

Chapter 14

Climate Change Scenarios and Their Potential Impact on World Agriculture

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1 What Causes the Climate System to Change?

The Earth's climate system is a complex interaction of a number of components, such as the ocean, atmosphere, ice masses (cryosphere) and living organisms (biosphere). Although the system is ultimately driven by solar energy, changes to any of the components, and how they interact with each other, as well as variability in the solar radiation received, can lead to a change in climatic conditions. There are many causes of climate change which operate on a variety of time scales. On the largest time scales are mechanisms such as the Milankovitch-Croll effect and geological processes.

The **Milankovitch-Croll** effect concerns the characteristic of the Earth's orbit around the sun and is thought to be responsible for governing the main glacial and interglacial episodes that are evident in the prehistoric climate record. Over a time scale of thousands of years variability is experienced in three important orbital characteristics. Firstly, the shape of the Earth's orbit is known to vary between that of a near-circle and a more exaggerated ellipse over a period of approximately 93 000 years. This controls how much solar radiation is received by the planet at a particular time during the year; a more circular orbit means less variation but an elliptic orbit will result in larger changes. A highly-elliptical orbit tends to *enhance* the seasons in one hemisphere and *moderate* them in the other. Many researchers cite this mechanism as the most important in triggering a glacial period due to cooler than normal summers which fail to melt seasonal snowfall in the middle and high latitudes.

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The second Milankovitch-Croll effect concerns the tilt of the Earth's axis of rotation. The axial tilt is known to vary between approximately 21° and 24° over 40 000 years. A larger degree of tilt amplifies the seasons in *both* hemispheres. At present the axial tilt of the Earth is approximately 23.5° and appears to be on a descending leg of a 40 000 year cycle [2].

The final Milankovitch-Croll effect concerns the 'precession' of the north pole, that is where into space the north pole points. The precession has the smallest periodicity, about 20 000 years, and is independent of the axial tilt variations, but can affect the climate of Earth by altering the dates on which the closest and farthest distances to the Sun are achieved. Again, this affects the degree of seasonality which is experienced in each hemisphere. For example, the closest point between the Earth and the Sun at present occurs on January 4th, during the southern hemisphere summer.

Geological processes known to influence climatic conditions occur on an even longer time scale than orbital variations, but produce major changes. Continental drift or plate-tectonics occurs very slowly but can alter the climate by a number of mechanisms. Firstly movement of continental plates can upset and redirect ocean currents moving heat from one sector of the planet to another. Secondly, movement of the major continental plates adjust the latitude at which that particular land mass resides affecting the severity of seasonality and the mean annual temperature. Thirdly, continental drift is responsible for mountain range formation serving not only to cool the climate of the uplifted region, but redirecting atmospheric circulation which has climate implications for adjacent regions. It is important, though, to grasp the tardy nature of these effects; the location of the major continental plates has been approximately unchanged for the last 50 million years.

One geological process which affects climatic conditions on a much shorter time scale is **volcanism**. Large, explosive volcanic eruptions can inject huge amounts of soot and ash into the middle atmosphere where they are beyond the cleansing effect of rainfall forming processes. The strong winds typical of the higher altitudes are effective in transporting these particles around the planet where they reflect solar radiation back into space creating a 'global soot veil'. The climate impacts of volcanic event usually decay after 1 or 2 years, however, some evidence suggests that lower-frequency so-called 'super-eruptions' whereby whole regions are seen to erupt can alter the climate for enough time to cause radical species loss. Fortunately the return periods of these events is close to 50 000 years [16].

In addition to geologic and orbital changes, the climate system is sensitive to inherent and periodic **internal variability** to any one of its components. A good example of this is the well known El-Nino event, where ocean upwelling in the Equatorial Pacific is weaker in one season than is the norm. The resulting changes to the wind patterns produces drought in some regions and floods in others as the weather systems respond to changes in sea surface temperatures. Other internal mechanism producing climatic changes include random (i.e. one off) changes to a particular ocean current which changes the pattern of heat distribution. It is important to acknowledge the **climate feedbacks** which exist and modify not only internal variabilities, but indeed any type of climatic change. For example,

the ocean current switch might warm a high latitude region reducing its snow cover meaning more exposed land surface is able to absorb solar heat in the winter leading to even more warming. It is an overriding aim of climate science today to increase our understanding of such relationships and how internal processes relate to one another and might upset one component of the system and what climatic change might occur as a result.

Aside from the natural mechanisms capable of causing widespread changes to climatic conditions discussed so far, there is **anthropogenic climate change**, that is climate change caused by man's activity. This has many guises such as alteration of the planet's reflectivity and thermal properties by changing land cover type, but the most well-known anthropogenic influence concerns the enhanced greenhouse effect. Certain gases within the Earth's atmosphere are transparent to incoming energy, but opaque to outgoing heat and are responsible for maintaining an average global temperature of around 15 °C. The greenhouse effect is natural, but since the industrialisation of many nations in the nineteenth century, additional quantities of greenhouse gases (namely CO₂) have been added to the atmosphere through the burning of carbon-rich fossil fuels. The vast additions to the atmosphere of CO₂ that have occurred in recent decades are now believed to have enhanced the natural greenhouse effect. Greenhouse theory and anthropogenic forcing of the climate system is discussed in greater depth in Sect. 3.

2 Past Climatic Changes

The Earth's climate system is changing today, but has experienced numerous changes in the past. Indeed, it is helpful to think of the climate system as constantly adjusting to the fluctuation in energy inputs and outputs (forcings) which result from the mechanisms explained in Sect. 1. Very recent climatic changes can be detected through analysis of thermometer readings. Reliable thermometer readings are generally accepted to have begun in the mid nineteenth century and accordingly the period from then up to the present is termed the **instrumental period**. However, climatic conditions can also be estimated further back in time through use of non-direct, **proxy**, measurements of climatic variables.

Climate reconstructions using the proxy method rely on a number of techniques, such as tree ring width data, analysis of ice core segments and chemical composition of ocean and geological sediments but to name a few. Proxy methods allow a reasonable estimate of temperature (and in some cases precipitation) for the past few thousand (tree ring) and hundreds of thousands (ice cores) of years. Whilst the *exact* dating of the latter records may be difficult the data are nonetheless sufficient to identify major climatic adjustments and help to place very recent climate change in the context of pre-human variations.

