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Editors

Plant and Microbe Adaptations to Cold in a Changing World

Proceedings from Plant and Microbe Adaptations to Cold 2012

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Participants for Plant and Microbe Adaptations to Cold 2012 Hokkaido University, Sapporo Japan June 24–28, 2012

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Preface

Global warming is affecting agriculture in a wide range of the climatic zones. In contrast to the extensive debate over the effects of global warming during summer growth, the impact of rising winter temperature on agricultural production has received considerably less attention. However, climate changes can certainly affect winter conditions, and small changes in winter climate can have even more drastic impacts in many regions of the world. The tendency of winter warming is most evident in the lower latitude winter transitional areas of cool temperate regions, which include major production areas of winter wheat and forage crops. In these areas, snow cover has the greatest impact on winter crop production in both positive and negative ways: snow cover beneficially protects plants from freezing injury while also providing optimal habitat for the major winter pathogens, known as snow molds, to prevail under snow cover. Climate change affects the depth, duration, and distribution of snow cover in the cool temperate regions, resulting in increased freezing damage of crops due to reduced snow cover in some areas, as well as increased snow mold damage due to prolonged snow cover in other areas. Changes in the flora and dynamics of snow mold fungi are also being reported. Fluctuations in snow cover also affect occurrence of soil frost and freeze-thaw cycles, which result in alteration of soil physical properties, ecosystem nutrient cycling and microbial activities. Overall, there are many emerging factors that can threaten the sustainability of agricultural production.

Plant and Microbe Adaptations to Cold (PMAC) is an interdisciplinary forum for research and extension scientists working in the fields of plant pathology, plant physiology, microbiology, and crop breeding, to advance our understanding of overwintering of crops and attempt to solve the problems associated with winter damage. The first PMAC conference was held in Sapporo, Japan in 1997 and the following meetings have been held every three years in different locations around the world. The PMAC conference came back to its place of origin after 15 years, and PMAC2012 was held June 24–28, 2012 at the Conference Hall of Hokkaido University, Sapporo, Japan. The PMAC2012 conference focused on global climate change, food security, and agriculture sustainability with the subtitle "Toward risk assessment and management of sustainable agriculture in the cool and cold regions," and the entire program was organized to reflect this theme. The sessions covered a wide range of topics from soil physical properties and crop protection from frost and pathogens to current breeding strategies. In order to widen the scope of the conference and enhance interdisciplinary discussion, experts in meteorology, soil science and ecology were also invited to participate in the program. What was unique about PMAC2012 was having a special panel discussion session on global warming management. This was a great opportunity for the scientists to better understand the realities of impacts on producers and the questions that needed to be addressed through discussion with the invited panel members representing farmers, agricultural co-operators, and policy makers. PMAC2012 gathered over 100 participants from 14 countries and hosted 41 oral and 42 poster presentations.

This book is a collection of contributions from invited and selected speakers at the conference. Each contribution includes important and timely topics on plant and microbe adaptations to cold. These contributions span the topics discussed at the conference. Publication of this book has been partially suported by OECD-CRP. We also thank Hannah Smith, Melissa Higgs, and Kevin Wright of Springer for their assistance in production of this volume. Finally, we express our gratitude to all the authors and reviewers whose dedicated efforts made this publication possible.

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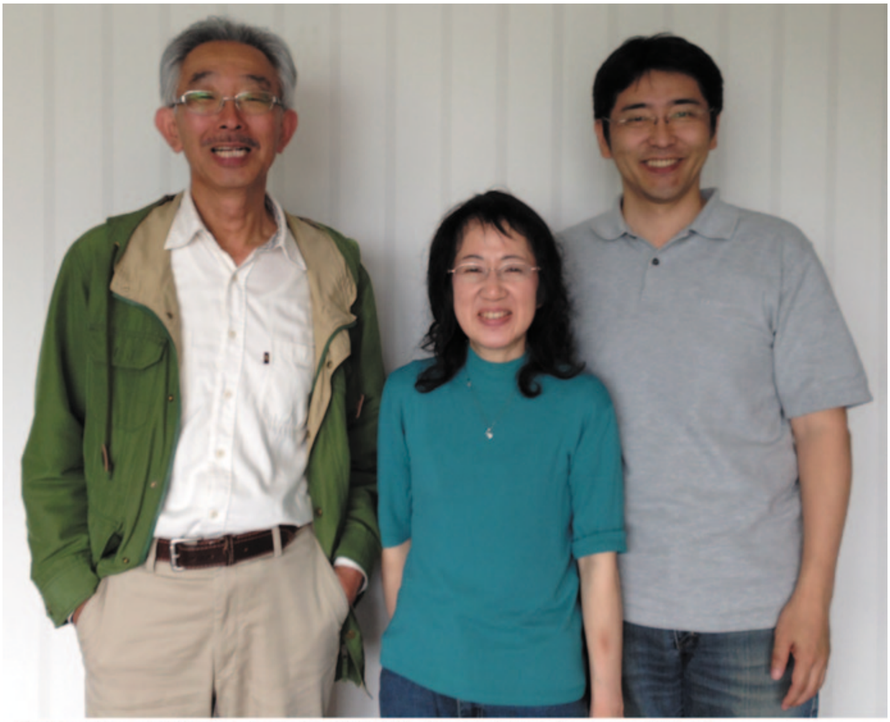

