Chapter 18. Detection and Attribution of Observed Impacts

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Executive Summary

Impacts of recent observed climate change on physical, biological, and human systems have been detected on all continents and in most oceans. This conclusion is strengthened by observations since the AR4 as well as through more extensive analyses of earlier observations. Most reported impacts of climate change are attributed to regional warming of the atmosphere and the ocean. The level of confidence in attribution of observed impacts to shifts in rainfall patterns is lower. There is emerging evidence of impacts of ocean acidification. [18.3-18.6]

For many natural systems, new or stronger evidence for substantial and wide-ranging impacts of climate change exists, including the cryosphere, water resources, coastal systems and ecosystems on land and in the ocean.

Cryosphere and water resources

Glaciers worldwide continue to shrink; new glacier lakes have formed and existing ones have changed; seasonal ice in many lakes and rivers forms later and breaks up earlier. A major part of these changes can be attributed with *high confidence* to climate change. [18.3.1.3, 18.5; Figure 18-3]

Widespread changes and degradation of permafrost of both high-latitude and high-elevation mountain regions have been observed over the past years and decades *(high confidence)*. The permafrost boundary has been moving polewards and to higher elevations, and the active layer thickness has increased at many sites (*medium confidence* in attribution to climate change). [18.3.1.3, 18.5]

Hydrological systems have changed in many regions, due to changing rainfall or melting glaciers, affecting water resources, water quality, and sediment transport (*medium confidence*). In many river systems, the frequency of floods has been altered by climate change (*low to medium confidence*). The duration of droughts in some regions has been altered by climate change (*medium confidence*). [18.3.1.1, 18.5]

Terrestrial and freshwater ecosystems

Across all climate zones and continents, an increasing range of species and communities in terrestrial ecosystems have been impacted by recent climate change and increasing atmospheric CO_2. Many plants and animals show changes in phenology (*high confidence*), productivity and / or geographic range (*medium confidence*). Elevated rates of extinction cannot be attributed to climate change. [18.3.2, 18.5]

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in animal community composition, especially in headwater streams. While confidence in detection of change is *high*, there is *low confidence* in attribution to climate change due to many confounding factors. [18.3.2.4, 18.5]

Several major terrestrial ecosystems are undergoing broad-scale changes that can be characterized as early warnings for coming regime shifts, in part due to climate change. For wide-spread shrub encroachment in the Arctic tundra there is *high confidence*, for boreal forest tree mortality there is *low confidence* of climate change as driver. The recession and degradation of the Amazon forest cannot be attributed to climate change. [18.3.2.4, 18.5.6, 18.5.7]

Oceans and coastal systems

The physical and chemical properties of the ocean have changed significantly over the past 60 years, due to anthropogenic climate change. As a result, marine organisms have moved to higher latitudes,

changed their depth distribution or their phenology (*high confidence*). Facilitated by changes in the distribution of sea ice and changes in ocean currents, organisms such as crustaceans, zooplankton and fish have migrated toward higher latitudes. These changes also affect coastal ecosystems including kelp forests and seagrass meadows [18.3.3, 18.3.4.1]

Climate change has influenced ocean primary productivity, with positive consequences for some fisheries and negative ones for others (*medium confidence*). Together with non-climate influences such as excess nutrient input from human activities, climate change has contributed to an increase in the frequency, geographical distribution, and severity of hypoxic areas in the ocean. [18.3.4.1, 18.3.4.2]

Due to the increased frequency of stress events arising from elevated sea temperatures, coral reefs have experienced increased mass bleaching and mortality (*very high confidence*). These events have contributed to the loss of reef building corals in many parts of the world since the early 1980s. [18.3.3, 18.3.4, Box 18-3, 18.5, Table 18-8, Box CC-CR]

Arctic sea ice has been shrinking in extent, thickness, composition, with observed impacts on marine biology and the livelihoods of indigenous people (*medium to high confidence*). [18.3.1.3, 18.3.4, 18.4.7, 18.5.7]

Despite the known sensitivity of coastal systems to sea-level rise, local perturbations from regional variability in the ocean and human activities preclude the confident detection of sea level-related impacts attributable to climate change outside of the Arctic. [18.3.3]

For managed ecosystems and human systems, the effects of changing social and economic factors often dominate over any direct impact of climate change. Despite this, numerous impacts of climate change have been detected.

Even accounting for changes in technology and other non-climate factors, agricultural crop yields have changed in many regions in response to climate. Yields have increased in some (mid to high latitude) regions, due to warming and higher CO_2 *(low confidence)*, and decreased in other (mainly low latitude) regions due to water shortages and higher temperatures *(medium confidence*). Despite the high sensitivity of crop yields to temperature extremes, observed trends in the agricultural markets cannot presently be attributed to climate change, due presence of other drivers. [18.4.1, Table 18-9]

The catch potential of fisheries has increased in some regions and decreased in others with consequences for the food and livelihood of involved human communities (*high confidence*). Fisheries at high latitudes are showing increased productivity due to sea ice retreats and increases in net primary productivity. In other regions, stratification of the water column driven by warming has reduced net primary productivity of the ocean. [18.3.4, 18.4.1.2, 18.5.7]

In some regions, increases in the prevalence of vector-borne diseases have been detected and attributed to warming. Dengue fever and malaria have increased in several regions of the world over the past few decades, but there is *very low confidence* in attribution of these trends to climate change. [18.4.5]

Climate impacts on Arctic indigenous groups have been detected and attributed to climate change. These include changes in seasonal migration and hunting patterns, health, and cultural identity (*medium confidence*). [18.4.7, Box 18-5, 18.5.7, Table 18-9]

Extreme climate events have impacted natural and physical livelihood assets, incomes, public health, and social institutions. Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, but with a documented contribution of climate change and variability in some cases. [18.4.4, 18.4.7]

> **Despite known vulnerabilities and increasing exposure to climatic stressors, impacts of climate change on human livelihoods have rarely been detected with confidence.** Such detection is complicated by the effects of other economic and social factors. There is emerging literature on the impact of climate on poverty, working conditions, violent conflict, migration, and economic growth, but evidence for detection or attribution remains limited. [18.4.3, 18.4.6, 18.4.7]

Detection and attribution of observed impacts of climate change supports assessments of current conditions with respect to "Reasons for Concern" formulated by earlier IPCC assessments. The degree to which projected damages are now manifest, or the detection of stronger early warning signals for expected impacts, can contribute to a more comprehensive risk assessment for dangerous anthropogenic interference with the climate system.

> **Increases in "risks to unique and threatened systems" are now documented with higher confidence by the observed impacts on Arctic marine and terrestrial ecosystems and indigenous livelihoods (*medium to high confidence*), tropical coral reefs (*high confidence*) and glaciers in most mountain regions (*high confidence*). Observed impacts thus confirm this reason for concern.** [18.6.2.1]
>
> **"Risks of extreme weather events" – extreme warming events continue to increase for warm water coral reefs (*high confidence*), confirming this reason for climate-related concern. Risks have also increased in some other systems, causing economic losses, however this is predominantly due to the increases in wealth and exposure.** [18.6.2.2]
>
> **Impacts of climate change have now been documented globally, covering all continents and the ocean (*high confidence*). However, research coverage is still insufficient and too heterogeneous to effectively address spatial or social disparities concerning the "distribution of impacts" beyond local case studies.** [18.6.2.3]
>
> **"Aggregate impacts" have been documented with measures of glacier volume and permafrost extent (*medium to high confidence*). There is limited evidence of a climate contribution to aggregate impacts on biospheric carbon fluxes, agricultural yields, fishery production and economic losses due to extreme weather, due to the presence of dominant non-climatic drivers. For the cryospheric impacts, observations clearly confirm the reason for concern.** [18.6.2.4]
>
> **"Risks from large-scale singularities" relating to irreversible shifts with significant feedback potential in the Earth system have yet to be observed. However, there is now robust evidence of significant early warning signals in observed impacts of climate change that indicate large-scale regime shifts for the Arctic region and the tropical coral reef systems. This evidence confirms reasons for concern.** [18.6.2.5]

Though evidence is improving, there is a persistent gap of knowledge regarding how large parts of the world are being affected by observed climate change. The number of attribution studies linking observed impacts to the anthropogenic component of climate change remains limited. Research to improve the timeliness and knowledge about the detection and attribution is needed in particular for the risk of extreme events. [18.7]

In most studies, the attribution of observed impacts and vulnerabilities is related to all changes in climate that represent deviations from historical means and / or historic variability. Only a smaller number of robust attribution studies link responses in physical and biological systems to *anthropogenic* climate change. [18.1]

Methods for rigorous assessment of observed impacts of climate change are evolving. Evidence for attribution comes from assessment of the relative contribution by all known drivers affecting the dynamics of a system to its behavior, using scientific methods, involving an assessment of confidence in both detection and attribution. Formal meta-analysis or aggregated assessments of many observations or studies can help to improve confidence. [18.2.1, Box 18-1]

18.1. Introduction

This chapter synthesizes the scientific literature on the detection and attribution of observed changes in physical, biological and human systems in response to the climate change that has occurred during the recent few decades. It assesses the degree to which detected changes in such systems can be attributed to observed climate change and where possible, separates out the relative importance of anthropogenic drivers of climate change. For most natural and essentially all human systems, climate is only one of many drivers that cause systems to change, which therefore requires a careful accounting of the importance of other confounding factors on the overall change in these systems.

18.1.1. Scope and Goals of the Chapter

Previous assessments, notably Rosenzweig *et al.* (2007), in the IPCC Fourth Assessment Report (AR4), and the increasing body of literature published since, indicated that numerous physical and biological systems are affected by recent climate change. Human systems have received comparatively little attention in this literature, with the exception of the food system, which is a coupled human/natural system. Rigorous formal assessment of the literature going beyond just detection of change across a variety of regions and sectors, to scientifically robust attribution to climate change and its anthropogenic drivers is critical for several purposes (Brander *et al.*, 2011; Hoegh-Guldberg, 2011; Stocker *et al.*, 2011). Only formal detection studies provide robust evidence of where climate change impacts already being observed and where they are not, supporting near-term planned adaptation if and where necessary.

For policy makers and the public, detection and attribution of observed impacts will be a key element to determine the necessity and degree of mitigation and adaptation efforts. Detection and attribution are vital parts of the evidence base requested of the IPCC by signatories to the United Nations Framework Convention on Climate change to judge policies aiming to stabilize “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous atmospheric interference with the climate system”.

Full attribution of changes in these systems to anthropogenic climate is extremely hard to accomplish for many complex systems with diverse responses and multiple significant confounding drivers (Parmesan *et al.*, 2011). There has, however, been a significant increase in studies attributing changes in some systems to local climate change without direct linkage to anthropogenic drivers. This chapter assesses the studies that exist for both full and partial attribution, and the methodologies that can be brought to bear on attribution and the uncertainties inherent in doing so.

18.1.2. Summary of Findings from the AR4

Rosenzweig *et al.* (2007) reported that “observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.” In particular, they highlighted several areas where this general conclusion could be supported by specific conclusions that were reported with *high confidence:*

- Changes in snow, ice and frozen ground had been seen to increase ground instability in mountain and other permafrost regions; these changes had led to changes in some Arctic and Antarctic ecosystems and produced increases in the number and size of glacial lakes.
- Some hydrological systems had been affected by increased runoff and earlier spring peak discharges; in particular many glacier- and snow-fed rivers and lakes had warmed, producing changes in their thermal structures and water quality.
- Spring events had appeared earlier in the year so that some terrestrial ecosystems had moved poleward and upward; these shifts in plant and animal ranges were attributed to recent warming.
- Shifts in ranges and changes in algal, plankton and fish abundance as well as changes in ice cover, salinity, oxygen levels and circulation had been associated with rising water temperatures in some marine and freshwater systems.

In terms of a global synthesis, this assessment noted “that it is likely that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems” (Rosenzweig *et al*., 2007). Though it was based on analyses of a very large number of observational datasets, the assessment noted a lack of geographic balance in data and literature on observed changes, with marked scarcity in low and middle income countries.

Observed impacts to human systems were less obviously attributed to anthropogenic climate change. Rosenzweig *et al*. (2007) concluded with *medium confidence* only that, “other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers”. They especially noted effects of temperature increases on:

- Some agricultural and forestry management practices in the higher latitudes of the Northern Hemisphere; these included earlier spring planting as well as changes in the disturbance regimes of fires and pests.
- Some aspects of human health, including heat-related mortality in Europe, changes in some vectors of infectious diseases across the world, and phenological changes in allergenic pollen in the mid to high latitudes of the Northern Hemisphere.
- Some human activities in the Arctic (such as hunting and travel) and in lower-elevation alpine areas (such as mountain sports).

18.2. Methodological Concepts for Detection and Attribution of Impacts of Climate Change

There are three substantial challenges to the detection and attribution of change in environmental systems to a changing climate. First, all systems are affected also by environmental factors other than climate; to detect a climate change impact, it is therefore necessary to control for the effects of such confounding factors. Second, the ability of many systems to adapt to change complicates the detection and attribution of any impacts; that is, adaptation can mask an impact. Detection (and attribution) of adaptation to climate change is in this chapter considered to be detection (and attribution) of a climate change impact (Box 18-1). Third, because systems are typically affected by local or regional climate change, attribution of a detected climate change impact to anthropogenic climate change can be difficult. To overcome these difficulties and to best account for all available knowledge on observed impacts, a range of methods is employed here. They are summarized in this section.

18.2.1 Concepts and Approaches

18.2.1.1. Detecting and Attributing Change in the Earth System

From an analysis perspective, the Earth system can be separated into three connected subsystems; we name them here as the climate system, the natural system, and the human system (Figure 18-1). Many external drivers may influence any system, including the changing climate and other confounding factors (Hegerl *et al*., 2010). Each climate, natural or human subsystem affects the other two directly or indirectly. For example, the human system may directly affect the natural system through deforestation, which in turn affects the climate system through changes in albedo; this can alter surface temperatures which in turn feed back on natural and human systems.

[INSERT FIGURE 18-1 HERE
Figure 18-1: Schematic of the subject covered in this chapter. The Earth system can be divided into three broad interacting systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone *et al*. (2013).]

If an observed change in the human system impacts the climate system, we call this an anthropogenic driver of climate change. In order to highlight potential reasons for concern (including the uncertainties in detection and attribution), impacts of any observed climate change are covered in this chapter, irrespective of whether the particular aspect of climate change has been identified as anthropogenic.

18.2.1.2. Concepts of Detection and Attribution of Climate Change Impacts

Concepts and approaches to detection and attribution have been evolving throughout the work of the IPCC. In 2010, an IPCC Expert Meeting on Detection and Attribution was held to reconcile methods and terminology across IPCC working groups. The report from this meeting (Hegerl *et al*., 2010), along with the discussion of Stone *et al*. (2013), is an important conceptual basis for this chapter.

***Detection** addresses the question of whether a system is changing beyond what might be considered normal behaviour in the absence of climate change*. While Hegerl *et al*. (2010) proposed a broad definition that could be used across IPCC Working Groups, this definition, used in this chapter and in other Working Group II chapters, is more specific in not just considering any observed changes (Stone *et al*., 2013). The appropriate reference normal behaviour may be stationary (e.g. glaciers) or non-stationary (e.g. economic activity), and the nature of that reference needs to be spelled out clearly. Typically, detection studies involve the initial assumption of climate being at least one of the drivers of that change, but other drivers (such as changes in land use) may be recognized to play a significant role too. For many systems, the role of these confounding factors may exceed that of climate change.

***Attribution** addresses the question of whether climate change has contributed substantially to the detected change in a system*. In practice, attribution studies ask how much of the observed change is due to climate change. Attribution requires the evaluation of the contributions of all external drivers to the system change.

Failure to include relevant factors in an attribution study can lead to erroneous conclusions. This is referred to as the omitted variable problem (Greene, 2003). It is a particular problem in time series regressions when both climate and non-climate factors may vary roughly monotonically over time. It is also important not to equate empirical correlation with causality (Holland, 1986). This underscores the crucial role that system understanding must play in high-quality detection and attribution studies.

Detection and attribution studies rely on quantitative or qualitative analysis. Quantitative studies adhere to basic principles of statistical inference. One is that effects of formal or informal variable selection – in which a range of statistical models is screened to identify the best-fitting model – must be taken into account to avoid spurious attribution (Chatfield, 1995).

Qualitative attribution studies typically involve the identification of multiple, intersecting “impact chains” that recognize confounding variables acting alongside climate change. These studies usually do not specifically isolate certain social or environmental changes to climate change alone but rather, they aim to identify dynamic interactions among an assemblage of intersecting forces in human-environment systems.

Evidence for testing the hypothesis that some observed change can be attributed to climate change may come from different sources. The nature of the tools used for testing hypotheses varies depending on the details of the study (Stone *et al*., 2013). Mechanistic models can be used, for example representing a system through a chain of explicit functions based on understanding of the individual processes that together comprise the mechanics of the system. These mechanistic models can sometimes be formulated numerically. In other cases, empirical models may be useful, relating the response of a system to external drivers according to mathematical relationships estimated through observation, experimentation, or survey. In practice, though, many modeling setups will contain both mechanistic and empirical components.

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Box 18-1. The Role of Climate Sensitivity and Adaptation for Impact Models in Human Systems

Impacts of climate change on a measurable attribute of a human system only occur if a) the attribute is sensitive to climate and b) a change in climate has occurred. A large literature has developed attempting to quantify both climate sensitivity of various systems and observed changes in climate.

The literature estimating the climate sensitivity of an outcome such as crop yields, heat related mortality or migration, has relied on observed climate variability either across space (e.g., Schlenker *et al.*, 2005), time (e.g., Mann and Emanuel, 2012), or space and time (Hsiang *et al.*, 2011; e.g., Dell *et al.*, 2012). While there is a rich literature using climate variability across space, the long observational weather time series required for exploring climate variability across space and time have limited the opportunities for study. A number of studies have instead estimated the weather sensitivity of outcomes in order to project the future impacts of weather under climate change (Deschênes and Greenstone, 2007; Deschênes and Greenstone, 2011), or attribute impacts for the past (Auffhammer *et al.*, 2006). The issue with impact studies using a weather based sensitivity measure is that they cannot provide estimates of impacts based on the climate sensitivity. For example, farmers may respond to an unusually hot summer, which is a weather event, by applying more irrigation water. However, in the long run farmers may respond to a warmer climate by switching crops, changing irrigation technology or abandoning farming altogether. The two sensitivities and resulting magnitudes of attributable impacts due to a change in weather versus a change in climate are therefore different.

In order to detect and attribute a change in a system to climate change, one needs to combine a measure of sensitivity of the outcome to climate with an observed measure of climate under climate change. This can be done via a multi-step approach (Hegerl *et al.*, 2010), whereby one estimates the outcome of interest using measures of climate sensitivity combined with measures of observed climate and compares these to a simulated outcome using the same sensitivity but removing the climate change from the climate input.

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18.2.1.3.Approaches to Attribution

There are many levels at which drivers and responses can be defined for observed impacts of climate change (Table 18-1). In practice, two different levels of external drivers are used:

- Attribution to climate change, where impacts are related to identified long-term trends in climate (including changes in variability patterns). Studies examining this relationship do not formally identify the role of anthropogenic emissions in the observed climate change or, by extension, in the observed impact, but they do indicate the degree to which the system is sensitive to long term climate change.
- Attribution to anthropogenic climate change, where impacts are related, via the climate, to anthropogenic emissions of greenhouse gases and other human activities that are affecting the climate. Because of the complexity of the causal chain, investigation of this relationship is extremely challenging (Parmesan *et al.*, 2011) and only a limited number of these studies have been performed to date.

Attribution studies use two main approaches (see Figure 18-2). Single-step methods consider all relevant systems in a single setup. The assessment tool can comprise a single model or a sequence of models, provided the output of each model is directly employed as an input for the next model in a logical sequence. The attribution analysis is performed through a comparison of the change in the final output from the model(s) against the observed change in the system of interest.

[INSERT FIGURE 18-2 HERE
Figure 18-2: A schematic diagram comparing approaches to attribution for an ecological system. The multi-step approach differs from the single-step approach in having a discontinuity between the attributed climate change and the observed weather driving the ecological model. Adapted from Stone *et al.* (2013).]

Multi-step attribution approaches comprise multiple attribution analyses, with an overall conclusion deduced from the collection of analyses. A multi-step approach could include an analysis of the attribution of changes in a measure of interest to changing climatic conditions and a separate analysis of how external climate drivers affected relevant climatic conditions. Typically, the separation of these analyses creates gaps or inconsistencies between the outputs from one step and the inputs to the next. These gaps must be assessed themselves with respect to their impact on the confidence in the overall attribution.

In areas where extensive monitoring records are available, such as for phenological measures in ecological systems, studies may be combined into a formal quantitative synthesis assessment. For instance, Rosenzweig *et al.* (2008) noted that the spatial pattern of observed changes in a large number of natural systems around the globe matched the pattern expected based on the observed warming pattern, and argued that other global factors such as land use change could not account for this pattern (see also Box 18-2).

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Box 18-2. Quantitative Synthesis Assessment of Detection and Attribution Studies

There are a number of powerful tools for quantitative synthesis assessment of detection and attribution across multiple studies. These tools include associative pattern analyses (e.g., Rosenzweig *et al*., 2008) and regression analyses (Chen *et al*., 2011) which compare expected changes due to anthropogenic climate change across multiple studies against observed changes.

Quantitative synthesis assessments have been particularly prominent in ecology, where measures of phenology (timing of seasonal events) and geographical range can be assembled across species into standardized indices (Parmesan and Yohe, 2003; Rosenzweig *et al*., 2008; Chen *et al*., 2011). Synthesizing across multiple species can increase our confidence in detection of general patterns of change in the biological indices. This confidence increases with the number of species / ecosystems observed, the number of independent studies, the geographical distribution of these observations, the temporal depth and resolution of the data, and the representativeness of species/ecosystems and locations studied.

Synthesis assessments examining climate change as the only driver can provide some insight into the attribution of biological responses to climate change because they can indicate whether plausible hypotheses are supported by data. However, increasing spatial coverage, numbers of species, etc. does not a priori increase confidence that climate change is a more credible explanation for biological change than alternative hypotheses. Additional data can contribute to confidence in causal relationships, i.e. attribution, in a synthesis assessment when it provides new evidence for explicit testing against a credible range of alternative hypotheses.

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18.2.2. Challenges to Detection and Attribution

18.2.2.1. Types and Quality of Observations

The nature of indicators can take many forms, some of which are more amenable for precise long-term monitoring than others. Many changing phenomena can be measured directly, e.g., the temperature of the surface waters of a lake. Often, however, important indicators are less specific and thus difficult to pinpoint, for instance the excess mortality and increased human vulnerability associated with heat waves, or the percentage of species migrating polewards or upwards.

The quality of observations of these indicators varies in space and time. Monitoring of ecosystems, for example, is often not designed with the intention of measuring incremental long-term changes and are not optimized for the detection of climate-related changes (Midgley *et al*., 2007). Consequently, the record length may be too short, too heterogeneous or discontinuous to be useful, or measuring standards may have been improved through time resulting in measurement artifacts. This latter factor is most visible in the extensive and long-running networks designed to monitor human health, where the priority is an accurate timely assessment of current health status and risk rather than the determination of long-term trends (see also 18.4.5).

18.2.2.2. Spatial and Temporal Characteristics of Change

Detection studies require observational data spanning a time period longer than the typical time scale of natural variability in the system in the absence of external drivers. A particular challenge is that this required time scale is usually difficult to discern from available observational records and thus other sources of information must be used to determine them (Hegerl *et al.*, 2010). Lags between changes in external drivers and responses to those drivers vary among different impact systems and within them, from seconds or minutes to centuries or millennia, and thus need to be recognised (Stone *et al.*, 2013).

Non-linear system response to change is a fundamental issue for detection studies. Some systems may respond by step-wise changes, other systems may have tipping points, showing little or no change until a certain threshold where they suddenly start to respond vigorously and often in a chaotic way (e.g., De Young and Jarre, 2009; Wassmann and Lenton, 2012, 18.6.2.5).

Change in environmental and human systems occurs on multiple spatial scales from local to global. Attribution of change to climate change (e.g., over the last several decades) faces different challenges at different spatial scales. At the local scale, detection may be straightforward due to the availability of long-term observations, but attribution may be difficult because many local factors have been changing as well (e.g., Parmesan *et al.*, 2013). Furthermore, local climate may be affected by localised drivers such as land cover change (De Noblet-Ducoudré *et al.*, 2012), which complicates the evaluation of the role of global anthropogenic emissions.

18.2.2.3. Publication Bias

Conclusions about the effect of climate change on natural and human systems in this report are based on a synthesis of findings in the scientific literature. A potential problem with this approach is publication bias, specifically the preferential publication of papers reporting statistically significant findings (Parmesan and Yohe, 2003). The effect of publication bias could be a false impression of the strength of the evidence in favor of a hypothesized effect. Methods exist for detecting and correcting for publication bias in formal quantitative synthesis analysis (Rothstein *et al.*, 2005). For instance, the availability of a large sample of observations from an existing phenological monitoring network has permitted the assessment that publication bias has not been an important factor in conclusions about the role of climate change in studies of the timing of leafing, flowering, and fruiting in Europe (Menzel *et al.*, 2006), but the lack of such long-term monitoring networks preclude such a conclusion for measures related to vector-borne diseases (Kovats *et al.*, 2001).

18.3. Detection and Attribution of Observed Climate Change Impacts in Natural Systems

The IPCC AR4 provided extensive reporting on observed impacts of climate change (in Rosenzweig *et al.*, 2007, but also other chapters of the WGII report). The scientific literature on this topic is growing quickly. Rather than a full analysis of this literature, the following section provides a synthetic overview of the state of knowledge across major sectors of natural systems, based largely on the respective sectoral chapters (3, 4, 5, 6) and chapter 30 of this report, and a methodological framework with these chapters.

18.3.1 Freshwater Resources

The availability of freshwater resources, and essentially all aspects of the hydrological cycle, are affected by climate change on all continents and probably most islands, with different characteristics of change in different regions. Observed changes in each of the components of the water system are assessed by the IPCC WGI in their chapters 2 and 10, and WGII in their chapters 3, 4 and the regional chapters.

Figure 18-3 presents a synthesis of confidence in detection of changes in freshwater resources and related systems (notably erosion and slope stability), and their attribution to climate change. Frozen components of freshwater systems tend to show higher confidence in detection and attribution, while components that are strongly influenced by non-climatic drivers, such as groundwater or river flow, have lower confidence.

