinoderms and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*) (Figure 2.6b). Ocean acidification acts together with other global changes (e.g., warming, progressively lower oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*), leading to interactive, complex and amplified impacts for species and ecosystems (Figure 2.5b). *{WGII SPM B-2, Figure SPM.6B, 5.4, 6.3.2, 6.3.5, 22.3, 25.6, 28.3, 30.5, Figure 6-10, Box CC-CR, Box CC-OA, Box TS.7}*

Carbon stored in the terrestrial biosphere is susceptible to loss to the atmosphere as a result of climate change, deforestation and ecosystem degradation (*high confidence*). The aspects of climate change with direct effects on stored terrestrial carbon include high temperatures, drought and windstorms; indirect effects include increased risk of fires, pest and disease outbreaks**.** Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century (*medium confidence*), posing risks for carbon storage, biodiversity, wood production, water quality, amenity and economic activity. There is a high risk of substantial carbon and methane emissions as a result of permafrost thawing. *{WGII SPM, 4.2–4.3, Figure 4-8, Box 4-2, Box 4-3, Box 4-4}*

Coastal systems and low-lying areas will increasingly experience submergence, flooding and erosion throughout the 21st century and beyond, due to sea level rise (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development and urbanization (*high confidence*). Climatic and non-climatic drivers affecting coral reefs will erode habitats, increase coastline exposure to waves and storms and degrade environmental features important to fisheries and tourism (*high confidence*). Some low-lying developing countries and small island states are expected to face very high impacts that could have associated damage and adaptation costs of several percentage points of gross domestic product (GDP) (Figure 2.5c). *{WGII 5.3–5.5, 22.3, 24.4, 25.6, 26.3, 26.8, 29.4, Table 26-1, Box 25-1, Box CC-CR}*

2.3.2 Water, food and urban systems, human health, security and livelihoods

The fractions of the global population that will experience water scarcity and be affected by major river floods are projected to increase with the level of warming in the 21st century (*robust evidence*, *high agreement*). *{WGII 3.4–3.5, 26.3, 29.4, Table 3-2, Box 25-8}*

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). In presently dry regions, the frequency of droughts will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence*, *high agreement*). The interaction of increased temperature; increased sediment, nutrient and pollutant loadings from heavy rainfall; increased concentrations of pollutants during droughts; and disruption of treatment facilities during floods will reduce raw water quality and pose risks to drinking water quality (*medium evidence*, *high agreement*). *{WGI 12.4, WGII 3.2, 3.4–3.6, 22.3, 23.9, 25.5, 26.3, Table 3-2, Table 23-3, Box 25-2, Box CC-RF, Box CC-WE}*

All aspects of food security are potentially affected by climate change, including food production, access, use and price stability (*high confidence*). For wheat, rice and maize in tropical and temperate regions, climate change without adaptation is projected to negatively impact production at local temperature increases of 2°C or more above late 20th century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the 2030–2049 period showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared with the late 20th century. Global temperature increases of ~4°C or more above late 20th century levels, combined with increasing food demand, would pose large risks to food security, both globally and regionally (*high confidence*) (Figure 2.4, 2.7). The relationship between global and regional warming is explained in 2.2.1. *{WGII 6.3–6.5, 7.4–7.5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-2, Table 7-3, Figure 7-1, Figure 7-4, Figure 7-5, Figure 7-6, Figure 7-7, Figure 7-8, Box 7-1}*

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Health impacts include greater likelihood of injury and death due to more intense heat waves and fires, increased risks from foodborne and waterborne diseases and loss of work capacity and reduced labour productivity in vulnerable populations (*high confidence*). Risks of undernutrition in poor regions will increase (*high confidence*). Risks from vector-borne diseases are projected to generally increase with warming, due to the extension of the infection area and season, despite reductions in some areas that become too hot for disease vectors (*medium confidence*). Globally, the magnitude and severity of negative impacts will increasingly outweigh positive impacts (*high confidence*). By 2100 for RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is expected to compromise common human activities, including growing food and working outdoors (*high confidence*). *{WGII SPM B-2, 8.2, 11.3–11.8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS}*

In urban areas, climate change is projected to increase risks for people, assets, economies and ecosystems, including risks from heat stress, storms and extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scarcity, sea level rise and storm surges (*very high confidence*). These risks will be amplified for those lacking essential infrastructure and services or living in exposed areas. *{WGII 3.5, 8.2–8.4, 22.3, 24.4–24.5, 26.8, Table 8-2, Box 25-9, Box CC-HS}*

Rural areas are expected to experience major impacts on water availability and supply, food security, infrastructure and agricultural incomes, including shifts in the production areas of food and non-food crops around the world (*high confidence*). These impacts will disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure and education. *{WGII 5.4, 9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5}*

Box 2.4 | Reasons For Concern Regarding Climate Change

Five Reasons For Concern (RFCs) have provided a framework for summarizing key risks since the IPCC Third Assessment Report**.** They illustrate the implications of warming and of adaptation limits for people, economies and ecosystems across sectors and regions. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. All warming levels in the text of Box 2.4 are relative to the 1986–2005 period. Adding ~0.6°C to these warming levels roughly gives warming relative to the 1850–1900 period, used here as a proxy for pre-industrial times (right-hand scale in Box 2.4, Figure 1). *{WGII Assessment Box SPM.1}*

The five RFCs are associated with:

1. **Unique and threatened systems:** Some ecosystems and cultures are already at risk from climate change (*high confidence*). With additional warming of around 1°C, the number of unique and threatened systems at risk of severe consequences increases. Many systems with limited adaptive capacity, particularly those associated with Arctic sea ice and coral reefs, are subject to very high risks with additional warming of 2°C. In addition to risks resulting from the *magnitude* of warming, terrestrial species are also sensitive to the *rate* of warming, marine species to the rate and degree of ocean acidification and coastal systems to sea level rise (Figure 2.5).

2. **Extreme weather events:** Climate change related risks from extreme events, such as heat waves, heavy precipitation and coastal flooding, are already moderate (*high confidence*). With 1°C additional warming, risks are high (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase progressively with further warming (*high confidence*).

3. **Distribution of impacts:** Risks are unevenly distributed between groups of people and between regions; risks are generally greater for disadvantaged people and communities everywhere. Risks are already moderate because of regional differences in observed climate change impacts, particularly for crop production (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high under additional warming of above 2°C (*medium confidence*).

4. **Global aggregate impacts:** Risks of global aggregate impacts are moderate under additional warming of between 1°C and 2°C, reflecting impacts on both the Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss, with associated loss of ecosystem goods and services, leads to high risks at around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates are available for additional warming of above 3°C.

5. **Large-scale singular events:** With increasing warming, some physical and ecological systems are at risk of abrupt and/or irreversible changes (see Section 2.4). Risks associated with such tipping points are moderate between 0 and 1°C additional warming, since there are signs that both warm-water coral reefs and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase at a steepening rate under an additional warming of 1 to 2°C and become high above 3°C, due to the potential for large and irreversible sea level rise from ice sheet loss. For sustained warming above some threshold greater than ~0.5°C additional warming (*low confidence*) but less than ~3.5°C (*medium confidence*), near-complete loss of the Greenland ice sheet would occur over a millennium or more, eventually contributing up to 7 m to global mean sea level rise.

(continued on next page)

Aggregate economic losses accelerate with increasing temperature (*limited evidence, high agreement*), but global economic impacts from climate change are currently difficult to estimate. With recognized limitations, the existing incomplete estimates of global annual economic losses for warming of ~2.5°C above pre-industrial levels are 0.2 to 2.0% of income (*medium evidence, medium agreement*). Changes in population, age structure, income, technology, relative prices, lifestyle, regulation and governance are projected to have relatively larger impacts than climate change, for most economic sectors (*medium evidence, high agreement*). More severe and/or frequent weather hazards are projected to increase disaster-related losses and loss variability, posing challenges for affordable insurance, particularly in developing countries. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales. (Box 3.1) *{WGII 3.5, 10.2, 10.7, 10.9–10.10, 17.4–17.5, 25.7, 26.7–26.9, Box 25-7}*

From a poverty perspective, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security and prolong existing poverty traps and create new ones, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries (Figure 2.4). *{WGII 8.1, 8.3–8.4, 9.3, 10.9, 13.2–13.4, 22.3, 26.8}*

Climate change is projected to increase displacement of people (*medium evidence, high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, such as floods and droughts. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer term climate variability and change, and migration can also be an effective adaptation strategy. *{WGII 9.3, 12.4, 19.4, 22.3, 25.9}*

Climate change can indirectly increase risks of violent conflict by amplifying well-documented drivers of these conflicts, such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to some forms of conflict. *{WGII SPM, 12.5, 13.2, 19.4}*

2.4 Climate change beyond 2100, irreversibility and abrupt changes

Many aspects of climate change and its associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases.

Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions (see Section 2.2.5 for the relationship between CO_2 emissions and global temperature change.). A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial timescale, except in the

Year

case of a large net removal of CO_2 from the atmosphere over a sustained period (Figure 2.8a, b). *{WGI SPM E.1, SPM E.8, 12.5.2}*

Stabilization of global average surface temperature does not imply stabilization for all aspects of the climate system. Shifting biomes, re-equilibrating soil carbon, ice sheets, ocean temperatures and associated sea level rise all have their own intrinsic long timescales that will result in ongoing changes for hundreds to thousands of years after global surface temperature has been stabilized. *{WGI SPM E.8, 12.5.2–12.5.4, WGII 4.2}*

Ocean acidification will continue for centuries if CO_2 emissions continue, it will strongly affect marine ecosystems (*high confidence*), and the impact will be exacerbated by rising temperature extremes (Figure 2.5b). *{WGI 3.8.2, 6.4.4, WGII SPM B-2, 6.3.2, 6.3.5, 30.5, Box CC-OA}*

Global mean sea level rise will continue for many centuries beyond 2100 (*virtually certain*). The few available analyses that go beyond 2100 indicate sea level rise to be less than 1 m above the pre-industrial level by 2300 for GHG concentrations that peak and decline and remain below 500 ppm CO_2-eq, as in scenario RCP2.6. For a radiative forcing that corresponds to a CO_2-eq concentration in 2100 that is above 700 ppm but below 1500 ppm, as in scenario RCP8.5, the projected rise is 1 m to more than 3 m by 2300 (*medium confidence*) (Figure 2.8c). There is *low confidence* in the available models' ability to project solid ice discharge from the Antarctic ice sheet. Hence, these models *likely* underestimate the Antarctica ice sheet contribution, resulting in an underestimation of projected sea level rise beyond 2100. *{WGI SPM E.8, 13.4.4, 13.5.4}*

There is little evidence in global climate models of a tipping point or critical threshold in the transition from a perennially ice-covered to a seasonally ice-free Arctic Ocean, beyond which further sea-ice loss is unstoppable and irreversible. *{WGI 12.5.5}*

There is *low confidence* in assessing the evolution of the Atlantic Meridional Overturning Circulation beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded. *{WGI SPM E.4, 12.4.7, 12.5.5}*

Sustained mass loss by ice sheets would cause larger sea level rise, and part of the mass loss might be irreversible. There is *high confidence* that sustained global mean warming greater than a threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures. Abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment. *{WGI SPM E.8, 5.6.2, 5.8.1, 13.4.3, 13.5.4}*

Within the 21st century, magnitudes and rates of climate change associated with medium to high emission scenarios (RCP4.5, RCP6.0 and RCP8.5) pose a high risk of abrupt and irreversible regional-scale change in the composition, structure and function of marine, terrestrial and freshwater ecosystems, including wetlands (*medium confidence*), as well as warm water coral reefs (*high confidence*). Examples that could substantially amplify climate change are the boreal-tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). *{WGII 4.3.3.1, Box 4.3, Box 4.4, 5.4.2.4, 6.3.1–6.3.4, 6.4.2, 30.5.3–30.5.6, Box CC-CR, Box CC-MB}*

A reduction in permafrost extent is *virtually certain* with continued rise in global temperatures. Current permafrost areas are projected to become a net emitter of carbon (CO_2 and CH_4) with a loss of 180 to 920 $GtCO_2$ (50 to 250 GtC) under RCP8.5 over the 21st century (*low confidence*). *{WGI TFE.5, 6.4.3.4, 12.5.5, WGII 4.3.3.4}*

Topic 3: Future Pathways for Adaption, Mitigation and Sustainable Development

Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development.