Analysis of oceanic and geological sediment has established that during the course of the past 800 000 years the Earth has experienced a number of warm **interglacial** and cold **glacial** periods, each of which last several (and maybe tens of)

thousands of years. It is also possible to determine that we are currently experiencing a warm interglacial period which began approximately 10 000–12 000 years ago and marks the start of the current epoch, the **Holocene** (e.g. [11]). The changes in temperature which accompanied the switch from the last glacial to the present interglacial period were not smooth and varied greatly over the planet. However, work focusing upon the British Isles has estimated that between 13 300 and 12 500 years before present, the mean temperature rose by 7–8 °C in summer and ~25 °C in winter [1].

With the advent of the Holocene Epoch and the flourishing of civilisations in the warmer climates, written historical records point to a number of climatic changes that have occurred over the past 1–2000 years. Lamb [11] notes historical writings that suggest the period between 900 and 300 BC were especially cold over Europe; Roman writers reported severe winters in Italy, which match records of glacial advances within the Alps (Hueberger 1968). Conversely, the final century BC seems to have been warmer and indicative of the onset of a less harsh climatic period. For instance, records suggest that Roman agriculture extended north and the Alpine Glaciers retreated [11].

Several climate reconstructions based upon proxy records (particularly tree ring widths) have recently become available with which to investigate climatic changes in the last 1000 years (Fig. 14.1). The last millennium is generally accepted to have experienced three main climatic epochs. The ‘**Medieval Warm Period**’ characterised the climate of the twelfth and thirteenth centuries, and was followed in the sixteenth and seventeenth centuries by the ‘**Little Ice Age**’. The final, more recent, climatic event has been **post-industrial warming**. The dates of the first two events are often the topic of much debate, particularly because many of the information pointing to their existence appears to vary in timing for different parts of the planet. Indeed, whether or not the terms are actually applicable in describing the average climatic conditions of the time is also increasingly questioned. Lamb [11] cited colonisation of high-latitude regions and evidence of vine cultivation in Britain as evidence supporting a pronounced Medieval Warm Period (MWP) for Europe at least. However, others (e.g. [10]) question the validity of the MWP pointing to a lack of a distinct rise in the proxy temperature record for the northern hemisphere average at this time and citing other reasons why agricultural changes may have occurred. The caveat is that, whilst some individual evidence may point to a warmer epoch, it is dangerous to infer a widespread warming event without hard and fast facts.

What is evident from many of the curves in Fig. 14.1 is the existence of a cooler period during the sixteenth and seventeenth centuries. Glacial advances within Europe have been shown to be widespread and loss of agricultural land would have resulted. Many reconstructed climate records indicate that the coldest annual temperature in the last 1000 years occurred in 1601 [10]. Nonetheless, the validity of the actual Little Ice Age has, like the MWP come under question itself. Some researchers point to the fact that many individual years during the Little Ice Age period saw temperatures as warm as present levels [10] and glacial advances occurred at different times during the supposed ‘cold’ centuries.

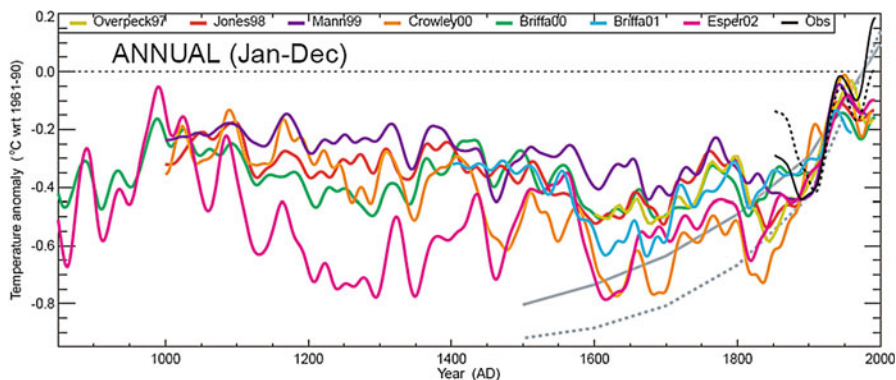


Fig. 14.1 Estimated and observed temperature curves

In 1815, as more reliable instrument-based measurements were becoming more frequent, the Indonesian volcano of Tambora causing a classic soot veil effect. The climatic and agricultural implications of the eruption were severe. Cool weather endured over northeastern USA, Canada and Europe the following year leading to catastrophic crop failures and a year ‘without a summer’ (e.g. [15]), highlighting the sensitivity of the climate system (and global agricultural) to violent, explosive eruptions.

The third climatic event of the last 1000 years, **Post-industrial warming**, can clearly be seen in the observed instrumental record (the black curve in Fig. 14.1 and a more detailed curve, Fig. 14.2) and lends weight to the argument of human-induced climate change. Two warming events are apparent and these constitute the *only* statistically-significant events of the instrumental record [10]. The first warming period occurred between 1920 and 1945; the second since 1975. Analysis of the observed record, in the context of the last 1000 years, reveals that the warmest temperatures globally were recorded between 2002 and 2014. According to the UK HadCRUT4 global temperature record (Morice et al. 2011), 2010 and 2014 were, jointly, the warmest individual years. Each of the last three decades have been warmer than any over decade since 1850, with the most recent decade succeeding the last. The lower, global curve in Fig. 14.2 shows that compared to temperatures representative of the mid twentieth century the annual global mean temperature of 2014 was ~ 0.6 °C warmer.

The instrumental record indicates that this warming has affected the middle-high latitudes of the northern hemisphere the most with winter months warming more rapidly than summer months. For these regions, insofar as agriculture is concerned, an extended growing season has also been observed in some records (e.g. Menzel and Fabian 1999), although changes to the rainfall regime of any individual region can complicate potential agricultural benefits.