[INSERT FIGURE 18-3 HERE
Figure 18-3: Levels of confidence in detection and attribution of observed climate change impacts for freshwater systems over the past several decades, based on expert assessment contained in this section 18.3.1 and augmented by subsections of chapter 3 as indicated. Numbered symbols refer to: Freshwater systems (18.3.1.1): 1 groundwater depletion (Ch.3.2.4), 2 changing river flow (Ch. 3.2.3), 3 changing flood frequency or intensity (Ch. 3.2.3), 4 reduction in lake and river ice duration or thickness (Ch. 18.3.1.2); Cryosphere: 5 shrinking glaciers (Ch. 3.2.2; 18.3.1.2), 6 changes in glacier lakes (Ch. 18.3.1.1), 7 erosion and degradation of arctic coastal permafrost (Ch. 18.3.1.2), 8 degradation and thaw of lowland and mountain permafrost (Ch. 18.3.1.2), Soils and rock (18.3.1.3): 9 increasing erosion (Ch.3.2.6), 10 changes in shallow landslides (Ch.3.2.6), 11 increasing frequency of alpine rock failures.]

18.3.1.1. The Regional Water Balance

The regional water balance is the net result of gains (precipitation, ice and snow melt, river and groundwater inflow) and losses (evapotranspiration, water use and river and groundwater outflow). Impacts of climate change include reduced availability of freshwater for use (one of the variables defining drought) or excess water (floods). Evapotranspiration, being a function of surface temperature, vegetation cover, soil moisture and wind, is affected by the changing climate, but also by changing vegetation processes and land cover.

At the global scale, human influence has contributed to large scale changes in precipitation patterns over land and, since the mid 20th century, in extreme precipitation (medium confidence, WGI AR5 Chapter10, Min *et al.*, 2011). More locations worldwide have experienced an increase than a decrease in heavy rainfall events, yet with significant regional and seasonal variations (Seneviratne *et al.*, 2012). While runoff has not changed in the majority of rivers, year-to-year variability has increased (WGI AR5 Chapter 2). At the regional scale, however, human influence has affected streamflow and also evapotranspiration (WGI AR5 Chapter 10).

Change in river flow is a direct indicator of a changing regional water balance. Globally, one-third of the top 200 rivers (ranked by river flow) show statistically significant trends during 1948–2004, with the rivers having downward trends (45) outnumbering those with upward trends (19) (Dai *et al.*, 2009). In the western United States, observed changes in the hydrological cycle (river flow, snow pack) during the second half of the 20th century have been linked to recent climate change, and 60% thereof were due to anthropogenic influences (Barnett *et al.*, 2008). Likewise, the Uruguay River in South America experienced a positive trend in average streamflow from 1960 to 2000, due to increased rainfall, with shorter-term peaks in runoff caused by changes in land cover (Saurral *et al.*, 2008). In the Yellow River in China, however, long-term change in streamflow are mostly attributed to anthropogenically enhanced soil erosion rather than to climatic changes (Zhang *et al.*, 2007). Changes in rainfall seasonality in monsoon systems also affect river flows. In South America, for example, wet seasons have increased in duration from an average of 170 days before 1972, to 195 days after (Carvalho *et al.*, 2010), with significant impacts on the Amazon and the La Plata basins.

18.3.1.2. Floods and Droughts

Floods, defined as impacts caused by the overtopping of river banks and levées, have increased in magnitude and frequency over recent decades in many river systems. There are limited instrumental records for these, and the existing gauging stations do not necessarily report whether impact-relevant overtopping has occurred. In addition, the highest annual flood will not necessarily imply the same overtopping each year. Other confounding factors, such as human alteration of river channels and land use also play a role, hence there is only *low to medium confidence* in global detection of a change in floods.

In regions with detected increase in heavy rainfall events and supposable consequences for pluvial floods (North America, Central Europe), both increases and decreases in floods have been found (Petrow and Merz, 2009; Villarini *et al*., 2009). An attribution study using a multi-step modeling framework of floods suggests that an anthropogenic signal is detectable for a 20% increase in flood risk for the autumn 2000 floods in England and Wales (Kay *et al*., 2011; Pall *et al*., 2011, see also 18.4.4.2).

In mountain areas, glacial lake outburst floods (GLOFs) are characterized by their low frequency and high magnitude with most devastating impacts on downstream areas. While there is no evidence for a change in frequency or magnitude of GLOFs anywhere in the world (Seneviratne *et al*., 2012), changes in the number and area of glacial lakes have been observed, with varying degrees of increasing trends in several regions over the Hindu Kush Himalayan mountain arc in the past two decades (Gardelle *et al*., 2011), and a similarly strong increase in lake numbers in the Andes of Peru in the second half of the 20th century (Carey, 2005), and in northern Patagonia from 1945 to 2011 (Loriaux and Casassa, 2013). The growing number of these lakes is of concern since it suggests an increased likelihood of GLOFs.

Since the 1950s some regions of the world have experienced more intense and longer droughts (*medium confidence*), although a global trend cannot currently be established (Seneviratne *et al*., 2012). Drought conditions have increased (with *medium confidence*) in Southern Europe and the Mediterranean, West Africa, East Asia, Southern Australia and New Zealand, and decreased in most of North America and Northern Australia (the rest of the world had either no change or insufficient data).

Groundwater storage has been reduced in large parts of the world, and this has been primarily attributed to human activities, such as in northeastern India where groundwater depletion, as detected by satellite data for the 21st century, was largely attributed to groundwater withdrawal for irrigation and other human use (Rodell *et al*., 2009). Attribution of groundwater change to climatic drivers is more rare (Taylor *et al*., 2012). For Kashmir (India), Jeelani (2008) suggests that the observed decline in groundwater recharge between 1981 and 2005 can be attributed to decreasing precipitation and glacier retreat, while a modeling study for southeast Spain indicates an effect of temperature related changes in evapotranspiration on groundwater (Aguilera and Murillo, 2009).

Water quality in watersheds and lakes is expected to change with increasing temperature through an increase in eutrophication. It is difficult, however, to link observed changes in water quality to climate change due to the counfounding factors. Eutrophication is mostly driven by other causes, such as untreated sewage inflows in urban and industrial areas and surface runoff delivering residues of fertilizers used in agriculture, and vegetation decay and manure inputs in flooding events (Kundzewicz and Krysanova, 2010). There is emerging evidence for downstream impacts on water quality due to upstream climate impacts, such as high sulfide content in rivers of Peru's Cordillera Blanca due to sulfide-rich rocks that became exposed as glaciers retreated (Fortner *et al*., 2011).

18.3.1.3. The Cryosphere

There is extensive evidence of significant recent changes in various componentes of the cryosphere, including glaciers, ice sheets and floating ice shelves, sea, lake and river ice, subsurface ice (permafrost) and snow (WGI AR5 Chapter 4). It is *likely* that there is an anthropogenic component in the changes observed in Arctic sea ice, Greenland surface melt, glaciers, permafrost and snow cover (WGI AR5 Chapter 10).

Changes in glaciers continue to provide a globally largely homogeneous but regionally variable signal of retreat. There is *high confidence* that glacier changes over the past 2-3 decades exceed internal variability, but only few studies are available that attribute these glacier changes to anthropogenic forcing (WGI AR5 Chapter 10). The absolute contribution of glaciers and ice caps to sea level rise has increased since the early 20th century and has been close to 1 mm yr^{-1} for the past two decades (WGI AR5 Chapter 4), around a third of total observed sea level rise. The decadal-scale mass loss of ice sheets and glaciers causes accelerated uplift of underlying land in the North Atlantic Region (Jiang *et al.*, 2010). There is *medium confidence* regarding the effects of decadal ice loss on seismicity due to unloading of the lithosphere beneath ice sheets (Hampel *et al.*, 2010) and Alaskan glaciers (Sauber and Ruppert, 2008), and on volcanic activity such as enhanced magma generation (Sigmundsson *et al.*, 2010). The strong and rapid downwasting observed on alpine glaciers has prompted a number of impacts. Expanding or new lakes at the margin of many retreating glaciers in the Alps of Europe, Himalayas, Andes and other mountain regions have altered the risk of outburst floods. In the Swiss Alps and the Peruvian Andes, outburst floods from several lakes in the 21st century have caused damages, and required risk reduction measures on the order of tens of millions USD (Huggel *et al.*, 2011; Carey *et al.*, 2012b). New glacier lakes have also become a tourist attraction, led to additional infrastructure, and stimulated assessment of potential for hydropower generation (Terrier *et al.*, 2011). There is also evidence of slope instabilities as a consequence of recent decadal scale glacier downwasting (Haeberli and Hohmann, 2008; Huggel *et al.*, 2011).

Depending on local conditions, variations in runoff in high-mountain regions are often attributed to glacier and climate change (Casassa *et al.*, 2009). Current understanding suggests that during the continuous shrinkage of glaciers a ‘peak meltwater’ exists, with increasing runoff trends before, and decreasing trend after this threshold (3.4.4). An increase in runoff from glacier areas has been documented for catchments in western and south-central China over the past several decades, and for western Canada and Europe (Zhang *et al.*, 2008; Moore *et al.*, 2009; Li *et al.*, 2010; Stahl *et al.*, 2010). In the Peruvian Andes there is evidence that ‘peak meltwater’ has recently been passed, based on runoff decrease during the dry season in seven out of nine glacier-fed catchments in the Cordillera Blanca (Baraer *et al.*, 2012), also confirmed by qualitative observations made by local people (Bury *et al.*, 2010; Carey *et al.*, 2012a). In the Swiss Alps, positive variations in river runoff have occurred primarily in highly glaciated catchments during warm periods of the 20th century (1940’s, 1990’s), while for less glaciated catchments a runoff decrease was detected for the warm and dry 1990s (Collins, 2006; Pellicciotti *et al.*, 2010). For large catchments (Po and Rhône catchments with <1% basin glacier cover), the contribution of glacier melt to total runoff in August was significantly lower for 2004-2008 than for the previous twenty years (Huss, 2011).

Earlier reported trends of Arctic sea ice decline in terms of extent and thickness have continued, with a significant increase of the rate of sea ice decline in the first decade of the 21st century (WGI AR5 Chapter 4). It is *likely* that at least some of the decline in Arctic sea ice extent can be attributed to anthropogenic climate forcing (WGI AR5 Chapter 10). Observations by Inuit people in the Canadian Arctic confirm with *high confidence* the instrumental observations on the various changes of sea ice (see Box 18-5). Antarctic sea ice has slightly increased over the past 30 years, yet with strong regional differences (WGI AR5 Chapter 4).

For lake and river ice, there is generally *high confidence* of later freeze-up and earlier break-up over the past 100+ years, yet with regional differences (WGI AR5 Chapter 4). Changes in lake and river ice can have effects on freshwater ecosystems, transport and traffic over frozen lakes and rivers, and ice induced floods during freeze-up and break-up events (Voigt *et al.*, 2011). Some evidence exists in Europe that ice-jam floods were reduced during the last century due to reduced freshwater freezing (Svensson *et al.*, 2006).

Combined in-situ and satellite observations indicate a decline in snow cover extent in most months of the period 1922-2010, with the largest decline in spring (8%) (WGI AR5 Chapter 4). Only few formal detection and attribution studies exist but they consistently indicate an anthropogenic influence on snow cover reduction (WGI AR5 Chapter 10), including an up to 60% contribution of anthropogenic climate forcing on changes in snow pack and runoff timing between 1950 and 1999 in the Western United States (Barnett *et al.*, 2008). Impacts on winter tourism have been observed (18.4.3.3).

Widespread changes and degradation of permafrost of both, high-latitude/low-land and high-elevation mountain regions, have been observed over the past years and decades (WGI AR5 Chapter 4). Generally, the permafrost boundary has been moving polewards and to higher elevations, and the active layer thickness has increased at many sites. While formal attribution studies are hardly available for any of the above mentioned permafrost attributes, several impacts have been related to permafrost changes, including an increase of flow speed of Alpine rock glaciers in particular in the 21st century, resulting in rock fall and debris flows (Kääb *et al.*, 2007; Delaloye *et al.*, 2010), expansion and deepening of thermokarst lakes, erosion at the Arctic coast, resulting in a doubling of the erosion rate at Alaska's northern coastline over the past 50 years (Karl *et al.*, 2009). Furthermore, expansion of channel networks (Toniolo *et al.*, 2009), increased river bank erosion (Costard *et al.*, 2007) and higher dynamics in shrinkage and expansion of lakes and ponds have been observed in the Arctic (Rowland *et al.*, 2010), as well as an increase in hillslope erosion and landsliding in Northern Alaska since the 1980's (Gooseff *et al.*, 2009). Complex feedbacks and interactions across surface systems, and spatial and temporal scales complicate detection of drivers and effects. For example, drying of land surface due to permafrost degradation may cause an increase in wildfires, in turn resulting in a loss of ground surface insulation and change in surface albedo that accelerates permafrost thawing (Rowland *et al.*, 2010; Forkel *et al.*, 2012).

18.3.1.4. Erosion, Landslides, and Avalanches

Erosion and landsliding typically increases during phases of deglaciation in mountain areas (Ballantyne, 2002; Korup *et al.*, 2012) and there is emerging evidence for this to occur during contemporary deglaciation (Schneider *et al.*, 2011; Uhlmann *et al.*, 2012). Erosion related to sediment flux changes from mountain areas has been observed in the Western Himalaya in relation with hydrologic extreme events (medium confidence, Wulf *et al.*, 2012), increasing over the past 60 years (Malik *et al.*, 2011), with important impacts on hydropower schemes. For southern China, there is robust evidence of decline in sediment load in some rivers since the 1980s and 1990s (Zhang *et al.*, 2008a). Dam construction is an important driver of the recent decline in sediment load, leaving only *low confidence* in attributing the change to any climate impacts for the Yangtze catchment in China (Xu *et al.*, 2008).

Changes in sediment yield, e.g. from rockfall or disintegration of rock glaciers, related or unrelated to climate impacts, can significantly influence frequency and magnitude of alpine shallow landslides and debris flows (Lugon and Stoffel, 2010), but no clear evidence exists so far for a change in frequency of shallow landslides and debris flows from recently deglaciated mountain areas in the European Alps (Jomelli *et al.*, 2004; Stoffel and Huggel, 2012).

Rock slope failures in mountain areas with permafrost occurrence have increased since the 1990s (*high confidence* in the Western European Alps, *medium confidence* for New Zealand Alps, and *low confidence* globally). There also is *high confidence* that glacier retreat and downwasting, permafrost degradation and high-temperature events have contributed to many high-mountain rock slope failures over the past 20 years (Allen *et al.*, 2010; Ravanel and Deline, 2011; Schneider *et al.*, 2011; Fischer *et al.*, 2012; Huggel *et al.*, 2012a). Damages and costs for risk reduction measures in Alpine areas have increased due to rock fall and debris flows, with climate change playing a major role in triggering complex downstream impact chains and feedback (*medium to high confidence* of influence of anthropogenic climate forcing), such as recently documented in the Swiss Alps with costs on the order of tens of millions USD (Huggel *et al.*, 2012b). Rock and ice avalanches, and other landslides from destabilized slopes have also impacted glacier lakes and caused downstream damage in several high-mountain regions (e.g., Xin *et al.*, 2008; Bajracharya and Mool, 2009; Künzler *et al.*, 2010; Carey *et al.*, 2012a; Huggel *et al.*, 2012b).

Other than for the above mentioned types of landslides, there is no clear evidence that their frequency or magnitude has changed over the past decades (Huggel *et al.*, 2012b). This is true for shallow landslides and also for regions with a relatively complete event record (e.g. Switzerland, see Hilker *et al.*, 2009). In general, detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology. In line with loss from other extreme events (see 18.4.4) an increase in terms of casualties, or loss due to landslides has been documented in South, East and South-East Asia over the past years, but are largely attributed to changes in exposure, i.e. population growth (Petley, 2010).

No change in snow avalanche activity has been detected so far in Europe (Laternser and Schneebeli, 2002; Voigt *et al*., 2011). However, the detection of changes in snow avalanche impacts, such as fatalities and property loss, is difficult over the past decades due to changes in snow sport activities and avalanche defense measures.

18.3.2. Terrestrial and Inland Water Systems

As documented by previous IPCC reports (notably Rosenzweig *et al*., 2007), numerous changes in terrestrial and inland water systems have been attributed to recent climate change. Confidence in such detection of change is often *very high,* reflecting high agreement among many independent sources of evidence of change, and robust evidence that changes in ecosystems or species are outside of their natural variation. Confidence in attribution to climate change is also often *high*, due to process understanding of responses to climate change, or strong correlations with climate trends and where confounding factors are understood to have limited importance. The scientific literature in this field is growing quickly, precluding a full review in this chapter. Therefore, statements of confidence for detection and attribution are given without references, as detailed traceability is provided in chapter 4.

Organisms respond to changing climate in a multitude of ways, including through their phenology (the timing of key life history events such as flowering in plants or migration of birds), productivity (the assimilation of carbon and nutrients in biomass), spatial distribution, mortality / extinction, or by invading new territory. Noticeable changes may occur at the level of individual organisms, ecosystems, landscapes, or by modification of entire biomes. Organisms and ecosystems are adapted to a variable environment, and they are capable to adapt to gradual change to some degree – for the scope of this chapter, available knowledge will be reviewed concerning changes in terrestrial and freshwater ecosystems that occur beyond natural variability and which can be assumed to be due to recent climate change and/or increased in atmospheric CO_2. Confidence in the detection of such change involves therefore assumptions about natural variability in these ecosystems, and confidence in the attribution of detected change to climate drivers (or CO_2) implies the assessment of confounding drivers such as land use change.

18.3.2.1. Phenology

Since the AR4 there has been a further significant increase in observations of phenology of plants and animals, showing that many, but not all species have changed functioning to some degree over the last decades to centuries on all continents (*high confidence* due to robust evidence but only moderate agreement across all species). New satellite-based analyses confirm earlier trends, showing, for example, that the onset of the growing season in the northern hemisphere has advanced by 5.4 days from 1982 to 2008 and its end has been delayed by 6.6 days (Jeong *et al*., 2011). Significant changes have been detected, by direct observation, for many different species, for example, for amphibians, birds (breeding, migration), mammals, and plants; a number of meta-analyses have been carried out summarizing this literature (e.g., Cook *et al*., 2012). Attribution of these changes to climate change is supported by more refined analyses that consider also the regional changes in several variables such as temperature, growing season length, precipitation, snow cover duration and others, as well as experimental evidence. The *high confidence* in attributing many observed changes in phenology to changing climate is a result of these analyses, as well as of improved knowledge of confounding factors such as land use and land management (for more references and details see 4.3.2.1).

18.3.2.2. Productivity and Biomass

Many terrestrial ecosystems are now net sinks for carbon over much of the Northern hemisphere and also in parts of the Southern hemisphere (*high confidence*). This is shown, for example, by inference from atmospheric chemistry, but also by direct observations of increased tree growth in many regions including Europe, the United States, tropical Africa and the Amazon. During the decade 2000 to 2009, global land net primary productivity was approx. 5% above the preindustrial level, contributing to a net carbon sink on land of 2.6 ± 0.7 Pg C yr^{-1} (Raupach *et al*., 2008; Le Quéré *et al*., 2009, WGI AR5 Chapter 6), despite ongoing deforestation. These trends are in part due to nitrogen deposition, afforestation and altered land management which makes direct attribution of the increase to climate change difficult (*low confidence* in attribution). The degree to which rising atmospheric CO_2 concentrations contribute to this trend remains a particularly important source of uncertainty (for more references and details, see 4.3.2.2 and 4.3.2.3).

18.3.2.3. Biodiversity

Each species responds differently to a changing environment, therefore the composition of species, genotypes, communities and even ecosystems varies in different ways from place to place, in response to climate change. The consequences are changing ranges of species, changing composition of the local species pool, invasions, mortality and ultimately extinctions. For different species and species groups, detected range shifts vary, and so do the confidence of detection and the degree of attribution to climate change. The number of species studied has considerably increased since the AR4. Overall, many terrestrial species have recently moved, on a global average, 17 km poleward and 11 m up in altitude per decade (e.g., Europe, North America, Chile, Malaysia), which corresponds to predicted range shifts due to warming (Chen *et al*., 2011) and is 2 to 3 times faster than previous estimates (Parmesan and Yohe, 2003; Fischlin *et al*., 2007), *high confidence* in detection. For example, over the last decades, arthropods have moved large and statistically significant distances towards the poles (many 10s of km). Species with short life cycles and high dispersal capacity – such as butterflies (*high confidence* in attribution) – are generally tracking climate more closely than longer-lived species or those with more limited dispersal such as trees (*medium confidence* in attribution). There are many less well-studied species for which detection of change and its attribution to climate change are more uncertain.

Across the world, species extinctions are at or above the highest rates of species extinction in the fossil record (*high confidence* in detection). However, only a small fraction of observed species extinctions have been attributed to climate change — most have been ascribed to non-climatic factors such as invasive species, overexploitation or habitat loss (*very low confidence* in attribution to climate change). For those species where climate change has been invoked as a causal factor in extinction (such as for the case of Central American amphibians), there is *low agreement* among investigators concerning the importance of climate variation in driving extinction and even less agreement that extinctions were caused by global warming. *Confidence* in the attribution of extinctions across all species to climate change is *very low*.

Species invasions have been increasing over the last several decades world-wide, notably in freshwater ecosystems (*very high confidence*), often causing biodiversity loss or other negative impacts. While there is a documented contribution of recent climate trends to establishment, growth, spread and survival of some invasive species populations, there is only *low confidence* that the species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated dispersal in mediating invasions (for more references and details see 4.3.2.5 and 4.3.2.6).

18.3.2.4. Impacts on Major Systems

The extent of recent change in major ecosystems such as the boreal forest, the Arctic tundra, or the Amazon forest has been characterized as a “regime shift” by some authors (e.g., Biggs *et al*., 2009), implying significant and broad-scale changes in both distribution and functioning of the ecosystem.

Field and satellite measurements indicate a substantial increase in shrub growth (often linked to permafrost thawing) in many areas of the Arctic tundra (*high confidence* in detection). This change corresponds to expectations, based on experiments, models and paleoecological responses to past warming, of broad-scale boreal forest encroachment into tundra, a process which takes decades and which would have very large impacts on ecosystem structure and function. The particular strength of warming over the last 50 years for most of the Arctic further facilitates attribution (*high confidence*). The change affects a significant area of the tundra biome and can be considered an early warning for an upcoming regime shift.

For the boreal forest, increases in tree mortality are observed in many regions, including wide-spread dieback related to insect infestations in North America, but there is *low confidence* in detection of a global trend. Local and regional mortality has in some cases been linked to climate fluctuations, but there is *low confidence* in attributing any perceived overall dieback to climate change. At the Southern "trailing end" of the shifting boreal zone, there are indications of enhanced mortality of plant species (notably trees), but there is *low confidence* in overall detection due to a lack of temporal and spatial coverage of observations. There is consequently also *low confidence* in attribution of the changes to climatic change.

In the humid tropical forests of the Amazon basin, increases in tree turnover (increased mortality and growth) have been detected with *medium confidence* for recent decades. These changes have been explained by a number of factors, including the direct effect of rising CO_2 on lianas, recovery from past disturbance and changing climate. Overall, there is *very low confidence* in attribution of these observations to climate change.

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in invertebrate and fish community composition, especially in headwater streams where species are more sensitive to warming (*high confidence* in detection, *low confidence* in attribution due to numerous confounding factors; 4.3.3.1, 4.3.3.3).

18.3.3. Coastal Systems and Low Lying Areas

In coastal waters, both average warming rate and changes in seasonal timing are larger than in the open oceans (see 5.3.3). Sea surface temperatures have warmed significantly during the past 30 years along more than 70% of the world's coastlines, albeit with large spatial and seasonal variation in the rates of change *(very high confidence)*. The frequency of extreme temperature events has changed in many areas (Lima and Wethey, 2012). Seawater pH also spans larger ranges and exhibits higher variability near coastlines, and anthropogenic ocean acidification can be enhanced or lessened by coastal geochemical processes (Borges and Gypens, 2010; Feely *et al*., 2010; Duarte *et al*., 2013, see also Box CC-OA), and extreme winds, changes in wave regime and sea level play important roles in coastal processes (seeTable 5-1).

While it is *extremely likely* that observed global sea level rise can at least in part be attributed to anthropogenic emissions (WGI AR5 Chapter 10.4.3), the evaluation of local sea level trends must consider important local confounding factors, such as regional variability in ocean and atmospheric circulation, subsidence, coastal erosion, and coastal modification (see also 5.3.2). Thus far, it has not been possible to isolate an anthropogenic climate signal in local sea level changes from the contributions of these confounding factors. A possible emerging exception is along the coasts of regions with melting glaciers and ice sheets, where local gravitational effects leading to a lowering of sea level may dominate other factors (Kopp *et al*., 2010; Tamisiea and Mitrovica, 2011). As a consequence, attribution of observed effects of relative sea level change to climate change is hardly possible (see Nicholls *et al*., 2007; Nicholls *et al*., 2009), despite attempts for very few locations, e.g. for flood damages in Venice (Carbognin *et al*., 2010).

18.3.3.1. Erosion, Shoreline Processes, and Coastal Aquifers

Throughout the world, beaches and dunes, as well as bluffs and cliffs, are eroding due to a variety of climate related processes, such as rising mean sea levels (Leatherman *et al*., 2000; Ranasinghe and Stive, 2009), more frequent extreme sea levels (Woodworth *et al*., 2011), changes in wave regimes (Tamura *et al*., 2010; Reguero *et al*., 2013), the loss of natural protective structures such as coral reefs (Grevelle and Mimura, 2008) or mangrove forests due to increased ocean temperatures or ocean acidification (Bongaerts *et al*., 2010), or permafrost degradation and sea ice retreat (Manson and Solomon, 2007). However, there are multiple non-climate related drivers involved in shoreline erosion, including dams capturing fluvial sands, subsidence due to resource extraction, mining and coastal engineering and development. Due to the fragmentary nature of the information available and to the multiple natural and anthropic stressors contributing to coastal erosion, confidence in attribution of shoreline changes to climate change is *very low*, with the exception of polar regions (Forbes, 2011, see also 18.5).

Coastal lagoons and estuaries, as well as deltas are highly susceptible to alterations of sediment input and accumulation (Syvitski *et al.*, 2005; Ravens *et al.*, 2009), processes that can be influenced by climate change via changes in sea level, storminess, and precipitation. However, the primary drivers of widespread observed changes in those systems are human drivers other than climate change (thereby *very low confidence* in attribution to climate change, see 5.4.2.6, 5.4.2.7).

Coastal aquifers are crucial for the water supply of densely populated coastal areas, in particular in Small Island environments. Aquifer recharge is sensitive to changes in temperature and precipitation; and rising sea levels and sea water overwash from storm surges can contribute to saline intrusion into groundwater (Post and Abarca, 2010; Terry and Falkland, 2010; White and Falkland, 2010, see also 29.3, Table 18-8). However, excessive groundwater extraction for coastal settlements and agriculture is the main cause for widely observed groundwater degradation in coastal aquifers (e.g., White *et al.*, 2007a; Barlow and Reichard, 2010). Attribution to climate change, in particular incremental sea level rise, is not supported in the literature (Rozell and Wong, 2010; White and Falkland, 2010).

