Climate change

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Editor's Note: This article was compiled and edited by **Mohan Munasinghe**, **Cutler J. Cleveland**, and **Laura De Angelo**. In the interests of maintaining scientific accuracy, this article is derived directly from material in the Synthesis Report and the Technical Summary of Working Group I, "The Physical Science Basis," of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The full Synthesis Report and Technical Summary are reproduced in **this Encyclopedia**, and are available in their **original PDF forms** at the IPCC web site. The relevant IPCC Lead Authors are listed in the **Acknowledgments** at the end of this article.

Introduction

Climate change refers to a change in the state of the climate that can be identified by changes in the average and/or the variability of its properties (e.g., **temperature**, **precipitation**), and that persists for an extended period, typically decades or longer. Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the **atmosphere** or in **land use**.

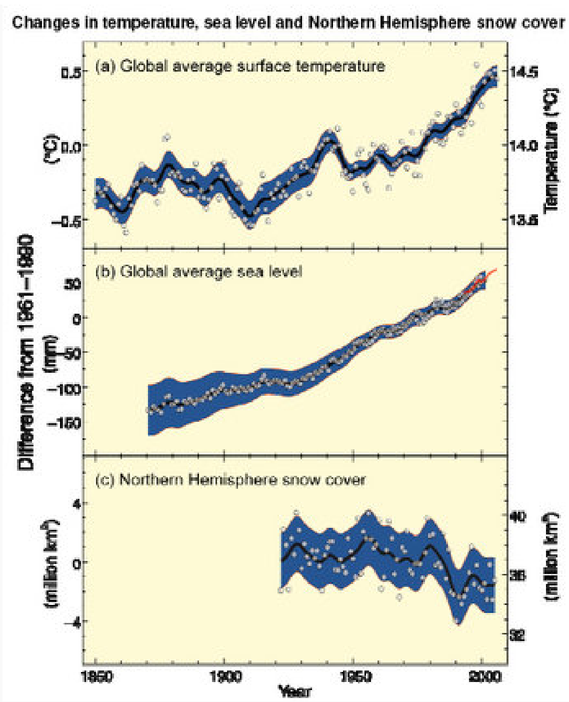

Figure 1. Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). (Source:**IPCC**)

The temperature of the Earth has risen by about of 0.74 °C over the last century. While that may seem like a small increase, it has had profound effects on the planet's physical and biological systems, which, in turn, have impacted society. A large majority of the climate science community has *very high confidence* that

the net effect of human activities since 1750 has been one of warming. They also conclude that most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic**greenhouse gas** (GHG) concentrations.
Global GHG emissions will continue to grow over the next few decades due to increases in the human activities that generate GHG, notably the **combustion**of fossil fuels and certain land use practices. A pronounced and swift change in climate change mitigation policies and related sustainable development practices could mitigate that trend. Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century. Higher temperatures would cause further widespread change, including: a decrease in snow cover and **sea ice**; an increase in frequency of hot extremes, heat waves and heavy precipitation; an increase in **tropical cyclone**intensity; precipitation increases in high latitudes and *likely* decreases in most subtropical land **regions**, among many other impacts; sea level rise, and accelerated species extinction, among many other impacts.
These phenomena would have far-reaching impacts on society. Altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems. Projected impacts include increased pest outbreaks in **agriculture**, increasing **water scarcity** and diminished water quality, increased risk of heat-related mortality, relocation of coastal populations and infrastructure, and declining **air quality in cities**. There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. Possible positive impacts of climate change include increased yields in colder environments and reduced energy demand for heating.
Some planned adaptation (of human activities) is occurring now; more extensive adaptation is required to reduce vulnerability to climate change. Unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt. **Making development more sustainable** by integrating climate change adaptation and mitigation measures into sustainable development strategy, can make a major contribution towards addressing climate change problems. Although the problems are complex, we know enough today to take the first effective steps on adaptation and mitigation.

Observed changes in climate and their effects

Warming of the earth is unequivocal, as is now evident from observations of increases in global average air and ocean **temperatures**, widespread melting of snow and ice and rising global average sea level. Eleven of the twelve years from 1995 to 2006 rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850). The temperature of the Earth has risen by about of 0.74 °C over the last century. The temperature increase is widespread over the globe and is greater at higher northern latitudes. Land **regions** have warmed faster than the **oceans**.

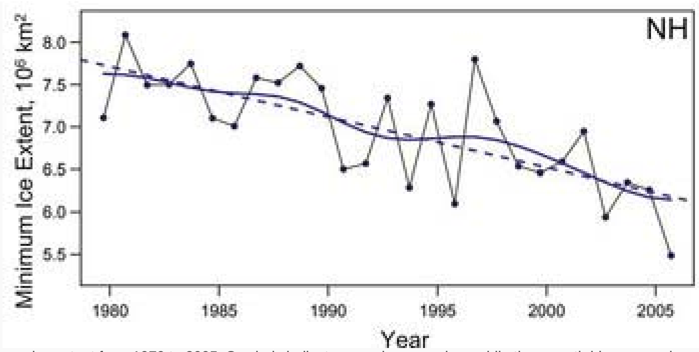

Figure 2. Summer minimum arctic sea ice extent from 1979 to 2005. Symbols indicate annual mean values while the smooth blue curve shows decadal variations. The dashed line indicates the linear trend, which is $-60 \pm 20 \times 103$ km^2 yr^{-1}, or approximately –7.4% per decade. (Source: updated from Comiso, 2002)

Rising sea level is consistent with warming. Global average sea level has risen since 1961 at an average rate of about 1.8 mm/yr and since 1993 at about 3.1 mm/yr. Sea level rise is caused by thermal expansion of the ocean, melting**glaciers** and ice caps, and the polar ice sheets.
Observed decreases in snow and ice extent are also consistent with warming. Satellite data since 1978 show that annual average **Arctic sea ice** extent has shrunk by about 2.7% per decade. Mountain glaciers and snow cover on average have declined in both hemispheres.