Adaptation and mitigation are two complementary strategies for responding to climate change. Adaptation is the process of adjustment to actual or expected climate and its effects in order to either lessen or avoid harm or exploit beneficial opportunities. Mitigation is the process of reducing emissions or enhancing sinks of greenhouse gases (GHGs), so as to limit future climate change. Both adaptation and mitigation can reduce and manage the risks of climate change impacts. Yet adaptation and mitigation can also create other risks, as well as benefits. Strategic responses to climate change involve consideration of climate-related risks along with the risks and co-benefits of adaptation and mitigation actions. *{WGII SPM A-3, SPM C, Glossary, WGIII SPM.2, 4.1, 5.1, Glossary}*

Mitigation, adaptation and climate impacts can all result in transformations to and changes in systems. Depending on the rate and magnitude of change and the vulnerability and exposure of human and natural systems, climate change will alter ecosystems, food systems, infrastructure, coastal, urban and rural areas, human health and livelihoods. Adaptive responses to a changing climate require actions that range from incremental changes to more fundamental, transformational changes[34]. Mitigation can involve fundamental changes in the way that human societies produce and use energy services and land. *{WGII B, C, TS C, Box TS.8, Glossary, WGIII SPM.4}*

Topic 3 of this report examines the factors that influence the assessment of mitigation and adaptation strategies. It considers the benefits, risks, incremental changes and potential transformations from different combinations of mitigation, adaptation and residual climate-related impacts. It considers how responses in the coming decades will influence options for limiting long-term climate change and opportunities for adapting to it. Finally, it considers factors—including uncertainty, ethical considerations and links to other societal goals—that may influence choices about mitigation and adaptation. Topic 4 then assesses the prospects for mitigation and adaptation on the basis of current knowledge of tools, options and policies.

3.1 Foundations of decision-making about climate change

Effective decision-making to limit climate change and its effects can be informed by a wide range of analytical approaches for evaluating expected risks and benefits, recognizing the importance of governance, ethical dimensions, equity, value judgments, economic assessments and diverse perceptions and responses to risk and uncertainty.

Sustainable development and equity provide a basis for assessing climate policies. Limiting the effects of climate change is necessary to achieve sustainable development and equity, including poverty eradication. Countries' past and future contributions to the accumulation of GHGs in the atmosphere are different, and countries also face varying challenges and circumstances and have different capacities to address mitigation and adaptation. Mitigation and adaptation raise issues of equity, justice and fairness and are necessary to achieve sustainable development and poverty eradication. Many of those most vulnerable to climate change have contributed and contribute little to GHG emissions. Delaying mitigation shifts burdens from the present to the future, and insufficient adaptation responses to emerging impacts are already eroding the basis for sustainable development. Both adaptation and mitigation can have distributional effects locally, nationally and internationally, depending on who pays and who benefits. The process of decision-making about climate change, and the degree to which it respects the rights and views of all those affected, is also a concern of justice. *{WGII 2.2, 2.3, 13.3, 13.4, 17.3, 20.2, 20.5, WGIII SPM.2, 3.3, 3.10, 4.1.2, 4.2, 4.3, 4.5, 4.6, 4.8}*

Effective mitigation will not be achieved if individual agents advance their own interests independently. Climate change has the characteristics of a collective action problem at the global scale, because most GHGs accumulate over time and mix globally, and emissions by any agent (e.g., individual, community, company, country) affect other agents. Cooperative responses, including international cooperation, are therefore required to effectively mitigate GHG emissions and address other climate change issues. The effectiveness of adaptation can be enhanced through complementary actions across levels, including international cooperation. The evidence suggests that outcomes seen as equitable can lead to more effective cooperation. *{WGII 20.3.1, WGIII SPM.2, TS.1, 1.2, 2.6, 3.2, 4.2, 13.2, 13.3}*

Decision-making about climate change involves valuation and mediation among diverse values and may be aided by the analytic methods of several normative disciplines. Ethics analyses the different values involved and the relations between them. Recent political philosophy has investigated the question of responsibility for the effects of emissions. Economics and decision analysis provide

[34] Transformation is used in this report to refer to a change in the fundamental attributes of a system (see Glossary). Transformations can occur at multiple levels; at the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. *{WGII SPM C-2, 2–13, 20.5, WGIII SPM, 6–12}*

quantitative methods of valuation which can be used for estimating the social cost of carbon (see Box 3.1), in cost–benefit and cost-effectiveness analyses, for optimization in integrated models and elsewhere. Economic methods can reflect ethical principles, and take account of non-marketed goods, equity, behavioural biases, ancillary benefits and costs and the differing values of money to different people. They are, however, subject to well-documented limitations. *{WGII 2.2, 2.3, WGIII SPM.2, Box TS.2, 2.4, 2.5, 2.6, 3.2–3.6, 3.9.4}*

Analytical methods of valuation cannot identify a single best balance between mitigation, adaptation and residual climate impacts. Important reasons for this are that climate change involves extremely complex natural and social processes, there is extensive disagreement about the values concerned, and climate change impacts and mitigation approaches have important distributional effects. Nevertheless, information on the consequences of emissions pathways to alternative climate goals and risk levels can be a useful input into decision-making processes. Evaluating responses to climate change involves assessment of the widest possible range of impacts, including low-probability outcomes with large consequences. *{WGII 1.1.4, 2.3, 2.4, 17.3, 19.6, 19.7, WGIII 2.5, 2.6, 3.4, 3.7, Box 3-9}*

Effective decision-making and risk management in the complex environment of climate change may be iterative: strategies can often be adjusted as new information and understanding develops during implementation. However, adaptation and mitigation choices in the near term will affect the risks of climate change throughout the 21st century and beyond, and prospects for climate-resilient pathways for sustainable development depend on what is achieved through mitigation. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if mitigation is delayed too long. Decision-making about climate change is influenced by how individuals and organizations perceive risks and uncertainties and take them into account. They sometimes use simplified decision rules, overestimate or underestimate risks and are biased towards the status quo. They differ in their degree of risk aversion and the relative importance placed on near-term versus long-term ramifications of specific actions. Formalized analytical methods for decision-making under uncertainty can account accurately for risk, and focus attention on both short- and long-term consequences. *{WGII SPM A-3, SPM C-2, 2.1–2.4, 3.6, 14.1–14.3, 15.2–15.4, 17.1–17.3, 17.5, 20.2, 20.3, 20.6, WGIII SPM.2, 2.4, 2.5, 5.5, 16.4}*

3.2 Climate change risks reduced by adaptation and mitigation

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*). Mitigation involves some level of co-benefits and of risks due to adverse side effects, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change, increasing the benefits from near-term mitigation efforts.

The risks of climate change, adaptation and mitigation differ in nature, timescale, magnitude and persistence (*high confidence*). Risks from adaptation include maladaptation and negative ancillary impacts. Risks from mitigation include possible adverse side effects of large-scale deployment of low-carbon technology options and economic costs. Climate change risks may persist for millennia and can involve very high risk of severe impacts and the presence of significant irreversibilities combined with limited adaptive capacity. In contrast, the stringency of climate policies can be adjusted much more quickly in response to observed consequences and costs and create lower risks of irreversible consequences (3.3, 3.4, 4.3). *{WGI SPM E.8, 12.4, 12.5.2, 13.5, WGII 4.2, 17.2, 19.6, WGIII TS.3.1.4, Table TS.4, Table TS.5, Table TS.6, Table TS.7, Table TS.8, 2.5, 6.6}*

Mitigation and adaptation are complementary approaches for reducing risks of climate change impacts. They interact with one another and reduce risks over different timescales (*high confidence*). Benefits from adaptation can already be realized in addressing current risks and can be realized in the future for addressing emerging risks. Adaptation has the potential to reduce climate change impacts over the next few decades, while mitigation has relatively little influence on climate outcomes over this timescale. Near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change beyond mid-century. The potential for adaptation differs across sectors and will be limited by institutional and capacity constraints, increasing the long-term benefits of mitigation (*high confidence*). The level of mitigation will influence the rate and magnitude of climate change, and greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*) (*3.3*). *{WGI 11.3, 12.4, WGII SPM A-3, SPM B-2, SPM C-2, 1.1.4.4, 2.5, 16.3–16.6, 17.3, 19.2, 20.2.3, 20.3, 20.6}*

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*) (Topic 2 and Figure 3.1a). Estimates of warming in 2100 without additional climate mitigation efforts are from 3.7°C to 4.8°C compared with pre-industrial levels (median climate response); the range is 2.5°C to 7.8°C when using the 5th to 95th percentile range of the median climate response (Figure 3.1). The risks associated with temperatures at or above 4°C include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, consequential constraints on common human activities, increased likelihood of triggering tipping points (critical thresholds) and limited potential for adaptation in some cases (*high confidence*). Some risks of climate change, such as risks to unique and threatened systems and risks associated with extreme weather events, are moderate to high at temperatures 1°C to 2°C above pre-industrial levels. *{WGII SPM B-1, SPM C-2, WGIII SPM.3}*

Substantial cuts in GHG emissions over the next few decades can substantially reduce risks of climate change by limiting warming in the second half of the 21st century and beyond (*high confidence*). Global mean surface warming is largely determined by cumulative emissions, which are, in turn, linked to emissions over different timescales (Figure 3.1). Limiting risks across Reasons For Concern would imply a limit for cumulative emissions of CO_2.

Such a limit would require that global net emissions of CO_2 eventually decrease to zero (Figure 3.1a,b) (*high confidence*). Reducing risks of climate change through mitigation would involve substantial cuts in GHG emissions over the next few decades (Figure 3.1c). But some risks from residual damages are unavoidable, even with mitigation and adaptation (*very high confidence*). A subset of relevant climate change risks has been estimated using aggregate economic indicators. Such economic estimates have important limitations and are therefore a useful but insufficient basis for decision-making on long-term mitigation targets (see Box 3.1). *{WGII 19.7.1, WGIII SPM.3, Figure 3.1}*

Mitigation involves some level of co-benefits and risks, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change (*high confidence*). Scenarios that are *likely* to limit warming to below 2°C or even 3°C compared with pre-industrial temperatures involve large-scale changes in energy systems and potentially land use over the coming decades (3.4). Associated risks include those linked to large-scale deployment of technology options for producing low-carbon energy, the potential for high aggregate economic costs of mitigation and impacts on vulnerable countries and industries. Other risks and co-benefits are associated with human health, food security, energy security, poverty reduction, biodiversity conservation, water availability, income distribution, efficiency of taxation systems, labour supply and employment, urban sprawl, fossil fuel export revenues and the economic growth of developing countries (Table 4.5). *{WGIII SPM.4.1, SPM.4.2, TS.3.1.4, Table TS.4, Table TS.5, Table TS.6, Table TS.7, Table TS.8, 6.6}*

Inertia in the economic and climate systems and the possibility of irreversible impacts from climate change increase the benefits of near-term mitigation efforts (*high confidence*). The actions taken today affect the options available in the future to reduce emissions, limit temperature change and adapt to climate change. Near-term choices can create, amplify or limit significant elements of lock-in that are important for decision-making. Lock-ins and irreversibilities occur in the climate system due to large inertia in some of its components such as heat transfer from the ocean surface to depth leading to continued ocean warming for centuries regardless of emission scenario and the irreversibility of a large fraction of anthropogenic climate change resulting from CO_2 emissions on a multi-century to millennial timescale unless CO_2 were to be removed from the atmosphere through large-scale human interventions over a sustained period (see also Box 3.3). Irreversibilities in socio-economic and biological systems also result from infrastructure development and long-lived products and from climate change impacts, such as species extinction. The larger potential for irreversibility and pervasive impacts from climate change risks than from mitigation risks increases the benefit of short-term mitigation efforts. Delays in additional mitigation or constraints on technological options limit the mitigation options and increase the long-term mitigation costs as well as other risks that would be incurred in the medium to long term to hold climate change impacts at a given level (Table WGIII SPM.2, blue segment). *{WGI SPM E-8, WGII SPM B-2, 2.1, 19.7, 20.3, Box 20-4, WGIII SPM.4.1, SPM.4.2.1, 3.6, 6.4, 6.6, 6.9}*

3.3 Characteristics of adaptation pathways

Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change. Taking a longer-term perspective, in the context of sustainable development, increases the likelihood that more immediate adaptation actions will also enhance future options and preparedness.