18.3.3.2. Coastal Ecosystems

Coastal habitats and ecosystems experience cumulative impacts of land- and ocean-based anthropogenic stressors (Halpern *et al.*, 2008). Most coral reefs, seagrass beds, mangroves, rocky reefs and shelves have undergone substantial changes. Coral reefs have been degraded due to both local anthropogenic factors such as unsustainable fishing and pollution, and global change factors such as increased heat waves, ocean warming and acidification (see also Box CC_CR). Coral bleaching is being detected with *high confidence* on all coasts, and warming is a major contributor (*high confidence*, for further discussion see Box 18-3, and Box CC_OA). Overexploitation and habitat destruction have been responsible for a large fraction of historical changes observed in coastal ecosystems (Lotze *et al.*, 2006).

Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2011). Increased loads of nutrients from anthropogenic sources generate coastal eutrophication and constitute the primary cause of increasing hypoxia, while upwelling of low oxygen waters and ocean warming constitute secondary drivers (see Zhang *et al.*, 2010). Persisting hypoxia can result in so-called “dead zones”, which have approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008).

Changes in abundance and distribution of rocky shore species have been observed since the late 1940s in the North East Atlantic (Hawkins *et al.*, 2008), and the role of temperature has been demonstrated by experiments (e.g., Peck *et al.*, 2009; Somero, 2012, see also 5.4.2.2). Distinguishing the response to climatic stressors from changes due to hydrology, or natural temporal and spatial fluctuations, is nevertheless challenging.

Globally, the range limits of many intertidal species have shifted up to 50 km per decade, much faster than most recorded shifts of terrestrial species (Helmuth *et al.*, 2006, see also Box 18-4). However, the geographical distribution of some species did not change in the past decades. This may be due to weak local warming (Rivadeneira and Fernández, 2005), or overriding effects of variables such as timing of low tide, hydrographic features, lack of suitable bottom types, larval dispersal, food supply, predation and competition (Helmuth *et al.*, 2002; Helmuth *et al.*, 2006; Poloczanska *et al.*, 2011). Changes in current patterns and increased storminess can dislodge benthic invertebrates and affect the distribution of propagules and recruitment.

Changes in musselbeds in response to higher temperatures induced by climatic change have been observed along the West coasts of the United States (Smith *et al.*, 2006a; Menge *et al.*, 2008; Harley, 2011). On Tatoosh Island (Washington, USA), a shift in community structure from a mussel to an algal-barnacle-dominated community has been attributed to rapidly declining pH (Wootton *et al.*, 2008; Wootton and Pfister, 2012).

Ocean warming is also leading to range shifts in vegetated coastal habitats such as coastal wetlands, mangrove forests and seagrass meadows (*medium confidence*, see 5.4.2.3). Extreme temperature events can alter marine and coastal communities, as shown for the European heatwave 2003 (Garrabou *et al.*, 2009), and the early 2011 heat wave off the Australian West Coast (Wernberg *et al.*, 2012).

Poleward expansion of mangrove forests, consistent with expected behavior under climate change, has been observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux *et al.*, 2011; Raabe *et al.*, 2012), and New Zealand (Stokes *et al.*, 2010). High temperatures have impacted seagrass biomass in the Atlantic Ocean (Reusch *et al.*, 2005; Díez *et al.*, 2012; Lamela-Silvarrey *et al.*, 2012), the Mediterranean Sea (Marbà and Duarte, 2010) and Australian waters (Rasheed and Unsworth, 2011). Extreme weather events contributed to the overall degradation of seagrass meadows in a Portuguese estuary (Cardoso *et al.*, 2008).

Decline in kelp populations attributed to ocean warming has occurred off the North coast of Spain (Fernández, 2011), as well as in southern Australia, where the poleward range expansion of some herbivores have also contributed to observed kelp decline (Johnson *et al.*, 2011; Wernberg *et al.*, 2011; Wernberg *et al.*, 2011). The spread of subtropical invasive macroalgal species (e.g., Lima *et al.*, 2007) may be adding to the stresses temperate seagrass meadows experience from ocean warming.

Overall, there is *high confidence* in detection of range shifts and biodiversity changes in intertidal and other coastal species, as well as in a decline in kelp forests, and increased mortality of seagrasses, and *high confidence* that climate change has contributed to these effects (5.4.4, Figure 5-5). For the widespread decline observed in salt marshes and mangroves, there is *very low confidence* in a role of climate change due to overriding effects of other human drivers.

18.3.3.3. Coastal Settlements, Infrastructure, and Economic Activities

Recent global (e.g., Menéndez and Woodworth, 2010; Woodworth *et al.*, 2011) and regional studies (e.g., Marcos *et al.*, 2009; Haigh *et al.*, 2010; Haigh *et al.*, 2011) have found that observed trends in extreme sea levels are mainly consistent with mean sea level trends (Woodworth *et al.*, 2011), indicating that the increasing frequency of extreme events affecting coastal infrastructures observed so far is related to rising mean sea level rather than to changes in the behaviour of severe storms. Increased damages from coastal flooding have been observed with *high confidence*, however, with exposure and subsidence constituting the major drivers, confidence in attribution to climate change is *very low* (Seneviratne *et al.*, 2012, see also 5.4.3, 5.4.4).

Increases in saltwater intrusion and flooding have been observed in low-lying agricultural areas of deltaic regions and Small Islands, but the contribution of climate change to this is not clear (e.g., Rahman *et al.*, 2011, see also 18.5.9). Both climate variability and change impact fishermen livelihoods (Badjeck *et al.*, 2010) and physiological and ecological properties of fish (e.g., Barange and Perry, 2009, see also 18.3.4, 18.4.1.2); however local and regional observations of climate impacts on output of coastal fisheries are scarce.

While vulnerability of coastal settlements and infrastructure to future climate change, in particular sea level rise and coastal flooding, is widely accepted and well-documented (seeTable 5-5), there is a shortage of studies on the role of climate change in observed impacts on coastal systems.

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Box 18-3. Detection and Attribution of Mass Coral Bleaching and Mortality to Climate Change

Declining water quality as well as increasing fishing pressure and coastal development have been implicated in the rapid decline in the abundance of corals and coral reefs over the past 50 years (Bryant *et al.*, 1998; Gardner *et al.*, 2003; Bruno and Selig, 2007; Sheppard *et al.*, 2010; Burke *et al.*, 2011; De'ath *et al.*, 2012). Since 1980, mass coral bleaching and mortality events began to occur on reefs throughout the tropics and subtropics with no precedent in the scientific literature (Box CC-CR). While bleaching of individual coral colonies has been reported prior to 1980 (Yonge and Nichols, 1931), mass coral bleaching events involving hundreds and thousands of coral colonies across entire reef and coastal regions have not (Hoegh-Guldberg, 1999; Baker *et al.*, 2008). These novel events are often followed by the mass mortality of coral communities, especially if conditions remain anomalously warm for long periods (ibid). In the very warm year of 1998, for example, mass coral bleaching affected almost every part of the seas associated with the tropics and subtropics resulting in the loss of 16% of the world's reef-building coral (Wilkinson and Hodgson, 1999).

There is broad agreement that mass coral bleaching can be triggered by small increases in sea temperature (> 1°C) above the summer maxima for a region over several weeks (very high confidence, Hoegh-Guldberg, 1999; Baker *et al.*, 2008; Strong *et al.*, 2011). The impact of temperature is also exacerbated by strong solar irradiance (Hoegh-Guldberg, 1999). There is also broad agreement that thermal stress impacts the ability of *Symbiodinium* to capture and process light, leading to the production of damaging reactive oxygen species which precedes the loss of symbionts (Jones *et al.*, 1998). As the symbiosis breaks down, the brown dinoflagellates leave their host corals, turning their tissues white and depriving corals of an important source of energy (Muscatine, 1986; Hoegh-Guldberg and Smith, 1989).

There is little or no evidence that reef-building corals and their *Symbiodinium* have, or evolved substantially in terms of the thermal tolerance over yearly or decadal time frames, or can be expected to do so (Hoegh-Guldberg, 2012). The relationship between elevated sea temperatures and mass coral bleaching remains robust enough to be used within algorithms that reliably detect and project the incidence of mass coral bleaching from satellites (Strong *et al.*, 2004; Strong *et al.*, 2011). Depending on the size of the thermal anomaly and exposure time, communities of reef-building corals have either recovered, or have experienced large-scale mortalities such as those seen worldwide in 1998 (Hoegh-Guldberg, 1999; Wilkinson and Hodgson, 1999; Baker *et al.*, 2008) and 2005 in the Caribbean (Eakin *et al.*, 2010). The detection of mass coral bleaching has been improved using satellite algorithms such as Degree Heating Weeks (DHW) (ibid).

Of the many variables investigated, only elevated sea temperature co-occurs consistently with mass coral bleaching and mortality events, and has a well worked physiological model associated with it (Hoegh-Guldberg, 1999). Consequently, given the relationship between global climate change and increased ocean temperatures, and that between coral bleaching and elevated temperature, the detected increase in the frequency of mass coral bleaching and mortality events can be attributed to anthropogenic climate change as the dominant driver with *very high confidence*.

_____ END BOX 18-3 HERE _____

18.3.4. Oceans

Since 1970, ocean temperatures have increased by around 0.1°C decade^{-1} in the upper 75 m and approximately 0.02°C decade^{-1} in the upper 500m, due to anthropogenic warming.

The increased flux of CO_2 from the atmosphere to the ocean has reduced the average pH of seawater by 0.1 pH units over the past century, with the greatest reduction occurring at high latitudes (Box CC-OA). These changes have been attributed to increases in the atmospheric concentration of greenhouse gases as result of human activities (*high to very high confidence*, WGI AR5 Chapter 10.4.1-10.4.4). Changes in wind speed, upwelling, water column stratification, surface salinity, ocean currents, solar irradiance, cloud distribution, and oxygen depth profile have also occurred (WGI AR5 Chapter 3.2 – 3.8; Figure 30-5, 30-6, 30-7).

Changes in the physical and chemical nature of ocean environments are predicted to have impacts on marine organisms and ecosystems, with many already having been observed across most ocean regions (see 6.2, 6.3, 6.5, 30.4, 30.5). However, the detection and attribution of recent changes in ocean systems is complicated by the influence of long-term variability such as the Pacific Decadal Oscillation (PDO), El Niño-Southern Oscillation (ENSO), and the Atlantic Multidecadal Oscillation (AMO). The fragmentary nature of ocean observations and the influence of confounding factors such as fishing, habitat alteration, and pollution also represent significant challenges to detection and attribution (Hoegh-Guldberg *et al.*, 2011; Parmesan *et al.*, 2011).

18.3.4.1.Impacts on Ocean System Properties and Marine Organisms and Ecosystems

Greater thermal stratification in many regions has reduced ocean ventilation and mixing depth, thereby reducing the availability of inorganic nutrients and hence primary productivity in surface layers, with controversial trends depending on methodology (see 6.1.3, 6.2.3, 30.5.6). However, upwelling has increased in some regions bringing greater concentrations of nutrients to surface waters, boosting productivity (see 30.5.5) and enhancing fisheries output (see also 18.4.1.2 for fisheries). Increases in productivity also occurred with warming and sea ice loss at high latitude. At a global scale a small increase in net primary production has been detected (Table 18-1, *medium confidence*).

Poleward shifts in the distributions of zooplankton, fish, seabirds and benthic invertebrate have been observed, particularly from the well-studied NE Atlantic, with a clear attribution to warming (*high confidence*, 6.3.2, 30.5.1). In many regions, Temperature exerts the strongest influence on ecosystems and the responses of ecological systems to changing temperature are well-studied. However, it is often difficult to clearly identify the interaction of temperature with other factors (6.3.5). Some studies have found changes in the abundance of fish species that are consistent with regional warming, with differences in response between species, in line with differential specializations of coexisting species (6.2, 6.3.2, Pörtner, 2012). Anthropogenic influences modulate responses to climate, e.g., due to exploitation status (Tasker, 2008; Belkin, 2009; Overland *et al.*, 2010; Schwing *et al.*, 2010), with more heavily exploited species being more sensitive to environmental variability in general, including temperature trends and extremes (Hsieh *et al.*, 2005; Stige *et al.*, 2006; Hsieh *et al.*, 2008).

Changes to water column mixing have combined with other factors such as nutrient loading to drive down oxygen concentrations and increase the number and extent of hypoxic zones. These zones are characterized by very low oxygen and high CO_2 levels and have been detected with *high confidence*, and attributed in part to enhanced stratification and microbial respiration caused by warming *(medium confidence,* see Table 18-1). In some cases, expanding or shifted hypoxia exerts strong local and regional effects on marine biota such as distribution shifts, habitat contraction or loss, and fish kills.

Laboratory experiments have shown that a broad range of marine organisms (e.g. corals, fish, pteropods coccolithophores, and macroalgae), physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth and neural function), and ecosystems processes (e.g., productivity, reef building and erosion) are sensitive to changes in pH and carbonate chemistry of seawater (*high confidence*, 6.2.2-5, 6.3.4, Box CC-OA). However, few field studies have been able to detect and attribute specific changes in marine ecosystems to anthropogenic ocean acidification due to the inability to identify the effect of ocean acidification from ocean warming or local factors (Wootton *et al.*, 2008; De Moel *et al.*, 2009; Moy *et al.*, 2009; Bednaršek *et al.*, 2012, see also 6.3.4).

[INSERT TABLE 18-1 HERE
Table 18-1: Observed changes in ocean system properties and their effects, with confidence levels for detection and attribution to climate change, based on assessment in Chapter 6.2, 6.3, and summarized in 6.6.1 and Figure 6-16. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.]

There has been a substantial increase in the number of studies documenting significant changes in marine species and processes since the AR4 (Hoegh-Guldberg and Bruno, 2010). A new meta-analysis using a database of long-term observations from peer-reviewed studies of biological systems, with nearly half of the time series extending prior to 1960, shows that a high proportion (81%) of observed responses are consistent with regional climate change (see 30.4). Poloczanska *et al.* (2013) argue that the high consistency of marine species' responses across geographic regions (coastal to open ocean, polar to tropical), taxonomic groups (phytoplankton to top predators), and types of responses (distribution, phenology, abundance) reported in their analysis support the detection of a widespread impact of climate change on marine populations and ecosystems (see 30.4 and 30.5 for more detail).

The impacts of climate change on marine organisms such as fish, invertebrates and marine algae include changes in abundance, distribution, and community structure and shifts in phenology and migration patterns. Table 18-2 gives examples of the manifestation of climate change on marine species.

[INSERT TABLE 18-2 HERE
Table 18-2: Observed changes on marine species and ecosystems, with confidence levels for assessment of detection of changes and their attribution to climate change, based on assessment in Chapter 6.2, 6.3, summarized in 6.6.1 and Figure 6-16, and 30.4. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.]

18.3.4.2. Observed Climate Change Effects across Ocean Regions

While climate change is evident across the Ocean, its impacts vary between ocean regions (Table 30.2; Figures 30-2, 30.3 and 30.5; WGI AR5 Chapter 3). Considerable differences in system understanding, data availability, and the potential contribution of climate change in relation to other factors add to the heterogeneity of the assessment. Attribution of regional heat content changes are less certain than on a global level, but warming patterns have been detected in all basins (Table 30-2, Figure 30-2) and attributed to anthropogenic influence with *high confidence* (WGI AR5 Chapters 3, 10.3.1, and 10.4), with the important exception of Eastern Boundary Upwelling Ecosystems (EBUE), where two of the four major upwelling systems show no change in sea surface temperatures over the last 60 years (table 30-2). These differences may relate to geographical differences that contribute to different levels of change in wind stress and hence upwelling, which influences the amount of cooler water flooding the surface layers of the water column in these regions (see Box 30.8.2). Recent research shows deep penetration of warming in some regions, and declining oxygen levels *(low to medium confidence*, see Table 18-3). Regional estimates of CO_2 uptake are in line with global estimates, and ocean acidification has been detected and attributed with *high confidence* in most regions (WGI AR5 Chapter 3.8.1, 30.5, Box CC-CAO). Table 18-3 shows confidence in detection and attribution of observed climate change impacts across the world's major open ocean regions, with the exception of the Deep Sea.

[INSERT TABLE 18-3 HERE
Table 18-3: Confidence in detection and attribution of observed climate change effects across ocean regions, based on expert assessment in Chapter 30.5 (respective subsections are given below). Confidence levels assigned are for detection / attribution, respectively.]

The high latitude spring bloom systems of the Northern Hemisphere show strong warming and associated effects (see above). In the North Pacific, the Bering Sea is one of the productive sub-regions and has undergone major changes in recent decades as a result of climate variability, climate change and fishing impacts (Litzow *et al.*, 2008; Mueter and Litzow, 2008; Jin *et al.*, 2009; Hunt, 2010). Loss of sea ice has led to the retreat of the cold pool in the Bering Sea, and northward expansion of productivity.

Marginal seas such as the East China Sea are also warming rapidly. There is *high confidence* that this has contributed to declining primary productivity and fisheries yields as well as other ecological changes (30.5.4.1). However, other human pressures including over-fishing, habitat alteration, and nutrient loading are important contributing factors and it is difficult to disentangle these from the impacts of climate change.

Semi-enclosed seas like the Black and Baltic Seas and the Arabian / Persian Gulf have their own specific environmental conditions and responses (30.5.3.1). The Baltic and Black Seas show an expansion of hypoxic zones attributed in part to climate change (*medium confidence*). Coral reefs in the Arabian / Persian Gulf and Red Seas appear to have experienced widespread bleaching in 1996 and 1998 associated with elevated temperature. It is highly likely that these impacts are associated with long-term variability that has, combined with climate change, resulted in warmer than normal summer sea temperatures that now periodically exceed the thermal tolerance of reef-building corals (*high confidence*).

Warming of the Mediterranean has been associated with mass mortality events as well as with invasions and subsequent spread of new warm water species, which has resulted in the 'tropicalisation' of fauna (30.5.3.1.3). In many tropical regions and the subtropical gyres of the Pacific, Indian, and Atlantic, periodic heat stress combined with other local stresses has driven mass coral bleaching and mortality (see also Box CC-CR, 30.5).

In other regions, such as the California Current upwelling system, high-quality databases support *very high confidence* in the detection of ecological changes, but attribution of these to climate change can be made with *very low confidence* due to large-scale environmental variability associated with ENSO and the PDO.

In overall terms, attributing observed local and regional changes in marine species and ecosystems to climate change remains an important question for on-going research (Stock *et al.*, 2010).

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Box 18-4. Differences in Detection and Attribution of Ecosystem Change on Land and in the Ocean

Marine and terrestrial ecosystems differ in fundamental ways. Gradients in turbulence, light, pressure and nutrients uniquely drive fundamental characteristics of organisms and ecosystems in the ocean. While the critical factor for transporting nutrients to marine primary producers ocean mixing driven by wind, water is the primary mode for transporting nutrients to land plants. In addition to these characteristics, marine ecosystems are often more technically difficult and costly to explore than terrestrial equivalents, which explains the low number and shorter scientific studies of marine ecosystems (Hoegh-Guldberg and Bruno, 2010). The latter has restricted the extent to which we can accurately detect and attribute of changes within the Ocean.

Impacts of climate change in terrestrial and marine systems differ significantly for the same types of measures, e.g., species phenology and range shifts, leading to differences in expert's interpretations of the data and possibly divergent levels of confidence in detection and attribution. There are also fundamental differences in exposure of organisms to recent warming, their biological responses and our ability to detect change through observations. Changes in temperature of ocean systems have generally been less than those of terrestrial ecosystems over the last four decades (Burrows *et al.*, 2011). Furthermore, despite higher variability the horizontal spatial gradient of temperature change (°C km^{-1}) is generally much higher in terrestrial ecosystems than in marine ecosystems. All else being equal, the net result is that species have generally needed to move much shorter distances in terrestrial ecosystems to stay within their preferred climates, also due to the influence of the topography such as mountain ranges (Burrows *et al.*, 2011), although many marine species can potentially exploit strong vertical thermal gradients to attenuate the need for range shifts in response to warming.

Species and ecosystems may respond very differently to these climate signals in ways that influence the ability to detect change. For example, a comparison of ectotherm species (i.e., species that do not actively regulate their body temperatures such as reptiles and fish) indicates that marine species' ranges have tracked recent warming at both their poleward and equatorial range limits, while many other terrestrial species' ranges have only tracked warming at their poleward range limits (Sunday *et al.*, 2012). Biological processes influencing phenological shifts may also differ substantially between systems. For example, the effect of climate on the timing of flowering of terrestrial plants at high latitudes is only moderately influenced by confounding effects, whereas the timing of phytoplankton blooms in high latitude marine systems is highly dependant on ocean temperature and associated stratification and changes in nutrient availability.

_____ End BOX 18-4 HERE _____

18.4. Detection and Attribution of Observed Climate Change Impacts in Human and Managed Systems

Observed impacts on human systems have received considerably less attention in previous IPCC reports and the scientific literature, compared to observed impacts on natural systems. Human systems' "normal state in the absence of climate change" is almost never stationary. Confounders other than climate change have been and continue to drive the normal evolution of these systems with climate often playing a relatively minor role. It is therefore difficult to detect and attribute the signal of climate change in the majority of human systems. The food system is one noteworthy exception. There is emerging literature estimating the climate *sensitivity* of many sectors within the human system, yet climate impacts are often not detectable over the impacts from non-climate confounders.

For some human systems, the only observed situations where a climate signal had a detectable and sometimes attributable impact are during extreme weather events. Extreme events for a variety of sectors are therefore discussed in a single section below. Overall, the literature has made significant progress for certain sectors, such as food systems, since AR4. The following sections provide a synthesis of findings with regard to food systems, cities, economic systems, human health, human security and human livelihoods and poverty, which are documented in greater detail in chapters 7, 8, 9, 10, 11, 12 and 13. We have also incorporated evidence from regional chapters and further available literature, especially for the discussion of extreme events, human security, and observed changes in indigenous communities.

18.4.1. Food Production Systems

Over the past several decades food production systems across the globe have changed significantly. Factors other than atmospheric CO_2 or climate, such as cultivar improvement and increased use of synthetic fertilizers, herbicides, and irrigation were primarily responsible for these changes. In a number of settings the effects of past changes in weather or CO_2 have been regarded as noise that obscures other effects of interest (Bell and Fischer, 1994). Due to the large number and relative importance of non-climate drivers in food systems and food security, formal detection and attribution of impacts is extremely difficult for this sector. The majority of confounders, such as fertilizer application or adoption of modern crop varieties, are not well measured in terms of their distribution across space and time. Further, it is difficult to quantify the exact relationship between these confounders and outcomes of interest (e.g., crop yields). The identification of a unique fingerprint from greenhouse gas emissions in these systems is therefore impractical. There are no known studies simulating historical trends in food-related outcomes with and without changes in anthropogenic emissions of greenhouse gases. A possible exception is the study by Auffhammer et al. (2006) who compared predicted rice yields in India using climate model simulations of temperature in the late 20th century with yields estimated from observed temperatures for 1930-1960, using the latter period as a surrogate for climate without recent changes in greenhouse gases. They find that rice yields in a world without greenhouse gas emissions would have been significantly higher, thus attributing negative impacts to emissions.

18.4.1.1.Agricultural Crops

In order to make attribution statements regarding crop changes to climate change, one needs to make assumptions about how farmers adapt. Some studies assume that farmers do not change their practices or technology as a response to changes in climate during the period of study. This may be a valid assumption in some cases (Schlenker and Roberts, 2009) yet there is evidence of significant adaptation to climate via technology for a variety of crops and locations (Zhang *et al.*, 2008b; Liu *et al.*, 2010).

A significant number of studies have provided impact estimates of observed changes in climate on cropping systems over the past few decades (see chapter 7.2). Based on this literature, there is *medium confidence* that over the past several decades observed climate trends have adversely affected wheat and maize production for many regions. There is *medium confidence* that observed climate trends since 1980 have had adverse impacts on global total production of these crops (Figure 7-2). There is *medium confidence* that climate change impacts on rice and soybean yields over this time period have been small in major production regions and globally (Figure 7-2). There is *high confidence* that in some cold regions warming has benefitted crop production in recent decades (Jaggard *et al.*, 2007; Chen *et al.*, 2011).

Many crop modeling studies focus on production for single sites or provinces and/or short time-series, rendering attribution of observed yields to climate change problematic. Some recent studies, however, examine outcomes at the continental or global scale (Lobell and Field, 2007; You *et al.*, 2009; Lobell *et al.*, 2011). At this scale, observed trends in some climatic variables, including mean summer temperatures, can be attributed to anthropogenic activity (e.g., Jones *et al*., 2008). These studies indicate that this observed warming has had significant negative impacts on trends in crop yields for certain crops. Figure 7-3 presents a summary of the detectability of changes in growing season climate and crop yield changes, as well as the ability to attribute changes to climate and CO_2 trends (in the case of yield changes) or anthropogenic emissions (in the case of growing season climate changes).

The recent literature has increasingly documented attibutable trends not only in the seasonal averages of climate variables, but also for extremes. Extreme rainfall events are widely recognized as important to cropping systems (Rosenzweig *et al*., 2002). Changes in the patterns of rainfall extremes have been attributed to anthropogenic activity (Min *et al*., 2011). A similar observation has been made for frost patterns in nearly every region of the world (Alexander *et al*., 2006; Zwiers *et al*., 2011), as well as for the occurrence of very hot nights (WGI AR5 Chapter 10.6.1). High nighttime temperatures are harmful to most crops, but this effect has been observed most frequently for rice yield (Peng *et al*., 2004; Wassmann *et al*., 2009; Welch *et al*., 2010) and quality (Okada *et al*., 2009). Daytime extreme heat is also damaging and sometimes lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009). At the global scale, trends in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Zwiers *et al*., 2011).

Further, changing atmospheric conditions are affecting crops both positively and negatively. It is *virtually certain* that the dramatic increase in atmospheric CO_2 conentrations since preindustrial times has improved water use efficiency and yields most notably in C_3 crops. It is important to note that these effeects are of relatively minor importance when explaining total yield trends (Amthor, 2001; Long *et al*., 2006; McGrath and Lobell, 2011).

Emissions of CO_2 have been associated with ozone (O_3) precursors (Morgan *et al*., 2006; Mills *et al*., 2007). There is *high confidence* that elevated O_3 currently suppresses global output of major crops, with reductions estimated at roughly 10% for wheat and soy and 3-5% for maize and rice (Van Dingenen *et al*., 2009). Detected impacts are most significant for India and China, but can also be found for soybean production in the United States in recent decades (Fishman *et al*., 2010).