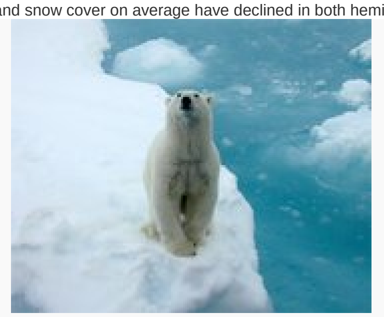

Figure 3. A decrease in arctic sea ice extent will have significant impacts on all aspects of arctic life. (Source: **NOAA**)

From 1900 to 2005, **precipitation** increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia but declined in the Sahel, the Mediterranean, southern Africa and parts of southern Asia.
It is *very likely* that over the past 50 years, cold days, cold nights and frosts have become less frequent over most land areas, and hot days and hot nights have become more frequent. It is *likely* that heat waves have become more frequent over most land areas, and the frequency of heavy precipitation events has increased over most areas.
There is evidence of an increase in intense **tropical cyclone** activity in the **North Atlantic** since about 1970. There is no clear trend in the annual numbers of tropical cyclones. It is difficult to determine longer-term trends in cyclone activity, particularly prior to 1970.
Average Northern Hemisphere **temperatures** during the second half of the 20th century were *very likely*higher than during any other 50-year period in the last 500 years.

There is widespread evidence from all continents and most **oceans** that many natural systems are being affected by regional climate changes, particularly temperature increases. These changes include:

- Changes in snow, ice and frozen ground have with *high confidence* increased the number and size of glacial lakes, increased ground instability in **mountain** and other permafrost regions and led to changes in some **Arctic** and **Antarctic** ecosystems.
- In terrestrial ecosystems, earlier timing of spring events and poleward and upward shifts in plant and animal ranges are with *very high confidence* linked to recent warming.
- In some **marine** and **freshwater** systems, shifts in ranges and changes in algal, **plankton** and fish abundance are with *high confidence* associated with rising water temperatures, as well as related changes in ice cover, salinity, **oxygen** levels and **circulation**.

Causes of change

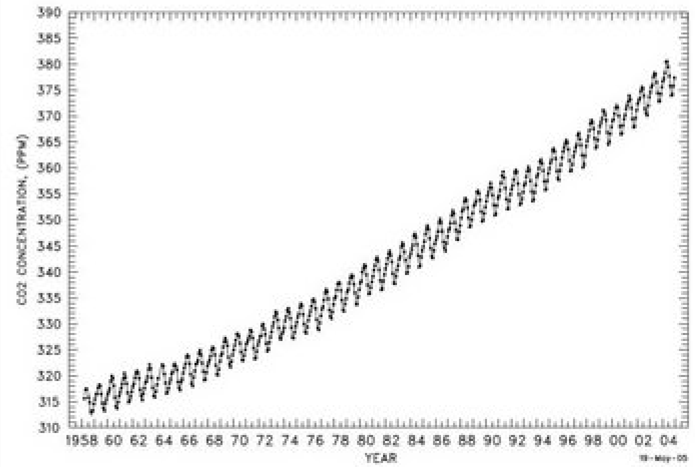

Figure 4. CO_2 concentration in the atmosphere. (Source: Keeling, C.D. and T.P. Whorf. 2005. **Atmospheric CO2 records from sites in the SIO air sampling network.** In **Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center**, **Oak Ridge National Laboratory**, **U.S. Department of Energy**, Oak Ridge, Tenn., U.S.A.)

The dominant factor in the **radiative forcing** of climate in the industrial era is the increasing concentration of various **greenhouse gases** in the**atmosphere**. Several of the major greenhouse gases occur naturally but increases in their atmospheric concentrations over the last 250 years are due largely to human activities. Other greenhouse gases are entirely the result of human activities. The contribution of each greenhouse gas to radiative forcing over a particular period of time is determined by the change in its concentration in the atmosphere over that period and the effectiveness of the gas in perturbing the radiative balance. Current concentrations of atmospheric **CO_2** and **CH_4** far exceed pre-industrial values found in polar ice core records of **atmospheric composition** dating back 650,000 years. Multiple lines of evidence confirm that the post-industrial rise in these gases does not stem from natural mechanisms.