Adaptation can contribute to the well-being of current and future populations, the security of assets and the maintenance of ecosystem goods, functions and services now and in the future. Adaptation is place- and context-specific, with no single approach for reducing risks appropriate across all settings (*high confidence*). Effective risk reduction and adaptation strategies consider vulnerability and exposure and their linkages with socio-economic processes, sustainable development, and climate change. Adaptation research since the IPCC Fourth Assessment Report (AR4) has evolved from a dominant consideration of engineering and technological adaptation pathways to include more ecosystem-based, institutional and social measures. A previous focus on cost–benefit analysis, optimization and efficiency approaches has broadened with the development of multi-metric evaluations that include risk and uncertainty dimensions integrated within wider policy and ethical frameworks to assess trade-offs and constraints. The range of specific adaptation measures has also expanded (4.2, 4.4.2.1), as have the links to sustainable development (3.5). There are many studies on local and sectoral adaptation costs and benefits, but few global analyses and *very low confidence*

Box 3.1 | The Limits of the Economic Assessment of Climate Change Risks

A subset of climate change risks and impacts are often measured using aggregate economic indicators, such as gross domestic product (GDP) or aggregate income. Estimates, however, are partial and affected by important conceptual and empirical limitations. These incomplete estimates of global annual economic losses for temperature increases of ~2.5°C above pre-industrial levels are between 0.2 and 2.0% of income (*medium evidence, medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence, high agreement*). Estimates of the incremental aggregate economic impact of emitting one more tonne of carbon dioxide (the social cost of carbon) are derived from these studies and lie between a few dollars and several hundreds of dollars per tonne of carbon in 2000 to 2015 (*robust evidence, medium agreement*). These impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable. Many estimates do not account for the possibility of large-scale singular events and irreversibility, tipping points and other important factors, especially those that are difficult to monetize, such as loss of biodiversity. Estimates of aggregate costs mask significant differences in impacts across sectors, regions, countries and communities, and they therefore depend on ethical considerations, especially on the aggregation of losses across and within countries (*high confidence*). Estimates of global aggregate economic losses exist only for limited warming levels. These levels are exceeded in scenarios for the 21st century unless additional mitigation action is implemented, leading to additional economic costs. The total economic effects at different temperature levels would include mitigation costs, co-benefits of mitigation, adverse side effects of mitigation, adaptation costs and climate damages. As a result, mitigation cost and climate damage estimates at any given temperature level cannot be compared to evaluate the costs and benefits of mitigation. Very little is known about the economic cost of warming above 3°C relative to the current temperature level. Accurately estimating climate change risks (and thus the benefits of mitigation) takes into account the full range of possible impacts of climate change, including those with high consequences but a low probability of occurrence. The benefits of mitigation may otherwise be underestimated (*high confidence*). Some limitations of current estimates may be unavoidable, even with more knowledge, such as issues with aggregating impacts over time and across individuals when values are heterogeneous. In view of these limitations, it is outside the scope of science to identify a single best climate change target and climate policy (3.1, 3.4). *{WGII SPM B-2, 10.9.2, 10.9.4, 13.2, 17.2–17.3, 18.4, 19.6, WGIII 3.6}* in their results. *{WGII SPM C-1, Table SPM.1, 14.1, 14.ES, 15.2, 15.5, 17.2, 17.ES}*

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts and expectations can benefit decision-making processes. Indigenous, local and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge into practices increases the effectiveness of adaptation as do effective decision support, engagement and policy processes (4.4.2). *{WGII SPM C-1}*

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and sub-national governments, for example by protecting vulnerable groups, by supporting economic diversification and by providing information, policy and legal frameworks and financial support (*robust evidence, high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence, high agreement*). *{WGII SPM C-1}*

A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*), but some near-term responses to climate change may also limit future choices. Integration of adaptation into planning, including policy design, and decision-making can promote synergies with development and disaster risk reduction. However, poor planning or implementation, overemphasizing short-term outcomes or failing to sufficiently anticipate consequences can result in maladaptation, increasing the vulnerability or exposure of the target group in the future or the vulnerability of other people, places or sectors (*medium evidence, high agreement*). For example, enhanced protection of exposed assets can lock in dependence on further protection measures. Appropriate adaptation options can be better assessed by including co-benefits and mitigation implications (3.5 and 4.2). *{WGII SPM C-1}*

Numerous interacting constraints can impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Other constraints include insufficient research, monitoring and observation and the financial and other resources to maintain them. Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes (see Sections 4.1 and 4.2 for details in relation to implementation). *{WGII SPM C-1}*

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Value-based judgments of what constitutes an intolerable risk may differ. Limits to adaptation emerge from the interaction among climate change and biophysical and/or socio-economic constraints. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, insufficient responses to emerging impacts are already eroding the basis for sustainable development. For most regions and sectors, empirical evidence is not sufficient to quantify magnitudes of climate change that would constitute a future adaptation limit. Furthermore, economic development, technology and cultural norms and values can change over time to enhance or reduce the capacity of systems to avoid limits. As a consequence, some limits are 'soft' in that they may be alleviated over time. Other limits are 'hard' in that there are no reasonable prospects for avoiding intolerable risks. *{WGII SPM C-2, TS}*

Transformations in economic, social, technological and political decisions and actions can enhance adaptation and promote sustainable development (*high confidence*). Restricting adaptation responses to incremental changes to existing systems and structures without considering transformational change may increase costs and losses and miss opportunities. For example, enhancing infrastructure to protect other built assets can be expensive and ultimately not defray increasing costs and risks, whereas options such as relocation or using ecosystem services to adapt may provide a range of benefits now and in the future. Transformational adaptation can include introduction of new technologies or practices, formation of new financial structures or systems of governance, adaptation at greater scales or magnitudes and shifts in the location of activities. Planning and implementation of transformational adaptation could reflect strengthened, altered or aligned paradigms and consequently may place new and increased demands on governance structures to reconcile different goals and visions for the future and to address possible equity and ethical implications: transformational adaptation pathways are enhanced by iterative learning, deliberative processes, and innovation. At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. *{WGII SPM C-2, 1.1, 2.5, 5.5, 8.4, 14.1, 14.3, 16.2-7, 20.3.3, 20.5, 25.10, Table 14-4, Table 16-3, Box 16.1, Box 16.4, Box 25.1}*

Building adaptive capacity is crucial for effective selection and implementation of adaptation options (*robust evidence, high agreement*). Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also increasing the adaptive capacity of human and natural systems (*medium evidence, high agreement*). This can involve complex governance challenges and new institutions and institutional arrangements. (4.2) *{WGII 8.1, 12.3, 14.1-3, 16.2, 16.3, 16.5, 16.8}*

Significant co-benefits, synergies and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use and biodiversity, but tools to understand and manage these interactions remain limited. Examples of actions with co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging, climate-altering air pollutants; (ii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iii) sustainable agriculture and forestry; and (iv) protection of ecosystems for carbon storage and other ecosystem services. *{WGII SPM C-1}*

3.4 Characteristics of mitigation pathways

There are multiple mitigation pathways that are *likely* to limit warming to below 2°C relative to pre-industrial levels. These pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges but on different timescales.

Without additional efforts to reduce GHG emissions beyond those in place today, global emission growth is expected to persist driven by growth in global population and economic activities (*high confidence*) (Figure 3.2). Global GHG emissions under most scenarios without additional mitigation (baseline scenarios) are between about 75 $GtCO_2$-eq/yr and almost 140 $GtCO_2$-eq/yr in 2100[35] which is approximately between the 2100 emission levels in the RCP6.0 and RCP8.5 pathways (Figure 3.2)[36]. Baseline scenarios exceed 450 ppm CO_2-eq by 2030 and reach CO_2-eq concentration levels between about 750 ppm CO_2-eq and more than 1300 ppm CO_2-eq by 2100. Global mean surface temperature increases in 2100 range from about 3.7°C to 4.8°C above the average for 1850–1900 for a median climate response. They range from 2.5°C to 7.8°C when including climate uncertainty (5th to 95th percentile range)[37]. The future scenarios do not account for possible changes in natural forcings in the climate system (see Box 1.1). *{WGIII SPM.3, SPM.4.1, TS.2.2, TS.3.1, 6.3, Box TS.6}*

Many different combinations of technological, behavioural and policy options can be used to reduce emissions and limit temperature change (*high confidence*). To evaluate possible pathways to long-term climate goals, about 900 mitigation scenarios were collected for this assessment, each of which describes different technological, socio-economic and institutional changes. Emission reductions under these scenarios lead to concentrations in 2100 from 430 ppm CO_2-eq to above 720 ppm CO_2-eq which is comparable to the 2100 forcing levels between RCP2.6 and RCP6.0. Scenarios with concentration levels of below 430 ppm CO_2-eq by 2100 were also assessed. *{WGIII SPM.4.1, TS3.1, 6.1, 6.2, 6.3, Annex II}*

Scenarios leading to CO_2-eq concentrations in 2100 of about 450 ppm or lower are *likely* to maintain warming below 2°C over the 21st century relative to pre-industrial levels (*high confidence*). Mitigation scenarios reaching concentration levels of about 500 ppm CO_2-eq by 2100 are *more likely than not* to limit warming to less than 2°C relative to pre-industrial levels, unless concentration levels temporarily exceed roughly 530 ppm CO_2-eq before 2100. In this case, warming is *about as likely as not* to remain below 2°C relative to pre-industrial levels. Scenarios that exceed about 650 ppm CO_2-eq by 2100 are *unlikely* to limit warming to below 2°C relative to pre-industrial levels. Mitigation scenarios in which warming is *more likely than not* to be less than 1.5°C relative to pre-industrial levels by 2100 are characterized by concentration levels by 2100 of below 430 ppm CO_2-eq. In these scenarios, temperature peaks during the century and subsequently declines (Table 3.1). *{WGIII SPM.4.1, Table SPM.1, TS.3.1, Box TS.6, 6.3}*

Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a *likely* chance to keep warming below 2°C relative to pre-industrial level) typically involve temporary overshoot[38] of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq by 2100 (Table 3.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century (*high confidence*). The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain, and CDR technologies and methods are, to varying degrees, associated with challenges and risks (see Box 3.3)[39]. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. *{WGIII SPM.4.1, Table SPM.1, TS.3.1, 6.3, 6.9.1, Figure 6.7, 7.11, 11.13}*

Limiting warming with a *likely* chance to less than 2°C relative to pre-industrial levels would require substantial cuts in anthropogenic GHG emissions[40] by mid-century through large-scale changes in energy systems and possibly land use. Limiting warming to higher levels would require similar changes but less quickly. Limiting warming to lower levels would require these changes more quickly (*high confidence*). Scenarios that are *likely* to maintain warming at below 2°C are characterized by a 40 to 70% reduction in GHG emissions by 2050, relative to 2010 levels, and emissions levels near zero or below in 2100 (Figure 3.2, Table 3.1). Scenarios with higher emissions in 2050 are characterized by a greater reliance on CDR technologies beyond mid-century, and vice versa. Scenarios that are *likely* to maintain warming at below 2°C include more rapid improvements in energy efficiency and a tripling to nearly a quadrupling of the share of zero- and low-carbon energy supply from renewable energy, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS) or BECCS by the year 2050 (Figure 3.2b). The scenarios describe a wide range of changes in land use, reflecting

Notes:

[a] The 'total range' for the 430 to 480 ppm CO_2-eq concentrations scenarios corresponds to the range of the 10th to 90th percentile of the subcategory of these scenarios shown in Table 6.3 of the Working Group III report.

[b] Baseline scenarios fall into the >1000 and 720 to 1000 ppm CO_2-eq categories. The latter category also includes mitigation scenarios. The baseline scenarios in the latter category reach a temperature change of 2.5°C to 5.8°C above the average for 1850–1900 in 2100. Together with the baseline scenarios in the >1000 ppm CO_2-eq category, this leads to an overall 2100 temperature range of 2.5°C to 7.8°C (range based on median climate response: 3.7°C to 4.8°C) for baseline scenarios across both concentration categories.

[c] The global 2010 emissions are 31% above the 1990 emissions (consistent with the historic greenhouse gas emission estimates presented in this report). CO_2-eq emissions include the basket of Kyoto gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) as well as fluorinated gases).

[d] The assessment here involves a large number of scenarios published in the scientific literature and is thus not limited to the Representative Concentration Pathways (RCPs). To evaluate the CO_2-eq concentration and climate implications of these scenarios, the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) was used in a probabilistic mode. For a comparison between MAGICC model results and the outcomes of the models used in WGI, see WGI 12.4.1.2, 12.4.8 and WGIII 6.3.2.6.

[e] The assessment in this table is based on the probabilities calculated for the full ensemble of scenarios in WGIII using MAGICC and the assessment in WGI of the uncertainty of the temperature projections not covered by climate models. The statements are therefore consistent with the statements in WGI, which are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) runs of the RCPs and the assessed uncertainties. Hence, the likelihood statements reflect different lines of evidence from both WGs. This WGI method was also applied for scenarios with intermediate concentration levels where no CMIP5 runs are available. The likelihood statements are indicative only *{WGIII 6.3}* and follow broadly the terms used by the WGI SPM for temperature projections: likely 66–100%, more likely than not >50–100%, about as likely as not 33–66%, and unlikely 0–33%. In addition the term more unlikely than likely 0–<50% is used.

[f] The CO_2-equivalent concentration (see Glossary) is calculated on the basis of the total forcing from a simple carbon cycle/climate model, MAGICC. The CO_2-equivalent concentration in 2011 is estimated to be 430 ppm (uncertainty range 340 to 520 ppm). This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI, i.e., 2.3 W/m^2, uncertainty range 1.1 to 3.3 W/m^2.

[g] The vast majority of scenarios in this category overshoot the category boundary of 480 ppm CO_2-eq concentration.

[h] For scenarios in this category, no CMIP5 run or MAGICC realization stays below the respective temperature level. Still, an *unlikely* assignment is given to reflect uncertainties that may not be reflected by the current climate models.

[i] Scenarios in the 580 to 650 ppm CO_2-eq category include both overshoot scenarios and scenarios that do not exceed the concentration level at the high end of the category (e.g., RCP4.5). The latter type of scenarios, in general, have an assessed probability of *more unlikely than likely* to stay below the 2°C temperature level, while the former are mostly assessed to have an *unlikely* probability of staying below this level.