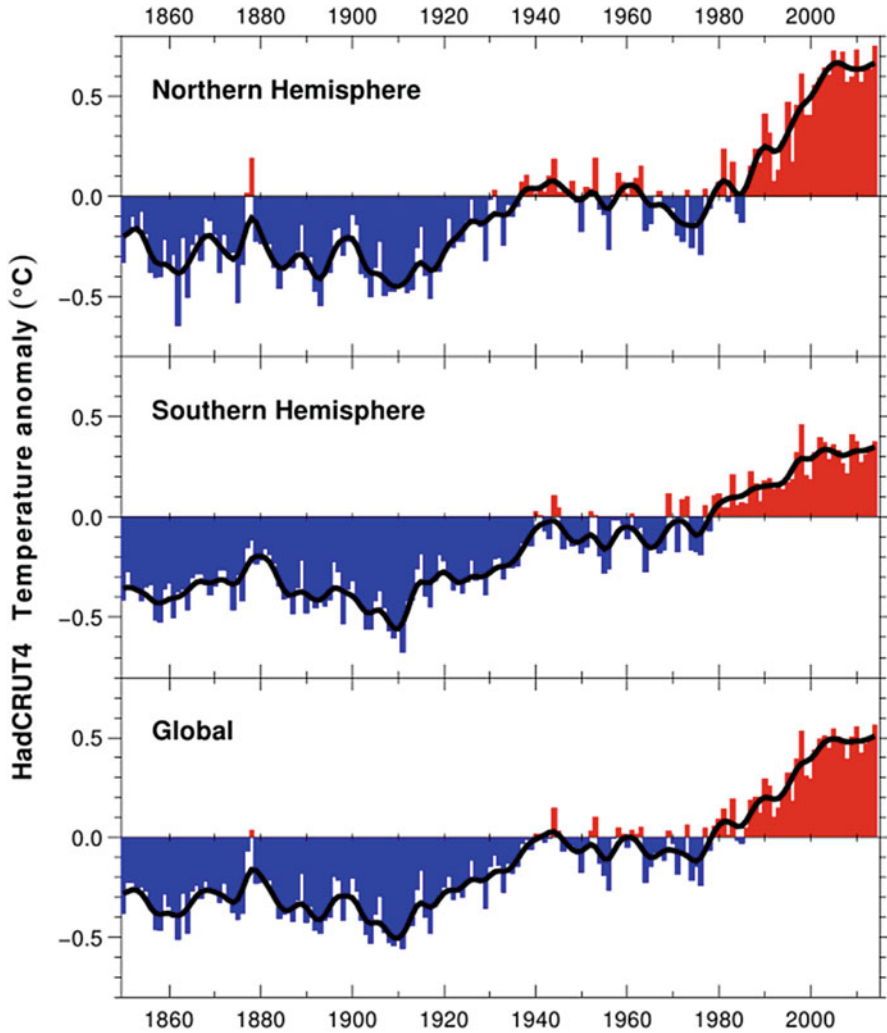


Fig. 14.2 The HadCRUT4 observed temperature record (Source: Climatic Research Unit, University of East Anglia; [12])

3 Anthropogenic Forcing of the Climate System

Anthropogenic forcing of the climate system is primarily achieved through the release of greenhouse gases to the atmosphere as a result of industrial (and to a lesser extent agricultural and domestic) activities. These gases include CO_2 , CH_4 (methane) nitrous oxide and halocarbon gases (which also have ozone-depleting characteristics).

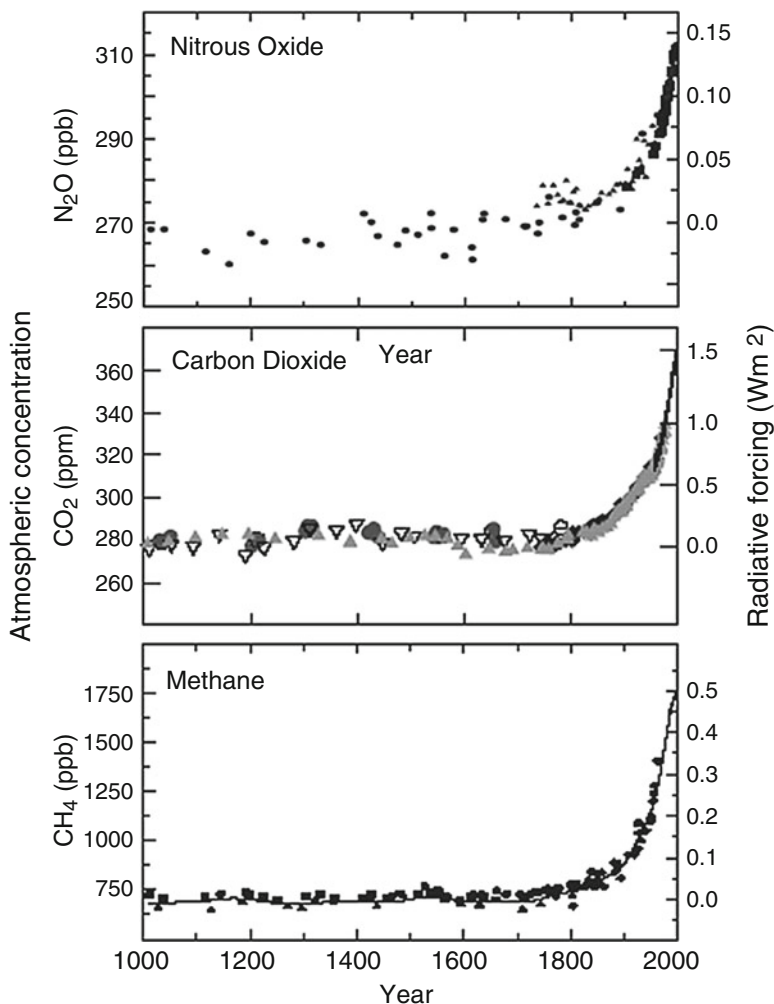


Fig. 14.3 CO₂, NO_x and CH₄ curves over last 1000 years

Greenhouse gases vary in their ability to intercept outgoing radiation. For example methane is a very chemically efficient greenhouse gas, but the gas most commonly associated with anthropogenic forcing is CO₂, due to its greater abundance within the atmosphere. Measured levels of CO₂, methane and nitrous oxides via instrumentation and analysis of air trapped in ice cores for the past 1000 years show marked and unprecedented increases in atmospheric concentrations in recent times (Fig. 14.3). The commencement of these increases coincides with the rapid industrialisation of the northern hemisphere during the late eighteenth and nineteenth centuries.