The total **radiative forcing** of the Earth's climate due to increases in the concentrations of the long-lived GHGs CO_2, CH_4 and **N_2O**, and *very likely* the rate of increase in the total forcing due to these gases over the period since 1750, are unprecedented in more than 10,000 years. It is *very likely* that the sustained rate of increase in the combined radiative forcing from these **greenhouse gases** over the past four decades is at least six times faster than at any time during the two millennia before the Industrial Era, the period for which ice core data have the required temporal resolution. The concentration of atmospheric CO_2 has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. Atmospheric CO_2 concentration increased by only 20 ppm over the 8000 years prior to **industrialisation**; multi-decadal to centennial-scale variations were less than 10 ppm and *likely* due mostly to natural processes. However, since 1750, the CO_2 concentration has risen by nearly 100 ppm. The annual CO_2 growth rate was larger during the last 10 years than it has been since continuous direct atmospheric measurements began. Increases in atmospheric CO_2 since pre-industrial times are responsible for a radiative forcing contribution that dominates all other radiative forcing agents considered in this report.

The **CH_4** abundance in 2005 of about 1774 ppb is more than double its pre-industrial value. Current atmospheric CH_4 levels are due to continuing anthropogenic emissions of CH_4, which are greater than natural emissions. Emissions from individual sources of CH_4 are not as well quantified as the total emissions but are mostly biogenic and include emissions from **wetlands**, ruminant animals, rice **agriculture**and biomass burning, with smaller contributions from industrial sources including fossil fuel-related emissions.

The **N_2O** concentration in 2005 was 319 ppb, about 18% higher than its pre-industrial value. The increase in N_2O is due primarily to human activities, particularly agriculture and associated **land use change**.

Attribution of climate change

Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence. Our ability to discern cause-and-effect in the climate system has improved significantly over time. The first IPCC Assessment Report (FAR) contained little observational evidence of a detectable anthropogenic influence on climate. Six years later, the IPCC Second Assessment Report (SAR) concluded that the balance of evidence suggested a discernible human influence on the climate of the 20th century. The TAR concluded that 'most of the observed warming over the last 50 years is *likely* to have been due to the increase in greenhouse gas concentrations'.

Confidence in the assessment of the human contributions to recent climate change has increased considerably since the TAR, in part because of stronger signals obtained from longer records, and an expanded and improved range of observations allowing attribution of **warming** to be more fully addressed jointly with other changes in the climate system. In addition, some apparent inconsistencies in the observational record (e.g., in the vertical profile of**temperature** changes) have been largely resolved.

The key results of the **IPCC's Fourth Assessment Report** in the area of attribution are:

- It is *extremely unlikely* (<5%) that the global pattern of warming observed during the past half century can be explained without external forcing. These changes took place over a time period when non-anthropogenic forcing factors (i.e., the sum of solar and volcanic forcing) would be *likely* to have produced cooling, not warming. Attribution studies show that it is *very likely* that these natural forcing factors alone cannot account for the observed warming.
- It is *very likely* that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century. Without the cooling effect of atmospheric**aerosols**, it is *likely* that greenhouse gases alone would have caused a greater global mean temperature rise than that observed during the last 50 years.
- It is *very likely* that the response to anthropogenic forcing contributed to sea level rise during the latter half of the 20th century, but decadal variability in sea level rise remains poorly understood.
- The observed pattern of tropospheric warming is *very likely* due to the influence of anthropogenic forcing, particularly that due to greenhouse gas increases.
- Difficulties remain in attributing **temperature** changes at smaller than continental scales and over time scales of less than 50 years.

Figure 5. The combustion of fossil fuels in power generation is a leading source of GHG emissions. (Source: **U.S. EPA**)

Projected climate change

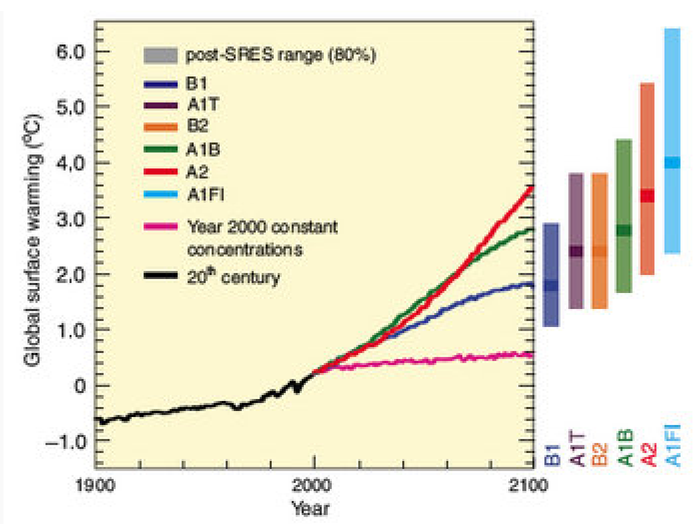

Figure 6. Solid lines are global averages of surface warming for scenarios shown as continuations of the 20th-century simulations. The pink line is not a scenario, but is for simulations where GHG concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099. All temperatures are relative to the period 1980-1999. (Source: **IPCC**)

Future **GHG** emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. The**Intergovernmental Panel on Climate Change (IPCC)** developed a set of scenarios to represent the range of driving forces and emissions in the scenario literature so as to reflect current understanding and knowledge about underlying uncertainties. Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties.