Editors; Naoyuki Matsumoto (left), Midori Yoshida (middle), Ryozo Imai (right).

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Global Change in Winter Climate and Agricultural Sustainability

Timothy Murray and Denis Gaudet

Introduction

There is no question that our climate is changing. Average air temperature of Earth has increased about 0.8 °C since 1880 and Earth area covered by snow and ice has decreased by 2.7 % per decade since 1978 (Hansen et al. 2006; IPCC 2007a). In addition, unusually warm or cool seasons, defined as those where average temperatures are two to three standard deviations greater than the mean, are becoming more common (Hansen et al. 2012b). Current models indicate that climate change will continue at the same rate for the next 15–20 years even with immediate efforts to mitigate greenhouse gas (GHG) production (IPCC 2007a).

All evidence indicates that human activities are a contributing factor to current climate change (IPCC 2007a), especially the production of the GHG: carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFC), and nitrous oxide (N_2O), which have been increasing even before the industrial revolution (IPCC 2007a). Agriculture contributes about 10 % of global GHG emissions; animal production, manure management, and soil cultivation contribute 52 % of CH_4 and 82 % of N_2O (Eaglesham and Hardy 2009). Changes in land use and deforestation also contribute to increased atmospheric CO_2 concentration (IPCC 2007a). Although there is a strong correlation between industrialization, fossil fuel use, and increased CO_2 emissions, some scientists hypothesize that human agricultural activities began to impact climate as long as 8,000 years ago, long before the industrial revolution (Ruddiman et al. 2011).

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There are many questions and great concern about how climate change will impact human activities, including our ability to sustain food production at the rate needed to feed a growing population. As scientists focusing on biotic and abiotic stresses of crop plants grown in the northern hemisphere, we have many questions about how climate change will impact crop productivity in these areas. One of the consequences of global climate change is the earlier appearance of spring and the delayed onset of fall, which effectively lengthens summer and shortens winter (IPCC 2007a). We will review some of the data for past climate change and its causes, and discuss future climate change and its potential impact on agricultural sustainability. Emphasis will be placed on changes in winter climate and the potential to influence plant and microbe interactions at low temperature during winter.

This discussion is not intended as an exhaustive review of the literature; that body of literature is large, growing rapidly, and beyond the scope or intent of this discussion. Interested readers are encouraged to consult the Intergovernmental Panel on Climate Change Fourth Assessment Report (FAR), Working Groups I and II (IPCC 2007a, b), and the other technical references cited herein for more information on climate change. In addition, the Fifth Assessment report will be published beginning in September 2013.

Past Climate Change

Climate and weather represent the same meteorological attributes of a region including temperature, precipitation, relative humidity, atmospheric pressure, wind speed and direction, atmospheric particle count, and others (IPCC 2007a). The difference between climate and weather is the time-scale over which these attributes are measured; climate represents long-term averages usually measured over a 30-year period, whereas weather represents the short-term variation in these same attributes from day-to-day or year-to-year. Consequently, the discussion of climate change focuses on significant, long-term changes in the average distribution of the meteorological variable in question and not the short-term changes that may occur over the course of a single year or season. Many discussions of climate change use the period from 1950 to 1980 as a baseline for comparison (Hansen et al. 2012a, b), but different time periods are used in some studies.