Since 1750, the global atmospheric concentration of CO₂ has increased by 31 %. Analysis of extended data sources indicate the current atmospheric concentration of CO₂ is the highest for the past 420 000 years, and is likely to be the highest within the last 20 million years [4]. The percentage increase in methane concentrations is greater, having risen 151 % since 1750, whilst concentrations of nitrous oxide have risen by 17 % [7] over the same period.

The impact that changes in the atmospheric concentration of any one greenhouse gas might have on the thermal properties of the atmosphere can be measured in terms of **radiative forcing**. In a steady, or unperturbed, state, the amount of energy leaving the top of the Earth's atmosphere *must* exactly match the amount of energy entering the system. If the energy input or output becomes unbalanced (i.e. does not exactly match) through either an increase in solar energy entering the system *or* a decrease in the energy able to leave the planet's atmosphere, then there is said to be a radiative forcing placed upon the system. This extra energy is expressed in watts per metre squared (the area referring to the top of the Earth's atmosphere, where the climate system is separated from space) and results in the climate system altering its temperature in order to emit more energy and once again achieve a steady balance.

The elevated radiative forcing associated with the increased concentrations of the three main greenhouse gases are shown on the right-hand axis of Fig. 14.3, although there are some uncertainties regarding these values. In total, however, increased atmospheric concentrations of CO₂, CH₄ and nitrous oxides are estimated to have placed an additional 2.1 Wm² of radiative forcing onto the climate system since 1750 [4].

Exactly how the climate system might respond to such an alteration to its energy balance has been the quest of climate science for many years. The resulting change in temperature necessary to restore the system to equilibrium depends upon a whole host of factors and is generally referred to as the **climate sensitivity**. Nonetheless, computer simulations of the Earth's climate indicate that the level of observed global warming evident in the instrumental record is consistent with the estimated response to the additional anthropogenic radiative forcing. It is this fact along with the geographical pattern of the observed warming that has led the IPCC to conclude that 'in the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the past 50 years is likely to have been due to the increase in greenhouse gas concentrations' [4].

4 Future Changes in Anthropogenic Forcing

Projections of future climate change can be developed by computer simulations of the Earth's climate system. Simulations must consider likely future changes to both natural and anthropogenic radiative forcing. In respect of the latter, the IPCC [7–9] has applied four possible future scenarios which attempt to quantify future greenhouse gas concentrations through to the year 2100 [18]. Estimates of greenhouse gas concentrations in each of the four scenarios are based upon changes that may

Table 14.1 Summary conditions of the IPCC RCP (Representative Concentration Pathway) scenarios

Scenario Component	RCP2.6	RCP4.5	RCP6	RCP8.5
Greenhouse gas emissions	Very low	Medium-low mitigation	Medium baseline; high mitigation	High baseline
		Very low baseline		
Agricultural area	Medium for cropland and pasture	Very low for both cropland and pasture	Medium for cropland but very low for pasture (total low)	Medium for both cropland and pasture
Air pollution	Medium-Low	Medium	Medium	Medium-high

After Ref. [18])

occur in important social and economic factors (e.g. global population, degree of globalisation, investment and use of sustainable energy sources etc.).

The four scenarios and their associated changes in social and economic factors are summarised in Table 14.1 and Fig. 14.4. The first of the four scenarios, **RCP2.6**, represents a world in which rapid economic growth occurs throughout the twenty-first century leading to higher GDP worldwide, along with cleaner more sustainable energy use. These changes lead to medium-low levels of air pollution. Global population increases for the first part of the century, peaking around the year 2070, before falling towards the end of the twenty-first century. Out of the four scenarios, RCP2.6 represents a world where greenhouse gas mitigation has worked most efficiently, with a decrease of global emissions starting in the year 2020 and very low levels throughout the century. Agricultural area is at a medium level for both cropland and pasture.

RCP4.5 represents a future world in which population and GDP growth increases at a relatively similar pace to RCP2.6, but primary energy consumption is higher. This leads to medium levels of air pollution and a continued increase in carbon dioxide emissions until the year 2050. After this, a decrease in CO₂ emissions pursues until 2080, followed by a period of sustained rates of emissions until the end of the century. A very low amount of agricultural land is being used for pasture and cropland.

The third scenario, **RCP6**, has the lowest increase in GDP throughout the century, but a higher rate of population growth, which peaks around 2080. Air pollution is at a medium level, but effort has been made to mitigate climate change. As a result, carbon dioxide emissions increase substantially, peaking in 2060 before declining towards the end of the century. This reflects the trend in primary energy consumption, which also peaks in the year 2060. A greater proportion of agricultural land is used for cropland, rather than for pasture.

Finally, **RCP8.5** represents a bleaker future in which population is a third greater than that in RCP2.6 by the end of the twenty-first century. Primary energy consumption is high, meaning that medium-high level air pollution persists, and considerably more carbon dioxide is emitted throughout the century as a result of