There is high agreement and much evidence that with current development policies and emissions trends, emissions will continue to grow over the next few decades.The IPCC Special Report on Emissions Scenarios (SRES) projects an increase of global GHG emissions by 25 to 90% between 2000 and 2030, with fossil fuels maintaining their dominant position in the global energy mix to 2030 and beyond. More recent scenarios without additional emissions mitigation are comparable in range.

For the next two decades a warming of about 0.2°C per decade is projected for a range of SRES emissions scenarios. Even if the concentrations of all GHGs and **aerosols** had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. Afterwards, temperature projections increasingly depend on specific emissions scenarios.
GHG emissions in this range will cause further **warming** and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century.
Based on these projected temperature increases, the IPCC projects a pattern of warming and other regional-scale features that include changes in **wind** patterns, **precipitation**, and some aspects of extremes and **sea ice**. These projected changes include:

- Warming is expected to be greatest over land and at most high northern latitudes, and least over the**Southern Ocean** (near Antarctica) and northern **North Atlantic**, continuing recent observed trends.
- Snow cover area is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions. Sea ice is projected to shrink in both the **Arctic** and **Antarctic** under all SRES scenarios. In some projections, Arctic late-summer **sea ice** disappears almost entirely by the latter part of the 21st century.
- It is *very likely* that hot extremes, heat waves, and heavy precipitation events will become more frequent.
- it is *likely* that future tropical **cyclones** (typhoons and **hurricanes**) will become more intense, with larger peak **wind** speeds and more heavy **precipitation** associated with ongoing increases of tropical sea-surface temperatures.
- Increases in the amount of precipitation are *very likely* in high-latitudes, while decreases are *likely* in most subtropical land **regions**, continuing observed patterns in recent trends.
- Anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if GHG concentrations were to be stabilised, due to the time scales required for the removal of this gas from the **atmosphere**.
- Contraction of the Greenland ice sheet is projected to continue to contribute to sea level rise after 2100.

Impacts of future climate changes

The most vulnerable groups will be the poor, the elderly, and children, including those living in rich countries. The most affected **regions** will be the **Arctic**, sub-Saharan Africa, small islands, and Asian megadeltas. High risks will be associated with low-lying **coastal** areas, **water resources** in dry tropics and subtropics,**agriculture** in low-latitude regions, key **ecosystems** (such as **coral reefs**), and human health in poor areas. Moreover, extreme weather events will worsen (especially **tropical cyclones** and heat waves). The result is that prospects for achieving many of the eight 2015 **Millennium Development Goals**—which include poverty reduction, better health and education, gender equality, and saving the environment—will become even more remote.

Figure 7. One of the projected impacts of future climate change is an increase in coastal flooding of low-lying areas such as Bangladesh. (Source: **UNEP**)

Ecosystems
The resilience of many **ecosystems** is *likely* to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g. flooding, drought, wildfire, insects,**ocean acidification**), and other global change drivers (e.g. **land-use change**, **pollution**, fragmentation of natural systems, over-exploitation of resources). Approximately 20-30% of plant and animal species assessed so far are *likely* to be at increased risk of extinction if increases in global average **temperature** exceed 1.5-2.5°C.

Food
Crop productivity is projected to increase slightly at mid- to high latitudes for local mean **temperature** increases of up to 1-3°C depending on the crop, and then decrease beyond that in some **regions**. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C), which would increase the risk of hunger. Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1-3°C, but above this it is projected to decrease.

Coasts
Coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea level rise. The effect will be exacerbated by increasing human-induced pressures on **coastal areas**. By the 2080s, many millions more people than today are projected to experience floods every year due to sea level rise.

Industry, settlements and society
The most vulnerable industries, settlements and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanisation is occurring. Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas.

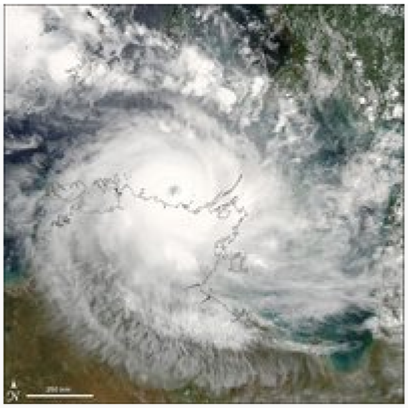

Figure 8. Tropical Cyclone Monica off the coast of Australia in 2006. Increased tropical cyclone activity is one projected impact of future climate change. (Source: **NASA**)

Health

The health status of millions of people is projected to be affected through, for example, increases in malnutrition; increased deaths, diseases and injury due to extreme weather events; increased burden of diarrhoeal diseases; increased frequency of cardio-respiratory diseases due to higher concentrations of ground-level**ozone** in urban areas related to climate change; and the altered spatial distribution of some infectious diseases. Climate change is projected to bring some benefits in temperate areas, such as fewer deaths from cold exposure, and some mixed effects such as changes in range and transmission potential of **malaria** in Africa. Overall it is expected that benefits will be outweighed by the negative health effects of rising **temperatures**, especially in developing countries.