18.4.1.2. Fisheries

There is a large literature focusing on the relationship between the dynamics of marine fish stocks and climate variability, suggesting that climate change has impacts on these stocks and on the fisheries that exploit them (Hollowed *et al*., 2001; Roessig *et al*., 2004; Shriver *et al*., 2006; Brander, 2007). Some fisheries and aquaculture do not show evidence of climate change impacts (e.g. aquaculture in the UK and Ireland, Callaway *et al*., 2012), while many others do with both positive and negative changes (30.6.2.1; Figure 30-15B, see also 18.3.4).

There is *high confidence* in the detection and attribution of shifts in the spatial distributions of marine fishes (Perry *et al*., 2005, 30.6.2.1) and in the timing of events like spawning and migration (Sydeman and Bograd, 2009, 30.4). The challenges produced by ocean warming and acidification vary from region to region, however, with decreases in many regions and increases (probably short-term) in some regions, especially at high latitudes (30.6.2.1; Figure 30-15B). The ability to attribute detected changes to climate change is confounded by the influence of other factors such as harvesting, habitat modification, technological development, pollution, and interannual to decadal climate variability (Brander, 2010).

Ecosystems such as kelp forests, mangroves and coral reefs provide habitat to fisheries which provide food and income to hundreds of millions of people worldwide. The strong linkage between increasing sea temperatures, the decline of carbonate reef frameworks (see Box 18-3), and habitat for key fisheries resources underpins a strong traceable account from global climate change to impacts on coastal fisheries (*high confidence*; see Box CC-CR, Figure 30-12, 30.5.2 - 30.5.4, 30.5.6).

Similar linkages between climate change and fisheries can be made for pelagic fisheries such as tuna. Shifts in tuna fisheries have occurred in the Indian and Pacific oceans, driven by climate variability (ENSO). The detected changes are consistent with the thermal biology of these important species and projections of change under further changes to ocean temperature (*high confidence*, 30.5.1.1.1, 30.5.6.1, 30.6.2.1).

18.4.1.3. Food Security

Food security depends crucially on the production and storage of food. The evidence on observed climate change impacts on food production therefore has implications for food security. Further, the term food security needs to be discussed at different spatial scales, as there is enough food available per capita globally, yet a significant share of humankind is affected by permanent or periodic food shortages. Quantifying the impact of climate change on food security is extremely challenging at any scale as there are significant numbers of non-climate confounders which affect food security at various spatial scales (7.1).

One measurable indicator of food security is the global price of food. Food prices have dropped slowly throughout the last century, yet even since AR4 there have been several periods of food price increase and periodic spikes in food prices (figure 7-4). Increased demand for crops recently has been partially driven by biofuel productions, which is both mandated by policy and market driven by oil price spikes (Roberts and Schlenker, 2010; Mueller *et al*., 2011; Wright, 2011). There is some evidence that supply side fluctuations also impacted food prices (figure 7.4). While not all significant weather events result in food price spikes, high price episodes are more probable during periods with low stored stocks. This can be due to more slowly growing supply relative to demand. Government interventions, such as export bans, can exacerbate price responses to weather events (Dawe, 2008). There is some recent evidence that climate trends have had some influence on global supply. Lobell *et al*. (2011) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO_2 over the study period were considered.

18.4.2. Cities and Urbanization

The world continues to urbanize rapidly. Both new and existing urban systems are evolving due to rapidly changing incomes, institutions and population. There is robust evidence across a set of case studies that climate has changed in many urban areas and that variability has increased, consistent with climate change projections. The most robust evidence has emerged from observational data for mean annual temperature and precipitation rates, days of extreme temperature, number of extreme rainfall events, and rate of sea level rise (8.2.2.1, 8.3). These shifts are associated with an increased probability of flooding, droughts, inland flooding, coastal flooding, storm surges, heat waves, and declines in the number of extreme cold days (see Hunt and Watkiss, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig *et al*., 2011for recent reviews).

Detection and attribution of climate change impacts in cities is extremely difficult due to the large role of other confounding factors. Opportunities to discern climate change signals in cities are complicated by the pattern and pace of urbanization which have consequences for local environmental conditions such as intensification of urban heat islands, land subsidence associated with groundwater withdrawal, and heightened flooding probability resulting from increase of impervious surfaces. These conditions interact with ongoing climate change and as a result make it difficult to provide evidence and attribution agreement of climate change signals in cities given the current state of observed data and models.

18.4.3. Economic Impacts, Key Economic Sectors and Services

18.4.3.1. Economic Growth

A negative cross sectional correlation between per capita income and temperature has been observed both across countries (Nordhaus, 2006) and across regions within countries (Dell *et al*., 2009a; Dell *et al*., 2009b). Such correlations should never be interpreted as causal, because the underlying mechanisms are usually complex. In low income countries, careful tracking of incomes and temperatures over an extended period, taking into account important confounders, shows that higher annual temperatures as well as higher temperatures averaged over 15 year periods result in substantially lower economic growth (Dell *et al.*, 2012). This effect is not limited to the level of per capita income, but also to its rate of growth.

Broadly, a 1 degree Celsius increase in annual average temperature has been found to lower economic growth in the same year by 1.3%, which is both statistically and economically significant (Dell *et al.*, 2012). Based on 15 year averages of weather, which is a measure of climate, the impacts become larger (1.9% for low income countries). The same relationships do not hold for high income countries. Generally, higher temperatures affect economic growth through impacts on the agricultural and industrial sectors (Dell *et al.*, 2012). One proposed mechanism for this is the impact of heat stress on workers in the workplace (Dash and Kjellstrom, 2011). Temperature shocks negatively affect the growth of developing countries' exports, for which 1 degree Celsius of warming in a given year reduces the growth rate of its exports by 2.0-5.7% (Jones and Olken, 2010). The export sectors most affected are agricultural and light manufacturing exports. There is no detectable effect for higher income countries (Jones and Olken, 2010).

18.4.3.2. Energy Systems

Energy production and consumption is growing rapidly globally, with much of the growth taking place in low income and emerging economies. Due to the large number of non-climate confounders, the literature on detection and attribution for the energy sector is sparse. There is a significant literature identifying the climate sensitivity of various parts of the energy sector. Higher temperatures have been shown to raise the demand for cooling and lower the demand for heating. Cooling demand is largest in the summer and it has been shown for some areas that peak loads during the summer months have increased and that this peak is highly correlated with summer maximum temperatures (Franco and Sanstad, 2008). The literature showing the opposing effects of warmer winters and summers on electricity and gas demand using statistical methods have confirmed this U-shaped relationship of energy and electricity demand in temperature for the United States and elsewhere (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Deschênes and Greenstone, 2011).

Production losses from thermal power plants increase when temperatures exceed standard design criteria (e.g., Erdem and Sevilgen, 2006), as would be expected to occur more frequently under climate change. Power generation facilities may also experience performance losses and other impacts related to changes in access to and temperature of cooling water, as well as sea level rise and extreme weather events (Durmayaz and Sogut, 2006; CCSP, 2007; Kopytko and Perkins, 2011, see also 10.2). Further, solar photovoltaic cells become less efficient during hot days (Skoplaki and Palyvos, 2009).

The impacts of higher temperatures and extreme weather events on energy delivery, transmission and distribution vary across different empirical studies, facility characteristics, geographic regions, and other factors. Barges and ocean vessels that transport energy resources have been shown to be particularly vulnerable to hurricanes, storms, and flooding; pipeline performance can be affected by increasing ambient and soil temperatures, as well as extreme events (CCSP, 2007, see also 10.2). Some studies have quantified the general relationship between temperature and electricity transmission and distribution infrastructure, finding that increased temperatures can accelerate the aging of transformer insulation, lead to efficiency losses, and create power system reliability issues (Swift *et al.*, 2001; Li *et al.*, 2005; Askari *et al.*, 2009).

18.4.3.3. Tourism

Tourism is a climate sensitive economic sector and ample research has been performed to understand its sensitivity to climate change and impacts of (future) climate change on tourism, yet little to no literature has focused on detection and attribution of observed impacts (cf. Scott *et al.*, 2008, see also 10.6). A comparatively well-studied area is the climate sensitivity of wintersports in lower lying areas. For example, the increase in investment in artificial snow machines in the European Alps can be attributed with *high confidence* to a general decrease of snow depth, snow cover duration and snow fall days since the end of the 1980's for low-elevation mountain stations (Durand *et al.*, 2009; Valt and Cianfarra, 2010; Voigt *et al.*, 2011), which in turn has been attributed to anomalous warm winter temperatures over the past 20 years (Marty, 2008). Increased variability in precipitation, shrinking glaciers and milder winters have been shown to negatively affect visitor numbers in winter sports areas in Europe and North America (Becken and Hay, 2007). Eijgelaar *et al*. (2010) argue that so-called “last chance tourism” is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. Farbotko (2010) uses a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. In contrast, Zeppel (2012) states a low level of concern for coral bleaching by tourists visiting the Great Barrier Reef.

18.4.4. Impacts of Extreme Weather Events

The impacts of extreme weather events depend on the frequency and intensity of the events, as well exposure and vulnerability. Climate change is expected to affect both the frequency and intensity of extreme weather events including extreme temperature, droughts, heavy rainfall, and tropical and extratropical cyclones (IPCC, 2012). There is *low to high* confidence that such changes have already occurred, depending on the type of extreme (WGI AR5 Chapter 10.6). However, the impacts of extreme weather events also depend on the vulnerability and exposure of systems. It is possible that climate change can affect vulnerability and exposure, but both can also be affected by non-climate confounders, most notably economic development.

18.4.4.1. Economic Losses due to Extreme Weather Events

Extreme weather events can have economic impacts arising from damage to private and public assets as well as the temporary disruption of economic activities. Although immediate economic impacts are most noticeable, long-term impacts are also possible, as are impacts beyond the area directly affected by the event. Some economic impacts are not readily monetizable and are thus excluded from most economic assessments (Handmer *et al*., 2012, their chapter 4.5.1, 4.5.3).

There is *high confidence* that economic costs of extreme weather events have increased over the period 1960-2000, with insured losses increasing more rapidly than overall losses (Handmer *et al*., 2012, their chapter 4.5.3.3, 4.5.4.1). This is also reflected by an increase in the frequency of extreme weather-related disasters over the same period (Neumayer and Barthel, 2011). Recent studies from Latin America (Mexico, Colombia, Peru) highlight both variability and positive trends in disaster frequency, (unadjusted) losses and other damage metrics (Saldaña-Zorrilla and Sandberg, 2009; Marulanda *et al*., 2010; Rodriguez-Oreggia *et al*., 2012; Huggel *et al*.). However, there is *high confidence* that the greatest contributor to increased cost is rising exposure associated with population growth and growing value of assets (Bouwer *et al*., 2007; Bouwer, 2011; Barthel and Neumayer, 2012; Handmer *et al*., 2012, their Chapter 4.2.2, Box 4.2 and 4.5.3.3).

To account for changes over time in the value of exposed assets, many studies attempt to normalize monetary losses by an overall measure of changes in asset value. Although there is considerable year-to-year variability associated with the occurrence of extreme weather events, most studies have found no detectable trend in normalized losses consistent with anthropogenic climate change. Studies of normalized insured losses, that in general meet higher data quality standards than data on overall losses due to thoroughly monitored payouts, have focused on developed countries including Australia, Germany, Spain, the US, Spain (Changnon, 2007; Changnon, 2008; Changnon, 2009a; Changnon, 2009b; Barredo *et al*., 2012; Barthel and Neumayer, 2012, see also 10.7.3; Sander *et al*., 2013), Studies of normalized losses from extreme winds associated with hurricanes in the US (Miller *et al*., 2008; Pielke Jr *et al*., 2008; Schmidt *et al*., 2010; Bouwer and Botzen, 2011) and the Caribbean (Pielke Jr *et al*., 2003), tornadoes in the US (Brooks and Doswell, 2002; Boruff *et al*., 2003; Simmons *et al*., 2012) and wind storms in Europe (Barredo, 2010) have failed to detect trends consistent with anthropogenic climate change, although some studies were able to find signals in loss records related to climate variability, such as century-scale damage and loss of life due to wildfires in Australia related to El Niño Southern Oscillation and Indian Ocean dipole phenomena (Crompton *et al*., 2010), or decadal-scale typhoon loss variablilty in the Western North Pacific (Welker and Faust, 2013).

Although there are a number of data issues that may limit the reliability of assessments of the economic impacts of extreme weather events (Crompton and McAneney, 2008; Bouwer and Botzen, 2011; Nicholls, 2011; Handmer *et* *al*., 2012, their Chapter 4.5.3.3, see also 10.7.3), there is *limited evidence* of a trend in the economic impacts of extreme weather events that is consistent with a change driven by observed anthropogenic climate change.

18.4.4.2. Detection and Attribution of the Impacts of Single Extreme Weather Events to Climate Change

Although most studies of the relationship between climate change and extreme weather events have focused on changes over time in their frequency and intensity, a few studies have focused on the contribution of climate change to specific events (WGI AR5 Chapter 10.6.2). Assessing the contribution of climate change to a specific event poses particular challenges, both in terms of methodology and communication of results (Allen, 2011; Curry, 2011; Hulme *et al*., 2011; Trenberth, 2011). If climate change was among the drivers for a specific extreme weather event, there remains the question how this contribution translates into associated impacts and damages. Only a few studies have attempted to evaluate the role of climate change in the impacts of individual extreme weather events. Pall et al. (2011) and Kay et al. (2011), using observational constraints on climate and hydrologic model simulations, concluded that greenhouse gas emissions have increased the probability of occurrence of a comparable flooding event in autumn 2000 over the UK. A similar study for recent high flood years in the Okavango Delta, Botswana, found a decreased probability of high floods (Wolski *et al*., 2013). The autumn 2000 UK studies did not evaluate the relative role of other factors, however, while the Okavango study argued that the effects of land use, land cover, and water management change in the Okavango Basin were negligible.

In highly temperature-sensitive regions such as high mountains there is *high confidence* that several extreme impact events of the 20th and 21st century can be qualitatively attributed to effects of climate change, namely glacier lake outburst floods due to glacier recession and subsequent formation of unstable lakes (Evans and Clague, 1994; Carey, 2005; Bajracharya and Mool, 2009), debris flows from recently deglaciated areas, and rock fall and avalanches following the loss of mechanical support accompanying glacier retreat (Haeberli and Beniston, 1998; Oppikofer *et al*., 2008; Huggel *et al*., 2012b; Stoffel and Huggel, 2012, see also 18.3.1.3). Similar multiple-step approaches can be used to evaluate the contributions of anthropogenic emissions to recent damaging extreme events (see Table 18-4).

Irrespective of whether a specific event can be attributed in part to climate change, there is ample evidence of the severity of related impacts on people and various assets. Both low- and high-income countries have been strongly impacted by extreme weather events in recent years, but the impacts relative to economic strength have been higher in low-income countries (Handmer *et al*., 2012). Similarly, at the national scale, poor or elderly people have been disproportionately affected, as documented for Hurricane Katrina in the US in 2005 (Elliott and Pais, 2006; Bullard and Wright, 2010) or the 2003 European heat wave (Fouillet *et al*., 2008). Exacerbating effects of extreme weather events are mostly of non-climatic nature, including increasing exposure and urbanization, land-use changes including deforestation, or increasingly vulnerable infrastructure.

An illustrative case is the flood damage in New York City during the landfall of Hurricane Sandy in 2012. The storm surge hazard is expected to increase with rising local sea level as a result of anthropogenic emissions, notwithstanding any changes in associated meteorology (Lin *et al*., 2012). However, increased exposure of buildings, people, and infrastructure in New York City has probably contributed to a much larger increase in risk over the past century (Aerts *et al*., 2013). Against that increase, though, there has been a major investment in reducing vulnerability and increasing resilience, partly in response to past extreme events (Tollefson, 2013). Determining a contribution from anthropogenic climate change amongst such large competing factors, including diagnosing the forces behind adaptation, remains a major challenge.

[INSERT TABLE 18-4 HERE
Table 18-4: Illustrative selection of some recent extreme impact events for which the role of climate has been assessed in the literature. The table shows confidence assessments as to whether the associated meteorological events made a substantial contribution to the impact event, as well as confidence assessments of a contribution of anthropogenic emissions to the meteorological event. The assessment of confidence in the findings is not necessarily a conclusion of the listed literature but rather results from assessment of the literature. Assessment of the role of

anthropogenic emissions in the impact event requires a multi-step evaluation. Partly based on Coumou and Rahmstorf (2012).]

18.4.5. Human Health

IPCC AR4 (Confalonieri *et al*., 2007) concluded that there was *weak to moderate evidence* (with *low to medium confidence*) of climate change effects on three main categories of health exposures: vectors of human infectious diseases (changes in distribution), allergenic pollen (changes in phenology), and extreme heat exposures (trend in increased frequency of very hot days and heat wave events).

For pollen production, changes in phenology have been consistently observed in mid to high latitudes with, for example, earlier onset in Finland (e.g., Yli-Panula *et al*., 2009) and Spain (D'Amato *et al*., 2007; García-Mozo *et al*., 2010, see also 4.3). In North America, the pollen season of ragweed (*Ambrosia* spp.) has been extended by 13-27 days since 1995 at latitudes above 44°N (Ziska *et al*., 2011). Allergic sensitization of humans has changed over a 25 year period in Italy, but the attribution to observed warming remains unclear (Ariano *et al*., 2010).

The most direct potential health impact of climate change is through exposure to higher temperatures. The association between very hot days and increases in mortality in temperate populations is very robust but depends on factors such as geographic location, the age structure of the population, and the prevalence of air-conditioning (11.2.2). Seneviratne *et al*. (2012) concluded that there is *medium* to *high confidence* in detection of non-zero trends in increasing frequency of hot days and nights, decreasing frequency of cold days and nights, and in the duration of heat waves and warm spells over temperate subcontinental regions, and that on the global scale it is *likely* that anthropogenic emissions have had at least a minor role in these changes. However, the translation of this trend in hazard to a trend in exposure is complicated by evidence of changes in social, environmental, and behavioral factors (e.g., Carson *et al*., 2006).

Overall, Confalonieri *et al*. (2007) concluded that there was a lack of evidence for observed effects in human health outcomes, and this remains the case. Disease patterns change considerably over time due to changes in exposures (e.g. smoking patterns), control measures (vaccination, drug resistance), and population structures (population aging). Therefore, observations of trends in health outcomes provide little insight into a role of climate change. The detection of a climate-change-induced trend for any health outcome requires that changes in reporting over time need to be taken into account. Adaptation is an added confounding factor, as health agencies are mandated to intervene, and people are liable to alter exposures, as soon as risks are identified. With regard to temperature-related mortality, Christidis *et al*. (2010) examined the roles of changing exposure and health care and of anthropogenic climate change in observed trends in excess mortality during cool and warm days. They concluded that anthropogenic climate change had at most a minor role in trends in temperature-related mortality in England and Wales over the three decades, relative to a major role for the combined trends of exposure and health care; however, assessment of the existence of a minor role for anthropogenic climate change may have been sensitive to the lack of interseasonal mortality relationships in their modeling setup (Rocklöv *et al*., 2009; Ha *et al*., 2011).

There is *limited evidence* regarding the role of observed warming in changes in tick-borne disease in mid to high latitudes. The upsurge of tick borne encephalitis (TBE) in the 1980-90s in central and Eastern Europe has been attributed to socio-economic factors (human behavior) rather than temperature (Šumilo *et al*., 2008; Šumilo *et al*., 2009). Changes in the observed incidence of TBE in central Sweden remain unexplained however (Randolph, 2010). Changes in the latitudinal and altitudinal distribution of ticks in Europe are consistent with observed warming trends (e.g., Gray *et al*., 2009), but there is no evidence so far of any associated changes in the distribution of human cases of tick-borne diseases. In North America, a northward expansion of the distribution of the tick vector (*Ixodes scapularis*) was observed in the period 1996 to 2004 (Ogden *et al*., 2010).

There is *limited evidence* of a change in the distribution of rodent-borne infections in the US (plague and tularaemia) consistent with observed warming (Nakazawa *et al*., 2007). Specifically, a northward shift of the southern edge of the distributions of the diseases (based on human case data for period 1965-2003) was observed. There was no change detected in the northern edge of the distributions though.

Malaria incidence has been monitored in the Kericho region of Kenya for over three decades, with a trend toward increasing incidence in the late 1990s. A local warming trend also occurred during the end of the observation period (Omumbo *et al.*, 2011). Other studies have confirmed that malaria incidence is sensitive to temperature and rainfall effects in nonlinear ways, but it is a complex ecological system, with changes in vector, human and parasite behavior that need to be considered. A mosquito-human model, however, has shown that predicted malaria cases exhibit a strongly non-linear response to observed warming (Alonso *et al.*, 2011). A detailed review by Chaves and Koenraadt (2010) concludes that there is *robust evidence* that decadal temperature changes have played at least a minor role in the malarial trends of the East African highlands, arguing that it may the combination of many factors that has been crucial. However, temperature trends should nonetheless not be considered the main or sole cause of such changes in malaria in the east African highland region, and globally the dominant trend has been a contraction of the geographical range of malaria and a decrease in malaria endemicity over the past century (Gething *et al.*, 2010).

18.4.6. Human Security

18.4.6.1. Violent Conflicts and Social Disruptions

A small number of studies have examined the connection between the collapse of civilizations and large-scale climate disruptions like severe or prolonged drought. DeMenocal (2001) summarized the evidence for a number of cases. However, attribution to climate change can be made with only *low confidence* due to limitations on both historical understanding and data. Similarly, a small number of studies have suggested that levels of warfare in Europe and Asia were relatively high during the Little Ice Age (Parker, 2008; Brook, 2010; Tol and Wagner, 2010; White, 2011; Zhang *et al.*, 2011), but again attribution to climate can only be made with *low confidence*. There is no evidence of a climate effect on inter-state conflict in the post-WWII period.

Most of the recent research in this area has focused on the relationship between climate variability – as opposed to climate change – and civil conflict, with most studies focusing on Africa. Although some studies have established statistical relationships (Miguel *et al.*, 2004; Hendrix and Glaser, 2007; Burke *et al.*, 2009; Hsiang *et al.*, 2011), their results have been questioned (Buhaug *et al.*, 2010; Buhaug and Theisen, 2012; Slettebak, 2012; Theisen *et al.*, 2012) and no consensus has been reached. Both the detection of a climate effect on civil conflict and its attribution to climate change can be made with only *low confidence*.

Very recent work has begun to examine links between climate variability and small-scale communal violence (Adano *et al.*, 2012; Butler and Gates, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012), but it is too early attach anything but *low confidence* to the detection of a climate effect and its attribution to climate change.

Finally, a number of efforts have been made to establish a link between violent crime and high temperatures (Anderson, 1987; Field, 1992; Anderson, 2001; Rotton and Cohn, 2001; Butke and Sheridan, 2010; Breetzke and Cohn, 2012; Gamble and Hess, 2012). However, the findings remain controversial with most studies identifying other factors as explaining variations in rates of violent crime (Kawachi *et al.*, 1999; Fajnzylber *et al.*, 2002; Neumayer, 2003; Cole and Gramajo, 2009) and the detection of a temperature effect on violent crime and its attribution to climate change can be made only with *low confidence*.

18.4.6.2. Migration

Large population movements, in response to climatic events, are sometimes considered a human security issue. Empirical detection of such relationships has been slow because data sets on population movements are not yet well developed. Moreover, the attribution of migration to climate change is difficult because economic, political, social, demographic, and other environmental drivers interact with climatic drivers to influence migration (Black *et al.*, 2011). Few studies measure or empirically demonstrate how rainfall or temperature changes cause a strengthening or weakening of the various forces driving migration, especially income levels and income variability (Lilleør and van den Broeck, 2011).

Some large sample studies have been able to detect population movements in response to natural disasters (Smith *et al.*, 2006b; Boustan *et al.*, 2012) and climate-induced agricultural losses (Feng *et al.*, 2012) in the United States, where data quality is high. In both the United States and African contexts, crop losses have also been associated with rural to urban population movements within a country (Barrios *et al.*, 2006; Feng *et al.*, 2012). By statistical attribution, Marchiori *et al.* (2012) estimate that anomalous temperature and rainfall have displaced roughly 128,000 people per year in Sub-Saharan Africa during 1960–2000.

Drought has prompted both short-distance (Tacoli, 2009) and long distance international migration, with the Mexican drought of the 1990s providing an example of the latter (Saldaña-Zorrilla and Sandberg, 2009; Feng *et al.*, 2010). In Burkina Faso, temporary moves to other rural areas have increased as a result of a reduction in rainfall (Henry *et al.*, 2004). Even though there is a statistically significant relationship between migration outcomes and rainfall variability, Kniveton et al. (2011) report from own fieldwork that only 27 of 3,517 households identified rainfall as a driver of migration.

18.4.7. Rural Areas, Livelihoods and Poverty

Much like for the other sectors discussed above, available research about climate related impacts on livelihood and poverty distinguishes between climate sensitivity and impacts driven by climate change (e.g. gradual temperature changes, and changes in climate variability). A climate sensitivity of livelihoods has been observed with *high confidence*, while there is a paucity of evidence about impacts of gradual climate change on livelihoods and poverty. Detection of changes in livelihood aspects is often difficult due to a lack of data. If trends are actually detected, many confounding factors contribute to detected changes. Because of the important confounders and the current limitations in attributing climate extremes and changes in variability to climate change (see 18.4.4.2), confidence in attribution of changes in livelihoods and poverty to climate change is typically *low* or *very low* (Nielsen and Reenberg, 2010).

Primarily negative impacts from historical climate variability and extremes, and to a much lesser degree from climate change, have been observed on people's natural, physical, economic, social and cultural assets (see Table 18-5). Impacted natural assets include land, water, fish stocks and livestocks (Osbahr *et al.*, 2008; Bunce *et al.*, 2010). There is growing concern about negative effects of climate change and ocean acidification on marine and coastal fisheries, and the livelihoods of fisherfolks (Cooley and Doney, 2009; Badjeck *et al.*, 2010), however there is no literature available discussing observed impacts.

[INSERT TABLE 18-5 HERE
Table 18-5: Cases of regional livelihood impacts attributable with varying degree to weather- and climate related events, climate change or climate variability.]

Natural and physical assets (e.g. settlements) of many poor people have been affected by weather- and climate-related extreme events. Poor people living in hazard exposed areas in Africa and Latin America were affected by floods and landslides in the 1990's and 2000's with some upward trend mainly due to increased urbanization (*low to medium confidence* for increasing floods and landslides, *high confidence* for increasing number of people affected) (Douglas *et al.*, 2008; Hardoy and Pandiella, 2009). Although there is evidence of a decline in average precipitation in West Africa since 1960 (Lacombe *et al.*, 2012) including repeated droughts (Dietz *et al.*, 2004; Armah *et al.*, 2011), which in some cases has been partly attributed to anthropogenic climate forcing (Jenkins *et al.*, 2005; Biasutti and Giannini, 2006), there is *limited evidence* of changes in poverty among affected small-holder and subsistence farmers that can be attributed to climate drivers such as rainfall decline and droughts.