Temperature is the most frequently discussed meteorological attribute in the context of “global warming.” However, it is important to remember that temperature is just one attribute and that other important changes are also occurring including the seasonal distribution of precipitation, length of the growing season, amount of snow fall, and others that have the potential to influence agricultural productivity (IPCC 2007a). It is also important to realize that climate change can occur relatively quickly in response to perturbations of the global energy balance and such changes have had significant impacts on human civilization in the past (Zhang et al. 2011). For example, the Little Ice Age in the northern hemisphere extended from about 1350–1850 AD, and was characterized by colder winters in Europe and North

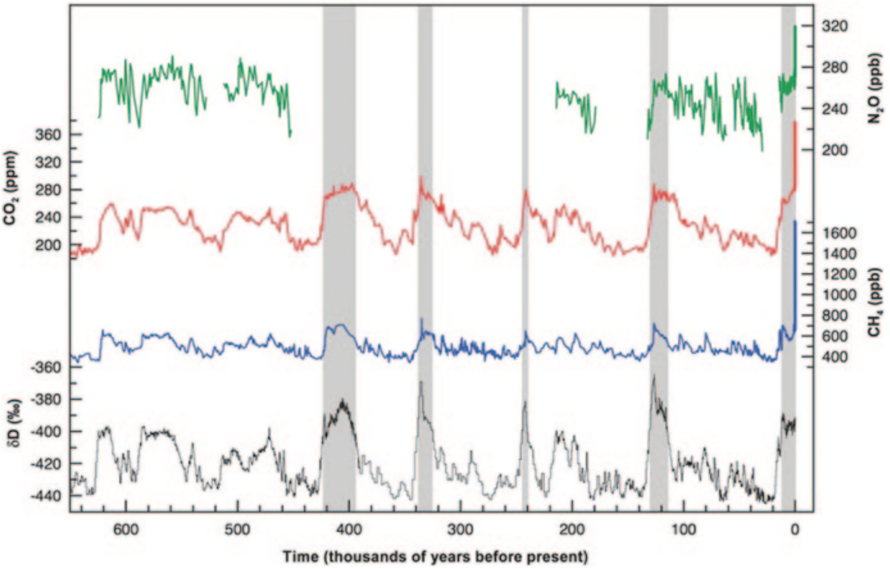

Fig. 1 Variations deuterium (δD; *black*) concentration in Antarctic ice, a proxy for local temperature, and atmospheric concentrations of the greenhouse gases: carbon dioxide (CO_2; *red*), methane (CH_4; *blue*), and nitrous oxide (N_2O; *green*) derived from air trapped in ice cores from Antarctica and recent atmospheric measurements. *Vertical shading* indicates recent interglacial warm periods. (IPCC 2007a, Fig. TS1)

America with locally greater snowfall and worldwide growth of glaciers (Nesje and Dahl 2003). Agricultural productivity and food supply responded to these changes quickly; other human crises including social disturbance, war, migration, famine, epidemics lagged by 5–30 years (Zhang et al. 2011). In the current context, climate change has the potential to threaten food security and destabilize government systems.

Paleological Climate Change Paleoclimate reconstruction is based on temperature proxies, which include air trapped in ice cores, tree rings, coral rings, lake and ocean sediments, and others. Based on these data, Earth's climate has changed many times over the past 650,000 years alternating between relatively warm and cold periods (Fig. 1) (IPCC 2007a). Using deuterium trapped in Antarctic ice cores to reconstruct local temperature change has identified five interglacial periods in the past 450,000 years, each followed by a cold period. The concentration of greenhouse gases has similarly varied over this time interval (Fig. 1), but current concentrations of atmospheric CO_2 (379 ppm) and CH_4 (1,774 ppb) are greater than preindustrial times and at any time in the past 650,000 years (IPCC 2007a).

Holocene Climate Variation About 12,000 years before present, global temperatures increased as Earth emerged from the most recent ice age (Fig. 2) and marked the beginning of the Holocene; the current interglacial period in which we live now.