Water

Climate change is expected to exacerbate current stresses on**water resources** from population growth and economic and **land-use change**, including urbanisation. Changes in **precipitation** and **temperature** lead to changes in runoff and water availability. The negative impacts of climate change on **freshwater systems** outweigh its benefits (*high confidence*). For example, the beneficial impacts of increased annual runoff in some areas are *likely* to be tempered by negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality and flood risk. Available research suggests a significant future increase in heavy rainfall events in many regions, including some in which the mean rainfall is projected to decrease. The resulting increased flood risk poses challenges to society, physical infrastructure and water quality.

Extreme events

Altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems. Examples include:

- Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights.
- Increased frequency of warm spells/heat waves over most areas.
- Increased frequency of heavy **precipitation** events over most areas.
- Increased areas affected by drought.
- Increased **tropical cyclone** activity.
- Increased incidence of extreme high sea level.

Risk of abrupt or irreversible changes

Anthropogenic warming could lead to some impacts that are abrupt or irreversible, depending upon the rate and magnitude of the climate change. Abrupt climate change on decadal time scales is normally thought of as involving **ocean circulation** changes. In addition on longer time scales, ice sheet and **ecosystem** changes may also play a role. If a large scale abrupt climate change were to occur, its impact could be quite high. For example, partial loss of ice sheets on polar land and/or the thermal expansion of **seawater** over very long time scales could imply metres of sea level rise, major changes in **coastlines** and inundation of low-lying areas, with greatest effects in **river** deltas and low-lying islands.

Climate change also is *likely* to lead to some irreversible impacts. Approximately 20-30% of species assessed so far are *likely* to be at increased risk of extinction if increases in global average warming exceed 1.5-2.5°C (relative to 1980-1999). As global average **temperature** increase exceeds about 3.5°C, model projections suggest significant extinctions (40-70% of species assessed) around the globe.

Impacts on regions

The impacts of climate change vary significantly among **regions**. Some regions are *likely* to be especially affected by climate change. These include:

- the **Arctic**, because of the impacts of high rates of projected warming on natural systems and human communities
- Africa, because of low adaptive capacity and projected climate change impacts
- small islands, where there is high exposure of population and infrastructure to projected climate change impacts
- Asian and African megadeltas, due to large populations and high exposure to sea level rise, storm surges and river flooding.

Within other areas, even those with high incomes, some people (such as the poor, young children and the elderly) can be particularly at risk, and also some areas and some activities.

Adaptation and mitigation options

Figure 9. The construction of coastal dikes, such as this on on the coasts of the Netherlands, is one approach to climate change mitigation.

Societies can respond to climate change by adapting to its impacts and by reducing **GHG** emissions (mitigation), thereby reducing the rate and magnitude of change. Adaptation refers to initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Examples are raising **river** or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc. Mitigation refers to technological change and substitution that reduce resource inputs and emissions per unit of output. In reference to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks. The capacity to adapt and mitigate is dependent on socio-economic and environmental circumstances and the availability of information and technology. However, much less information is available about the costs and effectiveness of adaptation measures than about mitigation measures.

Adaptation to climate change

Additional adaptation measures will be required to reduce the adverse impacts of projected climate change and variability, regardless of the scale of mitigation undertaken over the next two to three decades. Moreover, vulnerability to climate change can be exacerbated by other stresses. These arise from, for example, current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalisation, conflict and incidence of diseases such as HIV/AIDS. There is *high confidence* that there are viable adaptation options that can be implemented in some sectors at low cost, and/or with high benefit-cost ratios. However, comprehensive estimates of global costs and benefits of adaptation are limited.

A range of barriers limits both the implementation and, effectiveness of adaptation measures. The capacity to adapt is, dynamic and is influenced by a society's productive base, including, natural and man-made **capital**assets, social networks, and entitlements, human capital and institutions, governance, national income, health and technology. Even societies with high adaptive capacity remain vulnerable to climate change, variability and extremes.

Examples of planned adaptations include:

- **Water:** Expanded rainwater harvesting; water storage and conservation techniques; water re-use; desalination; water-use and irrigation efficiency
- **Agriculture:** Adjustment of planting dates and crop variety; crop relocation; improved land management, e.g. erosion control and **soil** protection through tree planting
- **Infrastructure/settlement:** Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of **marshlands**/**wetlands** as buffer against sea level rise and flooding; protection of existing natural barriers
- **Human health:** Heat-health action plans; emergency medical services; improved climate-sensitive disease surveillance and control; safe water and improved sanitation
- **Tourism**: Diversification of tourism attractions & revenues; shifting ski slopes to higher altitudes and**glaciers**; artificial snow-making
- **Transport:** Realignment/relocation; design standards and planning for roads, rail, and other infrastructure to cope with warming and drainage
- **Energy:** Strengthening of overhead transmission and distribution infrastructure; underground cabling for utilities; energy efficiency; use of renewable sources; reduced dependence on single sources of energy

Mitigation of climate change

Figure 10. Nuclear power, and other low-carbon sources such as solar, wind, and hydropower, are energy supply technologies that mitigate climate change. (Source: **U.S. DOE**)

No single technology can provide all of the mitigation, potential in any sector. The economic mitigation potential, which is generally greater than the **market** mitigation potential, can only be achieved when adequate policies are in place, and barriers removed.