In rural areas correlations have been found between climatic variability and extreme events and livelihood diversification in West Africa (Nielsen and Reenberg, 2010) and Mexico (Eakin, 2006) and in Mexico frequent impacts of natural disasters correlate with substantial income drops, marginalized, grain-intensive farming and low access to credit (Saldaña-Zorrilla and Sandberg, 2009).

Climate impacts disproportionately affect poor populations, thus increasing social and economic inequalities, both in urban and rural areas, and in low-, middle- and high-income countries. Climatic factors thereby interact with aspects of race, class, gender, ethnicity or age (Nightingale, 2011). Evidence for poor people in high income nations being disproportionately affected by weather- and climate related extreme events comes, for instance, from 2005 US Hurricane Katrina (Elliott and Pais, 2006; Bullard and Wright, 2010) or drought events in Australia (Alston, 2011). Glacial lake outburst floods in the Peruvian Andes also affect different populations depending on their degree of exposure, level of vulnerability, race, ethnicity, and socio-economic class (Carey, 2010; Carey *et al.*, 2012b). There has been an observed gender bias in impacts from climate variability and extremes, due to gender specific roles within the household, communities, and wider socio-political and institutional networks (Carr, 2008; Arora-Jonsson, 2011, see also Box 13-1).

For indigenous peoples, specific rights, including the right to life, adequate food, water, health, adequate housing, and the right to self-determination, are directly implicated by the impacts of climate change and variability (Ford, 2009b, see also Box 18-5). Livelihoods of indigenous people in the Arctic have been identified as among the most severely affected by both climate change and variability, including food security aspects, traditional travel and hunting, and cultural values and references (Beaumier and Ford, 2010; Pearce *et al.*, 2010). Negative effects on social and cultural assets by climatic and non-climatic stressors have also been identified in Africa with respect to social networks of the poorest, elderly and female-headed households (Osbahr *et al.*, 2008). Impacts of rising temperatures and increased variability of weather extremes on crops and livestock of indigenous people in highlands were furthermore reported from Tibet (Byg and Salick, 2009) and the Andes of Bolivia (McDowell and Hess, 2012). Shifts from transient to chronic poverty due to climate change and variability are suggested for livelihoods and households that, unlike more affluent ones, lack appropriate response to, and ability to cope with altered seasonalities, unpredictable seasons, and extreme events such as floods and droughts (Hardoy and Pandiella, 2009).

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Box 18-5. Detection, Attribution, and Traditional Ecological Knowledge (TEK)

Indigenous and local peoples often possess detailed knowledge of climate change that is derived from observations of environmental conditions over many generations. Consequently, there is increasing interest in merging this traditional ecological knowledge (TEK)—also referred to as indigenous ecological knowledge (IEK) or simply indigenous knowledge (IK)—with the natural and social sciences in order to better understand and detect climate change impacts (Huntington *et al.*, 2004; Parry *et al.*, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Ford *et al.*, 2011; Diemberger *et al.*, 2012). TEK, however, does not simply augment the sciences, but rather stands on its own as a valued knowledge system that can, together with or independently of the natural sciences, produce useful knowledge for climate change detection or adaptation (Agrawal, 1995; Cruikshank, 2001; Hulme, 2008; Berkes, 2009; Byg and Salick, 2009; Maclean and Cullen, 2009; Wohling, 2009; Ford *et al.*, 2011; Herman-Mercer *et al.*, 2011).

Cases in which TEK and scientific studies both detect the same phenomenon offer a higher level of confidence about climate change impacts and environmental change and the value of indigenous knowledge (Huntington *et al.*, 2004; Laidler, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Gamble *et al.*, 2010; Green and Raygorodetsky, 2010; Alexander *et al.*, 2011; Cullen-Unsworth *et al.*, 2011). For example, in Peru's Cordillera Blanca mountains, local residents and instrument-based scientific analysis both report increasingly rapid glacial recession, less snow in the upper watershed, decreased water supplies in glacier-fed basins, and an increase of falling glacier "blocks" since the latter half of the 20th century (Bury *et al.*, 2010; Carey, 2010; Baraer *et al.*, 2012; Carey *et al.*, 2012b). For another, in Tibet, many, but certainly not all, local residents observed warming temperatures, less snow, and shrinking glaciers, which are consistent with scientific interpretations (Byg and Salick, 2009). At Clyde River, Nunavut, Canada, Inuit and scientific observations have detected that wind speed has increased in recent years and that wind direction changes more often over short periods (within a day) than it did during past decades (Gearheard *et al.*, 2010). Finally, in the Canadian Arctic, Inuit sea ice experts and scientists have both observed the thinning of multiyear sea ice, the shortening of the sea ice season, and the declining extent of sea ice cover, with Inuit observers reporting less predictability in the sea ice and more hazardous travel and hunting at ice edges (Nichols *et al*., 2004; Laidler, 2006; Krupnik and Ray, 2007; Ford *et al*., 2009; Aporta *et al*., 2011).

TEK can also inspire scientists to study new issues in the detection of climate change impacts. In one case, experienced Inuit weather forecasters in Baker Lake, Nunavut, Canada, reported that it had become increasingly difficult for them to predict weather, suggesting an increase of weather variability and anomalies in recent years. To test Inuit observations, scientists analyzing hourly temperature data over a 50 year period confirmed that afternoon temperatures fluctuated much more during springtime during the last 20 years—precisely when Inuit forecasters noted unpredictability—than they had during the previous 30 years (Weatherhead *et al*., 2010).

Despite frequent confluence between TEK and scientific observations, there are sometimes discrepancies between them. These discrepancies indicate uncertainty in the identification of climate change impacts. Attribution of impacts to anthropogenic climate change, for example, tends to have much less convergence between TEK and the natural sciences. While community members in Canada's Northwest Territories report that less ice cracking during the last decade was a result of winter warming caused by climate change, scientists have concluded that the relationship between ice cracking and air temperature is much more complex and requires more research on water temperature, ice thickness, snow cover, and ice properties in order to attribute reduced ice cracking to global climate change (Woo *et al*., 2007).

Scale is another problem in the detection of climate change: TEK and scientific studies frequently focus on different and distinct scales that make comparison difficult. Local knowledge may fail to detect regional environmental changes while scientific regional or global scale analyses may miss local variation (Wohling, 2009; Gamble *et al*., 2010). In some cases TEK and scientific studies measure or note distinct phenomenon that cannot be compared or have inaccuracies (Gearheard *et al*., 2010). Furthermore, TEK based observations and related interpretations necessarily need to be viewed within the context of the respective cultural, social, and political backgrounds (Agrawal, 1995). Therefore, a direct translation of TEK into a western science perspective is often not feasible.

_____ END BOX 18-5 HERE _____

18.5. Detection and Attribution of Observed Climate Impacts across Regions

Since the AR4, significant new knowledge about detected impacts of recent climate change has been gained from all continents of the world, assessed in the regional chapters 22-29 of this report (for relevant information on Ocean regions from Chapter 30, see 18.3.2). The following sections provide a short overview about key findings for each of the eight world regions discussed in Chapters 22-29, along with a summary of relevant recent observed climate change. Further details of regional detection and attribution findings are summarized in 18.5.9 for various collections of natural, managed, and human systems.

18.5.1. Africa

For much of Africa, knowledge about recent climate change is limited, due to weak climate monitoring, and gaps in coverage continue to exist. On the other hand, the low natural temperature variability over the continent allows earlier detection of warming signals. Thus there is *medium to high confidence* in regional warming, with *low to high confidence* in attribution to anthropogenic emissions. A main regional feature has been the drying of the Sahel during the decades following 1970, but that trend has halted during the most recent decade (see also 22.2).

African environmental systems present many strong challenges for the potential detection and attribution of responses to climate change. Given the weak spatial and temporal variations in temperature, there is smaller scope for migrational and phenological responses to anthropogenic climate change than in other parts of the world. Furthermore, high quality monitoring is relatively sparse in time and space, and is often unsuitable for detecting changes across margins and borders where responses to climate change are most expected. The dearth of studies examining attribution questions means it is currently difficult to estimate the degree to which studies are selectively published based on results, and thus to determine whether each attribution study is only indicative of local reasons for concern or if it is more generally representative of a broader domain.

Since the AR4 there has been a particular research focus on three geographic domains: the effects of dryness in the Sahel since 1970 on tree density; the effects of surface warming and resulting increased stratification on the Great Lakes on the lake ecology; and the effect of warming on species ranges in southern Africa, where spatial temperature gradients are larger and there is more scope for range shifts as a measureable response.

18.5.2. Europe

Amongst all continents, Europe has the longest tradition in climate monitoring. Warming has been occurring across the continent in all seasons, with an associated decreasing frequency of cold extremes and increasing frequency of hot extremes (Seneviratne *et al*., 2012). The Southern parts of the continent (the Mediterranean) have been getting drier, while northern areas have been getting wetter (23.2.2.1), with a general increase in the frequency of extreme wet events everywhere (Seneviratne *et al*., 2012).

Significant warming-related impacts have long been observed in Northern and Central Europe, with substantial loss of Alpine glaciers, longer growing seasons, associated productivity increases and changed phenology of many plant and animal species on land as well as in the Atlantic Ocean. Higher temperatures and generally drier conditions have likely contributed to the stagnation of agricultural yields that would otherwise have been expected to increase as a consequence of improved agricultural practices and higher atmospheric CO_2. In the Mediterranean drier and hotter conditions have contributed to increased wildfires.

18.5.3. Asia

Asia spans a wide range of climate types and expected climate changes, but warming has been observed throughout the continent with northern areas amongst the fastest warming on the planet. Precipitation trends vary geographically, with a more frequent but weaker Indian monsoon (WGI AR5 Chapter 14.7.10), and contrasting increasing and drying trends over coastal and inland China (24.3.1).

Among the most wide-spread observed impacts of recent climate change in Asia are the degradation of permafrost occurring throughout its current distribution in Siberia, Central Asia and on the Tibetan Plateau, matching observations from elsewhere in the world and to a very high degree explained by warming. Substantial new evidence has been collected since AR4 on glaciers in Asia. Across most of Asia glaciers have been shrinking, except from some areas in the Karakorum and Pamir. In some rivers (e.g. in China) an increase in runoff was observed in glaciated catchments.

Plants and animals are changing their phenology and growth in many parts of Asia, largely due to climate change, many species are also shifting their distribution northwards or upwards in elevation. In the oceans of tropical Asia and around Japan, coral reefs and large seaweeds are in decline.

18.5.4. Australasia

There is *very high confidence* of warming over Australian and New Zealand during the past century, and *high confidence* in hot extremes becoming more frequent and cold extremes becoming less frequent (25.2, Table 25-1). Winters in southern areas of Australia have become drier in the past few decades and the northwest has become wetter, and precipitation increased over the south and west of both islands of New Zealand (*high confidence*). While there have been no significant trends in drought frequency over Australia, regional warming may have increased their hydrological intensity (*low confidence*, Table 25-1).

There is *high confidence* of a significant decline in late season snow depth several sites in Australia's Snowy Mountains, and a decline of glacier volume by 25% in New Zealand since the middle of the 20th century (table 25-1). In many Australian terrestrial ecosystems, some observed changes in the distributions, genetics, phenology of individual species, and in the structure and composition of some ecological communities can be attributed to recent climatic and atmospheric trends, but non-climatic drivers, such as changes in fire management, grazing and land-use, also play a significant role. The 1997-2009 drought has affected freshwater systems in the eastern states and the Murray Darling Basin, but for many freshwater systems, direct climate impacts are difficult to detect. In New Zealand, few changes in ecosystems have been attributed to climate change.

Climate change impacts have been profound in marine systems around Australia and New Zealand, involving large latitudinal shifts of climatic zones and associated biota. Many of these changes have been associated with ocean warming, although for others the impacts of interacting non-climate stresses, including habitat degradation, coastal pollution and fisheries are also significant. About 10% of the observed 50% decline in coral cover on the Great Barrier Reef has been attributed to bleaching, the remainder to cyclones and predators.

Exceptional heatwave conditions in Australia have been associated with substantial increases in excess deaths and heat-related hospital admissions (Khalaj *et al.*, 2010; Loughnan *et al.*, 2010).

18.5.5. North America

North America spans a wide range of climate types and observed climate changes. While the northwest of the continent has been amongst the fastest warming on the planet, the southeast of the USA has experienced slight cooling (26.2.2). Hot extremes have been becoming more frequent while cold extremes and frost days have been becoming less frequent over the past several decades. Trends in precipitation over western parts of the continent are strongly influenced by the variability of the El Niño/Southern Oscillation, with a matching drying and decreasing snowpack. The intensity of precipitation events has been increasing over most of the continent, but trends in dryness are spatially heterogeneous (26.2.2). There is *robust evidence* of an increase in intense tropical storms in the North Atlantic over the past several decades (WGI AR5 Chapter 2.6.3).

There is evidence for hydrological change in many parts of North America, particularly in catchments that are dominated by snowpack and ice. Terrestrial ecosystems have responded to warming with range shifts (upwards and polewards), changed phenology, productivity and mortality (insect outbreaks). In some regions, wildfires have become more frequent. Marine ecosystems significantly shift ranges northwards. Agricultural production is affected by increased drought conditions in the Southern US and Mexico. There is some evidence for infrastructural damage from more frequent climatic extremes.

18.5.6. Central and South America

Most of South America has been observed to be warming over the past half century, except for an observed cooling over a western coastal strip (27.2.1.1). Precipitation over much of Central and South America is strongly influenced by the El Niño/Southern Oscillation, with accompanying long-term variability. There has been in reduction in the number of dry summer months in the southern half of the continent, while observed trends over the Amazon are sensitive to the selection of time period (27.2.1.1).

Among the observed impacts of climate change in South and Central America there are some that stand with *high* or *very high confidence* in detection and attribution. These are: the retreat of tropical glaciers and ice-fields in the Andes, decreasing river flows in the western tropical Andes, increased streamflow in the La Plata basin and bleaching of coral reefs in the western Caribbean. Several impacts are associated to many confounding causes and although detection of change may be found with *high* levels of *confidence*, the confidence in attribution is *low* or *very low*. In this category are included the degrading and receding of the Amazon rainforest, mangrove degradation on the Northern coast of South America and the expansion of agricultural areas in climatically marginal regions of Argentina. With *high confidence* in detection and *medium confidence* in attribution, denoting perhaps an impact more sensitive to climate than in the previous case, are included the increase in agricultural yields in Southeastern South America and the increase in frequency and extension of dengue fever, yellow fever and malaria.

Although the number of articles in the literature and of consolidated datasets has both increased in Central and South America during the past decade, still there are many gaps to be filled in mainly in remote regions and regarding historic temporal coverage.

18.5.7. Polar Regions

The areas of largest observed warming are all polar: the northwest of North America, northern Asia, and the Antarctic Peninsula. While this occurs against a large background of natural variability, WGI AR5 Chapter 10 conclude that it is *likely* that there has been an anthropogenic contribution to Arctic warming; for the Antarctic, however, there is *low confidence* in attribution due a sparse monitoring network, an apparent lack of warming in the continental interior, and the contrasting effects of greenhouse gas emissions and stratospheric ozone depletion (10.3.1.1.4). The nature of polar regions means that warming can lead to large changes in other aspects of the climate system, in particular the observed decrease in summer sea ice cover, earlier thaw, earlier spring runoff, and melting of permafrost (28.2).

Recent changes in the Arctic tundra hydrology are attributed to permafrost degradation caused by increasing air temperature and reduced albedo. Swamp formation, lake drainage, and ecosystem shifts are among the observed consequences. Permafrost degradation also affects traditional living for local and indigenous communities.

The ongoing reduction of sea ice cover and duration has profound impacts on the subsistence of many species in the Arctic as well as the Antarctic. Polar bears are suffering from reduced vigor and reproduction, and arctic seabird populations are facing longer flight distances for provisioning of their offspring due to phenological mismatch, resulting in decreasing reproductive success. Antarctic penguin species show decreasing numbers, attributed to shrinking stock of their main prey, the Antarctic krill, which in turn is affected by sea ice loss.

Changing snow conditions affect arctic plants and animals in various ways. Mild spells in the winter, with increasing frequency of rain on snow events and the formation of ice crusts in the snow pack has affected the populations and cyclicity of arctic grazers (voles, ptarmigans, reindeer and caribou) with cascading effects on their predators, e.g., the Arctic fox: Decreasing range of snow-beds in the Arctic summer have strong impacts on animal communities and reindeer husbandry.

The most easily detected change in the physiognomy of the arctic tundra is the ongoing increase in shrub cover as seen in many studies from the North American as well as the Eurasian Low Arctic and Subarctic, attributed to increasing temperature. In the Antarctic Peninsula, the two resident species of vascular plants have passed a summer temperature threshold, and the attribution of the observed sudden increase in production of mature seeds is not confounded by other drivers.

18.5.8. Small Islands

Despite the widely accepted high vulnerability of many small islands to climate change, including their close relationship with Coral Reefs, there are only few formal studies on observed impacts. Detection of climate change impacts in small islands is challenging due to the strong presence of other anthropogenic drivers of local environmental change. Attribution is further challenged by the strong influence of natural variability compared to incremental changes of climate drivers, and the lack of long term monitoring, high quality data.

Observations of impacts of sea level rise on small islands are scarce. In many cases phenomena which are associated with expected impacts of sea level rise such as erosion, inundation, wave overwash are also strongly linked with on-going, known climate variability and extremes and cyclic processes such as ENSO, storms and extreme tidal phenomena. It is therefore difficult to quantify the degree to which such impacts can be attributed to climate change and sea level rise.

For example, there is evidence for higher than average sea level rise, with rates up to four times the global average (approximately 12 mm yr^{-1} between 1993 and 2009), in the tropical western Pacific region, where a large number of small island and atoll communities are located (Becker *et al.*, 2012; Meyssignac and Cazenave, 2012). However, these changes may be transient, caused by strong and persistent La Nina like conditions superimposed over sea-level rise and are therefore currently not unambiguously attributed to climate change (Becker *et al.*, 2012).

18.5.9. Impacts across Regions

In order to allow for comparison between the various regions of the world, the following synopsis regroups the main conclusions for various components of the physical, biological, and human systems. The regional synopses is divided into various systems, covering observed impacts of regional climate change for: snow, ice and mountains, rivers and lakes (Table 18-6); terrestrial ecosystems, droughts and wildfires (Table 18-7); marine ecosystems and coastal processes (Table 18-8); and human and managed systems such as food production, economic impacts, and health (Table 18-9). These assessments follow from discussions in the various sectoral and regional chapters of this report and in earlier sections of this chapter.

Broadly, there is now at least *robust evidence* for observed impacts in most of the categories of physical and biological systems listed in most of the regions. There is also evidence of observed impacts on food production in many of the regions, while detection of impacts in other human systems remains limited. Further interpretation of these regional synopses within the "Reasons for Concern" framework forms the basis of the synthesis assessment of 18.6.

[INSERT TABLE 18-6 HERE
Table 18-6: Observed impacts of climate change on snow, ice and mountains, and rivers and lakes, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

[INSERT TABLE 18-7 HERE
Table 18-7: Observed impacts of climate change on terrestrial ecosystems, and occurrence of Drought and Wildfire, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

[INSERT TABLE 18-8 HERE
Table 18-8: Observed impacts of climate change on Marine and marine influenced Ecosystems, and Coastal processes, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

[INSERT TABLE 18-9 HERE
Table 18-9: Observed impacts of climate change on Human Systems across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

18.6. Synthesis: Detected Impacts of Climate Change and Reasons for Concern

18.6.1. Approach and History

A key motivation for the effort in assessing observed changes is the possibility that observed impacts could constitute indications of future expected changes. Observed losses in glacial volume, for example, lend additional plausibility to model-based expectations that additional warming could result in additional ice loss. Due to the complex nonlinear behavior of most environmental systems, it cannot always be assumed that past impacts scale linearly to future impacts. Likewise, absence of past impacts cannot constitute evidence against the possibility of future impacts. Nonetheless, detection and attribution of observed impacts may serve as part of the foundation for a climatic risk analysis. In order to do so, the total body of observed impacts needs to undergo a synthetic analysis pointing towards the conceivable risks.

The AR4 precursor of the current chapter (Rosenzweig *et al*., 2007) organized its efforts around a geographically distributed empirical analysis of correlation across numerous detailed and localized studies of changing systems as described in Rosenzweig *et al.* (2008). Rather than expand that approach using the quickly growing scientific literature, the goal for this synthesis is to organize findings on detection and attribution in a way that fully covers the disciplinary, sectoral and geographic diversity of observed impacts. The approach aims to establish current conditions concerning the risk analysis model formulated earlier by the IPCC through the establishment of a limited number of “Reasons for Concern” (RFC). The RFC concept was developed in IPCC-TAR (Smith *et al*., 2001), adopted for a second time in IPCC-AR4 (IPCC, 2007a), and updated in Smith *et al.* (2009). The RFCs respond directly to requests from countries that the IPCC assesses the science with respect to the United Nations Framework Convention on Climate Change’s (UNFCCC) commitment to “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1992), without being policy prescriptive in terms of the definition of “dangerous”. For the present synthesis, the goal is not to determine the levels of warming that correspond to a particular level of impact (as done in, e.g., IPCC, 2007b, Figure SPM.2); instead this analysis seeks to establish, qualitatively, the importance of impacts already observed in relation to the critical levels for concern indicated by the red colour of each bar portrayed in IPCC (2007a), using the levels revised by Smith *et al.* (2009).

While the summary of observed impacts, taken for themselves, cannot constitute an assessment of a probability-based measure of risk for dangerous anthropogenic interference, the degree to which the earlier projected impacts now have occurred can be useful for policy-relevant conclusions about the risks (chapters 1, 19). The actual quantification of risk for a given aspect of dangerous interference depends on the metrics chosen for the societal importance of a given impact and is not part of this analysis. Instead, the degree of concern is expressed in qualitative terms only, with an assessment of confidence in the assessment using standard IPCC terminology (Mastrandrea *et al*., 2010, 18.2). This is thought to directly support the development of policy-relevant conclusions about the risks expressed by each RFC.

As described more fully in Chapter 1 and earlier documentation, the five RFCs are (1) “Risks to Unique and Threatened Systems”, (2) “Risks of Extreme Weather Events”, (3) “Distribution of Impacts”, (4) “Aggregate Impacts”, and (5) “Risks of Large-Scale Discontinuities”. Their broad definitions imply significant overlap, hence some observed impacts are referred to under more than one RFC. For consistency with the earlier assessments, the definitions and naming conventions in Smith *et al.* (2009) were nevertheless followed as rigorously as possible.

18.6.2. Five Reasons for Concern

18.6.2.1. Risks to Unique and Threatened Systems

The RFC of “Risks to Unique and Threatened Systems” is concerned with the potential for increased damage to, or irreversible loss of, plant and animal species, physical systems, and human livelihoods which are known to be highly sensitive to temporal and/or spatial variations in climate. Figure 18-4 displays current evidence derived from detection and attribution studies concerning observed impacts to unique and threatened systems as a result of observed changes in climate. Changes in the three indicated physical systems have at least *high confidence* in detection and at least *medium confidence* in attribution, with regional assessments also tending to have *high confidence*. There is at least *medium confidence* in both detection and attribution for at least one each of ecosystems, physical systems, and human systems, indicating observational evidence for moderate to strong reasons for concern for all three classes.

[INSERT FIGURE 18-4 HERE
Figure 18-4: Confidence in detection and attribution of observed impacts on unique and threatened systems as a result of recent climate change. Assessments are for confidence in detection of a change and for confidence in attribution of a major role of observed climate change. Large letters denote conclusions for the full-scale system, while small letters denote conclusions for regional subsets of the systems. System changes include shrinking / receding glaciers, mountain and lowland permafrost degradation, Arctic coastal permafrost degradation, increased mortality and bleaching of warm water reef-building corals, increased shrub cover and permafrost decay in the northern tundra, increased tree mortality in the Amazon, increased tree mortality in boreal forests, changes in Arctic marine ecosystems, decline in extent of mangroves and coastal wetlands, and impacts on livelihoods of indigenous Arctic peoples. See Table 18-10 for details and references.]

The systems with strongest detection and attribution evidence cover the Arctic, warm-water coral reefs, and mountains. In the Arctic, there is at least *medium confidence* of impacts on glaciers, permafrost, the tundra, marine ecosystems, and livelihoods of indigenous peoples, reflecting macroscopic changes across both natural and human systems and across the physical and ecological subregions. Evidence for the detection and attribution of shrinkage and recession of glaciers comes from all continents, while evidence for attribution of coral bleaching spans a similarly broad area of the tropical oceans (see Table 18-10). These observed impacts confirm the reason for concern about risks to unique and threatened systems.

[INSERT TABLE 18-10 HERE
Table 18-10: Reported confidence of detection of observed changes in "Unique and Threatened Systems" and attribution of observed changes to observed climate change. Assessments are for global or the indicated regional domain, with regional variations indicated in the final column.]

18.6.2.2. Risk of Extreme Weather Events

"This RFC tracks increases in extreme events with substantial consequences for societies and natural systems. Examples include increase in the frequency, intensity, or consequences of heat waves, floods, droughts, wildfires, or tropical cyclones" (Smith *et al.*, 2009). The risk of impacts by an extreme weather event is a combination of the probability of an extreme weather hazard and the consequences of the realization of that hazard. Hence, a change in the risk of impacts of extreme weather events could be caused by a change in the probability, intensity, or sequencing of the weather event itself (which are manifestations of recent climate change), or by a change in exposure, vulnerability, or the resilience of the impacted system. It follows that assessments of change in risk to anthropogenic climate change are particularly influenced by new evidence concerning the dominant drivers of change, whether climate change is one of those major drivers or not.

In the TAR, WGII found itself unable to detect a climatic component in the causal analysis of the increasing losses from extreme weather events, but outlined instead the significant vulnerabilities that could be expected if extreme weather events would increase with future climate change (IPCC, 2001, Technical Summary). In the AR4, detection and attribution was reported in terms of likelihood and supported in terms of consequence, with the conclusion that "It is now more likely than not that human activity has contributed to observed increases in heat waves, intense precipitation events, and the intensity of tropical cyclones. There are, as well, more observations of climate change impacts from extremes than in the TAR. Responses to some recent extreme climate events have also revealed higher levels of vulnerability across the globe, producing significant loss of life and property damage in both developing and developed countries" (IPCC, 2007b).

The current assessment confirms that, in many human systems, combined changes in exposure, vulnerability, and resilience have dominated past trends in risk. For instance, while there is *high confidence* that monetary losses related to extreme weather events have increased over the past 3-4 decades (ISDR, 2009, 10.7.3, 18.4.2), it is generally accepted that climate change has not been a major driver of that change in risk: instead, trends in exposure, wealth, and vulnerability of human systems have been the major factors for the increase in losses (IPCC, 2012, 10.7.3, 18.4.2). There has been considerable recent research and assessment into various components of the overall chain involved in extreme weather risk. Table 18-11 summarizes some notable new evidence concerning changes in hazard and damage associated with extreme weather events that has been reported in the SREX, the WGI contribution to the AR5, and throughout this WGII contribution to the AR5.