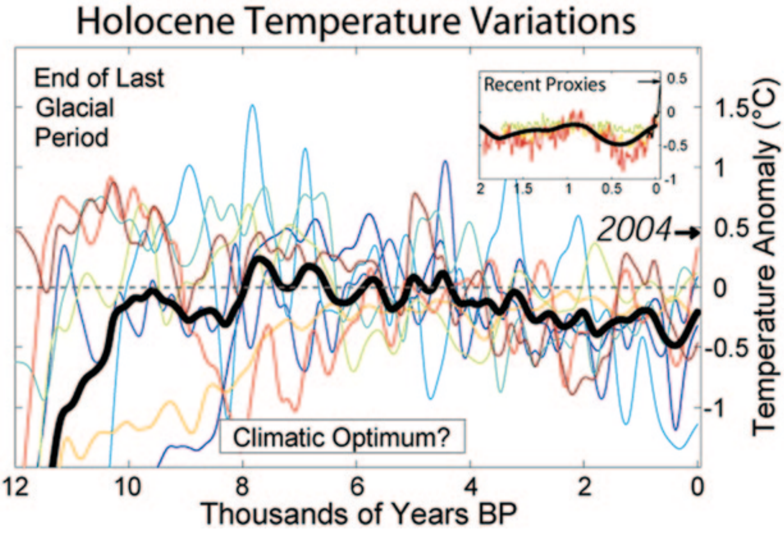

Fig. 2 Eight records (*thin colored lines*) of local temperature variability for the period from 10,000 BC to 2,000 CE (12,000 BP to the present) throughout the Holocene, and the average of these records (*black line*). Data are plotted relative to the mid-twentieth century average temperature. The global average temperature in 2004 is indicated. The inset plot compares the most recent two millennia of the average to other recent reconstructions. (Image created by Robert A. Rohde, Global Warming Art, http://en.wikipedia.org/wiki/File:Holocene_Temperature_Variations.png)

It is difficult to measure temperatures accurately during this period and there is no generally agreed upon method of determining Holocene temperatures; however, it is generally agreed that temperatures since the end of the last glacial period have been relatively stable compared with prior times. The beginning of the Holocene and its stable, warmer temperatures correspond roughly with the emergence of agriculture.

Instrumental Record The instrumental record is the period when humans began recording temperatures directly, first with thermometers and later by remote sensing from satellites. The oldest and longest continuous instrumental temperature record dates from 1659 for the Midlands region of England (Manley 1974), but it encompasses a limited geographic area. Mostly reliable global temperature records began about 1850 and three major databases maintain temperature records from the 1850s onward; the HADCRUT3 dataset at the United Kingdom Met Office Hadley Centre, GISTEMP dataset at the United States National Aeronautics and Space Administration (NASA), and GHCN database at the National Oceanic and Atmospheric Administration (NOAA) (Hansen et al. 2010). All of these databases provide global monthly mean surface temperatures collected from hundreds or thousands of observation sites. Analysis of temperature change during the instrumental period begins about 1880 because that is when the number of locations was sufficient to provide representative global coverage and magnitude of the error rate in measurement became less than temperature change (Hansen et al. 2010). Changes in temperature

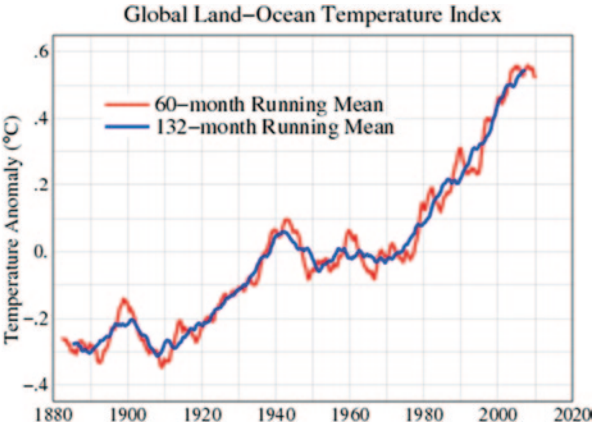

Fig. 3 Five-year (60-month) and 11-year (132-month to minimize the solar cycle effect) running means of the surface temperature deviation from the 1951–1980 mean. (With permission from: Sato and Hansen, http://www.columbia.edu/~mhs119/Temperature/)

during the instrumental record are often compared to the mean from 1950 to 1980 (Hansen et al. 2006, 2012a, b) or from 1961 to 1990 (IPCC 2007a).