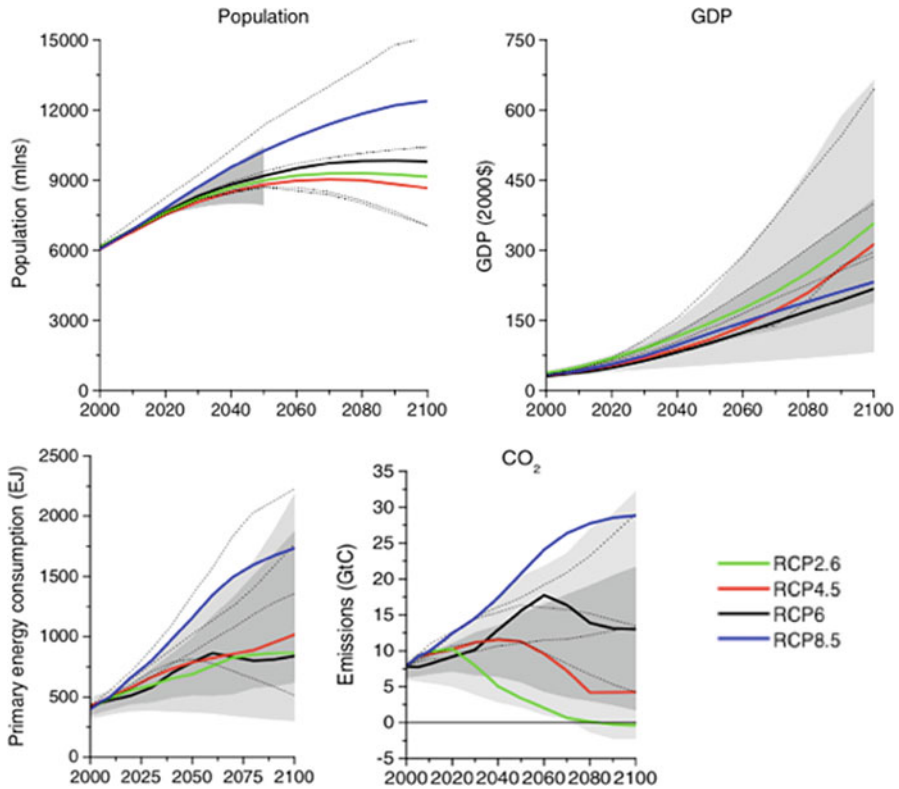


Fig. 14.4 Socio-economic trajectories of each RCP scenario (After [18])

minimum mitigation effort. Similar to RCP2.6, a medium proportion of agricultural area is used equally for cropland and pasture.

5 Implications of RCP Scenarios on Global-Mean Climate

Projections of future climate change during the present century can be made by simulating the Earth's climate using complex global circulation models (GCMs). GCMs are mathematical approximations of the real physical climate system and are able to model the transport and exchange of energy between a number of the climate system's components. For example, all GCMs used by the IPCC to develop future climate change scenarios have interactive atmospheric and oceanic components, including representation of seasonal sea ice. Most GCMs also have an interactive land surface scheme which simulates the moisture and energy fluxes between the ground and the atmosphere; these fluxes change geographically within the model depending upon the imposed land surface type.

Although GCMs represent the most complex and cutting edge tools with which to project future climate change, there are many uncertainties associated with their results, which should be acknowledged. For instance, some real-world climate system components are poorly understood, and so their approximation by mathematical equations is difficult. A good example of this, and an ongoing debate in climate change, is the role that changing characteristics of clouds might play on the future climate. Uncertainties in the future climate projections also arise via the constraints and costs associated with the current level of computing power. For example, although some physical processes are very well understood it is necessary to simulate them on a crude geographical scale so that the cost of running simulations is kept practical. However, specific regional climate models (RCMs) have also been developed for specifically simulating the climate of a singular region only (as opposed to the whole globe). RCMs are able to approximate processes on a finer geographical scale and some of their results are considered in Sect. 6. The focus in this section, however, is the *global* response of the climate system to future changes in forcing.

5.1 Temperature

Due to the abnormally high levels of CO₂ in the Earth's atmosphere at present global-mean temperature increases can be expected during the present century even if all greenhouse gas emissions were to cease immediately. Such an event is, of course very unlikely; the RCP scenarios provide outlines for more likely changes in anthropogenic forcing in the coming century and are described in Sect. 4. The mean global temperature response to each RCP scenario (Fig. 14.5) is different, reflecting the extent to which greenhouse gas concentrations either stabilise, decrease or rise during the twenty-first century. For example, the temperature response in a fossil-fuel intensive future (RCP8.5, red line & uncertainty bar in Fig. 14.5) by the year 2100 could be anywhere between ~2.5 and 4.8 °C above mean 1986–2005 conditions. However, if a RCP2.6-type scenario is followed in the present century (blue line & uncertainty bar in Fig. 14.5) then the temperature response, although positive, may be somewhat lower, in the range of ~0.25–1.75 °C above the 1986–2005 mean. Acknowledging these ranges, the IPCC concluded in their fifth assessment report that 'global surface temperature change for the end of the twenty-first century is likely to exceed 1.5 °C relative to 1850–1900 for all RCP scenarios except RCP2.6' [7]. With this increase in mean surface air temperature, it is expected that there will be more frequent extreme high temperature events, and a lower frequency of extreme low temperature events.

Some of the projected temperature increases are more conservative than those previously estimated (e.g. IPCC 2007). This is, in part, due to improvements in the model used to simulate future changes in temperature, for example refined cloud and aerosol processes, and a wider representation (though still not complete) of important climate processes. In a general sense, low-level clouds and aerosols, have

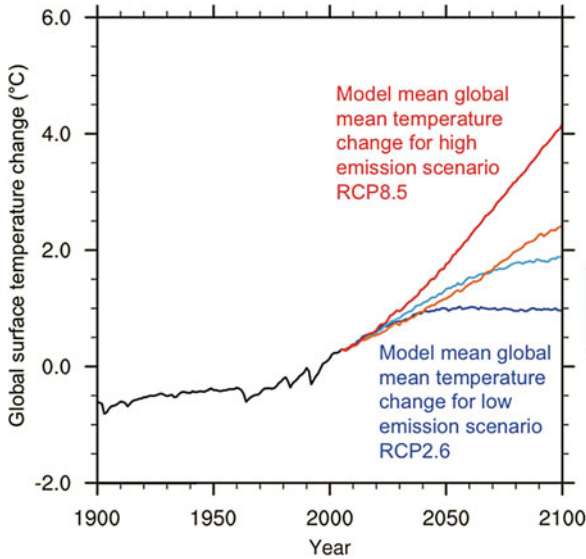


Fig. 14.5 Simulated mean global temperature change in twenty-first century with respect to 1986–2005 values under the four IPCC RCP scenarios (RCP2.6, dark blue; RCP4.5, light blue; RCP6.0, orange; RCP8.5, red) [7]

a negative forcing upon the climate system, reflecting incoming solar radiation and acting to offset some of the greenhouse-related warming.

5.2 Precipitation

As with temperature, globally-averaged precipitation is projected to rise during the twenty-first century. The precipitation increase can be directly linked to the rise in temperature. Not only do evaporation rates increase under warmer conditions, but a warmer atmosphere is also able to hold more moisture. The IPCC (2013) also indicate that increased levels of precipitation will be accompanied by a simultaneous increase in precipitation variability; although on average more rainfall will fall, this may be delivered by short, intense outbursts leaving other periods prone to drought.