[INSERT TABLES 18-11a AND 18-11b HERE
Table 18-11a: Confidence in detection of changes in extreme weather hazard and attribution of a major role of changing greenhouse gas concentrations in the observed changes.
Table 18-11b: Confidence in detection of observed trends in damage in various systems and attribution of a major role of observed changes in extreme weather to those observed trends.]

With regard to extreme weather hazard, temperature extremes have changed in many regions as a consequence of climate change (*high confidence*), with lower confidence in weather extremes that are less directly related to temperature or that occur on smaller spatial and time scales (where the connection with global mean temperature is less secure) (Seneviratne *et al.*, 2012, WGI AR5 Chapter 10.6.1). Given the documented sensitivity of many systems to hot temperatures, the increase in extreme heat hazard implies a significant reason for concern. Indeed, for some systems there is evidence that local trends in temperature extremes have had a direct impact (Table 18-11b). There is also evidence that other trends in extreme weather hazard which are closely tied to global or regional warming, such as hazards related to sea level rise or sea ice retreat, have also been leading to increased damage.

Most of the evidence of attributable changes in impact risk due to weather extremes concerns corals or Arctic systems (see Figure 18-5). Evidence in both cases is *robust*. Outside of these systems, however, evidence is *limited* and highly localised. Recent detection and attribution literature has shed light on various components of the impact risk chain, but is otherwise limited in its extent for evaluating changes in impact risk for systems other than warm-water coral reefs and Arctic systems. Overall, observed impacts confirm reasons for concern about the risks of extreme weather events.

[INSERT FIGURE 18-5 HERE
Figure 18-5: Left: confidence in detection of observed changes in extreme weather hazards and attribution of a major role of changing greenhouse gas concentrations in the observed changes. Right: confidence in detection of observed changes in damages related to extreme weather and attribution of major role to observed changes in extreme weather.]

18.6.2.3. Distribution of Impacts

This RFC concerns the disparities of impacts between regions, countries, and populations. Evidence of differentiated climate change impacts have been projected for all IPCC regions since the days of the TAR. However, because of major geographical gaps in detection and attribution evidence the TAR did not report any observed regionally differentiated impacts, and nor did the AR4. The “before present” segments of the RFC box were therefore left uncolored in both the TAR and Smith *et al.* (2009). The survey of recent studies presented in 18.5 indicates that the gap is being reduced. While evidence for detected impacts is still more exhaustive from Europe and North America, considerable confidence in conclusions has been developed elsewhere since the AR4, particularly in Central and South America and Australasia. Tables 18-6 through 18-9 summarize what we have learned from the more recent evidence, as assessed in this chapter and other chapters throughout this report based on a consistent interpretation of the underlying criteria. Figure 18-6 portrays the assessment visually.

In terms of level of confidence, it is no longer the case that observed evidence to support the regional RFC is dominated by any particular region. The number of studies and coverage of systems may still be asymmetrically distributed, but rigorous analyses of observed climate change effects and attribution (to a lesser but not insignificant degree) have emerged from Central and South America, Australasia, Asia, Africa, and Small Islands. The synthesis of assessments for natural systems in the middle-to-high range for detection and the middle-to-high range for detection and attribution spans all major regions. The number of systems covered is only an indicative metric of coverage, because many options exist for aggregation and disaggregation of evidence. Thus detection and attribution analyses currently do not provide evidence of differing severity of impacts between continents. There exists, however, a particular emphasis on evidence concerning the Arctic where systems exhibit a high sensitivity to climate change. Given the strong levels of confidence in changes across a broad range of Arctic systems, this emphasis indicates a stronger severity of impacts on the Arctic generally.

Coverage of human and managed systems is noticeably less extensive and more concentrated in the traditionally well-studied regions. Notwithstanding these differences, the qualitative conclusion that observed impacts have now been detected and attributed with *medium* to *high confidence* across the various IPCC-defined regions of the world is new and noteworthy. These higher confidence impacts generally concern the UNFCCC's metric that "food production is not threatened"; confidence in detection and attribution of observed impacts in other human systems generally remains much lower.

Throughout its assessments, the IPCC has repeatedly noted that there is significant disparity between the vulnerability of countries, regions, and social groups, due to differences in adaptive capacity. The AR4 cited examples that indicate how impacts of extreme events differ between social groups (Wilbanks *et al.*, 2007). The current coverage of detection and attribution studies is insufficient for broad evaluation of social disparities in impacts. Additional research effort is required to more fully address the nature of differences in impacts on various groups (18.7).

[INSERT FIGURE 18-6 HERE
Figure 18-6: Confidence in detection of observed changes in natural systems (panel a) and human and managed systems (panel b) across regions, and confidence in attribution of such trends to observed climate change. Based on assessments developed in Tables 18-6 through 18-9.]

18.6.2.4.Aggregate Impacts

The original intent of the Aggregate Impacts (or Aggregate Damages) RFC was to assess economic impacts, damages, and economic risk driven by climate change at a globally aggregated level. However, while some observed impacts are calibrated using a common monetary currency, others are now directly measured in a common calibrated metric or are otherwise qualitatively comparable across the globe and thus amenable to aggregation. In recognition of this, the scope of the RFC has been expanded over time (Smith *et al.*, 2009). Consequently, a variety of globally comparable impacts are considered here.

Table 18-2 lists various aggregate systems for which: the extent is global or near-global; there is a quantitatively or qualitatively calibrated measure for comparison across space and subsystems; the detection and attribution evidence has sufficient geographical distribution for a spatially representative sample. Confidence assessments for both detection and attribution span a wide range. Confidence is highest in cryospheric systems (glaciers and permafrost), with confidence in detection at least *medium* for various ecosystem measures but confidence in attribution lower (see Figure 18-7). Within human and managed systems, confidence in attribution to observed climate change is *low or very low* because of the dominating contribution of other drivers of change, including increased wealth, changes in exposure, new crop varietals, and new technologies. Overall, detection and attribution analysis reveals evidence for concern that risk of changes in aggregate measures has already changed, but also reveals *limited evidence* of a climate change influence on aggregate measures which do not concern the cryosphere.

Overall, the synthesis of aggregated impact measures confirms the concern for globally aggregated impacts of recent climate change being detected for a variety of systems and metrics.

[INSERT TABLE 18-12 HERE
Table 18-12: Confidence in detection of impacts on aggregate impact measures and confidence in attribution of at least a minor role of climate change in those observed changes.]

[INSERT FIGURE 18-7 HERE
Figure 18-7: Confidence in detection of changes in aggregate impact measures and attribution of at least a minor role of climate change in those trends]

18.6.2.5.Risks of Large-Scale Discontinuities

The RFC of “Risks of Large-Scale Discontinuities” “represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts” (Smith *et al*., 2009). Such discontinuities are hence a source of future risk, as they refer to thresholds in the Earth system that, once passed, will alter the nature of the system itself. While several of the identified “tipping elements” form part of the physical climate-ocean-cryosphere system (and are discussed in WGI), there are also elements in the biosphere that exhibit non-linear behavior with potentially strong feedbacks on the Earth system (Lenton *et al*., 2008; Leadley *et al*., 2010).

For observed impacts, the concern translates into a question of the possible presence of “early warning signals” for discontinuities that may be derived from monitoring changes in some climate or natural systems (Collie *et al*., 2004; deYoung *et al*., 2008; Andersen *et al*., 2009; Lenton, 2011). To this effect, conceptual, observational and modelling studies of climate-change-induced biome or large-scale ecological regime shifts have intensified over the last decade (deYoung *et al*., 2008; Marengo *et al*., 2011; e.g., Duarte *et al*., 2012b; Mann *et al*., 2012).

Evidence from detection and attribution analysis supports concerns that both the Arctic and the global warm-water coral reef system are experiencing irreversible regime shifts, attributable to recent climate change, while observations from the boreal and Amazon forest are less conclusive.

- For the Arctic region, new evidence indicates a biophysical regime shift is taking place, with social and economic consequences (Post *et al*., 2009; CAFF, 2010; Callaghan *et al*., 2010; AMAP, 2011; Duarte *et al*., 2012b, see also 18.3.1, 24.4.2.2, 28.2). For the marine biota in the Arctic Ocean, the rapid reduction of summer ice cover is now severely affecting pelagic ecosystems as well as ice-dependent mammals such as seals and polar bears (Duarte *et al*., 2012a). Thawing of Arctic permafrost and shrub encroachment on the tundra have both been detected with *high confidence* (18.3.2.4, 18.5.8, 24.4.2.2), driven by warming and an associated prolongation of the growing season. Wide-spread hydrological changes have been observed in the tundra region, as a result of increasing winter rains and the degradation of permafrost, leading to lake formation or disappearance within a few years’ time (CAFF, 2010; Callaghan *et al*., 2013) and cascading consequences for the tundra food webs (Post *et al*., 2009; Callaghan *et al*., 2013; Hansen *et al*., 2013).
- Warm-water coral reefs have been lost at a large scale due to thermal stress and other impacts, as was noted by AR4 already. Increased mass bleaching and mortality of corals has been detected and attributed globally with *very high confidence* (see Box 18-3), with at least *high confidence* regionally in tropical Asia, Japan, the Australian Great Barrier Reef, the western Caribbean and coast of Central America, and the waters around other small tropical islands (6.3.2, 24.4.3.2, 27.3.3.1, 29.3.1.2). This irreversible loss of biodiversity has significant feedbacks within the marine biosphere, and cascading consequences for regional marine ecosystems as well as the human livelihoods which depend on them. The additional evidence for ongoing change and its attribution to warming gained since the AR4 strengthens the conclusion that coral reef loss constitutes a strong warning signal for the irreversible loss of an entire biome.
- Dieback and degradation in the Boreal forests and the Amazonian rainforest have been identified as potential tipping elements, due to their large extent and the possible feedbacks with the carbon cycle (Lenton *et al*., 2008; Malhi *et al*., 2009; Leadley *et al*., 2010; Marengo *et al*., 2011, see also 4.3.3.1, 4.3.3.4). For the boreal forest, increases in tree mortality are observed in many regions (4.3.3), including wide-spread dieback related to insect infestations in North America (26.4.1), but there is *low confidence* in detection of this as a global trend attributable to climate change. In the humid tropical forests of the Amazon basin, tree turnover (both mortality and growth) has increased during recent decades. A number of factors have likely played a role, including the direct effect of rising CO_2 on lianas, recovery from past disturbance, and changing climate. The reason for concern about the Amazon forest is the interaction between global climate change, regional climate change related to deforestation, and the high susceptibility of forests to fire, which together could lead to degradation of forests in large areas of the Amazon above deforestation itself (Malhi *et al*., 2009). There are indications of droughts in the Amazon and evidence that dry years and deforestation increase the vulnerability of forests to fire, but there is only *very low confidence* in attribution of observed changes in tree turnover to climate change. In conclusion, there is currently

insufficient evidence from observed climate change impacts to support a climate-related warning sign of possible large-scale discontinuities in the boreal and Amazonian forest.

In the TAR, the risk of large-scale discontinuities was evaluated to be a concern only after a few degrees warming. At the time of the AR4, new understanding of physical climate processes led to a major revision of that assessment by Smith *et al*. (2009), bringing concerns forward that discontinuities could occur with much less warming. While the present analysis does not indicate the manifestation of a tipping point being reached, it does indicate significant early warning indicators for possible regime shifts in the Arctic region and for the world's warm-water coral ecosystems. Observations therefore confirm the reasons for concern about risks from large-scale singularities.

18.6.3. Conclusion

The body of scientific evidence on observed impacts of recent climate change, after rigorous assessment of scientific confidence in its attribution to recent trends, lends new qualitative support to four out of five reasons for concern established by earlier IPCC assessments. Specifically, concerns are confirmed for risks to unique and threatened systems, risks stemming from extreme weather events, globally aggregated impacts and – in terms of early warnings – risks of large-scale discontinuities. Only the spatial or social disparities covered under "distribution of impacts" are still insufficiently studied to permit a synthesis of available observations for the characterization of a global concern. While the Arctic stands out as a region with robust evidence of impacts across numerous systems, current detection and attribution literature does not address whether the severity of those impacts differs from other regions. Across RFCs, the critical evidence often comes from the same environmental systems, notably the Arctic region, warm-water coral reef systems and mountain glaciers, but there are also important observations from impacted hydrological systems and human systems including agriculture.

Detection and attribution studies evaluate the agreement between observations and process understanding, with the important requirement for direct observational evidence of the impacts. This sets a higher bar for establishing confidence in past changes than is generally used for assessing confidence in projected future changes, because observational evidence has important gaps, while the plausibility of future changes can be established on the basis of process knowledge only (WGI AR5 Chapter 10.2.5).

Despite this constraint, the evidence gathered since the AR4 on detection and attribution of observed impacts from climate change has reached a level at which it can inform evaluation of many of the aspects of present-day climate change risk as described by the RFCs. In particular, the geographic distribution of studies is reaching the point where assessment of the global nature of impacts is possible:

- There is now *robust evidence* of observed changes in natural systems in all of the regional groupings used in this report. There is at least *medium confidence* in attribution of observed changes in various components of the cryosphere to observed climate change for each of the inhabited continents. There is also at least *medium confidence* in attribution of observed changes in terrestrial ecosystems to observed climate change for six continents (exception being South America) and for some small islands, and for marine ecosystems surrounding six continents (exception being Africa) and for some small islands.
- There is *good evidence* of the detection of impacts in human systems on the inhabited continents. There is at least *medium confidence* in detection of impacts on food production in all the inhabited continents.
- While the current detection and attribution literature does not reveal observational evidence of geographical differences in the severity of climate change impacts between continents, it does indicate that the unique systems of the Arctic region and warm water coral reefs are undergoing rapid changes in response to observed warming in ways that are potentially irreversible.

18.7. Gaps, Research Needs, Emerging Issues

While the literature formalizing accepted approaches and methods for detection and attribution studies on human and natural systems is relatively recent, the underlying question is one with a long tradition: how to detect a relationship between cause (climate change) and effect (impacts)? The literature on climate change impacts has largely focused on providing estimates of *future* impacts covering the globe and almost any possible affected human and natural system, *observed* impacts have received comparably little attention. In order to provide better guidance for the policy-relevant risk assessment of future impacts, the coverage of impacts that have already occurred needs to be strengthened

With the exception of the food system, detection and attribution studies are most scarce in human systems. While sensitivity to climate variability is clear for many important economic sectors and infrastructures, this is not mirrored in the literature available on observed impacts of climate change.

In part, this is due to the fact that human systems are extremely complex and evolving at a very rapid pace, with many other drivers and their interactions challenging assessments of the comparatively weak recent climate signals. Human systems are also capable of autonomous and planned adaptation, including adaptation to predicted climate change, complicating the diagnosis of impacts of observed climate change. The literature on observed climate adaptation response is sparse. More fundamentally, much of the research on the relation between past climate change and impacts in human systems has been of a nature that has not fit into the deterministic, quantitative detection and attribution framework adopted in earlier Assessment Reports (Stone *et al*., 2013). Fully including human systems into a complete understanding of observed impacts should be a priority for assessing future vulnerability to climate change.

The current detection and attribution literature does not provide a sufficiently comprehensive sampling of the distribution of impacts around the world, for instance between poor and wealthy populations. This dearth of studies reflects inadequate or a lack of long term monitoring or observational systems, an insufficient network density of meteorological observations, and/or lack of research funding, together leading to limited research capability. One other important reason is that in some sub-regions, particularly in the tropics, temperature sensitivities are poorly understood because rainfall is the primary climate driver, and precipitation trends under anthropogenic climate change are not as clearly understood as temperature trends.

Another challenge lies in addressing changes in impacts of extreme weather events and their relation to climate change, as well as determining the role of climate change in special events in impact systems. In some cases difficulty arises from dominating influences of non-climate factors on the extent of actual impacts of extreme weather events and the often highly nonlinear interactions of those factors, but a general characteristic lies in the difficulty of characterizing changes in the frequency or intensity of events that occur only very rarely.

Frequently Asked Questions

FAQ 18.1: What are the main challenges in detecting climate change impacts?

Detection addresses the question of whether a system has changed beyond its expected behavior in the absence of climate change. One challenge in detection is distinguishing between a change in a system and natural variability in the system. Most natural and human systems will exhibit variability over time even in the absence of a change in external factors. Particularly over short periods of time, this kind of natural variability can give the appearance of a systematic change. For example, even in the absence of changes in external factors, some wild populations can undergo prolonged periods of boom or bust. Distinguishing natural variability from systematic change usually requires an understanding of the charateristics of the former. This can be based on an analysis of historical data or an understanding of the dynamics of the system. A second challenge to detection is distinguishing between between a change in the system that is potentially attributable to climate change and one that is due to a change in non-climatic factors. For example, wild populations may change as a result of harvesting or habitat loss unconnected to climate change. Distinguishing such changes from those potentially attributable to climate change requires an understanding of the non-climatic factors that can affect the system and how these factors have changed.

FAQ 18.2: What is the main challenge in attributing changes in a system to climate change?

Attribution addresses the question of whether changes detected in a system can be attributed to climate change. Once a climate-related effect on a system has been detected, the main challenge in attribution is determining whether this effect is due to climate change rather than natural climate variability. For example, widespread flooding in Australia and other parts of the western Pacific during 2010 and 2011 was caused by unusually heavy rainfall. However, this heavy rainfall was found to be related to the occurrence of La Niña, part of the naturally occurring ENSO variation, and therefore the flooding is not attributable to climate change.

FAQ 18.3: Why are detection and attribution of climate impacts important?

In deciding how to respond to climate change, policy-makers and others need to understand what the future impacts of climate change will be. One way to gain understanding about the future impacts of climate is to identify impacts of climate change that has already occurred. For example, it has been predicted that climate change will cause a poleward shift in the geographical ranges of species. Detecting such a shift in response to climate change that has already occurred would tend to validate this prediction.

FAQ 18.4: Is it possible to attribute a single event, like a disease outbreak or the extinction of a species, to climate change?

Scientists are usually reluctant to attribute a single event to climate change and instead tend to focus on the frequency or severity of classes of events. One reason for this is that the scientific knowledge needed to attribute a single event to climate change is much greater than that needed to attribute a change in the frequency or severity of classes of events. For example, there is good evidence that there has been an increase in the frequency of heat waves in many parts of the world and that this increase can be attributed to climate change. However, claiming that, in the absence of climate change, a particular heat wave would not have occurred is largely beyond present scientific capabilities.

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Table 18-1: Observed changes in ocean system properties and their effects, with confidence levels for detection and attribution to climate change, based on assessment in Chapter 6.2, 6.3, and summarized in 6.6.1 and Figure 6-16. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.

Process	**confidence in**		**Context**	**Ref**
	detection	**attribution**		
Impacts of ocean acidification on pelagic marine biota	*low*	*low*	e.g., reduction in foraminiferan, coccolithophores and pteropod shell weight. Attribution supported by experimental evidence and physiological knowledge	[1]
Expansion of midwater hypoxic zones	*high*	*med*	oxygen minimum zones (OMZs) caused by enhanced stratification and bacterial respiration due to effects of warming	[2]
Regional and local impacts of expanding OMZs	*medium*	*low - medium*	reduction of biodiversity, compression of oxygenated habitat for intolerant species, range expansion for tolerant taxa	[3]
Direct temperature effects on marine biota related to limited physiological tolerance ranges	*very high*	*high*	e.g., large scale latitudinal shifts of species distribution, changes in community composition; attribution supported by experimental and statistical evidence as well as physiological knowledge	[4]
Increase in global net primary production	*medium*	*low*	discrepancy between satellite observations and open ocean time-series sites; in higher latitudes, NPP is increasing due to sea ice decline and warming	[5]
Changes in microbial processes	*low*	*low*	*low confidence* and limited understanding of microbial processes, drivers and interactions	[6]
Large scale shifts in biogeochemical pathways	*low*	*low*	*low confidence* for large scale shifts in biogeochemical pathways such as oxygen production, carbon sequestration and export production, nitrogen fixation, climate-feedback by DMS production, nutrient recycling	[7]

Key references and traceable account for the statements above:[1] (Wootton *et al*., 2008; De Moel *et al*., 2009; Moy *et al*., 2009; Bednaršek *et al*., 2012); 6.2.2, 6.3.4; [2] (Stramma *et al*., 2008; Stolper *et al*., 2010); 6.2.2; [3] (Levin *et al*., 2009; Ekau *et al*., 2010; Stramma *et al*., 2010; Stramma *et al*., 2012), 6.3.3; [4] (Merico *et al*., 2004; Perry *et al*., 2005; Pörtner and Farrell, 2008; Beaugrand *et al*., 2010; Alheit *et al*., 2012); 6.2.2, 6.3.2; [5] (Behrenfeld *et al*., 2006; Saba *et al*., 2010; Arrigo and Van Dijken, 2011); 6.3.1; [6] 6.2.2.4; [7] 6.3.3;6.3.4;6.3.5

Table 18-2: Observed changes on marine species and ecosystems, with confidence levels for assessment of detection of changes and their attribution to climate change, based on assessment in Chapter 6.2, 6.3, summarized in 6.6.1 and Figure 6-16, and 30.4. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.

Process	**confidence in**		**Context**	**Ref**
	detection	**attribution**		
Range shifts of fish and macroalgae	*high*	*high*	changes in species biogeographical ranges to higher latitudes or greater depths	[1a]
Changes in community composition	*high*	*high*	due to effects of warming, hypoxia, and sea ice retreat	[1b]
Changes in abundance	*high*	*high*	observed in fish, corals and intertidal species	[1c]
Impacts on marine air breathers, e.g. walruses, penguins, and other sea-birds	*high*	*high*	observed effects include changing abundance, phenology, species distribution and turtle sex ratios, and are mostly mediated through changes in resource availability including prey	[2]
Impacts on warm-water reef-building corals	*very high*	*very high*	effects mostly attributed to warming and rising extreme temperatures, though ocean acidification may contribute	[3]
Increments in fish species richness in temperate and high latitude zones	*high*	*medium*	effect associated with loss of sea ice and latitudinal species shifts due to warming trends	[4]
Change in regional fishery catch potential due to species shifts	*high*	*high*	partly attributable to climate change, and to fishing pressure	[5]
Change in fishery catch potential following changes in net primary production	*low*	*low*	effect associated with warming	[6]

Key references and traceable account for the statements above: [1a,b,c] (Müller *et al*., 2009; Stige *et al*., 2010); 6.3.2, 30.4; [2] (Grémillet and Boulinier, 2009; McIntyre *et al*., 2011); [3] (Hoegh-Guldberg, 1999; Hoegh-Guldberg *et al*., 2007; Baker *et al*., 2008; Veron *et al*., 2009); [4] (Hiddink and ter Hofstede, 2008; Beaugrand *et al*., 2010); 6.3.7, 6.5.2; [5] Figure 6-16.5a; [6] Figure 6-16 5b

Table 18-3: Confidence in detection and attribution of observed climate change effects across ocean regions, based on expert assessment in Chapter 30.5 (respective subsections are given below). Confidence levels assigned are for detection / attribution, respectively.

	high latitude spring bloom systems	**equatorial upwelling**	**semi-enclosed seas**	**coastal boundary systems**	**Eastern boundary upwelling ecosystems**	**Subtropical gyres**
	30.5.1	30.5.4	30.5.6	30.5.3	30.5.2	30.5.5
Regional warming	*very high-high / high*	*very high-high / very high-high*	*very high-high / high*	*very high / high*	*medium/medium-low**	*very high-high / very high-high*
Declining oxygen	*medium / medium-low*	*medium / medium-low*	*medium / medium-low*	*high / medium*	*medium / medium*	*medium / low-medium*
Declining primary productivity	n/s	n/s	n/s	*medium / medium-low*	*medium-low / medium-low*	*medium / medium*
Shifts in phenology	*high / high-medium*	n/s	*medium / medium-low*	*medium / medium-low*	*medium / medium-low*	n/s
Changes in abundance and species distribution	*high / high*	n/s	*high / high*	*medium / medium-low*	*medium / medium-low*	n/s

* California and Canary systems only

Table 18-4: Illustrative selection of some recent extreme impact events for which the role of climate has been assessed in the literature. The table shows confidence assessments as to whether the associated meteorological events made a substantial contribution to the impact event, as well as confidence assessments of a contribution of anthropogenic emissions to the meteorological event. The assessment of confidence in the findings is not necessarily a conclusion of the listed literature but rather results from assessment of the literature. Assessment of the role of anthropogenic emissions in the impact event requires a multi-step evaluation. Partly based on Coumou and Rahmstorf (2012).

Year	**Region**	**Extreme impact event**		**Meteorological Event**	
		Impact / damage	**Confidence in contribution of extreme weather event to observed damage**	**Meteorological event**	**Confidence in contribution of anthropogenic emissions to extreme weather event**
2003	Europe	excess death toll exceeding 70,000 *(Robine et al., 2008)*	*very high*	hottest summer in at least 500 years (Luterbacher *et al*., 2004; Schär and Jendritzky, 2004; Stott *et al*., 2004; Christidis *et al*., 2010)	*high*
2005	North Atlantic / USA	1,700 deaths and over US$100 Bn in damage (Beven *et al*., 2008)	*very high*	record number of tropical storms, hurricanes and category 5 hurricanes since 1970 (Emanuel, 2005; Webster *et al*., 2005; Trenberth and Shea., 2006; Pielke Jr *et al*., 2008; Vecchi *et al*., 2008; Landsea *et al*., 2009; Knutson *et al*., 2010)	*very low*
2006-2007	Europe	partial second flowering or extended flowering in 2006, early flowering in 2007 (Luterbacher *et al*., 2007)	*high*	hottest record fall and winter in at least 500 years (Luterbacher *et al*., 2007; Van Oldenborgh, 2007; Yiou *et al*., 2007; Cattiaux *et al*., 2009)	*medium*
2010	Western Russia	burned area > 12,500km (Müller, 2011)	*low*	hottest summer since 1500 (Barriopedro *et al*., 2011; Dole *et al*., 2011; Rahmstorf and Coumou, 2011; Otto *et al*., 2012)	*medium*
2011	Thailand	prolonged (up to 2 month) inundation of urban and industrialized areas, insured loss US$ 8-11 B, total loss ca. US$45 (SwissRe, 2011; WorldBank, 2011)	*very high*	wettest monsoon on record in middle and upper Chao Phraya Basin (Van Oldenborgh *et al*., 2012)	*very low*
2010	Colombia	exceptionally heavy rainfall and floods, 4 M people affected, US$ 7.8 Bn total damage (Hoyos et al., 2013)	*very high*	ENSO-related second and third highest SST in Caribean on record in late 2010; second most active storm and hurricane season (Trenberth and Fasullo, 2012)	*low*
2010	Pakistan	worst ever known floods in the region, 2000 people killed, 20 M affected, total loss US$ 40Bn (Hong *et al*., 2011)	*very high*	Exceptionally high rainfall amounts over northern Pakistan with unusual atmospheric circulation patterns (Houze Jr *et al*., 2011; Webster *et al*., 2011; Galarneau *et al*., 2012)	*very low*
2011	Queensland, Australia	>200,000 people affected, >30,000 homes flooded, damages and cost to economy US$ 2.5 – 10 B (Van den Honert and McAneney, 2011; Hayes and Goonetilleke, 2012)	*very high*	2010 wettest year on record for Queensland, with extreme precipitation in January 2011 on saturated ground; record high Southern Oscillation Index in 2010 (Van den Honert and McAneney, 2011; Cai and Van Rensch, 2012; Hayes and Goonetilleke, 2012)	*low*

Table 18-5: Cases of regional livelihood impacts attributable with varying degree to weather- and climate related events, climate change or climate variability.