Average temperature of Earth has increased about 0.8 °C since 1880 (Fig. 3), and approximately 0.2 °C per decade since 1975, accounting for two-thirds of the warming since 1880 (Hansen et al. 2010). Regression analysis of global temperature change over different time scales shows an increasing rate of warming from 1880 to the present (Fig. 4; IPCC 2007a). Rates of warming during the instrumental record ranged from a low of 0.045 °C per decade for 150 years to a high of 0.177 °C per decade for the most recent 25-year period ending in 2005. Hansen et al. (2010) concluded that despite the perception that global warming declined in the past decade, the rate of warming from 2000 to 2010 is as great as it was in the previous 2 decades. Hansen et al. (2012a) also note that 9 of the 10 warmest years in the instrumental record have occurred since 2000, and the record high global 12-month running mean temperature occurred in 2010. Thus, global warming has not diminished during the early years of the twenty-first century (Hansen et al. 2010) and will very likely continue to increase over the next 15–20 years (IPCC 2007a).

Severe or extreme weather events are usually defined as those two or more standard deviations different than the mean. Heat waves, drought, heavy precipitation, and tropical cyclones are becoming more common with climate change (IPCC 2007a). Other indicators of global climate change especially relevant to agriculture include the number of cold days, cold nights, and frost events, which have all decreased since records have been kept, and the number of hot days and hot nights, which have increased over most land areas (IPCC 2007a).

Winter Climate Change Spatial and temporal distribution of climate change is not uniform around Earth. Warming has been greater over land than sea and in northern latitudes than in low (tropical) or southern latitudes (Fig. 5) (Hansen et al. 1999, 2010; IPCC 2007a). Since 1900, average temperatures have increased about 0.9, 0.5, and 0.4 °C in the northern, low, and southern latitudes, respectively. Since 1950, the 50-year average temperature is very likely higher than at any other time in the

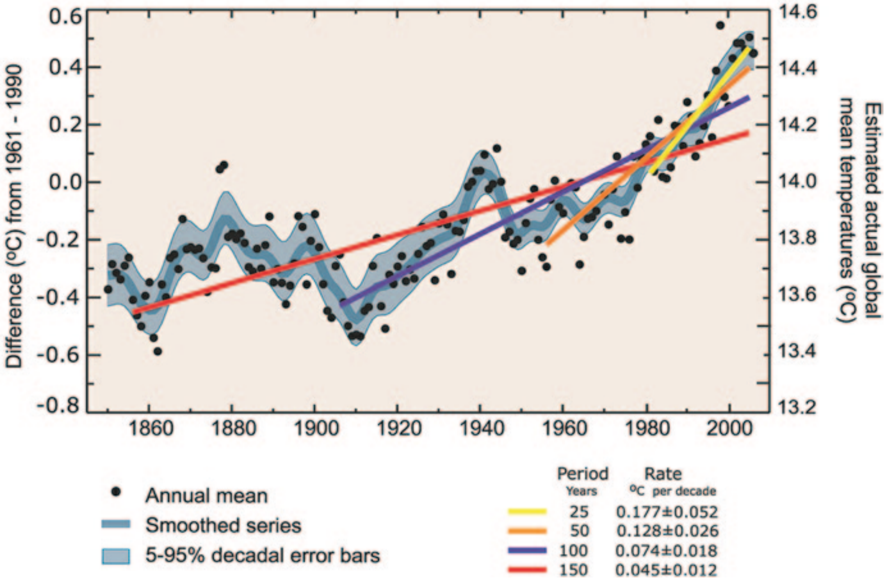

Fig. 4 Annual global mean temperatures (*black dots*) with linear fits to the data. The left axis is temperature anomalies relative to the 1961–1990 average and the right axis is estimated actual temperatures. Linear trends are shown for the last 25 (*yellow*), 50 (*orange*), 100 (*purple*), and 150 years (*red*). The smooth *blue curve* shows decadal variations, with the 90% error range shown as a *pale blue band* about that line. The total temperature increase from the period 1850–1899 to the period 2001–2005 is 0.76±0.19 °C. (IPCC 2007a, Fig. TS6)

past 500 years and the highest in the past 1,300 years (IPCC 2007a). The northern latitudes have greater land mass than mid latitudes or southern latitudes and a greater percentage of global industrialization, which partially explains the greater increase in temperature (Hansen et al. 1999). It is also likely that temperature change in arctic regions is underestimated due to the limited number of observation stations and methods by which temperatures are extrapolated (Hansen et al. 2010).

Increasing temperatures have resulted in decreased snow cover in the northern hemisphere in every month except November and December, with a total decrease in spring snow cover of about 5% since the 1980s (Fig. 6). On average, snow melt in spring was almost 2 weeks earlier in 2000 than in 1972 (IPCC 2007a). Similarly, the average area covered by seasonally frozen soil has decreased about 7% since 1901, and freeze-up and break-up dates for river and lake ice are 5.8 days/century later and 6.5 days/century earlier, respectively (IPCC 2007a). In other words, winter is getting shorter and spring and fall are getting longer.