[j] In these scenarios, global CO_2-eq emissions in 2050 are between 70 to 95% below 2010 emissions, and they are between 110 to 120% below 2010 emissions in 2100.

different assumptions about the scale of bioenergy production, afforestation and reduced deforestation. Scenarios leading to concentrations of 500 ppm CO_2-eq by 2100 are characterized by a 25 to 55% reduction in GHG emissions by 2050, relative to 2010 levels. Scenarios that are *likely* to limit warming to 3°C relative to pre-industrial levels reduce emissions less rapidly than those limiting warming to 2°C. Only a limited number of studies provide scenarios that are *more likely than not* to limit warming to 1.5°C by 2100; these scenarios are characterized by concentrations below 430 ppm CO_2-eq by 2100 and 2050 emission reduction between 70 and 95% below 2010. For a comprehensive overview of the characteristics of emissions scenarios, their CO_2-equivalent concentrations and their likelihood to keep warming to below a range of temperature levels, see Table 3.1. *{WGIII SPM.4.1, TS.3.1, 6.3, 7.11}*

Reducing emissions of non-CO_2 climate forcing agents can be an important element of mitigation strategies. Emissions of non-CO_2 gases (methane (CH_4), nitrous oxide (N_2O), and fluorinated gases) contributed about 27% to the total emissions of Kyoto gases in 2010. For most non-CO_2 gases, near-term, low-cost options are available to reduce their emissions. However, some sources of these non-CO_2 gases are difficult to mitigate, such as N_2O emissions from fertilizer use and CH_4 emissions from livestock. As a result, emissions of most non-CO_2 gases will not be reduced to zero, even under stringent mitigation scenarios (see Figure 4.1). The differences in radiative properties and lifetimes of CO_2 and non-CO_2 climate forcing agents have important implications for mitigation strategies (see also Box 3.2). *{WGIII 6.3.2}*

All current GHG emissions and other climate forcing agents affect the rate and magnitude of climate change over the next few decades. Reducing the emissions of certain short-lived climate forcing agents can reduce the rate of warming in the short term but will have only a limited effect on long-term warming, which is driven mainly by CO_2 emissions. There are large uncertainties related to the climate impacts of some of the short-lived climate forcing agents. Although the effects of CH_4 emissions are well understood, there are large uncertainties related to the effects of black carbon. Co-emitted components with cooling effects may further complicate and reduce the climate impacts of emission reductions. Reducing emissions of sulfur dioxide (SO_2) would cause warming. Near-term reductions in short-lived climate forcing agents can have a relatively fast impact on climate change and possible co-benefits for air pollution. *{WGI 8.2.3, 8.3.2, 8.3.4, 8.5.1, 8.7.2, FAQ 8.2, 12.5, WGIII 6.6.2.1}*

Delaying additional mitigation to 2030 will substantially increase the challenges associated with limiting warming over the 21st century to below 2°C relative to pre-industrial levels (*high confidence*). GHG emissions in 2030 lie between about 30 $GtCO_2$-eq/yr and 50 $GtCO_2$-eq/yr in cost-effective scenarios that are *likely* to *about as likely as not* to limit warming to less than 2°C this century relative to pre-industrial levels (2100 atmospheric concentration levels of about 450 ppm CO_2-eq to about 500 ppm CO_2-eq) (Figure 3.3, left panel). Scenarios with GHG emission levels of above 55 $GtCO_2$-eq/yr require substantially higher rates of emissions reductions between 2030 and 2050 (median estimate of 6%/yr as compared to 3%/yr in cost-effective scenarios; Figure 3.3, middle panel); much more rapid scale-up of zero and low-carbon energy over this period (more than a tripling compared to a doubling of the low-carbon energy share relative to 2010; Figure 3.3, right panel); a larger reliance on CDR technologies in the long term; and higher transitional and long-term economic impacts (Table 3.2). (3.5, 4.3) *{WGIII SPM.4.1, TS.3.1, 6.4, 7.11}*

Estimated global emission levels by 2020 based on the Cancún Pledges are not consistent with cost-effective long-term mitigation trajectories that are at least *about as likely as not* to limit warming to below 2°C relative to pre-industrial levels (2100 concentration levels of about 500 ppm CO_2-eq or below), but they do not preclude the option to meet this goal (*high confidence*). The Cancún Pledges are broadly consistent with cost-effective scenarios that are *likely* to limit temperature change to below 3°C relative to pre-industrial levels. *{WGIII SPM.4.1, 6.4, 13.13, Figure TS.11}*

Estimates of the aggregate economic costs of mitigation vary widely depending on methodologies and assumptions but increase with the stringency of mitigation (*high confidence*). Scenarios in which all countries of the world begin mitigation immediately, in which there is a single global carbon price, and in which all key technologies are available have been used as a cost-effective benchmark for estimating macroeconomic mitigation costs (Figure 3.4). Under these assumptions, mitigation scenarios that are *likely* to limit warming to below 2°C through the 21st century relative to pre-industrial levels entail losses in global consumption—not including benefits of reduced climate change (3.2) as well as co-benefits and adverse side effects of mitigation (3.5, 4.3)—of 1 to 4% (median: 1.7%) in 2030, 2 to 6% (median: 3.4%) in 2050, and 3% to 11% (median: 4.8%) in 2100, relative to consumption in baseline scenarios that grows anywhere from 300% to more than 900% over the century[41]. These numbers correspond to an annualized reduction of consumption growth by 0.04 to 0.14 (median: 0.06) percentage points over the century relative to annualized consumption growth in the baseline that is between 1.6% and 3% per year (Figure 3.4). In the absence or under limited availability of mitigation technologies (such as bioenergy, CCS, and their combination BECCS, nuclear, wind and solar), mitigation costs can increase substantially depending on the technology considered (Table 3.2). Delaying additional mitigation reduces near-term costs but increases mitigation costs in the medium- to long-term (Table 3.2). Many models could not limit *likely* warming to below 2°C over the 21st century relative to pre-industrial levels, if additional mitigation is considerably delayed, or if availability of key technologies, such as bioenergy, CCS and their combination (BECCS) are limited (*high confidence*) (Table 3.2). *{WGIII SPM.4.1, Table SPM.2, Table TS.2, TS.3.1, 6.3, 6.6}*

[41] Mitigation cost ranges cited here refer to the 16th to 84th percentile of the underlying sample (see Figure 3.4).

Mitigation efforts and associated cost are expected to vary across countries. The distribution of costs can differ from the distribution of the actions themselves (*high confidence*). In globally cost-effective scenarios, the majority of mitigation efforts takes place in countries with the highest future GHG emissions in baseline scenarios. Some studies exploring particular effort-sharing frameworks, under the assumption of a global carbon market, have estimated substantial global financial flows associated with mitigation in scenarios that are *likely* to *more unlikely than likely* to limit warming during the 21st century to less than 2°C relative to pre-industrial levels. *{WGIII SPM.4.1, TS.3.1, Box 3.5, 4.6, 6.3.6, Table 6.4, Figure 6.9, Figure 6.27, Figure 6.28, Figure 6.29, 13.4.2.4}*

Notes:

[a] Delayed mitigation scenarios are associated with greenhouse gas emission of more than 55 $GtCO_2$-eq in 2030, and the increase in mitigation costs is measured relative to cost-effective mitigation scenarios for the same long-term concentration level.

[b] Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and impose no additional limitations on technology relative to the models' default technology assumptions.

[c] The range is determined by the central scenarios encompassing the 16th to 84th percentile range of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm CO_2-eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm CO_2-eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation.

[d] No CCS: carbon dioxide capture and storage is not included in these scenarios. Nuclear phase out: no addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20% global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations and industry was around 18 EJ/yr in 2008). EJ = Exajoule = 10^{18} Joule.

[e] Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline gross domestic product (GDP, for scenarios from partial equilibrium models) for the period 2015–2100, discounted at 5% per year.

Box 3.2 | Greenhouse Gas Metrics and Mitigation Pathways

This box focuses on emission-based metrics that are used for calculating CO_2-equivalent emissions for the formulation and evaluation of mitigation strategies. These emission metrics are distinct from the concentration-based metric used in SYR (CO_2-equivalent concentration). For an explanation of CO_2-equivalent emissions and CO_2-equivalent concentrations, see Glossary.

Emission metrics facilitate multi-component climate policies by allowing emissions of different greenhouse gases (GHGs) and other climate forcing agents to be expressed in a common unit (so-called 'CO_2-equivalent emissions'). The Global Warming Potential (GWP) was introduced in the IPCC First Assessment Report, where it was also used to illustrate the difficulties in comparing components with differing physical properties using a single metric. The 100-year GWP (GWP_{100}) was adopted by the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol and is now used widely as the default metric. It is only one of several possible emission metrics and time horizons. *{WGI 8.7, WGIII 3.9}*

The choice of emission metric and time horizon depends on type of application and policy context; hence, no single metric is optimal for all policy goals. All metrics have shortcomings, and choices contain value judgments, such as the climate effect considered and the weighting of effects over time (which explicitly or implicitly discounts impacts over time), the climate policy goal and the degree to which metrics incorporate economic or only physical considerations. There are significant uncertainties related to metrics, and the magnitudes of the uncertainties differ across metric type and time horizon. In general, the uncertainty increases for metrics along the cause–effect chain from emission to effects. *{WGI 8.7, WGIII 3.9}*

The weight assigned to non-CO_2 climate forcing agents relative to CO_2 depends strongly on the choice of metric and time horizon (*robust evidence, high agreement*). GWP compares components based on radiative forcing, integrated up to a chosen time horizon. Global Temperature change Potential (GTP; see Glossary) is based on the temperature response at a specific point in time with no weight on temperature response before or after the chosen point in time. Adoption of a fixed horizon of, for example, 20, 100 or 500 years for these metrics will inevitably put no weight on climate outcomes beyond the time horizon, which is significant for CO_2 as well as other long-lived gases. The choice of time horizon markedly affects the weighting especially of short-lived climate forcing agents, such as methane (CH_4) (see Box 3.2, Table 1; Box 3.2, Figure 1a). For some metrics (e.g., the dynamic GTP; see Glossary), the weighting changes over time as a chosen target year is approached. *{WGI 8.7, WGIII 3.9}*

Notes:

[a] Global Warming Potential (GWP) values have been updated in successive IPCC reports; the AR5 GWP_{100} values are different from those adopted for the Kyoto Protocol's First Commitment Period which are from the IPCC Second Assessment Report (SAR). Note that for consistency, equivalent CO_2 emissions given elsewhere in this Synthesis Report are also based on SAR, not AR5 values. For a comparison of emissions using SAR and AR5 GWP_{100} values for 2010 emissions, see Figure 1.6.

[b] No single lifetime can be given for CO_2. *{WGI Box 6.1, 6.1.1, 8.7}*

The choice of emission metric affects the timing and emphasis placed on abating short- and long-lived climate forcing agents. For most metrics, global cost differences are small under scenarios of global participation and cost-minimizing mitigation pathways, but implications for some individual countries and sectors could be more significant (*medium evidence, high agreement*). Different metrics and time horizons significantly affect the contributions from various sources/sectors and components, particularly short-lived climate forcing agents (Box 3.2, Figure 1b). A fixed time independent metric that gives less weight to short-lived agents such as CH_4 (e.g., using GTP_{100} instead of GWP_{100}) would require earlier and more stringent CO_2 abatement to achieve the same climate outcome for 2100. Using a time-dependent metric, such as a dynamic GTP, leads to less CH_4 mitigation

Box 3.3 | Carbon Dioxide Removal and Solar Radiation Management Geoengineering Technologies—Possible Roles, Options, Risks and Status

Geoengineering refers to a broad set of methods and technologies operating on a large scale that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most methods seek to either reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management, SRM) or increase the removal of carbon dioxide (CO_2) from the atmosphere by sinks to alter climate (Carbon Dioxide Removal, CDR, see Glossary). Limited evidence precludes a comprehensive assessment of feasibility, cost, side effects and environmental impacts of either CDR or SRM. *{WGI SPM E.8, 6.5, 7.7, WGII 6.4, Table 6-5, Box 20-4, WGIII TS.3.1.3, 6.9}*

CDR plays a major role in many mitigation scenarios. Bioenergy with carbon dioxide capture and storage (BECCS) and afforestation are the only CDR methods included in these scenarios. CDR technologies are particularly important in scenarios that temporarily overshoot atmospheric concentrations, but they are also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. Similar to mitigation, CDR would need to be deployed on a large scale and over a long time period to be able to significantly reduce CO_2 concentrations (see Section 3.1). *{WGII 6.4, WGIII SPM 4.1, TS.3.1.2, TS 3.1.3, 6.3, 6.9}*

Several CDR techniques could potentially reduce atmospheric greenhouse gas (GHG) levels. However, there are biogeochemical, technical and societal limitations that, to varying degrees, make it difficult to provide quantitative estimates of the potential for CDR. The emission mitigation from CDR is less than the removed CO_2, as some CO_2 is released from that previously stored in oceans and terrestrial carbon reservoirs. Sub-sea geologic storage has been implemented on a regional scale, with no evidence to date of ocean impact from leakage. The climatic and environmental side effects of CDR depend on technology and scale. Examples are associated with altered surface reflectance from afforestation and ocean de-oxygenation from ocean fertilization. Most terrestrial CDR techniques would involve competing demands for land and could involve local and regional risks, while maritime CDR techniques may involve significant risks for ocean ecosystems, so that their deployment could pose additional challenges for cooperation between countries. *{WGI 6.5, FAQ 7.3, WGII 6.4, Table 6.5, WGIII 6.9}*