There is substantial economic potential for the mitigation of global, GHG emissions over the coming decades that could offset the projected growth of global emissions, or reduce emissions below current levels No single technology can provide all of the mitigation, potential in any sector. The economic mitigation potential, which is generally greater than the market mitigation potential, can only be achieved when adequate policies are in place, and barriers removed. Bottom-up studies suggest that mitigation opportunities, with net negative costs have the potential to reduce emissions, by around 6 $GtCO_2$-eq/yr in 2030, realising which requires dealing with implementation barriers.

Future energy infrastructure investment decisions, expected to exceed US$20 trillion between 2005 and 2030, will have long-term impacts on GHG emissions because of the long lifetimes of energy plants and other infrastructure capital stock. The widespread diffusion of low-carbon technologies may take many decades, even if early investments in these technologies are made attractive. Initial estimates show that returning global energy-related CO_2 emissions to 2005levels by 2030 would require a large shift in investment patterns, although the net additional investment required ranges from negligible to 5 to 10%.

Key mitigation technologies and practices currently commercially available include the following:

- **Energy supply:** Improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); combined heat and power; early applications of Carbon Dioxide Capture and Storage (CCS) (e.g. storage of removed CO_2 from natural gas)
- **Buildings:** Efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases
- **Industry:** More efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO2 gas emissions; and a wide array of process-specific technologies
- **Agriculture:** Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH_4 emissions; improved nitrogen fertiliser application techniques to reduce N_2O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency
- **Forestry:** Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use
- **Transport:** More fuel efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorised transport (cycling, walking); land-use and transport planning
- **Waste:** Landfill CH_4 recovery; waste incineration with energy recovery; composting of organic waste; controlled wastewater treatment; recycling and waste minimisation

Policies and instruments

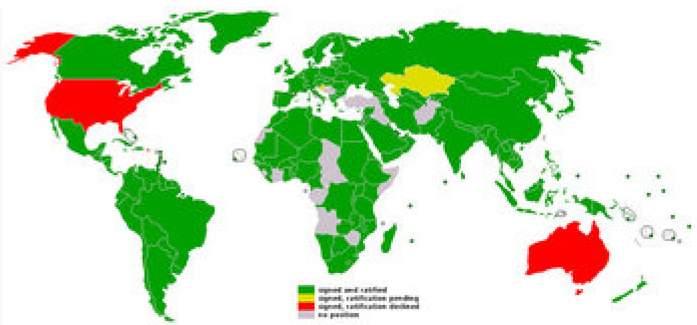

Figure 11. As of November 2007, a total of 175 countries and other governmental entities had ratified the Kyoto Protocol.

A wide variety of policies and instruments are available to governments to create the incentives for mitigation and action. Their applicability depends on national circumstances and sectoral context. These policies and instruments include integrating climate policies in wider development policies, regulations and standards, taxes and charges, tradable permits, financial incentives, voluntary agreements, information instruments, and research, development and demonstration.

An effective **carbon**-price signal could realise significant mitigation potential in all sectors. Modelling studies show that global carbon prices rising to US$20-80/$tCO_2$-eq by 2030 are consistent with stabilisation at around 550ppm CO_2-eq by 2100. For the same stabilisation level, induced technological change may lower these price ranges to US$5-65/$tCO_2$-eq in 2030. There is substantial evidence that mitigation actions can result in near-term co-benefits (e.g. improved health due to reduced **air pollution**) that may offset a substantial fraction of mitigation costs. There is also evidence changes in lifestyle, behaviour patterns and management practices can contribute to climate change mitigation across all sectors.

Many options exist for reducing global **GHG** emissions through international cooperation. Notable achievements of the **United Nations Framework Convention on Climate Change** (UNFCCC) and its **Kyoto Protocol** are the establishment of a global response to climate change, stimulation of an array of national policies, and the creation of an international carbon market and new institutional mechanisms that may provide the foundation for future mitigation efforts. Progress has also been made in addressing adaptation within the UNFCCC and additional international initiatives have been suggested. Greater cooperative efforts and expansion of **market** mechanisms will help to reduce global costs for achieving a given level of mitigation, or will improve environmental effectiveness. Such efforts can include diverse elements such as emissions targets; sectoral, local, sub-national and regional actions; RD&D programmes; adopting common policies; implementing development-oriented actions; or expanding financing instruments.

Key uncertainties

The **IPCC** has identified a number of uncertainties whose resolution would improve our understanding of climate change. Some of the key uncertainties include:

- Climate data coverage remains limited in some **regions** and there is a notable lack of geographic balance in data and literature on observed changes in natural and managed systems, with marked scarcity in developing countries.
- Analysing and **monitoring** changes in extreme events, including drought, tropical **cyclones**, extreme **temperatures**, and the frequency and intensity of **precipitation**, is more difficult than for climatic averages as longer data time-series of higher spatial and temporal resolutions are required.
- Difficulties remain in reliably simulating and attributing observed**temperature** changes to natural or human causes at smaller than continental scales.
- Uncertainty in equilibrium climate sensitivity creates uncertainty in the expected warming for a given CO_2-eq stabilisation scenario. Uncertainty in the **carbon cycle** feedback creates uncertainty in the emission trajectory required to achieve a particular stabilisation level.