The average global precipitation response under the IPCC RCP2.6 scenario by 2100 amounts to an increase of 0.05 mm day^{-1} , with respect to mean 1986–2005 conditions. The comparative change under the stronger RCP8.5 scenario is 0.15 mm day^{-1} and there are strong regional contrasts in this response in all RCPs (see below). Significant advances in the understanding of precipitation changes under global warming have occurred in recent years, particularly with respect to the rate of change, under warming and the interplay with the energetic budget of the climate system (e.g. [14]). Thus, it is known that the *rate* of global

precipitation change, per degree of global warming, is attenuated under warmer conditions – with precipitation rising between 1 and 3 % per degree of global warming but the highest of these rates occurring under the RCP2.6 and RCP4.5 scenarios [7]. Accompanying the trend towards a wetter planet, there is evidence to suggest that the additional precipitation will be delivered by more intense precipitation events [4].

5.3 Sea Level Rise

The range of projected globally averaged sea level rise in the twenty-first century is large, lying between 0.26 and 0.98 m for the full set of RCP scenarios according to the IPCC (Fig. 14.6). The mean increase by the year 2100 is 0.54 m which represents a two to four increase in the rate of sea level rise which was recorded in the twentieth century. The amount of sea level rise experienced in each scenario differs only slightly in the first half of the twenty-first century (for those same reasons outlined in Sect. 5.1). Greater inter-scenario differences can be seen in the years after 2060, with larger rises in sea levels associated with the fossil-fuel intensive scenarios.

The majority of the projected sea level rise is due to thermal expansion of the oceans as the planet becomes warmer. Additional sea level rise is caused by the input of fresh water from glaciers and the major ice sheets of Greenland and the

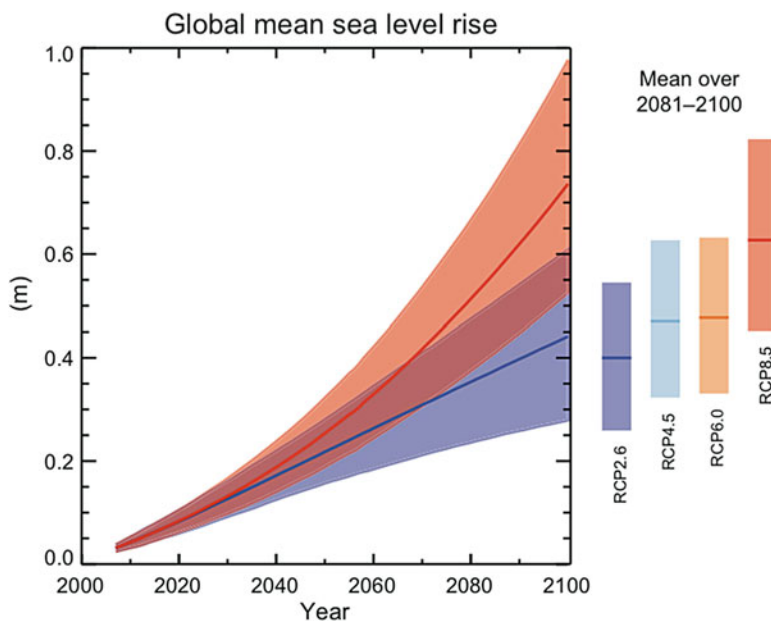


Fig. 14.6 Global sea level rise for each IPCC RCP 2006–2100 [7]

Antarctic. Regional variations around this global mean change will occur due to ocean circulation patterns and the resulting accumulation and distribution of mass that these circulation patterns cause.

5.4 Mitigation Possibilities Within the Agricultural Sector

The magnitude of temperature, precipitation and sea level change depends upon which greenhouse gas scenario best describes the future levels of greenhouse gas emissions. Since the ratification of the Kyoto Protocol many of the world's governments committed to reducing greenhouse gas emissions to at least 5 % beneath their recorded emissions in 1990 with further binding agreements imminent. Much of the focus in meeting mitigation commitments has addressed how to lower greenhouse gas emissions from the major sources, such as transportation and energy production. However, there are opportunities to lower emissions within other sectors and agriculture is no exception, and in itself is responsible for 20 % of all anthropogenic greenhouse gas emissions (mainly in the form of methane and nitrous oxides).

Significant reductions in agriculturally-sourced greenhouse gas emissions can be achieved through a change in a number of agricultural practises, outlined in the 2001 and 2013 report of the Third Working Group [5, 6, 9]. For instance, a reduction in land use intensity and employing conservation tillage techniques (to protect the top soil) would both act to increase (or at least maintain) soil carbon uptake. Rice paddy fields are a major source of methane, the warm, shallow waters being ideal for methanogenesis; a shift towards rice crop varieties which can be grown under drier conditions would reduce emissions from this source. Another source of methane emissions is livestock. Shifting from meat to plant production would help in this case.

Insofar as nitrous oxides are concerned, significant reductions in agricultural emissions could be achieved by altering fertilising methods. One option is to replace the use of synthetic nitrogen sources with organic manures. Slow-release fertilisers and genetically-modified leguminous plants are also available, both of which limit the amount of nitrous oxides released into the atmosphere.

6 Implications of RCP Scenarios on Regional Climate

When viewed globally, the likely future climatic changes to the RCP scenarios can be summarised fairly simply. A warmer, wetter world seems likely. But for each region of the planet, the response is not so straight forward. Changes to the climate may not reflect the global response, or may do for one season but not for another. This section examines in more detail projected regional changes in climate for the current century.

6.1 North America

Surface mean temperatures in North America are projected to be between 0.5 and 1 °C warmer (with respect to 1986–2005 conditions) under an RCP2.6 scenario by 2081–2100. Precipitation is also projected to increase for most parts of the continent, excluding some areas of the south western USA and parts of Mexico. For the 2081–2100 period, simulations based upon multiple GCM experiments indicate the majority of North America may see 0–10 % more mean precipitation. The moderate RCP4.5 projections, with greater greenhouse gas concentrations compared to RCP2.6, suggest mean temperatures could be around 1–3 °C warmer for most parts of the continent, with temperatures reaching up to 7 °C at higher latitudes during the winter time. Precipitation could increase by between 0 and 20 % for most locations excluding, again, parts of the southern USA and Mexico. Precipitation here may decrease by up to 10 %. For RCP8.5, mean temperature and precipitation changes are more prominent. North America could experience temperatures 3–5 °C warmer on average and at some locations between 0 and 50 % more precipitation could be expected. Similar to previously mentioned scenarios, parts of Mexico and the southern United States could expect to see a decrease in precipitation, for example of up to 20 % compared to the 1986–2005 baseline period.