As a result of increasing temperatures and decreased duration of winter, the intensity of biotic and abiotic stresses that affect agricultural crops in the northern hemisphere will change in response to local climate change, with specific stressors increasing in some areas and decreasing in others.

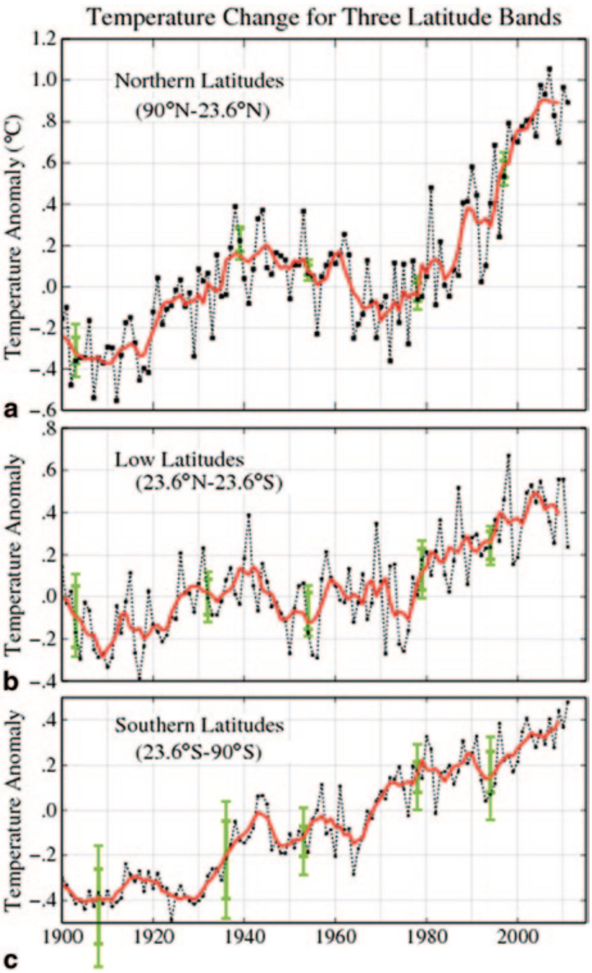

Fig. 5 Annual and 5-year running mean temperature changes relative to the base period 1951–1980 for three latitude bands. *Green bars* are 95 % confidence intervals based on spatial sampling analysis. Mean temperature increase for the northern latitudes is about 0.9 °C compared with 0.5 and 0.4 °C for the mid and southern latitudes, respectively. (With permission from: J. Hansen http://data.giss.nasa.gov/gistemp/graphs_v3/)

Causes of Climate Change

It is clear from the preceding discussion that significant changes have occurred in the global climate. Climate change is the result of changes in Earth's energy balance, which is the net difference by energy absorbed from the sun and energy radiated back into space (IPCC 2007a). Warming occurs when less energy is reflected back into space and conversely, cooling occurs when more energy is reflected back into space than is received. In climate science language, the factors affecting the energy balance are known as drivers that contribute positively or negatively to climate forcing, i.e., changes in the energy balance. Changes in the Paleoclimate were driven by natural processes, but climate change since 1850 also has a human-caused or anthropogenic contribution.