SRM is untested, and is not included in any of the mitigation scenarios, but, if realisable, could to some degree offset global temperature rise and some of its effects. It could possibly provide rapid cooling in comparison to CO_2 mitigation. There is *medium confidence* that SRM through stratospheric aerosol injection is scalable to counter radiative forcing from a twofold increase in CO_2 concentrations and some of the climate responses associated with warming. Due to insufficient understanding there is no consensus on whether a similarly large negative counter radiative forcing could be achieved from cloud brightening. Land albedo change does not appear to be able to produce a large counter radiative forcing. Even if SRM could counter the global mean warming, differences in spatial patterns would remain. The scarcity of literature on other SRM techniques precludes their assessment. *{WGI 7.7, WGIII TS.3.1.3, 6.9}*

If it were deployed, SRM would entail numerous uncertainties, side effects, risks and shortcomings. Several lines of evidence indicate that SRM would itself produce a small but significant decrease in global precipitation (with larger differences on regional scales). Stratospheric aerosol SRM is *likely* to modestly increase ozone losses in the polar stratosphere. SRM would not prevent the CO_2 effects on ecosystems and ocean acidification that are unrelated to warming. There could also be other unanticipated consequences. For all future scenarios considered in AR5, SRM would need to increase commensurately, to counter the global mean warming, which would exacerbate side effects. Additionally, if SRM were increased to substantial levels and then terminated, there is *high confidence* that surface temperatures would rise very rapidly (within a decade or two). This would stress systems that are sensitive to the rate of warming. *{WGI 7.6–7.7, FAQ 7.3, WGII 19.5, WGIII 6.9}*

SRM technologies raise questions about costs, risks, governance and ethical implications of development and deployment. There are special challenges emerging for international institutions and mechanisms that could coordinate research and possibly restrain testing and deployment. Even if SRM would reduce human-made global temperature increase, it would imply spatial and temporal redistributions of risks. SRM thus introduces important questions of intragenerational and intergenerational justice. Research on SRM, as well as its eventual deployment, has been subject to ethical objections. In spite of the estimated low potential costs of some SRM deployment technologies, they will not necessarily pass a benefit–cost test that takes account of the range of risks and side effects. The governance implications of SRM are particularly challenging, especially as unilateral action might lead to significant effects and costs for others. *{WGIII TS.3.1.3, 1.4, 3.3, 6.9, 13.4}*

3.5 Interaction among mitigation, adaptation and sustainable development

Climate change is a threat to equitable and sustainable development. Adaptation, mitigation and sustainable development are closely related, with potential for synergies and trade-offs.

Climate change poses an increasing threat to equitable and sustainable development (*high confidence*). Some climate-related impacts on development are already being observed. Climate change is a threat multiplier. It exacerbates other threats to social and natural systems, placing additional burdens particularly on the poor and constraining possible development paths for all. Development along current global pathways can contribute to climate risk and vulnerability, further eroding the basis for sustainable development. *{WGII SPM B-2, 2.5, 10.9, 13.1–13.3, 20.1, 20.2, 20.6, WGIII SPM.2, 4.2}*

Aligning climate policy with sustainable development requires attention to both adaptation and mitigation (*high confidence*). Interaction among adaptation, mitigation and sustainable development occurs both within and across regions and scales, often in the context of multiple stressors. Some options for responding to climate change could impose risks of other environmental and social costs, have adverse distributional effects and draw resources away from other development priorities, including poverty eradication. *{WGII 2.5, 8.4, 9.3, 13.3–13.4, 20.2–20.4, 21.4, 25.9, 26.8, WGIII SPM.2, 4.8, 6.6}*

Both adaptation and mitigation can bring substantial co-benefits (*medium confidence*). Examples of actions with co-benefits include (i) improved air quality (see Figure 3.5); (ii) enhanced energy security, (iii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iv) sustainable agriculture and forestry; and (v) protection of ecosystems for carbon storage and other ecosystem services. *{WGII SPM C-1, WGIII SPM.4.1}*

Strategies and actions can be pursued now that will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being and effective environmental management (*high confidence*). Prospects for climate-resilient pathways are related fundamentally to what the world accomplishes with climate change mitigation (*high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades. Delaying mitigation actions may reduce options for climate-resilient pathways in the future. *{WGII SPM C-2, 20.2, 20.6.2}*

Box 3.4 | Co-benefits and Adverse Side effects

A government policy or a measure intended to achieve one objective often affects other objectives, either positively or negatively. For example, mitigation policies can influence local air quality (see Figure 3.5). When the effects are positive they are called 'co-benefits', also referred to as 'ancillary benefits'. Negative effects are referred to as 'adverse side effects'. Some measures are labelled 'no or low regret' when their co-benefits are sufficient to justify their implementation, even in the absence of immediate direct benefits. Co-benefits and adverse side effects can be measured in monetary or non-monetary units. The effect of co-benefits and adverse side effects from climate policies on overall social welfare has not yet been quantitatively examined, with the exception of a few recent multi-objective studies. Many of these have not been well quantified, and effects can be case and site-specific as they will depend on local circumstances. *{WGII 11.9, 16.3.1, 17.2, 20.4.1, WGIII Box TS.11, 3.6, 5.7}*

Co-benefits of mitigation could affect achievement of other objectives, such as those related to energy security, air quality, efforts to address ecosystem impacts, income distribution, labour supply and employment and urban sprawl (see Table 4.2 and Table 4.5). In the absence of complementary policies, however, some mitigation measures may have adverse side effects (at least in the short term), for example on biodiversity, food security, energy access, economic growth and income distribution. The co-benefits of adaptation policies may include improved access to infrastructure and services, extended education and health systems, reduced disaster losses, better governance and others. *{WGII 4.4.4, 11.9, 15.2, 17.2, 20.3.3, 20.4.1, WGIII Box TS.11, 6.6}*

Comprehensive strategies in response to climate change that are consistent with sustainable development take into account the co-benefits, adverse side effects and risks that may arise from both adaptation and mitigation options. The assessment of overall social welfare impacts is complicated by this interaction between climate change response options and pre-existing non-climate policies. For example, in terms of air quality, the value of the extra tonne of sulfur dioxide (SO_2) reduction that occurs with climate change mitigation through reduced fossil fuel combustion depends greatly on the stringency of SO_2 control policies. If SO_2 policy is weak, the value of SO_2 reductions may be large, but if SO_2 policy is stringent, it may be near zero. Similarly, in terms of adaptation and disaster risk management, weak policies can lead to an adaptation deficit that increases human and economic losses from natural climate variability. 'Adaptation deficit' refers to the lack of capacity to manage adverse impacts of current climate variability. An existing adaptation deficit increases the benefits of adaptation policies that improve the management of climate variability and change. *{WGII 20.4.1, WGIII Box TS.11, 6.3}*

Topic 4: Adaptation and Mitigation

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself. Effective implementation depends on policies and cooperation at all scales and can be enhanced through integrated responses that link mitigation and adaptation with other societal objectives.

Topic 3 demonstrates the need and strategic considerations for both adaptation and global-scale mitigation to manage risks from climate change. Building on these insights, Topic 4 presents near-term response options that could help achieve such strategic goals. Near-term adaptation and mitigation actions will differ across sectors and regions, reflecting development status, response capacities and near- and long-term aspirations with regard to both climate and non-climate outcomes. Because adaptation and mitigation inevitably take place in the context of multiple objectives, particular attention is given to the ability to develop and implement integrated approaches that can build on co-benefits and manage trade-offs.

4.1 Common enabling factors and constraints for adaptation and mitigation responses

Adaptation and mitigation responses are underpinned by common enabling factors. These include effective institutions and governance, innovation and investments in environmentally sound technologies and infrastructure, sustainable livelihoods and behavioural and lifestyle choices.

Innovation and investments in environmentally sound infrastructure and technologies can reduce greenhouse gas (GHG) emissions and enhance resilience to climate change (*very high confidence*). Innovation and change can expand the availability and/or effectiveness of adaptation and mitigation options. For example, investments in low-carbon and carbon-neutral energy technologies can reduce the energy intensity of economic development, the carbon intensity of energy, GHG emissions, and the long-term costs of mitigation. Similarly, new technologies and infrastructure can increase the resilience of human systems while reducing adverse impacts on natural systems. Investments in technology and infrastructure rely on an enabling policy environment, access to finance and technology and broader economic development that builds capacity (Table 4.1, Section 4.4). *{WGII SPM C-2, Table SPM.1, Table TS.8, WGIII SPM.4.1, Table SPM.2, TS.3.1.1, TS 3.1.2, TS.3.2.1}*

Adaptation and mitigation are constrained by the inertia of global and regional trends in economic development, GHG emissions, resource consumption, infrastructure and settlement patterns, institutional behaviour and technology (*medium evidence, high agreement*). Such inertia may limit the capacity to reduce GHG emissions, remain below particular climate thresholds or avoid adverse impacts (Table 4.1). Some constraints may be overcome through new technologies, financial resources, increased institutional effectiveness and governance or changes in social and cultural attitudes and behaviours. *{WGII SPM C-1, WGIII SPM.3, SPM.4.2, Table SPM.2}*

Vulnerability to climate change, GHG emissions, and the capacity for adaptation and mitigation are strongly influenced by livelihoods, lifestyles, behaviour and culture (*medium evidence, medium agreement*) (Table 4.1). Shifts toward more energy-intensive lifestyles can contribute to higher energy and resource consumption, driving greater energy production and GHG emissions and increasing mitigation costs. In contrast, emissions can be substantially lowered through changes in consumption patterns (see 4.3 for details). The social acceptability and/or effectiveness of climate policies are influenced by the extent to which they incentivize or depend on regionally appropriate changes in lifestyles or behaviours. Similarly, livelihoods that depend on climate-sensitive sectors or resources may be particularly vulnerable to climate change and climate change policies. Economic development and urbanization of landscapes exposed to climate hazards may increase the exposure of human settlements and reduce the resilience of natural systems. *{WGII SPM A-2, SPM B-2, Table SPM.1, TS A-1, TS A-2, TS C-1, TS C-2, 16.3.2.7, WGIII SPM.4.2, TS.2.2, 4.2}*

For many regions and sectors, enhanced capacities to mitigate and adapt are part of the foundation essential for managing climate change risks (*high confidence*). Such capacities are place- and context-specific and therefore there is no single approach for reducing risk that is appropriate across all settings. For example, developing nations with low income levels have the lowest financial, technological and institutional capacities to pursue low-carbon, climate-resilient development pathways. Although developed nations generally have greater relative capacity to manage the risks of climate change, such capacity does not necessarily translate into the implementation of adaptation and mitigation options. *{WGII SPM B-1, SPM B-2, TS B-1, TS B-2, 16.3.1.1, 16.3.2, 16.5, WGIII SPM.5.1, TS.4.3, TS.4.5, 4.6}*

Improving institutions as well as enhancing coordination and cooperation in governance can help overcome regional constraints associated with mitigation, adaptation and disaster risk reduction (*very high confidence*). Despite the presence of a wide array of multilateral, national and sub-national institutions focused on adaptation and mitigation, global GHG emissions continue to increase and identified adaptation needs have not been adequately addressed. The implementation of effective adaptation and mitigation options may necessitate new institutions and institutional arrangements that span multiple scales (*medium confidence*) (Table 4.1). *{WGII SPM B-2, TS C-1, 16.3.2.4, 16.8, WGIII SPM.4.2.5, SPM.5.1, SPM.5.2, TS.1, TS.3.1.3, TS.4.1, TS.4.2, TS.4.4}*

4.2 Response options for adaptation

Adaptation options exist in all sectors, but their context for implementation and potential to reduce climate-related risks differs across sectors and regions. Some adaptation responses involve significant co-benefits, synergies and trade-offs. Increasing climate change will increase challenges for many adaptation options.