- Climate models differ considerably in their estimates of the strength of different feedbacks in the climate system, particularly **cloud** feedbacks, oceanic **heat** uptake, and carbon cycle feedbacks, although progress has been made in these areas.
- Large scale **ocean circulation** changes beyond the 21st century cannot be reliably assessed because of uncertainties in the meltwater supply from Greenland ice sheet and model response to the **warming**.
- Projections of climate change and its impacts beyond about 2050 are strongly scenario- and model-dependent, and improved projections would require improved understanding of sources of uncertainty and enhancements in systematic observation networks.
- Understanding of how development planners incorporate information about climate variability and change into their decisions is limited. This limits the integrated assessment of vulnerability.
- Barriers, limits and costs of adaptation are not fully understood, partly because effective adaptation measures are highly dependent on specific geographical and climate risk factors as well as institutional, political and financial constraints.
- Estimates of mitigation costs and potentials depend on assumptions about future socio-economic growth, technological change and **consumption** patterns.

Figure 12. The effects of meltwater supply from the Greenland ice sheet is one source of uncertainty in our understanding of the impacts of climate change. (Source: **Reuters**/**University of Colorado**: Konrad Steffen)

Conclusions

Figure 13. Africa is especially vulnerable to climate change impacts because of low adaptive capacity. (Source: **NASA**)

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean **temperatures**, widespread melting of snow and ice, and rising global average sea level. Many natural systems, on all continents and in some **oceans**, are being affected by regional climate changes. Observed changes in many physical and biological systems are consistent with warming. As a result of uptake of anthropogenic **CO_2** since 1750, the **acidity of the surface ocean** has increased. Global total annual anthropogenic **GHG** emissions, weighted by their 100-year global warming potentials (GWPs), have grown by 70% between 1970 and 2004. As a result of anthropogenic emissions, atmospheric concentrations of **N_2O** now far exceed pre-industrial values spanning many thousands of years, and **CH_4**and **CO_2** now far exceed the natural range over the last 650,000 years. Most of the global average warming over the past 50 years is *very likely* due to anthropogenic GHG increases and it is *likely*that there is a discernible human-induced warming averaged over each continent (except **Antarctica**). Anthropogenic warming over the last three decades has *likely* had a discernible influence at the global scale on observed changes in many physical and biological systems.

With current development policies and emissions trends, global GHG emissions will continue to grow over the next few decades. For the next two decades a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios. Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely*be larger than those observed during the 20th century.

The most vulnerable groups include the poor, the elderly and children. Some systems, sectors and **regions**are *likely* to be especially affected by climate change. The systems and sectors are some **ecosystems**(**tundra**, **boreal forest**, **mountain**, **Mediterranean**-type, **mangroves**, **salt marshes**, **coral reefs** and the**sea-ice** biome), low-lying **coasts**, **water resources** in dry tropics and subtropics and in areas dependent on snow and ice melt, **agriculture** in low-latitude regions, and human health in areas with low adaptive capacity. The regions are the **Arctic**, Africa, small islands and Asian and African megadeltas. Within other regions, even those with high incomes, some people, areas and activities can be particularly at risk.

Some planned adaptation (of human activities) is occurring now; more extensive adaptation is required to reduce vulnerability to climate change. Unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt. A wide range of mitigation options are currently available or projected to be available by 2030 in all sectors, with the economic mitigation potential at costs that range from net negative up to 100 US$/t CO_2-equivalent, sufficient to offset the projected growth of global emissions or to reduce emissions to below current levels in 2030. Many impacts can be reduced, delayed or avoided by mitigation. Delayed emission reductions significantly constrain the opportunities to achieve lower stabilisation levels and increases the risk of more severe climate change impacts. **Making development more sustainable** by integrating **climate change adaptation** and mitigation measures into sustainable development strategy, can make a major contribution towards addressing **climate change**problems. Although the problems are complex, we know enough today to take the first effective steps on adaptation and mitigation.