6.2 Europe and Eurasia

In the ‘best case’ scenario, RCP2.6, GCM simulations indicate that average temperatures could be between 0.5 and 1.5 °C warmer by the 2081–2100 period, with the greatest warming seen in Nordic countries. Average precipitation is projected to increase at most locations (+0–10 %), apart from the Iberian Peninsula, parts of south western France, Turkey, and parts of Greece (–0–10 %). Climate model simulations forced with the RCP4.5 greenhouse gas concentration pathway suggests average temperature increases, for the same period, could range between 0.5 and 3 °C for most parts of Europe and Eurasia. Stronger warming is projected over north eastern Europe, Russia, and Asia exceeding with rises of ~9 °C during the winter season. The mean GCM response for precipitation is a decrease in average totals over a large proportion of western and southern Europe during the spring and summer months by as much as 0–20 %, with respect to 1986–2005 values. In contrast, north eastern Europe, and parts of Eurasia can expect up to 20 % more precipitation in some areas. During the autumn and winter months, however, precipitation is expected to increase by between 0 and 30 % for most locations in Europe and Eurasia, except Spain, parts of France, and neighbouring Mediterranean countries. Under the RCP8.5 scenario, average temperature rises could exceed 2 °C at most locations, with increases of up to 7 °C predicted within some Nordic locations, in Russia, parts of Belarus and Ukraine, and some regions situated in central and southern Asia. When examining average precipitation for this scenario,

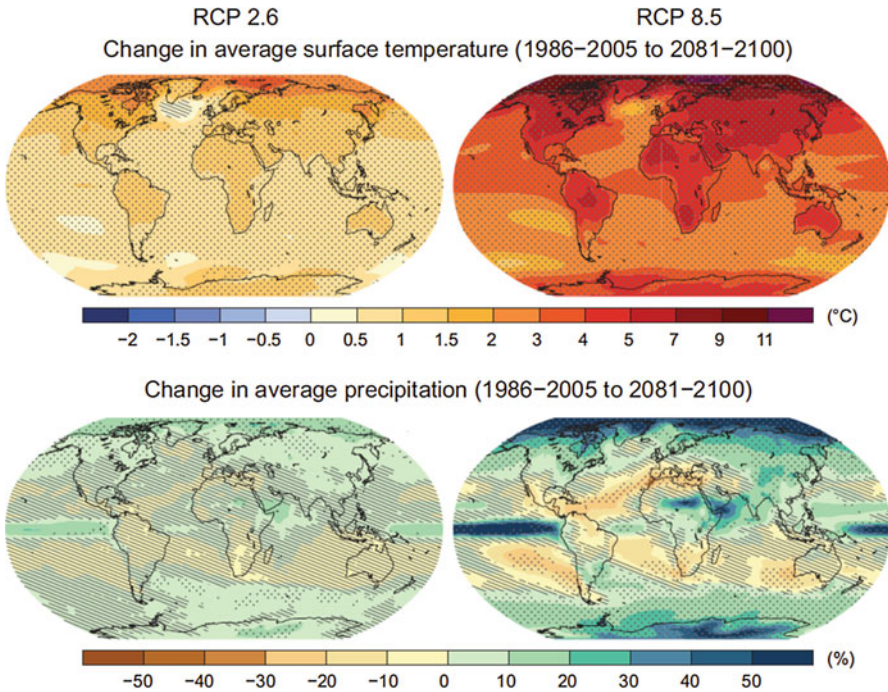


Fig. 14.7 Changes in average annual surface air temperature (*top row*) and precipitation (*bottom row*) by 2081–2100 using multiple GCM simulations under RCP2.6 (*left*) and RCP8.5 (*right*) greenhouse gas concentration pathways (Source: [7])

the Mediterranean region is predicted to receive between 0 and 30 % less rainfall, with parts of southern Spain, Italy, Greece and Turkey being hardest hit. On the other hand, the vast majority of Europe and Asia could record between 0 and 40 % more precipitation on average. Parts of Scandinavia, Siberia, China, and India are projected to experience the largest increases in precipitation (Fig. 14.7).

7 Impacts of Future Climate Change on Agriculture

As much as the effects of future climate change vary from region to region, the same can be said of the implications of any change upon agriculture. For example, projected temperature increases may well be of benefit to some farmers located in the temperature mid-latitudes, but not so beneficial for those within equatorial or tropical regions, where crops already grow close to the limits of their heat tolerance (eg [13]). Indeed, the agricultural implications of any change in climate must consider a number of factors, such as the seasonality of temperature/precipitation changes, changes to the hydrological cycle and possible changes in soil fertility. Nonetheless, from a global standpoint, new simulations of the impact of climate

change upon primary crop types (wheat, rice and maize), indicate that just 10 % of projections exhibit yield increases of 10 % or more (relative to late twentieth century levels) for the 2030–2049 period [8, 9]. Simultaneously, 10 % of projections show a 25 % fall in yields for the same time period. Beyond this time-frame the risks of severe agricultural impacts are scaled with the varying degrees of global warming predicted by the varying RCPs. Below, a brief outline of the probable implications upon agriculture within Europe and North America as a result of climate change in the next century is presented.

7.1 Europe

A regional modelling analysis of potential future European agricultural changes shows prevailing north-south (i.e. zonal) separations in response to possible future climate change [8, 9]. These changes are also model dependent – that is they reflect the inter-model variability of the future projections of controlling factors (namely temperature and precipitation), As one of the world’s largest cereal producers (and traders) major studies have focussed upon the possible impacts of future climate change upon crops such as wheat, but also oil crops such as sunflower and rapeseed [3].

Possible changes in wheat yield due to climate change by 2030 are depicted in Fig. 14.8 for two climate models, representing the upper and lower limits of model variability. Differences between the patterns of yield decrease (red) and increases (green) in the top two panels are stark and can be attributed to the difference in spatial temperature and precipitation projections in each driving climate model. For the HadCM3 driving climate model (top right) yield increases occur over southern Europe which here is a combination of the co-called carbon fertilization effect and a climatically-driven shortening of the crop cycle, which allows for the avoidance of the maximum (high summer) moisture stress phase. Nonetheless, consistent yield decreases can be seen in both, within the Iberian Peninsula and elements of central/eastern Europe. The regional modelling analyses of Donatelli et al. [3] also allows for the inclusion of rudimentary adaptation practices in future agriculture – for example modification of the sowing phase of crops to best-fit the evolving climatic conditions. In fact, when this is accounted for in the projections, (bottom row), the distribution of yield decreases is severely attenuated (and generally limited to Iberia).