People, governments and the private sector are starting to adapt to a changing climate. Since the IPCC Fourth Assessment Report (AR4), understanding of response options has increased, with improved knowledge of their benefits, costs and links to sustainable development. Adaptation can take a variety of approaches depending on its context in vulnerability reduction, disaster risk management or proactive adaptation planning. These include (see Table 4.2 for examples and details):

- Social, ecological asset and infrastructure development
- Technological process optimization
- Integrated natural resources management
- Institutional, educational and behavioural change or reinforcement
- Financial services, including risk transfer
- Information systems to support early warning and proactive planning

There is increasing recognition of the value of social (including local and indigenous), institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Effective strategies and actions consider the potential for co-benefits and opportunities within wider strategic goals and development plans. *{WGII SPM A-2, SPM C-1, TS A-2, 6.4, 8.3, 9.4, 15.3}*

Opportunities to enable adaptation planning and implementation exist in all sectors and regions, with diverse potential and approaches depending on context. The need for adaptation along with associated challenges is expected to increase with climate change (*very high confidence*). Examples of key adaptation approaches for particular sectors, including constraints and limits, are summarized below. *{WGII SPM B, SPM C, 16.4, 16.6, 17.2, 19.6, 19.7, Table 16.3}*

Freshwater resources

Adaptive water management techniques, including scenario planning, learning-based approaches and flexible and low-regret solutions, can help adjust to uncertain hydrological changes due to climate change and their impacts (*limited evidence, high agreement*). Strategies include adopting integrated water management, augmenting supply, reducing the mismatch between water supply and demand, reducing non-climate stressors, strengthening institutional capacities and adopting more water-efficient technologies and water-saving strategies. *{WGII SPM B-2, Assessment Box SPM.2 Table 1, SPM B-3, 3.6, 22.3–22.4, 23.4, 23.7, 24.4, 27.2–27.3, Box 25-2}*

Terrestrial and freshwater ecosystems

Management actions can reduce but not eliminate risks of impacts to terrestrial and freshwater ecosystems due to climate change (*high confidence*). Actions include maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods) and reduction of other stressors. Management options that reduce non-climatic stressors, such as habitat modification, overexploitation, pollution and invasive species, increase the inherent capacity of ecosystems and their species to adapt to a changing climate. Other options include improving early warning systems and associated response systems. Enhanced connectivity of vulnerable ecosystems may also assist autonomous adaptation. Translocation of species is controversial and is expected to become less feasible where whole ecosystems are at risk. *{WGII SPM B-2, SPM B-3, Figure SPM.5, Table TS.8, 4.4, 25.6, 26.4, Box CC-RF}*

Coastal systems and low-lying areas

Increasingly, coastal adaptation options include those based on integrated coastal zone management, local community participation, ecosystems-based approaches and disaster risk reduction, mainstreamed into relevant strategies and management plans (*high confidence*). The analysis and implementation of coastal adaptation has progressed more significantly in developed countries than in developing countries (*high confidence*). The relative costs of coastal adaptation are expected to vary strongly among and within regions and countries. *{WGII SPM B-2, SPM B-3, 5.5, 8.3, 22.3, 24.4, 26.8, Box 25-1}*

Marine systems and oceans

Marine forecasting and early warning systems as well as reducing non-climatic stressors have the potential to reduce risks for some fisheries and aquaculture industries, but options for unique ecosystems such as coral reefs are limited (*high confidence*). Fisheries and some aquaculture industries with high-technology and/or large investments have high capacities for adaptation due to greater development of environmental monitoring, modelling and resource assessments. Adaptation options include large-scale translocation of industrial fishing activities and flexible management that can react to variability and change. For smaller-scale fisheries and nations with limited adaptive capacities, building social resilience, alternative livelihoods and occupational flexibility are important strategies. Adaptation options for coral reef systems are generally limited to reducing other stressors, mainly by enhancing water quality and limiting pressures from tourism and fishing, but their efficacy will be severely reduced as thermal stress and ocean acidification increase. *{WGII SPM B-2, SPM Assessment Box SPM.2 Table 1, TS B-2, 5.5, 6.4, 7.5, 25.6.2, 29.4, 30.6-7, Box CC-MB, Box CC-CR}*

Food production system/Rural areas

Adaptation options for agriculture include technological responses, enhancing smallholder access to credit and other critical production resources, strengthening institutions at local to regional levels and improving market access through trade reform (*medium confidence*). Responses to decreased food production and quality include: developing new crop varieties adapted to changes in CO_2, temperature, and drought; enhancing the capacity for climate risk management; and offsetting economic impacts of land use change. Improving financial support and investing in the production of small-scale farms can also provide benefits. Expanding agricultural markets and improving the predictability and reliability of the world trading system could result in reduced market volatility and help manage food supply shortages caused by climate change. *{WGII SPM B-2, SPM B-3, 7.5, 9.3, 22.4, 22.6, 25.9, 27.3}*

Urban areas/Key economic sectors and services

Urban adaptation benefits from effective multi-level governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector and appropriate financing and institutional development (*medium confidence*). Enhancing the capacity of low-income groups and vulnerable communities and their partnerships with local governments can also be an effective urban climate adaptation strategy. Examples of adaptation mechanisms include large-scale public-private risk reduction initiatives and economic diversification and government insurance for the non-diversifiable portion of risk. In some locations, especially at the upper end of projected climate changes, responses could also require transformational changes such as managed retreat. *{WGII SPM B-2, 8.3–8.4, 24.4, 24.5, 26.8, Box 25-9}*

Human health, security and livelihoods

Adaptation options that focus on strengthening existing delivery systems and institutions, as well as insurance and social protection strategies, can improve health, security and livelihoods in the near term (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programmes that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response and alleviate poverty (*very high confidence*). Options to address heat related mortality include health warning systems linked to response strategies, urban planning and improvements to the built environment to reduce heat stress. Robust institutions can manage many transboundary impacts of climate change to reduce risk of conflicts over shared natural resources. Insurance programmes, social protection measures and disaster risk management may enhance long-term livelihood resilience among the poor and marginalized people, if policies address multi-dimensional poverty. *{WGII SPM B-2, SPM B-3, 8.2, 10.8, 11.7–11.8, 12.5–12.6, 22.3, 23.9, 25.8, 26.6, Box CC-HS}*

Significant co-benefits, synergies and trade-offs exist between adaptation and mitigation and among different adaptation responses; interactions occur both within and across regions and sectors (*very high confidence*). For example, investments in crop varieties adapted to climate change can increase the capacity to cope with drought, and public health measures to address vector-borne diseases can enhance the capacity of health systems to address other challenges. Similarly, locating infrastructure away from low-lying coastal areas helps settlements and ecosystems adapt to sea level rise while also protecting against tsunamis. However, some adaptation options may have adverse side effects that imply real or perceived trade-offs with other adaptation objectives (see Table 4.3 for examples), mitigation objectives or broader development goals. For example, while protection of ecosystems can assist adaptation to climate change and enhance carbon storage, increased use of air conditioning to maintain thermal comfort in buildings or the use of desalination to enhance water resource security can increase energy demand, and therefore, GHG emissions. *{WGII SPM B-2, SPM C-1, 5.4.2, 16.3.2.9, 17.2.3.1, Table 16-2}*

4.3 Response options for mitigation

Mitigation options are available in every major sector. Mitigation can be more cost-effective if using an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize energy supply, reduce net emissions and enhance carbon sinks in land-based sectors.

A broad range of sectoral mitigation options is available that can reduce GHG emission intensity, improve energy intensity through enhancements of technology, behaviour, production and resource efficiency and enable structural changes or changes in activity. In addition, direct options in agriculture, forestry and other land use (AFOLU) involve reducing CO_2 emissions by reducing deforestation, forest degradation and forest fires; storing carbon in terrestrial systems (for example, through afforestation); and providing bioenergy feedstocks. Options to reduce non-CO_2 emissions exist across all sectors but most notably in agriculture, energy supply and industry. An overview of sectoral mitigation options and potentials is provided in Table 4.4. *{WGIII TS 3.2.1}*

Well-designed systemic and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors with efforts in one sector affecting the need for mitigation in others (*medium confidence*). In baseline scenarios without new mitigation policies, GHG emissions are projected to grow in all sectors, except for net CO_2 emissions in the AFOLU sector (Figure 4.1, left panel). Mitigation scenarios reaching around 450 ppm CO_2-eq[42] concentration by 2100[43] (*likely* to limit warming to 2°C above pre-industrial levels) show large-scale global changes in the energy supply sector (Figure 4.1, middle and right panel). While rapid decarbonization of energy supply generally entails more flexibility for end-use and AFOLU sectors, stronger demand reductions lessen the mitigation challenge for the supply side of the energy system (Figures 4.1 and 4.2). There are thus strong interdependencies across sectors and the resulting distribution of the mitigation effort is strongly influenced by the availability and performance of future technologies, particularly BECCS and large scale afforestation (Figure 4.1, middle and right panel). The next two decades present a window of opportunity for mitigation in urban areas, as a large portion of the world's urban areas will be developed during this period. *{WGIII SPM.4.2, TS.3.2}*

Decarbonizing (i.e., reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low stabilization levels (of about 450 to about 500 ppm CO_2-eq, at least *about as likely as not* to limit warming to 2°C above pre-industrial levels) (*medium evidence, high agreement*). In most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the industry, buildings and transport sectors. In scenarios reaching 450 ppm CO_2-eq concentrations by 2100, global CO_2 emissions from the energy supply sector are projected to decline over the next decade and are characterized by reductions of 90% or more below 2010 levels between 2040 and 2070. *{WGIII SPM.4.2, 6.8, 7.11}*

Efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy in scenarios reaching atmospheric CO_2-eq concentrations of about 450 to about 500 ppm by 2100 (*robust evidence, high agreement*). Near-term reductions in energy demand are an important element of cost-effective mitigation strategies, provide more flexibility for reducing carbon intensity in the energy supply sector, hedge against related supply-side risks, avoid lock-in to carbon-intensive infrastructures and are associated with important co-benefits (Figure 4.2, Table 4.4). Emissions can be substantially lowered through changes in consumption patterns (e.g., mobility demand and mode, energy use in households, choice of longer-lasting products) and dietary change and reduction in food wastes. A number of options including monetary and non-monetary incentives as well as information measures may facilitate behavioural changes. *{WGIII SPM.4.2}*

Decarbonization of the energy supply sector (i.e., reducing the carbon intensity) requires upscaling of low- and zero-carbon electricity generation technologies (*high confidence*). In the majority of low-concentration stabilization scenarios (about 450 to about 500 ppm CO_2-eq , at least *about as likely as not* to limit warming to 2°C above pre-industrial levels), the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and CCS, including BECCS) increases from the current share of approximately 30% to more than 80% by 2050 and 90% by 2100, and fossil fuel power generation without CCS is phased out almost entirely by 2100. Among these low-carbon technologies, a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale since AR4 (*robust evidence, high agreement*) and nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle power plants or combined heat and power plants, provided that natural gas is available and the fugitive emissions associated with extraction and supply are low or mitigated. *{WGIII SPM.4.2}*

Behaviour, lifestyle and culture have a considerable influence on energy use and associated emissions, with high mitigation potential in some sectors, in particular when complementing technological and structural change (*medium evidence, medium agreement*). In the transport sector, technical and behavioural mitigation measures for all modes, plus new infrastructure and urban redevelopment investments, could reduce final energy demand significantly below baseline levels (*robust evidence, medium agreement*) (Table 4.4). While opportunities for switching to low-carbon fuels exist, the rate of decarbonization in the transport sector might be constrained by challenges associated with energy storage and the relatively low energy density of low-carbon transport fuels (*medium confidence*). In the building sector, recent advances in technologies, know-how and policies provide opportunities to stabilize or reduce global energy use to about current levels by mid-century. In addition, recent improvements in performance and costs make very low energy construction and retrofits of buildings economically attractive, sometimes even at net negative costs (*robust evidence, high agreement*). In the industry sector, improvements in GHG emission efficiency and in the efficiency of material use, recycling and reuse of materials and products, and overall reductions in product demand (e.g., through a more intensive use of products) and service demand could, in addition to energy efficiency, help reduce GHG emissions below the baseline level. Prevalent approaches for promoting energy efficiency in industry include information programmes followed by economic instruments, regulatory approaches and voluntary actions. Important options for mitigation in waste management are waste reduction, followed by re-use, recycling and energy recovery (*robust evidence, high agreement*). *{WGIII SPM.4.2, Box TS.12, TS.3.2}*

The most cost-effective mitigation options in forestry are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions. In agriculture, the most cost-effective mitigation options are cropland management, grazing land management and restoration of organic soils (*medium evidence, high agreement*). About a third of mitigation potential in forestry can be achieved at a cost <20 USD/tCO_2-eq emission. Demand-side measures, such as changes in diet and reductions of losses in the food supply chain, have a significant, but uncertain, potential to reduce GHG emissions from food production (*medium evidence, medium agreement*). *{WGIII SPM 4.2.4}*

Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (*robust evidence, medium agreement*). Evidence suggests that bioenergy options with low lifecycle emissions, some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land use management and governance. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. *{WGIII SPM.4.2}*

Mitigation measures intersect with other societal goals, creating the possibility of co-benefits or adverse side-effects. These intersections, if well-managed, can strengthen the basis for undertaking climate mitigation actions (*robust evidence, medium agreement*). Mitigation can positively or negatively influence the achievement of other societal goals, such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development (see also Section 4.5). On the other hand, policies towards other societal goals can influence the achievement of mitigation and adaptation objectives. These influences can be substantial, although sometimes difficult to quantify, especially in welfare terms. This multi-objective perspective is important in part because it helps to identify areas where support for policies that advance multiple goals will be robust. Potential co-benefits and adverse side effects of the main sectoral mitigation measures are summarized in Table 4.5. Overall, the potential for co-benefits for energy end-use measures outweigh the potential for adverse side effects, whereas the evidence suggests this may not be the case for all energy supply and AFOLU measures. *{WGIII SPM.2}*

4.4 Policy approaches for adaptation and mitigation, technology and finance

Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national. Policies across all scales supporting technology development, diffusion and transfer, as well as finance for responses to climate change, can complement and enhance the effectiveness of policies that directly promote adaptation and mitigation.