Impacted Population	Climate-related driver	Impact on livelihood	Reference
Small-scale farmers, Ghana	Drought	Landscape transformation, poverty	(Tschakert *et al*., 2011)
Middle-class farmers, Australia	Drought	Landscape transformation, income loss from agriculture, social conflict, poverty	(Alston, 2011)
High Arctic native people	Warming	Changing ice and snow conditions, dwindling access to hunting grounds	(Ford, 2009a; Ford, 2009b, see also Box 18-5)
Urban populations in Maputo, Accra, Nairobi, Lagos, Kampala	Flood frequency and severity increase	Direct impacts on people and loss of physical assets (e.g. housing)	(Douglas *et al*., 2008)
Industry workers in India	Temperature variability and heat waves	Limited ability to carry out physical work, health impacts	(Ayyappan *et al*., 2009; Balakrishnan *et al*., 2010; Dash and Kjellstrom, 2011)
Farmers in Subarnabad, Bangladesh	Sea-level rise	Salt water intrusion, shift from agriculture to shrimp farming, loss of agricultural livelihoods	(Pouliotte *et al*., 2009)
Women farmers, Ghana	Rainfall-related climate variability	Pressure from husbands limiting involvement in agriculture, poverty	(Carr, 2008)
Cambodian rice farmers	Warming, rainfall-related climate variability	Shift in income generation patterns between men and women	(Resurreccion, 2011)
Poor children in Africa and Latin America	Weather and climate-related events	Food price shocks, reduced caloric intake, physical stunting, long-term effects such as reduced lifetime earnings	(Alderman, 2010)
Smallholder farmers in highlands of Bolivia	Rising temperatures and higher variability in weather and climate-related extremes	Stress on household resources due to need to respond to increasing plant pests, switching to other crop types or livestock	(McDowell and Hess, 2012)

Table 18-6: Observed impacts of climate change on snow, ice and mountains, and rivers and lakes, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Snow, Ice and Mountains	Rivers and Lakes
Africa	**Retreat of tropical highland glaciers in East Africa** *very high* / *medium confidence* [22.5.1, (Mölg *et al*., 2008; Taylor *et al*., 2009; Mölg *et al*., 2012)]	**Reduced discharge in West African rivers** *medium* / *low confidence* (d'Orgeval and Polcher, 2008; Dai *et al*., 2009; Di Baldassarre *et al*., 2010) **Decreased flood frequency in Okavango delta** *low* / *low confidence* (Wolski *et al*., 2013) **Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba** *high* / *high confidence* [22.3.2.2, (Tierney *et al*., 2010; Ndebele-Murisa *et al*., 2011; Powers *et al*., 2011)]
Europe	**Retreating glaciers in the Alps** *very high* / *high confidence*, (Bauder *et al*., 2007; Paul and Haeberli, 2008; Zemp *et al*., 2008; Zemp *et al*., 2009) **Increase in rock slope failures in Western Alps** *high* / *medium confidence* [18.3.1.4; (Fischer *et al*., 2012; Huggel *et al*., 2012a)]	**Changes in the occurrence of extreme river discharges and floods** *low* / *very low confidence* (Schmocker-Fackel and Naef, 2010; Beniston *et al*., 2011; Cutter *et al*., 2012; Vorogushyn and Merz, 2012; Kundzewicz *et al*., 2013)
Asia	**Permafrost degradation in Siberia, Central Asia, and the Tibetan Plateau** *high* / *high confidence* [Box 3-2, WGI AR5 Chapter 10.5.3, (Romanovsky *et al*., 2010; Yang *et al*., 2012)] **Mountain glaciers across Asia are shrinking** *high* / *medium confidence* [WGI AR5 Chapter 4.3.2-4.3.3; Box 3-1; (Bolch *et al*., 2012; Cogley, 2012; Kääb *et al*., 2012; Yao *et al*., 2012; Gardner *et al*., 2013; Stokes *et al*., 2013)]	**Changes in water availability in many Chinese rivers** *high* / *low confidence* [24.4.1.2; (Casassa *et al*., 2009; Zongxing *et al*., 2010)] **Increased runoff in many rivers due to shrinking glaciers in the Himalayas and Central Asia** *high* / *high confidence* [24.4.1.2; Box 3-1; (Casassa *et al*., 2009; Zongxing *et al*., 2010; Shrestha and Aryal, 2011; Zhang *et al*., 2011)] **Surface water degradation in various parts of Asia partially related to climate change** *medium* / *medium confidence* [24.4.1.2; (Prathumratana *et al*., 2008; Delpla *et al*., 2009; Huang *et al*., 2009)] **Earlier timing of maximum spring flood in Russian rivers** *high* / *high confidence* [28.2.1.1; (Shiklomanov *et al*., 2007; Tan *et al*., 2011)]
Australasia	**Reduction in glacier ice volume in New Zealand** *high* / *low confidence* [WGI AR5 Chapter 4.3.3; Table 25-1; (Nicholls, 2006; Chinn *et al*., 2012)] **Significant decline in late-season snow depth at four alpine sites in Australia (1957-2002)** *high* / *medium confidence* (Hennessy *et al*., 2008)	n/s

North America	**Observed snowpack show primarily decreasing trends** in the amount of water stored in spring snowpack from 1960-2002 *high* / *high confidence* (Stewart *et al*., 2005; Mote, 2006)	**Observed shift to earlier peak flow in snow dominated rivers in Western North America** *high* / *high confidence* [WGI AR5 Chapter 2.6.2; (Barnett *et al*., 2008)] **Runoff increases in the Midwestern and Northwestern US, decreases in Southern states** *high / medium confidence* (Georgakakos *et al*., 2013)
South and Central America	**Retreat of tropical Andean glaciers** in Venezuela, Colombia, Ecuador, Peru and Bolivia (second half of the 20th century) and glaciers and ice-fields in the extra tropical Andes (Central-South Chile and Argentina) *high* / *high confidence* [27.3.1.1; (Vuille *et al*., 2008; Bradley *et al*., 2009; Jomelli *et al*., 2009; Poveda and Pineda, 2009; Rabatel *et al*., 2013)] **Increased landslide frequency due to heavy precipitation in SE South America** *medium* / *low confidence* [27.2.1.1; (Donat *et al*., 2013; Marengo *et al*., 2013; Silva Dias *et al*., 2013)]	**Changes in extreme flows in Amazon River** *high* / *medium confidence* [27.2.1.1; (Rodríguez-Morales *et al*., 2010; Butt *et al*., 2011; Wang *et al*., 2011; Espinoza *et al*., 2013)] **Changes in discharge patterns in rivers in the Western Andes** due to retreating glaciers and reduced snowpack; for major river basins in Colombia discharge has decreased during the last 30-40 years *high* / *high confidence* [27.3.1.1; (Vuille *et al*., 2008; Bradley *et al*., 2009; Jomelli *et al*., 2009; Poveda and Pineda, 2009; Rabatel *et al*., 2013)] **Increased stream flow in Sub-basins of the La Plata River**, attributed to increasing precipitation, but also to trends in land use changes that have reduced evapotranspiration *very high* / *high confidence* [27.3.1.1; (Pasquini and Depetris, 2007; Krepper *et al*., 2008; Conway and Mahé, 2009; Krepper and Zucarelli, 2010; Doyle and Barros, 2011)]
Polar Regions	**Decreasing Arctic sea ice cover in summer, reduction in glacier ice volume**, due to warming *high* / *high confidence* [WGI AR5 Chapter 10.5.1.1; (ACIA, 2005; AMAP, 2011)] **Decreasing snow cover duration across the entire Arctic** *high* / *medium confidence* [28.2.3.4, 5; (AMAP, 2011; Callaghan *et al*., 2011)] **Widespread permafrost degradation**, especially in the southern Arctic *high* / *high confidence* (AMAP, 2011; Olsen *et al*., 2011) **Increased ice mass loss along coastal Antarctica** *medium* / *very low* [WGI AR5 Chapter 4.2.3, 4.4, 4.6, 10.5.2.1]	**Increased river discharge for large circumpolar rivers** (1997–2007) *high* / *low confidence* [28.2.1.1; (Overeem and Syvitsky, 2010)] **Winter minimum flows have risen in most sectors of the Arctic** due to enhanced groundwater input due to permafrost thawing *high* / *medium* [28.2.1.1; (Tan *et al*., 2011)] **Increasing surface lake water temperatures 1985–2009 and prolonged ice-free seasons**, due to warming *medium* / *medium confidence* [28.2.1.1; (Callaghan *et al*., 2010; Schneider and Hook, 2010)] **Thermokarst lakes disappear due to permafrost degradation in the low Arctic, while new ones are being created in areas of formerly frozen peat** *high* / *high confidence* (Riordan *et al*., 2006; Marsh *et al*., 2008; Prowse and Brown, 2010)

Table 18-7: Observed impacts of climate change on terrestrial ecosystems, and occurrence of drought and wildfires, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Terrestrial Ecosystems	**Drought and Wildfire**
Africa	**Tree density decreases in Sahel and semi-arid Morocco** *high* / *medium confidence* [22.3.2.1.2; (Gonzalez *et al*., 2012; Le Polain de Waroux and Lambin, 2012)] **Climate-driven range shifts of several southern plants and animals**: South African bird species polewards; Madagascan reptiles and amphibians upwards; Namib aloe contracting ranges. *high* / *medium confidence* [22.3.2.1; (Foden *et al*., 2007; Raxworthy *et al*., 2008; Hockey and Midgley, 2009; Hockey *et al*., 2011)]	**Increased drought in the Sahel since 1970, partially wetter conditions since 1990** *medium* / *medium confidence* [22.2.2.1; (Hoerling *et al*., 2006; Giannini *et al*., 2008; Greene *et al*., 2009; Seneviratne *et al*., 2012)] **Wildfires increase on Mt. Kilimanjaro** due to warming and drying trends *medium* / *low confidence* [22.5.1; (Hemp, 2005)]
Europe	**Earlier greening, earlier leaf emergence and fruiting in temperate and boreal trees** *high* / *high confidence* [4.4.1.1; (Menzel *et al*., 2006)] **Increased colonization of alien plant species in Europe** *medium* / *medium confidence* [4.2.4.7; (Walther *et al*., 2009)] **Earlier arrival of migratory birds in Europe since 1970** *medium* / *medium confidence* [4.4.1.1; (Møller *et al*., 2008)] **Upward shift in tree-line in Europe** *medium* / *low confidence* [18.3.2.1; (Gehrig-Fasel *et al*., 2007; Lenoir *et al*., 2008)]	**Increasing burnt forest areas during recent decades** *high* / *high confidence* (Hoinka *et al*., 2009; Koutsias *et al*., 2012)
Asia	**Changes in plant phenology and growth occur in many parts of Asia**, observed from ground observations as well as from satellites (earlier greening), particularly in the North and the East *high* / *medium confidence* [24.4.2.2; 4.2.1, Box 4-1; (Ma and Zhou, 2012; Panday and Ghimire, 2012; Shrestha *et al*., 2012; Ogawa-Onishi and Berry, 2013)] **Many plant and animal species have shifted their distribution**, particularly in the North of Asia, generally upwards in elevation or polewards *high* / *medium confidence* [24.4.2.2; (Moiseev *et al*., 2010; Chen *et al*., 2011; Jump *et al*., 2012; Ogawa-Onishi and Berry, 2013)] **Siberian larch forests are being invaded by pine and spruce during recent decades, Mongolian larches show decreasing growth** *medium* / *low confidence* (Kharuk *et al*., 2010; Dulamsuren *et al*., 2011; Lloyd *et al*., 2011) **Advance of shrubs into the Siberian tundra** *high* / *medium* confidence [28.2.3.1; (Blok *et al*., 2011)]	

Australasia	**Climate-related changes in genetics, growth distribution and phenology of many species** (earlier emergence of butterflies, change in plant flowering dates, breeding times of bird, decline in body size of passerine birds etc.) *medium* / *medium confidence* [table 25-3; (Green, 2010; Kearney *et al.*, 2010; Keatley and Hudson, 2012)] **Change in timing of migration of water and land birds in Australia** possibly due to changes in precipitation rather than changes in temperature *low* / *low confidence* [25.6.1, Table 25-3; (Chambers, 2008)] **Expansion of some wetlands and corresponding contraction of adjacent woodlands in SE Australia** *medium* / *low confidence* [table 25-3; (Banfai and Bowman, 2007; Bowman *et al.*, 2010; Keith *et al.*, 2010)]	**No significant change in drought occurrence in Australia** (over 20th century, using rainfall only) **or New Zealand** (since 1972, using a soil water balance model) *medium-low* / *n.a.* [table 25-1. 3.5.1; (Cai *et al.*, 2009; Potter *et al.*, 2010; Kingsford and Watson, 2011; IPCC, 2012)]
North America	**Species distribution shifts upward in elevation and northward in latitude across multiple taxa** *high* / *medium confidence* [26.4.1, 2; (Kelly and Goulden, 2008)] **Phenology changes** *high* / *medium confidence* [26.4.2; (Parmesan, 2006)] **Increases in tree mortality at regional scales and insect infestations in forests** *medium* / *low confidence* [26.4.1; (Peng *et al.*, 2011)]	**Increases in wildfire activity, including fire frequency and duration, length of fire season, and area burned** *high* / *medium confidence* [Box 26.2; (Westerling *et al.*, 2006)]
South and Central America	**Degrading and receding rainforest in the Amazon** *high* / *very low confidence* [27.2.2.1;¸(Etter *et al.*, 2006; Nepstad *et al.*, 2006; Oliveira *et al.*, 2007; Wassenaar *et al.*, 2007; Killeen *et al.*, 2008; Nepstad and Stickler, 2008)]	**Increase dryness for most of the west coast of South America and in the Andes between 35.6°S and 39.9°S since 1950** *medium* / *low confidence* [table 27-1; (Christie *et al.*, 2011; Dai, 2011)]
Polar Regions	**Increase in shrub cover in tundra in North America and Eurasia** *high* / *high confidence* [28.2.3.2; (Tape *et al.*, 2006; Walker *et al.*, 2006; Henry and Elmendorf, 2010; Blok *et al.*, 2011; Elmendorf *et al.*, 2012; Tape *et al.*, 2012)] **Significant advance of Arctic tree-line in latitude and altitude, due to warming**, although the pace is lower than expected due insect outbreaks, land use history *high* / *medium confidence* [28.2.3.3; (AMAP, 2011; Hedenås *et al.*, 2011; Van Bogaert *et al.*, 2011)] **Snow-bed ecosystems and tussock tundra are retreating, due to prolonged thawing season and less precipitation in the form of snow** *high* / *high confidence* [28.2.3.2; (Björk and Molau, 2007; Molau, 2010a; Hedenås *et al.*, 2011; Callaghan *et al.*, 2013)] **Animal populations in the tundra being affected by increasing occurrence of ice layers in the annual snow pack due to rain-on-snow events** *medium* / *medium confidence* (Callaghan *et al.*, 2013; Hansen *et al.*, 2013) **Breeding area and population size of subarctic birds has changed**, due to warming and shrub encroachment in the tundra *high* / *medium confidence* (Molau, 2010b; Callaghan *et al.*, 2013)	**Increasing drought in high Arctic polar deserts** *high* / *high confidence* [28.2.1.1; (Smol and Douglas, 2007)] **Increased frequency of wildfires in the conifer forest at the southern fringe of the Arctic**, due to increasing summer temperature *high* / *medium confidence* (Mann *et al.*, 2012) **Tundra wildfires are increasing in frequency in the Low Arctic,** due to increasing summer air temperature and subsequent surface drought *high* / *medium confidence* [28.2.3.6; (Mack *et al.*, 2011)]

	Plant species in the West Antarctic Peninsula and nearby islands have increased over the past 50 years *high* / *high confidence* [28.2.3.2; (Fowbert and Smith, 1994; Parnikoza *et al*., 2009)] **Increasing phytoplankton productivity in Signy Island lake waters** *high* / *high confidence* [28.2.1.2; (Quayle *et al*., 2002; Laybourn-Parry, 2003)]	
Small Islands	**Upward trend in tree-lines and associated fauna on high elevation islands** *low* / *low confidence* [29.3.2.1; (Benning *et al*., 2002; Jump *et al*., 2006)] **Changes in tropical bird populations in Mauritius, due to changes in rainfall** *medium* / *medium confidence* [29.3.2.1; (Senapathi *et al*., 2011)]	**Increased drought frequency in Seychelles and Southern Jamaica** over past 30 years, decrease in rainfall over past 100 years in the Caribbean islands may have contributed to multiple water stress *low* / *very low confidence* [29.3.3.2; (Payet and Agricole, 2006; Cashman *et al*., 2010; Gamble *et al*., 2010)]

Table 18-8: Observed impacts of climate change on marine ecosystems, and coastal processes, across eight major world regions, with confidence in detection / confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Marine Ecosystems	**Coastal Processes**
Europe	**Poleward shifts in the distributions** of zooplankton, fish, seabirds and benthic invertebrate, and conversion of polar into more temperate and temperate into more subtropical system Characteristics in NE Atlantic *high* / *high confidence* [Table 6-8, 6.3.2, 30.5.1, 18.3.3.1, (Beaugrand *et al*., 2009; Philippart *et al*., 2011)] **Phenology changes and retreat of colder water plankton** to the north in the Northeast Atlantic, with mean poleward movement of plankton reaching up to 200–250 km per decade between 1958–2005 *medium* / *medium confidence* **[**6.3.2, Table 6-8, Fig 6-16; (Beaugrand *et al*., 2002; Edwards and Richardson, 2004; Beaugrand *et al*., 2009; Philippart *et al*., 2011)] **Shift in distribution of Atlantic cod** due to warming, interacting with regime shift and regional changes in Plankton Phenology in North Sea *high* / *medium confidence* [6.3.2, Fig 6-16; (Perry *et al*., 2005; Pörtner *et al*., 2008; Beaugrand *et al*., 2009; Beaugrand *et al*., 2010)] **Decreasing abundance of eelpout** (Helcom indicator species) in Wadden Sea *medium* / *high confidence* [6.3.2, Fig 6-16; (Pörtner and Knust, 2007)]	

Asia	**Coral reefs and large seaweeds decline in tropical Asian and Japanese waters** *high* / *high confidence* [24.4.3.2; (Krishnan *et al*., 2011; Nagai *et al*., 2011; Coles and Riegl, 2012)] **Shift from sardines to anchovies in Japanese Sea** *medium* / *medium confidence* [6.3.22, Fig 16-6; (Takasuka *et al*., 2007; Takasuka *et al*., 2008)]	**Coastal erosion is accelerating in Arctic Asia**, due to changes in permafrost, storm wave energy and sea-ice retreat *medium* / *low confidence* (Razumov, 2010; Lantuit *et al*., 2011; Handmer *et al*., 2012)
Australasia	**Mass bleaching of corals in the Great Barrier Reef**, changes in coral calcification rates and changes in coral disease dynamics (e.g., black band disease, white syndrome) *high* / *high confidence* [6.3.2, 25.6.2, Box 18-3; (Cooper *et al*., 2008; De'ath *et al*., 2012)] **Multiple impacts of climate change on marine ecosystems from warming oceans**, although other environmental changes may play a role. Examples are increase of growth rates in fish, range shifts of intertidal invertebrates, retreat of seaweeds, range shift in near-shore fish related to kelp decline, increasing abundance of northern marine species in Tasmania, declines in recruitment of rock lobster and of abalone, decline in growth rate and biomass of phytoplankton, retreat of macroalgae, southward expansion of some tropical seabirds in Australia *high* / *high confidence* (Thresher *et al*., 2007; Figueira *et al*., 2009; Ling *et al*., 2009; Pitt *et al*., 2010; Chambers *et al*., 2011; Neuheimer *et al*., 2011; Wernberg *et al*., 2011; Wernberg *et al*., 2011, see also Table 25-3)	
North America	**Northwest Atlantic fish show northward range shift** in response to warming since the 1960s, with some of the shifts being correlated with the Atlantic multidecadal Oscillation *high* / *medium confidence* [Table 6-8, Fig 6-16 (Nye *et al*., 2009; Lucey and Nye, 2010; Nye *et al*., 2011)] **Earlier onset of migration of Pink Salmon in Alaska, collapse of spawning migration of Sockeye Salmon in Fraser River, BC**, due to warming *high* / *high confidence* [(Eliason *et al*., 2011; Kovach *et al*., 2012)] **Loss of biomass of midwater fish off California Coast** *high* / *high confidence* [6.3.3, 6.6.3]	**Coastal roads affected by flooding** during high tides in the US, though contribution of climate change to relative sea-level rise uncertain *low* / *very low confidence* (Moser and Davidson, 2013)
South and Central America	**Bleaching of coral reefs in the western Caribbean near the coast of Central America** *very high* / *high confidence* [27.3.3.1, (Guzman *et al*., 2008; Manzello *et al*., 2008; Carilli *et al*., 2009; Eakin *et al*., 2010)]	**Mangrove degradation on Northern South American coast** *high* / *low confidence* (Alongi, 2008; Lampis, 2010; Polidoro *et al*., 2010; Giri *et al*., 2011)
Polar Regions	**Many arctic and subarctic marine non-migratory mammals (walrus, seals, whales) are negatively affected by sea ice loss** *high* / *high confidence* [28.2.2.1.3, (Laidre *et al*., 2008; McIntyre *et al*., 2011)] **Reduced growth rate and body mass, lower survival and reproductive capacity of polar bears, linked to reduced off-shore range and sea-ice loss due to warming** *high* / *high confidence* [28.2.2.1.2; (Amstrup *et al*., 2010)] **Arctic seabirds experience reduced reproductive success, due to earlier sea-ice break-up** *medium* / *medium confidence* [28.2.2.1.1; (Gaston *et al*., 2009; Grémillet and Boulinier, 2009)]	**Increased coastal erosion in Arctic**, due to prolonged ice-free season at shore, increased exposure to wave activity, and degrading permafrost *high* / *high confidence* [28.2.4, 5; 28.3.4, (Forbes, 2011)]

	Acidification of Southern Ocean waters has resulted in reduced thickness of foraminifera shells *medium* / *medium confidence* [6.3.4, 28.2.2.2, (Moy *et al*., 2009)] **Antarctic krill density in the Scotia Sea has declined** by ca. 30 % since the 1980s, due to reduced winter sea ice extent and duration *medium* / *medium confidence* (Atkinson *et al*., 2004; Trivelpiece *et al*., 2011) **Many Southern Ocean species of seals and seabirds, e.g. penguins and Albatross, show negative responses to warmer conditions** *high* / *medium confidence* [28.2.2.2; (Croxall *et al*., 2002; Patterson *et al*., 2003; Jenouvrier *et al*., 2005; Véran *et al*., 2007; Forcada *et al*., 2008; Trathan *et al*., 2011)]	
Small Islands	**Coral bleaching near many tropical small islands** *high* / *high confidence* [29.3.1.2,3; (Alling *et al*., 2007; Bruno and Selig, 2007; Oxenford *et al*., 2008)] **Degradation of mangroves, wetlands and seagrass** in small islands, mostly due to disturbances and only a lesser extent possibly due to sea-level rise *high* / *low confidence* [29.3.1.4; (McKee *et al*., 2007; Gilman *et al*., 2008; Schleupner, 2008; Krauss *et al*., 2010; Marbà and Duarte, 2010; Rankey, 2011)] **Degradation of freshwater dependent ecosystems**, due to saline intrusion following sea level rise and more frequent and intense hurricanes in the Florida Keys, USA *low* / *low confidence* [29.3.2.1; (Ross *et al*., 2009; Goodman *et al*., 2012)]	**Shoreline erosion is widespread and increasing on many small islands**, though impact of sea-level rise can presently not be discriminated from climate variability and local disturbance *high* / *low confidence* [29.3.1.1, 2; (Yamano *et al*., 2007; Cambers, 2009; Novelo-Casanova and Suarez, 2010; Storey and Hunter, 2010; Ford, 2012)] **More frequent inundation in low-lying flood prone areas, increasing appearance of freshwater lenses at surface** *medium* / *low confidence* [29.3.1.1, 2;(Webb, 2006; Webb, 2007; Yamano *et al*., 2007; Ballu *et al*., 2011)] **Increases in groundwater degradation**, mostly driven by over-pumping or pollution. Limited evidence for saline intrusion due to sea level rise or overtopping *high* / *low confidence* [29.3.2.2; (White *et al*., 2007a; White *et al*., 2007b; Terry and Falkland, 2010; White and Falkland, 2010)]

Table 18-9: Observed impacts of climate change on human systems across eight major world regions, with confidence in detection / confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Impacts on Human Systems: Health, Food production, Infrastructure and Livelihoods
Africa	**Malaria increases in Kenyan highlands**, partly due to warming *low / low confidence* [22.3.5.2, (Prudhomme O'Meara *et al*., 2010; Alonso *et al*., 2011; Stern *et al*., 2011)]
	Reduced productivity of Great Lakes and Lake Kariba, partly due to warming *high / low confidence* [23.3.2.2, 23.3.4.4; (Descy and Sarmento, 2008; Hecky *et al*., 2010; Ndebele-Murisa *et al*., 2011; Marshall, 2012)] **Fruit-bearing trees in Sahel decline** *medium / medium confidence* (Wezel and Lykke, 2006; Maranz, 2009)
Europe	**Increased allergic sensitization to pollen in Northern Italy** *very low / very low confidence* [11.3; (Ariano *et al*., 2010)] **Shift from cold-related mortality to heat-related mortality in England and Wales** *medium / low confidence* [18.4.5; (Christidis *et al*., 2010)]
	Stagnation of wheat yields in some countries in recent decades, due to warming and/or drought *high / medium confidence* (Brisson *et al*., 2010; Kristensen *et al*., 2011) **Positive yield impacts for wheat, sugar beet and potato in the UK since 1980** *low / low confidence* [Fig 7-3; (Gregory and Marshall, 2012)]
Asia	**Negative impacts on aggregate wheat yields in South Asia** *medium/low confidence* [Fig.7-3, 7.2.1.1] **Negative impacts on aggregate wheat and maize yields in China** *low / low confidence* [Fig.7-3, 7.2.1.1]
	Increases in water-borne diseases have been linked to warming in Israel *low / low confidence* (Paz *et al*., 2007)
Australasia	**Wine-grape maturation has advanced in recent decades, partly due to warming** *high / medium confidence* (Webb *et al*., 2012)
North America	**Yields of grains, forage, livestock and dairy have declined due to increasing temperatures** unless where accompanied by increased precipitation; soil organic content has declined; salinity has increased; climate change has affected product quality *high / low confidence* [26.5.1; (Hayhoe *et al*., 2004; Lin, 2007; Hatfield *et al*., 2008; Wolfe *et al*., 2008; Schlenker and Roberts, 2009; Craine *et al*., 2010)] **Reduced economic returns from agriculture following extreme heat and storms, particularly in Mexico** *high / low confidence* [Boxes 26.1, 26.2, 26.4; (Swanson *et al*., 2007; Chen and McCarl, 2009)]
	Direct and indirect economic impacts of climate extremes on industry through reduced supply of raw material, the production process, the transportation of goods, and the demand for certain products *high / medium confidence* [26.8; (Lazo *et al*., 2011)] **Damages from climate extremes on infrastructure, especially in the transport and housing sectors** *medium / low* confidence [26.8; (Morton *et al*., 2011)] **Impacts of extreme events on economy, lives and livelihoods in urban and rural settlements** *medium / low confidence* [26.7.1, 26.7.2; (Kurz *et al*., 2008; MacDonald, 2010)]
Central and South America	**Increase in frequency and extension of dengue fever and yellow fever** *high / low confidence* [27.3.7.1; (Teixeira *et al*., 2009; Rodríguez-Morales *et al*., 2010; Jentes *et al*., 2011)]
	Increase in frequency and extension of malaria *high / medium confidence* [27.3.7.1; (Rodríguez-Morales *et al*., 2010; Poveda *et al*., 2011)]
	Increase in agricultural yields in Southeastern South America *high / medium confidence* [27.3.4.1; (Magrin *et al*., 2007; Barros, 2010)] **Expansion of agricultural areas in climatically marginal regions of Argentina** *high / low confidence* [27.3.4; (Barros, 2010; Hoyos *et al*., 2012)] **Reduction in fish stocks (Peru, Colombia, Brazil)** *low / very low confidence* [27.3.7.1; (Allison *et al*., 2009; Freire and Pauly, 2010)]
Polar Regions	**Impact on livelihoods of high Arctic indigenous peoples** *medium / medium confidence* [18.4.5, Box 18-5; (Ford *et al*., 2009; Beaumier and Ford, 2010; Pearce *et al*., 2010)]

Small Islands	**Degradation of coastal fisheries** *high* / *low confidence* [29.3.3; 18.4.5; 30.4, 6.3.2] **Casualties and damage from extreme weather events** *very high* / *very low confidence* [29.3.3]

Table 18-10: Reported confidence of detection of observed changes in "Unique and Threatened Systems" and attribution of observed changes to observed climate change. Assessments are for global or the indicated regional domain, with regional variations indicated in the final column.