Changes in rapeseed crop yield are less pronounced than wheat, indicating less limitation by future precipitation and co-incidental positive impacts relating to the carbon fertilization effect. Negative changes appear to be very effectively curtailed by adaptation practices – within the 2030 time-frame at least. Yields, however, for sunflower, grown predominantly in central and southern Europe show consistent decreases in Eastern Europe, the strongest of which are simulated over the agricultural zones adjacent to the Black Sea.

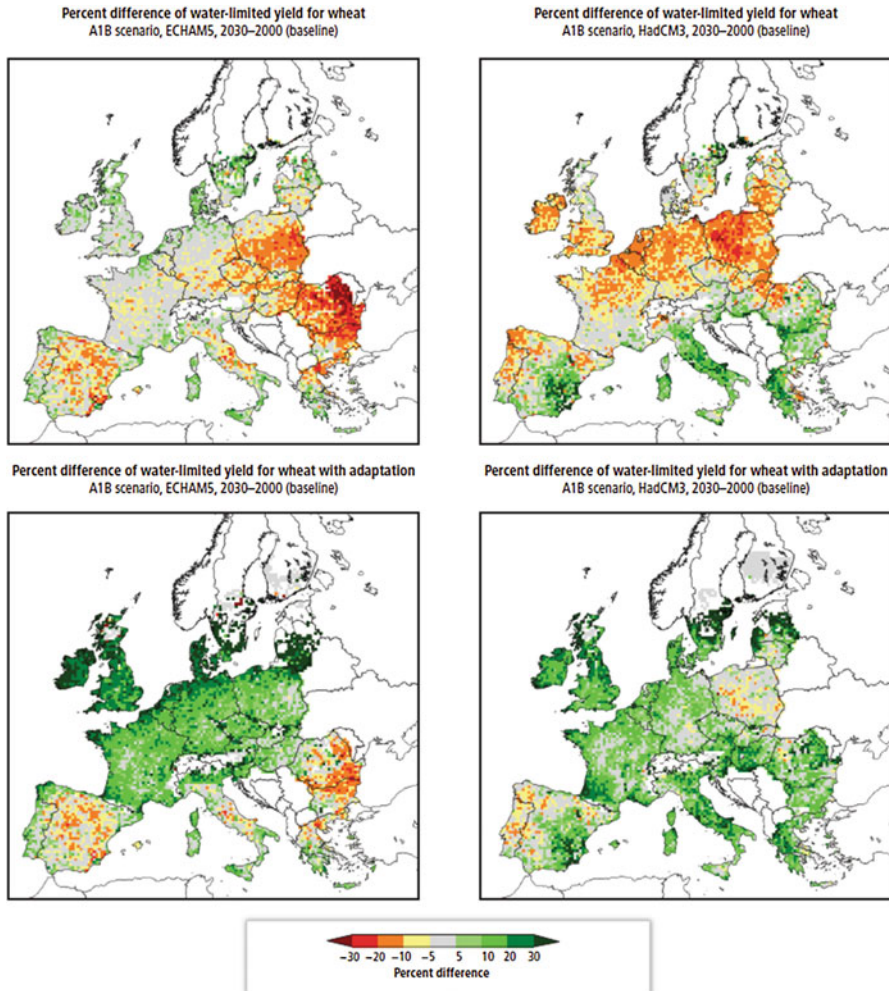


Fig. 14.8 Simulated changes in wheat yield for two GCM simulations (*left and right column*) by 2030 under the IPCC AR4 A1B [5] emissions scenario. Changes are expressed with reference to the simulated 2000 baseline. *Top row* shows changes with no assumed adaptation practices and the *lower* shows changes including basic adaptations (Source: [3, 8])

7.2 North America

The diverse regional impacts of potential climate change upon North American agriculture reflects the continent’s size and encompassment of several climatic regimes (as with Europe, to a degree). Corn, wheat, vines, cotton and citrus are all important crops in this region, but it is perhaps the first two which are of greatest importance as major mainstay (and exported) human foods both directly and

indirectly (via cattle feed). In recent decades crop yields have been observed to increase within the United States (US) due to regional precipitation (and some temperature) change, and in Canada primarily due to changes in temperature [7]. However, it is considered that continuation of temperatures changes will be detrimental, with optimal temperatures for most crops now having been realised.

Yields of all major crops, by mid century, are projected to decrease and decreases are expected to accelerate towards the latter part of the century. GCM and crop model results indicate, for example, that corn is shown to be especially sensitive to projected increases in daily temperatures greater than 29 °C (Schlenker and Roberts 2009) with associated decreases in yields between 30 and 82 % by 2099, depending upon emission scenario. Commensurate changes in soy and cotton yields are also likely. Increases in precipitation, especially within the eastern sector (e.g. Greater Mississippi Basin) will offset (but not totally compensate) temperature-driven decreases in yield, and where both temperature increases and precipitation decreases are projected, decreases in crop yields can be expected to be greater. Such regions include central and western United States and extend into Central America and Mexico [7].

The severity of climate-driven changes will be modulated by future availability of irrigation reserves (e.g. groundwater). Quantities of these reserves are difficult to estimate, but it is known that, already, such North American reserves are under severe stress given that present-day abstraction rates (e.g. Gleeson et al. 2012) exceed natural replenishment. Evolving reliance on groundwater reserves are underway in areas such as California due to limited precipitation and surface water availability in recent years. The volume of water in the High Plains aquifer is of particular importance also given its proximity – and supply – to the vast United States corn belt: again present-day abstraction for use in irrigation far exceed present-day recharge rates (Gleeson et al. 2012). Sources of irrigation for agriculture in central and western are also reliant upon snow volumes. In this respect, a reduced snow pack (i.e. more liquid precipitation), and projected advances of the melting phase, have detrimental consequences for agriculture, even if mean precipitation levels were to increase [7].

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