4.4.1 International and regional cooperation on adaptation and mitigation

Because climate change has the characteristics of a collective action problem at the global scale (see 3.1), effective mitigation will not be achieved if individual agents advance their own interests independently, even though mitigation can also have local co-benefits. Cooperative responses, including international cooperation, are therefore required to effectively mitigate GHG emissions and address other climate change issues. While adaptation focuses primarily on local to national scale outcomes, its effectiveness can be enhanced through coordination across governance scales, including international cooperation. In fact, international cooperation has helped to facilitate the creation of adaptation strategies, plans, and actions at national, sub-national, and local levels. A variety of climate policy instruments have been employed, and even more could be employed, at international and regional levels to address mitigation and to support and promote adaptation at national and sub-national scales. Evidence suggests that outcomes seen as equitable can lead to more effective cooperation. *{WGII SPM C-1, 2.2, 15.2, WGIII 13.ES, 14.3, 15.8, SREX SPM, 7.ES}*

The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum focused on addressing climate change, with nearly universal participation. UNFCCC activities since 2007, which include the 2010 Cancún Agreements and the 2011 Durban Platform for Enhanced Action, have sought to enhance actions under the Convention, and have led to an increasing number of institutions and other arrangements for international climate change cooperation. Other institutions organized at different levels of governance have resulted in diversifying international climate change cooperation. *{WGIII SPM.5.2, 13.5}*

Existing and proposed international climate change cooperation arrangements vary in their focus and degree of centralization and coordination. They span: multilateral agreements, harmonized national policies and decentralized but coordinated national policies, as well as regional and regionally-coordinated policies (see Figure 4.3). *{WGIII SPM.5.2}*

While a number of new institutions are focused on adaptation funding and coordination, adaptation has historically received less attention than mitigation in international climate policy (*robust evidence, medium agreement*). Inclusion of adaptation is increasingly important to reduce the risk from climate change impacts and may engage a greater number of countries. *{WGIII 13.2, 13.3.3, 13.5.1.1, 13.14}*

The Kyoto Protocol offers lessons towards achieving the ultimate objective of the UNFCCC, particularly with respect to participation, implementation, flexibility mechanisms, and environmental effectiveness (*medium evidence, low agreement*). The Protocol was the first binding step toward implementing the principles and goals provided by the UNFCCC. According to national GHG inventories through 2012 submitted to the UNFCCC by October 2013, Annex B Parties with quantified emission limitations (and reduction obligations) in aggregate may have bettered their collective emission reduction target in the first commitment period,[44] but some emissions reductions that would have occurred even in its absence were also counted. The Protocol's Clean Development Mechanism (CDM) created a market for emissions offsets from developing countries, the purpose being two-fold: to help Annex I countries fulfill their commitments and to assist non-Annex I countries achieve sustainable development. The CDM generated Certified Emission Reductions (offsets) equivalent to emissions of over 1.4 $GtCO_2$-eq[42] by October 2013, led to significant project investments, and generated investment flows for a variety of functions, including the UNFCCC Adaptation Fund. However, its environmental effectiveness has been questioned by some, particularly in regard to its early years, due to concerns about the additionality of projects (that is, whether projects bring about emissions that are different from business as usual (BAU) circumstances), the validity of baselines, and the possibility of emissions leakage (*medium evidence, medium agreement*). Such concerns about additionality are common to any emission-reduction-credit (offset) program, and are not specific to the CDM. Due to market forces, the majority of single CDM projects have been concentrated in a limited number of countries, while Programmes of Activities, though less frequent, have been more evenly distributed. In addition, the Kyoto Protocol created two other 'flexibility mechanisms': Joint Implementation and International Emissions Trading. *{WGIII SPM.5.2, Table TS.9, 13.7, 13.13.1.1, 14.3}*

Several conceptual models for effort-sharing have been identified in research. However, realized distributional impacts from actual international cooperative agreements depend not only on the approach taken but also on criteria applied to operationalize equity and the manner in which developing countries' emissions reduction plans are financed. *{WGIII 4.6, 13.4}*

Policy linkages among regional, national and sub-national climate policies offer potential climate change mitigation benefits (*medium evidence, medium agreement*). Linkages have been established between carbon markets and in principle could also be established between and among a heterogeneous set of policy instruments including non-market-based policies, such as performance standards. Potential advantages include lower mitigation costs, decreased emission leakage and increased market liquidity. *{WGIII SPM.5.2, 13.3, 13.5, 13.6, 13.7, 14.5}*

Regional initiatives between national and global scales are being developed and implemented, but their impact on global mitigation has been limited to date (*medium confidence*). Some climate policies could be more environmentally and economically effective if implemented across broad regions, such as by embodying mitigation objectives in trade agreements or jointly constructing infrastructures that facilitate reduction in carbon emissions. *{WGIII Table TS.9, 13.13, 14.4, 14.5}*

International cooperation for supporting adaptation planning and implementation has assisted in the creation of adaptation strategies, plans and actions at national, sub-national and local levels (*high confidence*). For example, a range of multilateral and regionally targeted funding mechanisms have been established for adaptation; UN agencies, international development organizations and non-governmental organisations (NGOs) have provided information, methodologies and guidelines; and global and regional initiatives supported and promoted the creation of national adaptation strategies in both developing and developed countries. Closer integration of disaster risk reduction and climate change adaptation at the international level, and the mainstreaming of both into international development assistance, may foster greater efficiency in the use of resources and capacity. However, stronger efforts at the international level do not necessarily lead to substantive and rapid results at the local level. *{WGII 15.2, 15.3, SREX SPM, 7.4, 8.2, 8.5}*

4.4.2 National and sub-national policies

4.4.2.1 Adaptation

Adaptation experience is accumulating across regions in the public and private sector and within communities (*high confidence*). Adaptation options adopted to date (see Table 4.6) emphasize incremental adjustments and co-benefits and are starting to emphasize flexibility and learning (*medium evidence, medium agreement*). Most assessments of adaptation have been restricted to impacts, vulnerability and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions (*medium evidence, high agreement*). *{WGII SPM A-2, TS A-2}*

National governments play key roles in adaptation planning and implementation (*robust evidence, high agreement*). There has been substantial progress since the AR4 in the development of national adaptation strategies and plans. This includes National Adaptation Programmes of Action (NAPAs) by least developed countries, the National Adaptation Plan (NAP) process, and strategic frameworks for national adaptation in Organisation for Economic Co-operation and Development (OECD) countries. National governments can coordinate adaptation efforts of local and sub-national governments, for example by protecting vulnerable groups, by supporting economic diversification, and by providing information, policy and legal frameworks and financial support. *{WGII SPM C-1, 15.2}*

While local government and the private sector have different functions, which vary regionally, they are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence*, *high agreement*). There is a significant increase in the number of planned adaptation responses at the local level in rural and urban communities of developed and developing countries since the AR4. However, local councils and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Steps for mainstreaming adaptation into local decision-making have been identified but challenges remain in their implementation. Hence, scholars stress the important role of linkages with national and sub-national levels of government as well as partnerships among public, civic and private sectors in implementing local adaptation responses. *{WGII SPM A-2, SPM C-1, 14.2, 15.2}*

Institutional dimensions of adaptation governance, including the integration of adaptation into planning and decision-making, play a key role in promoting the transition from planning to implementation of adaptation (*robust evidence, high agreement*). The most commonly emphasized institutional barriers or enablers for adaptation planning and implementation are: 1) multilevel institutional co-ordination between different political and administrative levels in society; 2) key actors, advocates and champions initiating, mainstreaming and sustaining momentum for climate adaptation; 3) horizontal interplay between sectors, actors and policies operating at similar administrative levels; 4) political dimensions in planning and implementation; and 5) coordination between formal governmental, administrative agencies and private sectors and stakeholders to increase efficiency, representation and support for climate adaptation measures. *{WGII 15.2, 15.5, 16.3, Box 15-1}*

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include public-private finance partnerships, loans, payments for environmental services, improved resource pricing, charges and subsidies, norms and regulations and risk sharing and transfer mechanisms. Risk financing mechanisms in the public and private sector, such as insurance and risk pools, can contribute to increasing resilience, but without attention to major design challenges, they can also provide disincentives, cause market failure and decrease equity. Governments often play key roles as regulators, providers or insurers of last resort. *{WGII SPM C-1}*

4.4.2.2 Mitigation

There has been a considerable increase in national and sub-national mitigation plans and strategies since AR4. In 2012, 67% of global GHG emissions[42] were subject to national legislation or strategies versus 45% in 2007. However, there has not yet been a substantial deviation in global emissions from the past trend. These plans and strategies are in their early stages of development and implementation in many countries, making it difficult to assess their aggregate impact on future global emissions (*medium evidence, high agreement*). *{WGIII SPM.5.1}*

Since AR4, there has been an increased focus on policies designed to integrate multiple objectives, increase co-benefits and reduce adverse side effects (*high confidence*). Governments often explicitly reference co-benefits in climate and sectoral plans and strategies. *{WGIII SPM.5.1}*

Sector-specific policies have been more widely used than economy-wide policies (Table 4.7) (*medium evidence, high agreement*). Although most economic theory suggests that economy-wide policies for mitigation would be more cost-effective than sector-specific policies, administrative and political barriers may make economy-wide policies harder to design and implement than sector-specific policies. The latter may be better suited to address barriers or market failures specific to certain sectors and may be bundled in packages of complementary policies *{WGIII SPM.5.1}*

In principle, mechanisms that set a carbon price, including cap and trade systems and carbon taxes, can achieve mitigation in a cost-effective way, but have been implemented with diverse effects due in part to national circumstances as well as policy design. The short-run environmental effects of cap and trade systems have been limited as a result of loose caps or caps that have not proved to be constraining (*limited evidence, medium agreement*). In some countries, tax-based policies specifically aimed at reducing GHG emissions—alongside technology and other policies—have helped to weaken the link between GHG emissions and gross domestic product (GDP) (*high confidence*). In addition, in a large group of countries, fuel taxes (although not necessarily designed for the purpose of mitigation) have had effects that are akin to sectoral carbon taxes (*robust evidence, medium agreement*). Revenues from carbon taxes or auctioned emission allowances are used in some countries to reduce other taxes and/or to provide transfers to low-income groups. This illustrates the general principle that mitigation policies that raise government revenue generally have lower social costs than approaches which do not. *{WGIII SPM.5.1}*

Economic instruments in the form of subsidies may be applied across sectors, and include a variety of policy designs, such as tax rebates or exemptions, grants, loans and credit lines. An increasing number and variety of RE policies including subsidies—motivated by many factors—have driven escalated growth of RE technologies in recent years. Government policies play a crucial role in accelerating the deployment of RE technologies. Energy access and social and economic development have been the primary drivers in most developing countries whereas secure energy supply and environmental concerns have been most important in developed countries. The focus of policies is broadening from a concentration primarily on RE electricity to include RE heating and cooling and transportation. *{SRREN SPM.7}*

The reduction of subsidies for GHG-related activities in various sectors can achieve emission reductions, depending on the social and economic context (*high confidence*). While subsidies can affect emissions in many sectors, most of the recent literature has focused on subsidies for fossil fuels. Since AR4 a small but growing literature based on economy-wide models has projected that complete removal of subsidies to fossil fuels in all countries could result in reductions in global aggregate emissions by mid-century (*medium evidence, medium agreement*). Studies vary in methodology, the type and definition of subsidies and the time frame for phase out considered. In particular, the studies assess the impacts of complete removal of all fossil fuel subsides without seeking to assess which subsidies are wasteful and inefficient, keeping in mind national circumstances. *{WGIII SPM.5.1}*

Regulatory approaches and information measures are widely used and are often environmentally effective (*medium evidence, medium agreement*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. *{WGIII SPM.5.1}*

Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters. The effect on natural gas export revenues is more uncertain. The availability of CCS would reduce the adverse effect of mitigation on the value of fossil fuel assets (*medium confidence*). *{WGIII SPM.5.1}*

Interactions between or among mitigation policies may be synergistic or may have no additive effect on reducing emissions (*medium evidence, high agreement*). For instance, a carbon tax can have an additive environmental effect to policies such as subsidies for the supply of RE. By contrast, if a cap and trade system has a sufficiently stringent cap to affect emission-related decisions, then other policies have no further impact on reducing emissions (although they may affect costs and possibly the viability of more stringent future targets) (*medium evidence, high agreement*). In either case, additional policies may be needed to address market failures relating to innovation and technology diffusion. *{WGIII SPM.5.1}*

Sub-national climate policies are increasingly prevalent, both in countries with national policies and in those without. These policies include state and provincial climate plans combining market, regulatory and information instruments, and sub-national cap-and-trade systems. In addition, transnational cooperation has arisen among sub-national actors, notably among institutional investors, NGOs seeking to govern carbon offset markets, and networks of cities seeking to collaborate in generating low-carbon urban development. *{WGIII 13.5.2, 15.2.4, 15.8}*

Co-benefits and adverse side effects of mitigation could affect achievement of other objectives such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development: *{WGIII SPM.2}*

- Mitigation scenarios reaching about 450 or 500 ppm CO_2-equivalent by 2100 show reduced costs for achieving air quality and energy security objectives, with significant co-benefits for human health, ecosystem impacts and sufficiency of resources and resilience of the energy system. *{WGIII SPM.4.1}*

- Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations (*low confidence*). These potential adverse side effects can be avoided with the adoption of complementary policies such as income tax rebates or other benefit transfer mechanisms (*medium confidence*). The costs of achieving nearly universal access to electricity and clean fuels for cooking and heating are projected to be between USD 72 to 95 billion per year until 2030 with minimal effects on GHG emissions (*limited evidence, medium agreement*) and multiple benefits in health and air pollutant reduction (*high confidence*). *{WGIII SPM.5.1}*