Impact on unique or threatened system	**Source for overarching assessment**	**Confidence in**		**Regional details, with corresponding subsections and confidence in detection/confidence in attribution**
		detection	**attribution**	
Shrinking / receding glaciers	18.3.1	*very high*	*high*	Tropical Highland Glaciers, East Africa (22.5.1): *very high* / *medium* European Alps: *very high* / *high* Asia (24.4.2.2): *high* / *medium* New Zealand (Table 25-1): *high* / *low* North America: *high* / *high* Andean tropical glaciers and extra tropical icefields (27.3.1.1): *high* / *high* Polar glaciers: *high* / *high*
Mountain and lowland permafrost degradation	18.3.1.2	*high*	*medium*	Europe: *medium* / *medium* Siberia, Central Asia and Tibetan Plateau (24.4.2.2): *high* / *high* North America: *medium* / *medium* Southern Arctic (28.2.1.1): *high* / *high*
Arctic coastal permafrost degradation	18.3.1.2, 24.4.3.2, 28.2.1.1	*high*	*high*	
Warm water reef building corals – increased mortality and bleaching	5.3.1.6, 6.3.2.1.2, 30.3.1.1, 30.5, 30.8.2, Box 18-3	*very high*	*high*	Asia (24.4.3.2): *high* / *high* Australian Great Barrier Reef: *high* / *high* Western Caribbean (27.3.3.1): *very high* / *high* Coastal reefs surrounding small islands (29.3.1): *high* / *high*
Shrub increase and permafrost decay in Arctic tundra¸ onset of biome shift	18.3.2.4, 28.2.3.2	*high*	*high*	
Increased tree mortality in the Amazon; onset of biome shift	4.3.3	*low*	*very low*	
Increased tree mortality in boreal forests; onset of biome shift	4.3.3	*low*	*low*	
Changes in Arctic marine ecosystems	18.5.7, 28.2.2.1	*high*	*medium*	
Decline in extent of mangroves and coastal wetlands	27.3.3.1, 29.3.1.4	*very high*	*very low*	Mangrove degradation northern South American coast (27.3.3.1): *high* / *low* Impacts on mangroves and sea grasses in coastal areas of small islands (29.3.1.4): *high* / *low*
Livelihood impacts on indigenous Arctic peoples	18.4.7, Box 18-5	*medium*	*medium*	

Table 18-11a: Confidence in detection of changes in extreme weather hazard and attribution of a major role of changing greenhouse gas concentrations in the observed changes.

Observed changes in extreme weather or hydrologic hazard	**Confidence in**		**Assessment***
	detection	**attribution**	
Increasing frequency and intensity of extreme hot events	*high*	*high*	WGI AR5 Chapter 10.6.1
Decreasing frequency and intensity of extreme cold events	*high*	*high*	WGI AR5 Chapter 10.6.1
Increases in the number and intensity of heavy precipitation events	*medium*	*medium*	WGI AR5 Chapter 10.6.1
Increases in tropical cyclone activity	*low*	*low*	WGI AR5 Chapter 10.6.1
Changes in tornadoes or hail	*very low*	*very low*	Chapter 10.6.1
More intense and longer dry spells in some low and mid latitude regions	*low*	*low*	WGI AR5 Chapter 10.6.1
Changes in inland flood magnitude and frequency	*low*	*low*	3.2.3, 18.3.1.1
Increasingly frequent coastal flooding	*medium*	*low*	29.3.1.1, 29.3.2.2, 5.3.3.3

*more detailed regional information consistent with AR5 WGI Chapter 10 assessment can be found in Seneviratne *et al*. (2012)

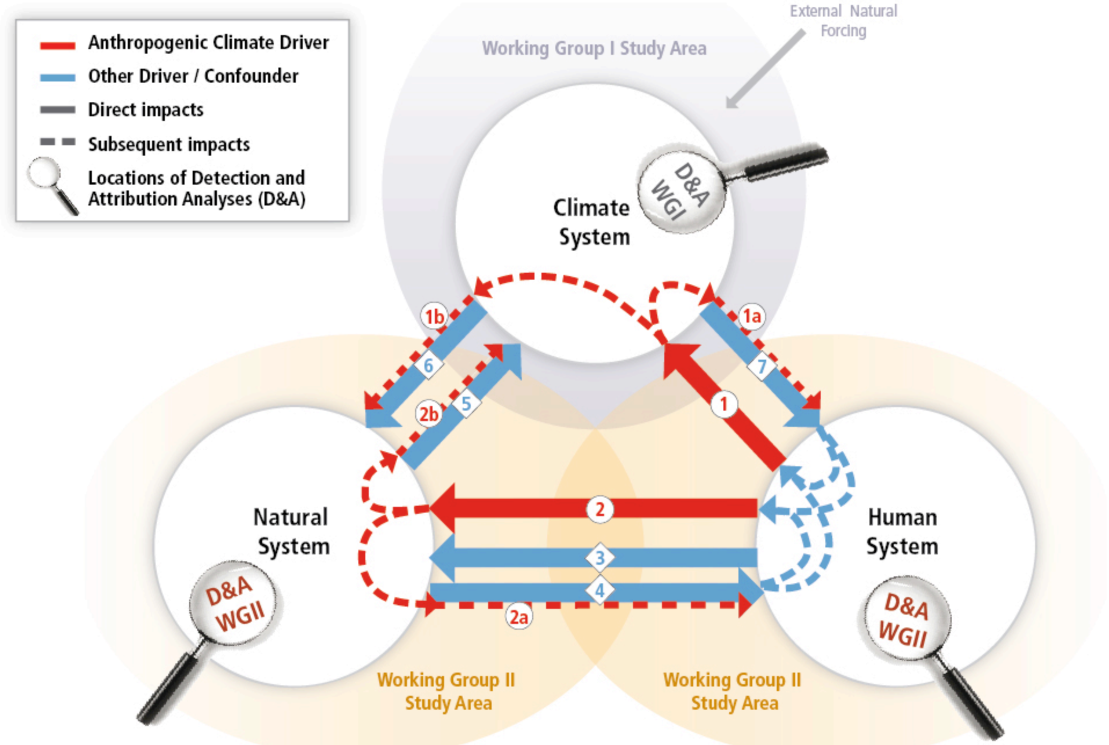
Table 18-11b: Confidence in detection of observed trends in damage in various systems and attribution of a major role of observed changes in extreme weather to those observed trends.

Observed changes in impacts of extreme weather	**Relevant weather extremes**	**Confidence in**		**Assessment**
		detection	**attribution**	
Increased coral bleaching	Hot surface waters	*very high*	*high*	5.3.1.6, 6.3.2, Box 18-3, 24.4.3.2, 27.3.3.1, 29.3.1, 30.3.1.1, 30.5. 30.8.2
Increased beach erosion in low and mid latitudes	High storm waves and surges	*high*	*very low*	5.3.1.2
Increased erosion of Arctic coastal bluffs	Lack of sea ice protection from wind storms	*high*	*high*	24.4.3.2, 28.2, 28.3.4
Increased South American landslide frequency	Heavy precipitation	*medium*	*low*	27.2.1.1
Cascading food web effects on Arctic grazers and predators	Higher frequency of rain-on-snow events	*high*	*high*	28.2.1.1
Increased drought in high Arctic deserts	Warm spells	*high*	*high*	28.2.1.1
Increased monetary losses due to extreme weather events	Storms, floods	*very high*	*very low*	10.7, 18.4.4.2

Table 18-12: Confidence in detection of impacts on aggregate impact measures and confidence in attribution of at least a minor role of climate change in those observed changes.

Global aggregated impact measure	**Reference chapters**	**Confidence in**	
		detection	**attribution**
Glacier ice volume reduction	18.3.1.3; 3.2.2	*very high*	*high*
Shift of permafrost boundary to higher altitudes and latitudes, and increase of active layer thickness	18.3.1.3	*high*	*medium*
Increase in terrestrial net primary production and C stocks	18.3.2.2	*high*	*low*
Negative yield impacts on global wheat against trends in technology, practice, and coverage	18.4.1.1, Fig 7-3	*very low*	*very low*
Negative yield impacts on global maize against trends in technology, practice, and coverage	18.4.1.1, Fig 7-3	*low*	*low*
Small increase in marine net primary production	Table 18-1	*medium*	*low*
Change in fishery productivity	Table 18-2; Fig 30.14, 6.6.1	*high*	*low*
Increase in monetary losses due to extreme weather	18.4.4.2 and 10.7	*very high*	*very low*

Figure 18-1: Schematic of the subject covered in this chapter. The Earth system can be divided into three broad interacting systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone *et al*. (2013).



	Example of Drivers	Example of Impacts	
		Direct impacts	Subsequent impacts
1 1a 1b	Emission of CO_2	Warming	Altered crop yield Shift in species phenology
2 2a 2b	Emission of CO_2	Carbon fertilization of plants	Increase in forestry yield Change in humidity
3	Pollution of river catchment	Decrease in fisheries	
4	Plague of crop pests	Decrease in crop yield	
5	Forest fire	Increased windiness	
6	El Nino event	More wildfires	
7	El Nino event	Fisheries	

Figure 18-2: A schematic diagram comparing approaches to attribution for an ecological system. The multi-step approach differs from the single-step approach in having a discontinuity between the attributed climate change and the observed weather driving the ecological model. Adapted from Stone *et al*. (2013).

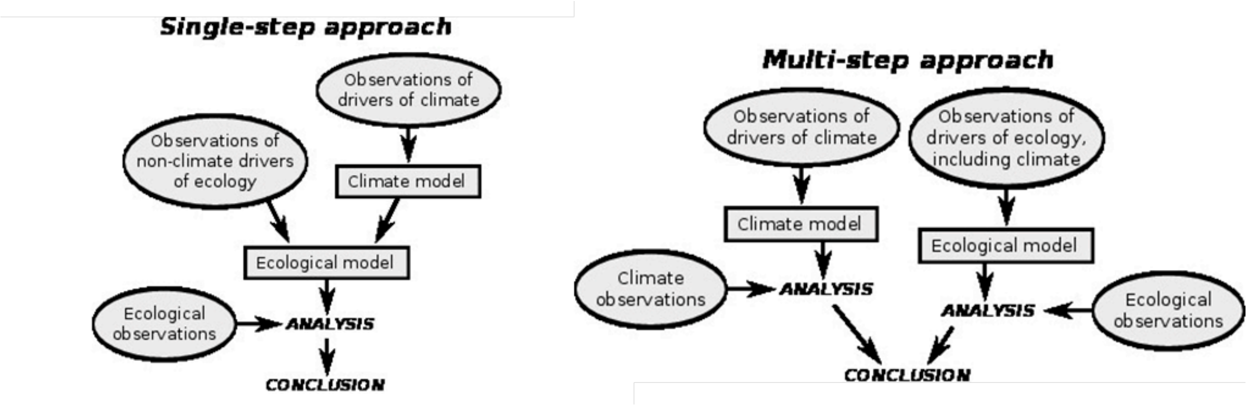


Figure 18-3: Levels of confidence in detection and attribution of observed climate change impacts for freshwater systems over the past several decades, based on expert assessment contained in this section 18.3.1 and augmented by subsections of chapter 3 as indicated. Numbered symbols refer to: Freshwater systems (18.3.1.1): 1 groundwater depletion (Ch.3.2.4), 2 changing river flow (Ch. 3.2.3), 3 changing flood frequency or intensity (Ch. 3.2.3), 4 reduction in lake and river ice duration or thickness (Ch. 18.3.1.2); Cryosphere: 5 shrinking glaciers (Ch. 3.2.2, 18.3.1.2), 6 changes in glacier lakes (Ch. 18.3.1.1), 7 erosion and degradation of arctic coastal permafrost (Ch. 18.3.1.2), 8 degradation and thaw of lowland and mountain permafrost (Ch. 18.3.1.2), Soils and rock (18.3.1.3): 9 Increasing erosion (Ch.3.2.6), 10 changes in shallow landslides (Ch.3.2.6), 11 increasing frequency of Alpine rock failures

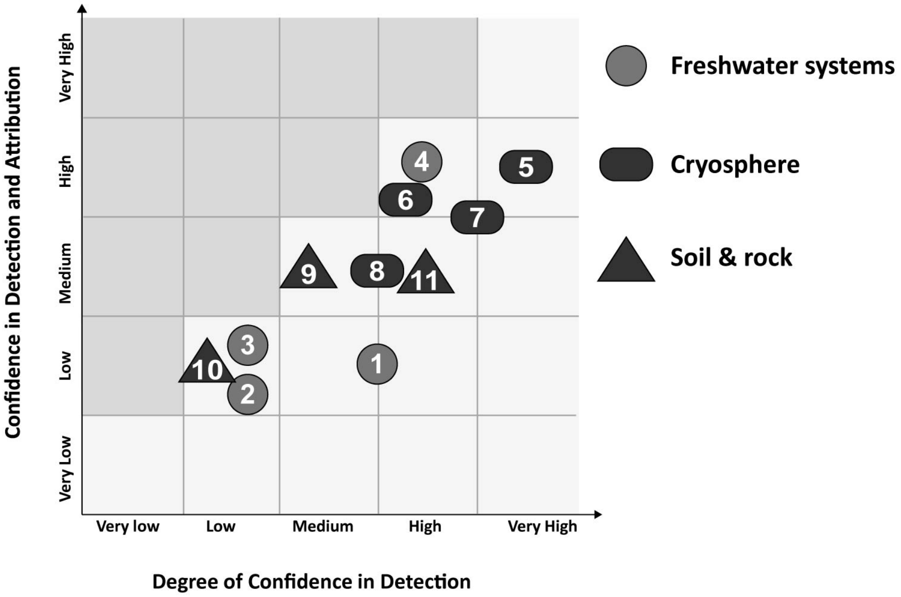


Figure 18-4: Confidence in detection and attribution of observed impacts on unique and threatened systems as a result of recent climate change. Assessments are for confidence in detection of a change and for confidence in attribution of a major role of observed climate change. Large letters denote conclusions for the full-scale system, while small letters denote conclusions for regional subsets of the systems. System changes include shrinking / receding glaciers, mountain and lowland permafrost degradation, Arctic coastal permafrost degradation, increased mortality and bleaching of warm water reef-building corals, increased shrub cover and permafrost decay in the northern tundra, increased tree mortality in the Amazon, increased tree mortality in boreal forests, changes in Arctic marine ecosystems, decline in extent of mangroves and coastal wetlands, and impacts on livelihoods of indigenous Arctic peoples. See Table 18-10 for details and references.

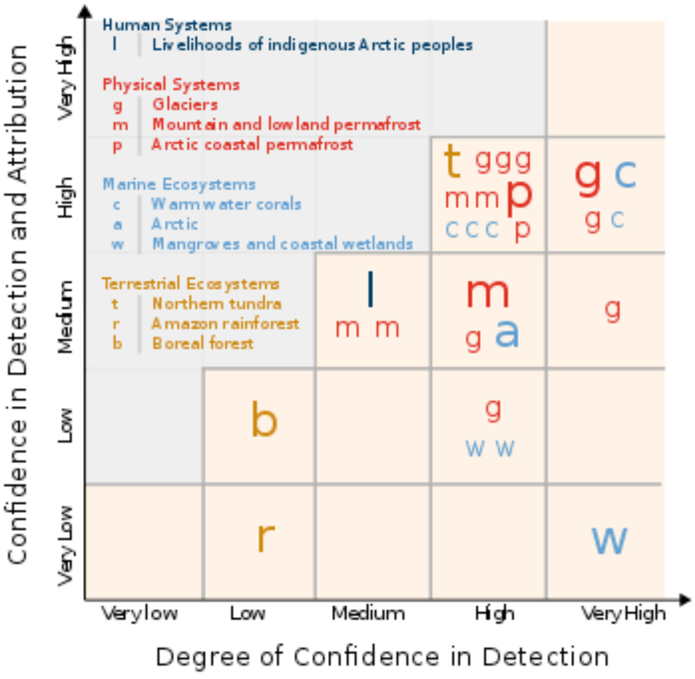


Figure 18-5: Left: confidence in detection of observed changes in extreme weather hazards and attribution of a major role of changing greenhouse gas concentrations in the observed changes. Right: confidence in detection of observed changes in damages related to extreme weather and attribution of major role to observed changes in extreme weather.

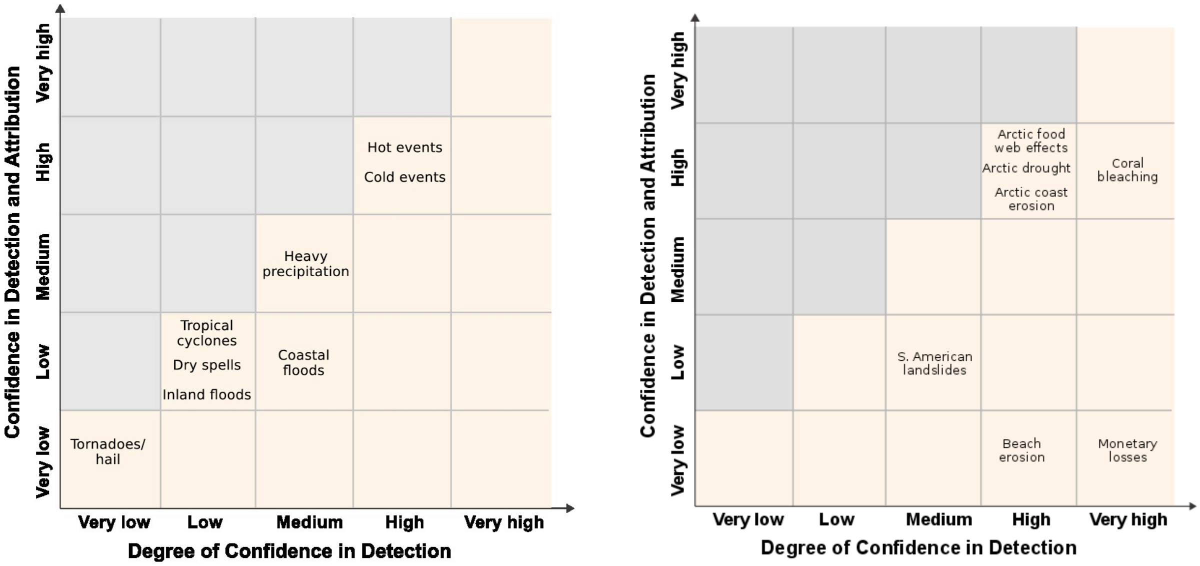
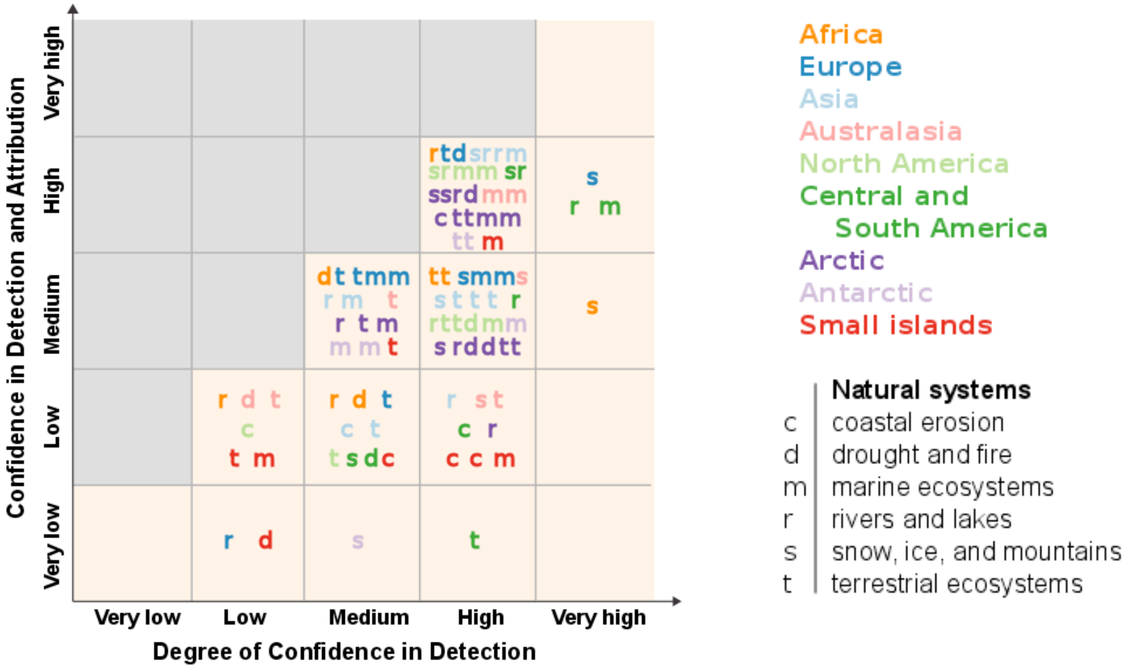
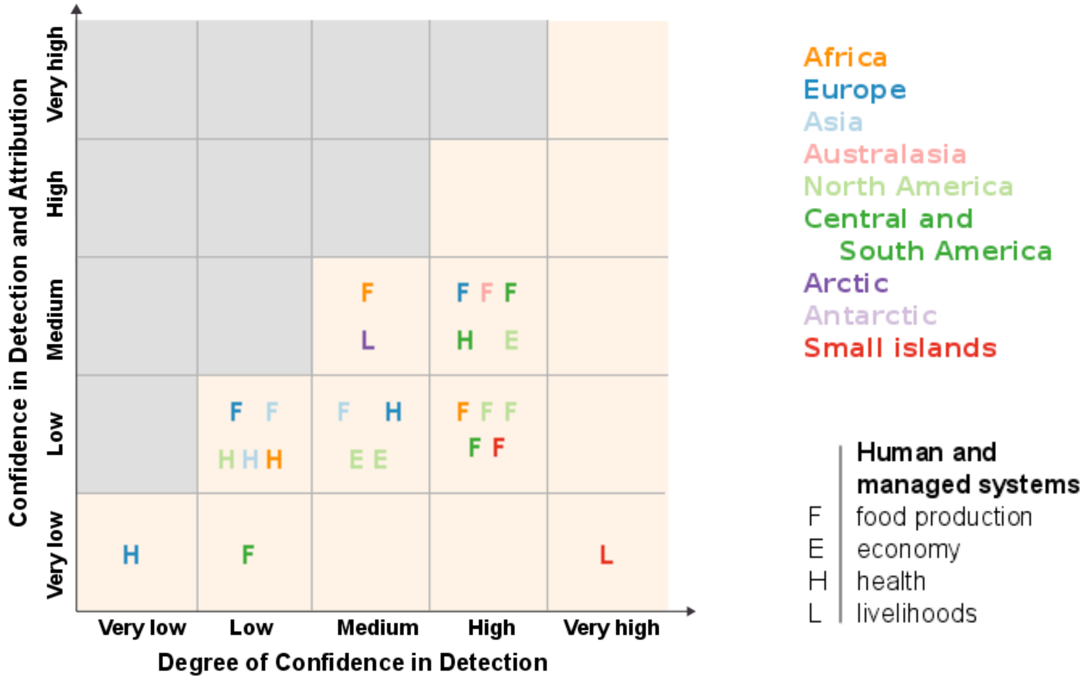


Figure 18-6: Confidence in detection of observed changes in natural systems (panel a) and human and managed systems (panel b) across regions, and confidence in attribution of such trends to observed climate change. Based on assessments developed in Tables 18-6 through 18-9.



Panel a: Regional Impacts on Natural Systems



Panel b: Regional Impacts on Human Systems

Figure 18-7: Confidence in detection of changes in aggregate impact measures and attribution of at least a minor role of climate change in those trends