Glossary of Key terms

Adaptation: Initiatives and measures to reduce the vulnerability of natural and human systems, against actual or expected climate change effects. Examples are raising **river** or **coastal** dikes, the substitution, of more temperature-shock resistant plants for sensitive ones, etc.
Aerosols: airborne solid or liquid particles, with a typical size between 0.01 and 10 micrometer (a millionth of a **meter**) that reside in the **atmosphere** for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly through acting as cloud condensation nuclei or modifying the optical properties and lifetime of **clouds**.
Anthropogenic emissions: emissions of **greenhouse gases**, greenhouse gas precursors, and **aerosols**, associated with human activities, including the burning of fossil fuels, **deforestation**, **land-use changes**, livestock, fertilisation, etc.
Barrier: any obstacle to reaching a goal, adaptation or mitigation potential that, can be overcome or attenuated by a policy, programme, or measure. Barrier removal includes correcting **market failures** directly or reducing the transactions costs in the public and private sectors by e.g. improving institutional capacity, reducing risk and uncertainty.
Bottom-up models: bottom-up models represent reality by aggregating characteristics of specific activities and processes, considering technological, engineering and, cost details.
Climate: in a narrow sense is usually defined as the average weather, or, more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO)World Meteorological Organization. The relevant quantities are most often surface variables such as **temperature**, **precipitation** and **wind**. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate model: a numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions, and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrisations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.
Climate prediction: a climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual or long-term time scales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature.
Climate projection: a projection of the response of the climate system to emission or concentration scenarios of **greenhouse gases** and **aerosols**, or **radiative forcing** scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.
Climate scenario: a plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.
Climate sensitivity: the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent **carbon dioxide** concentration.
Climate system: the climate system is the highly complex system consisting of five major components: the**atmosphere**, the hydrosphere, the **cryosphere**, the land surface and the **biosphere**, and the interactions between them.
Emission scenario: a plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.
External forcing: a forcing agent outside the climate system causing a change in the climate system.**Volcanic** eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and**land use change** are external forcings.
Extreme weather event: an event that is rare at a particular place and time of year. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally.
Global surface temperature; an estimate of the global mean surface air **temperature**. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.
Global Warming Potential (GWP): an index, based upon radiative properties of well mixed greenhouse gases, measuring the **radiative forcing** of a unit mass of a given well mixed greenhouse gas in today's **atmosphere**integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation.
Greenhouse effect: greenhouse gases effectively absorb thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by **clouds**. Thus greenhouse gases trap **heat**within the surface-troposphere system. This is called the greenhouse effect.
Greenhouse gas (GHG): gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), **carbon dioxide** (CO_2), **nitrous oxide** (N_2O), **methane** (CH_4) and **ozone** (O_3) are the primary greenhouse gases in the Earth's atmosphere.
Ice sheet: a mass of land ice that is sufficiently deep to cover most of the underlying bedrock topography, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base).
Kyoto Protocol: The **Kyoto Protocol** to the **United Nations Framework Convention on Climate Change**(UNFCCC) was adopted in 1997 in Kyoto, Japan, at the Third Session of the Conference of the Parties (COP) to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in Annex B of the Protocol (most Organization for Economic Cooperation and Development countries and countries with economies in

transition) agreed to reduce their anthropogenic greenhouse gas emissions (**carbon dioxide**, **methane**, **nitrous oxide**, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride) by at least 5% below 1990 levels in the commitment period 2008 to 2012. The Kyoto Protocol entered into force on 16 February 2005.
Mean Sea Level: normally defined as the average relative sea level over a period, such as a month or a year, long enough to average out transients such as waves and **tides**. *Relative sea level* is sea level measured by a tide gauge with respect to the land upon which it is situated.
Methane (CH_4): one of the six **greenhouse gases** to be mitigated under the Kyoto Protocol and is the major component of natural gas and associated with all hydrocarbon fuels, animal husbandry and **agriculture**.
Mitigation: technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks.
Nitrous oxide (N_2O): one of the six types of greenhouse gases to be curbed under the Kyoto Protocol. The main anthropogenic source of nitrous oxide is agriculture (**soil** and animal manure management), but important contributions also come from sewage treatment, **combustion** of fossil fuel, and chemical industrial processes. Nitrous oxide is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical **forests**.
Projection: a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasise that projections involve assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.
Radiative forcing: The change in the net—downward minus upward—irradiance (expressed in **Watts** per square **metre**, W/m^2) at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun.
Scenario: a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.
Sensitivity: the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change.
Sink: any process, activity or mechanism which removes a **greenhouse gas**, an **aerosol** or a precursor of a greenhouse gas or aerosol from the atmosphere.
Top-down models: top-down models apply **macroeconomic theory**, econometric and optimization techniques to aggregate economic variables.
Uncertainty: an expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgement of a team of experts.
United Nations Framework Convention on Climate Change (UNFCCC): The **Convention** was adopted on 9 May 1992 in New York and signed at the 1992 **Earth Summit in Rio de Janeiro** by more than 150 countries and the European Community. Its ultimate objective is the “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”.
Vulnerability: the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Treatment of Uncertainty

This article expressed scientific uncertainty using the system developed by the the **Intergovernmental Panel on Climate Change (IPCC)** in the preparation of the **Fourth Assessment Report (AR4)**.
Where uncertainty is assessed qualitatively, it is characterised by providing a relative sense of the amount and quality of evidence (that is, information from theory, observations or models indicating whether a belief or proposition is true or valid) and the degree of agreement (that is, the level of concurrence in the literature on a particular finding). This approach is used by WG III through a series of self-explanatory terms such as: *high agreement*, *much evidence*; *high agreement*, *medium evidence*; *medium agreement*, *medium evidence*; etc.
Where uncertainty is assessed more quantitatively using expert judgement of the correctness of underlying data, models or analyses, then the following scale of confidence levels is used to express the assessed chance of a finding being correct: *very high confidence* at least 9 out of 10; *high confidence* about 8 out of 10;*medium confidence* about 5 out of 10; *low confidence* about 2 out of 10; and *very low confidence* less than 1 out of 10.
Where uncertainty in specific outcomes is assessed using expert judgment and statistical analysis of a body of evidence (e.g. observations or model results), then the following likelihood ranges are used to express the assessed probability of occurrence: *virtually certain* >99%; *extremely likely* >95%; *very likely* >90%; *likely*>66%; *more likely than not* > 50%; *about as likely as not* 33% to 66%; *unlikely* <33%; *very unlikely* <10%;*extremely unlikely* <5%; *exceptionally unlikely* <1%.

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