Whether or not side effects materialize, and to what extent side effects materialize, will be case- and site-specific, and depend on local circumstances and the scale, scope and pace of implementation. Many co-benefits and adverse side effects have not been well-quantified. *{WGIII SPM.4.1}*

4.4.3 Technology development and transfer

Technology policy (development, diffusion and transfer) complements other mitigation policies across all scales from international to sub-national, but worldwide investment in research in support of GHG mitigation is small relative to overall public research spending (*high confidence*). Technology policy includes technology-push (e.g., publicly-funded R&D) and demand-pull (e.g., governmental procurement programmes). Such policies address a pervasive market failure because, in the absence of government policy such as patent protection, the invention of new technologies and practices from R&D efforts has aspects of a public good and thus tends to be under-provided by market forces alone. Technology support policies have promoted substantial innovation and diffusion of new technologies, but the cost-effectiveness of such policies is often difficult to assess. Technology policy can increase incentives for participation and compliance with international cooperative efforts, particularly in the long run. *{WGIII SPM.5.1, 2.6.5, 3.11, 13.9, 13.12, 15.6.5}*

Many adaptation efforts also critically rely on diffusion and transfer of technologies and management practices, but their effective use depends on a suitable institutional, regulatory, social and cultural context (*high confidence*). Adaptation technologies are often familiar and already applied elsewhere. However, the success of technology transfer may involve not only the provision of finance and information, but also strengthening of policy and regulatory environments and capacities to absorb, employ and improve technologies appropriate to local circumstances. *{WGII 15.4}*

4.4.4 Investment and finance

Substantial reductions in emissions would require large changes in investment patterns (*high confidence*). Mitigation scenarios in which policies stabilize atmospheric concentrations (without overshoot) in the range from 430 to 530 ppm CO_2-eq by 2100[45] lead to substantial shifts in annual investment flows during the period 2010–2029 compared to baseline scenarios. Over the next two decades (2010–2029), annual investments in conventional fossil fuel technologies associated with the electricity supply sector are projected to decline in the scenarios by about USD 30 (2 to 166) billion (median: –20% compared to 2010) while annual investment in low carbon electricity supply (i.e., renewables, nuclear and electricity with CCS) is projected to rise in the scenarios by about USD 147 (31 to 360) billion (median: +100% compared to 2010) (*limited evidence, medium agreement*). In addition, annual incremental energy efficiency investments in transport, industry and buildings is projected to rise in the scenarios by about USD 336 (1 to 641) billion. Global total annual investment in the energy system is presently about USD 1,200 billion. This number includes only energy supply of electricity and heat and respective upstream and downstream activities. Energy efficiency investment or underlying sector investment is not included (Figure 4.4). *{WGIII SPM.5.1, 16.2}*

There is no widely agreed definition of what constitutes climate finance, but estimates of the financial flows associated with climate change mitigation and adaptation are available. See Figure 4.5 for an overview of climate finance flows. Published assessments of all current annual financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to climate change and climate variability show USD 343 to 385 billion per year

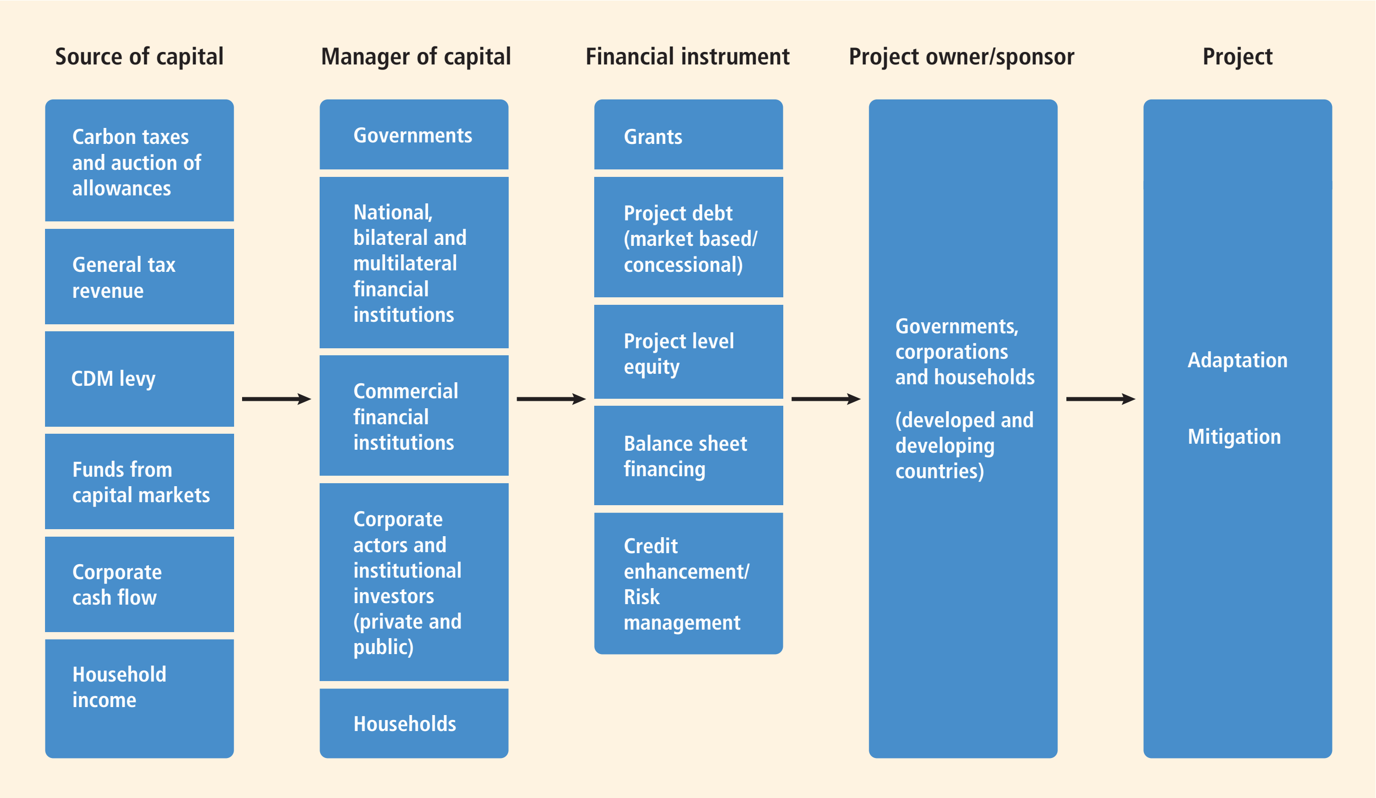

Figure 4.5 | Overview of climate finance flows. Note: Capital should be understood to include all relevant financial flows. The size of the boxes is not related to the magnitude of the financial flow. *{WGIII Figure TS.40}*

globally (*medium confidence*). Out of this, total public climate finance that flowed to developing countries is estimated to be between USD 35 and 49 billion per year in 2011 and 2012 (*medium confidence*). Estimates of international private climate finance flowing to developing countries range from USD 10 to 72 billion per year including foreign direct investment as equity and loans in the range of USD 10 to 37 billion per year over the period of 2008–2011 (*medium confidence*). *{WGIII SPM.5.1}*

In many countries, the private sector plays central roles in the processes that lead to emissions as well as to mitigation and adaptation. Within appropriate enabling environments, the private sector, along with the public sector, can play an important role in financing mitigation and adaptation (*medium evidence, high agreement*). The share of total mitigation finance from the private sector, acknowledging data limitations, is estimated to be on average between two-thirds and three-fourths on the global level (2010–2012) (*limited evidence, medium agreement*). In many countries, public finance interventions by governments and international development banks encourage climate investments by the private sector and provide finance where private sector investment is limited. The quality of a country's enabling environment includes the effectiveness of its institutions, regulations and guidelines regarding the private sector, security of property rights, credibility of policies and other factors that have a substantial impact on whether private firms invest in new technologies and infrastructures. Dedicated policy instruments and financial arrangements, for example, credit insurance, feed-in tariffs, concessional finance or rebates provide an incentive for mitigation investment by improving the return adjusted for the risk for private actors. Public-private risk reduction initiatives (such as in the context of insurance systems) and economic diversification are examples of adaptation action enabling and relying on private sector participation. *{WGII SPM B-2, SPM C-1, WGIII SPM.5.1}*

Financial resources for adaptation have become available more slowly than for mitigation in both developed and developing countries. Limited evidence indicates that there is a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). Potential synergies between international finance for disaster risk management and adaptation to climate change have not yet been fully realized (*high confidence*). There is a need for better assessment of global adaptation costs, funding and investment. Studies estimating the global cost of adaptation are characterized by shortcomings in data, methods and coverage (*high confidence*). *{WGII SPM C-1, 14.2, SREX SPM}*

4.5 Trade-offs, synergies and integrated responses

There are many opportunities to link mitigation, adaptation and the pursuit of other societal objectives through integrated responses (*high confidence*). Successful implementation relies on relevant tools, suitable governance structures and enhanced capacity to respond (*medium confidence*).

A growing evidence base indicates close links between adaptation and mitigation, their co-benefits and adverse side effects, and recognizes sustainable development as the overarching context for climate policy (see Sections 3.5, 4.1, 4.2 and 4.3). Developing tools to address these linkages is critical to the success of climate policy in the context of sustainable development (see also Sections 4.4 and 3.5). This section presents examples of integrated responses in specific policy arenas, as well as some of the factors that promote or impede policies aimed at multiple objectives.

Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, encompassing connections among human health, water, energy, land use and biodiversity (*very high confidence*). Mitigation can support the achievement of other societal goals, such as those related to human health, food security, environmental quality, energy access, livelihoods and sustainable development, although there can also be negative effects. Adaptation measures also have the potential to deliver mitigation co-benefits, and vice versa, and support other societal goals, though trade-offs can also arise. *{WGII SPM C-1, SPM C-2, 8.4, 9.3–9.4, 11.9, Box CC-WE, WGIII Table TS.3, Table TS.4, Table TS.5, Table TS.6, Table TS.7}*

Integration of adaptation and mitigation into planning and decision-making can create synergies with sustainable development (*high confidence*). Synergies and trade-offs among mitigation and adaptation policies and policies advancing other societal goals can be substantial, although sometimes difficult to quantify especially in welfare terms (see also Section 3.5). A multi-objective approach to policy-making can help manage these synergies and trade-offs. Policies advancing multiple goals may also attract greater support. *{WGII SPM C-1, SPM C-2, 20.3, WGIII 1.2.1, 3.6.3, 4.3, 4.6, 4.8, 6.6.1}*

Effective integrated responses depend on suitable tools and governance structures, as well as adequate capacity (*medium confidence*). Managing trade-offs and synergies is challenging and requires tools to help understand interactions and support decision-making at local and regional scales. Integrated responses also depend on governance that enables coordination across scales and sectors, supported by appropriate institutions. Developing and implementing suitable tools and governance structures often requires upgrading the human and institutional capacity to design and deploy integrated responses. *{WGII SPM C-1, SPM C-2, 2.2, 2.4, 15.4, 15.5, 16.3, Table 14-1, Table 16-1, WGIII TS.1, TS.3, 15.2}*

An integrated approach to energy planning and implementation that explicitly assesses the potential for co-benefits and the presence of adverse side effects can capture complementarities across multiple climate, social and environmental objectives (*medium confidence*). There are strong interactive effects across various energy policy objectives, such as energy security, air quality, health and energy access (see Figure 3.5) and between a range of social and environmental objectives and climate mitigation objectives (see Table 4.5). An integrated approach can be assisted by tools such as cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and expected utility theory. It also requires appropriate coordinating institutions. *{WGIII Figure SPM.6, TS.1, TS.3}*

Explicit consideration of interactions among water, food, energy and biological carbon sequestration plays an important role in supporting effective decisions for climate resilient pathways (*medium evidence, high agreement*). Both biofuel-based power generation and large-scale afforestation designed to mitigate climate change can reduce catchment run-off, which may conflict with alternative water uses for food production, human consumption or the maintenance of ecosystem function and services (see also Box 3.4). Conversely, irrigation can increase the climate resilience of food and fibre production but reduces water availability for other uses. *{WGII Box CC-WE, Box TS.9}*

An integrated response to urbanization provides substantial opportunities for enhanced resilience, reduced emissions and more sustainable development (*medium confidence*). Urban areas account for more than half of global primary energy use and energy-related CO_2 emissions (*medium evidence, high agreement*) and contain a high proportion of the population and economic activities at risk from climate change. In rapidly growing and urbanizing regions, mitigation strategies based on spatial planning and efficient infrastructure supply can avoid the lock-in of high emission patterns. Mixed-use zoning, transport-oriented development, increased density and co-located jobs and homes can reduce direct and indirect energy use across sectors. Compact development of urban spaces and intelligent densification can preserve land carbon stocks and land for agriculture and bioenergy. Reduced energy and water consumption in urban areas through greening cities and recycling water are examples of mitigation actions with adaptation benefits. Building resilient infrastructure systems can reduce vulnerability of urban settlements and cities to coastal flooding, sea level rise and other climate-induced stresses. *{WGII SPM B-2, SPM C-1, TS B-2, TS C-1, TS C-2, WGIII SPM.4.2.5, TS.3}*