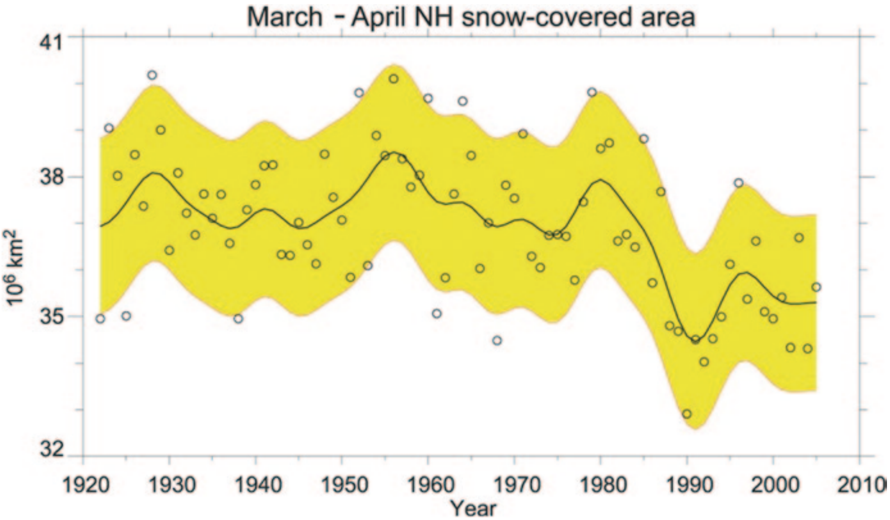

Fig. 6 Northern hemisphere March-April snow-covered area from a station-derived snow cover index prior to 1972 and satellite data from1972 onwards. The total decrease in snow-covered area is about 5 % since the 1980s. *Open circles* are annual means, the *smooth curve* is the 10-year mean, and the *shaded area* shows decadal variations with the 5–95 % data range shaded in *yellow*. (IPCC 2007a, Fig. 4.2)

Natural Processes Past climate change was driven by natural processes only, the largest of which is total solar radiation received by Earth. Total solar radiation is affected by changes in energy output of the sun, which cycles from high to low and back to high over the 11-year solar cycle with a total change in energy output of about 0.1 % (Fröhlich and Lean 2004). Total solar radiation is also affected by Earth's orbital oscillation around the sun, or the Milankovitch cycles, which includes distance to the sun (precession), axis tilt (obliquity), and eccentricity of Earth's orbit (IPCC 2007a). Consequently, solar forcing resulting from orbital oscillation is cyclical with periodicities ranging from 19,000 to 400,000 years.

Volcanic eruptions also impact Earth's energy balance. Data collected since 1980 demonstrate significant changes in atmospheric temperatures following the eruptions of El Chichón in 1982 and Pinatubo in 1991 resulting from the particulate matter and sulfur-containing compounds emitted into the atmosphere that effectively block solar radiation from reaching Earth's surface and at the same time, absorb radiation reflected from Earth's surface, thus preventing it from reaching space; the net effect is surface warming (IPCC 2007a).

The ocean thermohaline circulation pattern, also called meriodonal overturning circulation (MOC) is another natural force that influences Earth's climate (IPCC 2007a). The MOC is a series of deep and shallow currents that traverse Earth's oceans, driven by changes in temperature and density resulting from changes in salinity. One complete circuit around the globe takes about 1,600 years and results in warm surface water being distributed to cooler areas near the poles and cold water

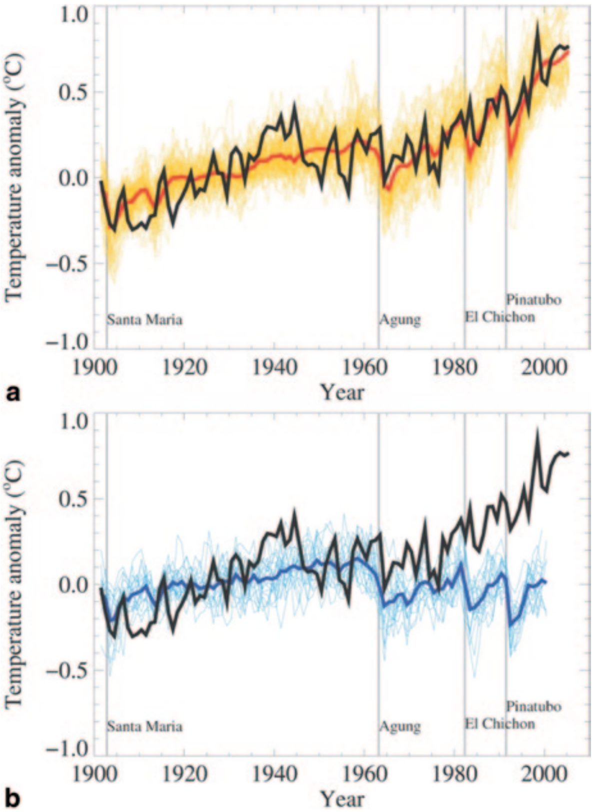

Fig. 7 Comparison between global mean surface temperature anomalies (°C) from observations (*black line*) and Atmosphere–Ocean General Circulation Model simulations using **a** anthropogenic and natural forcings and **b** natural forcings only. Data are global mean temperature anomalies relative from 1901 to 1950. *Vertical gray lines* indicate major volcanic events. Data in **a** are obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings showing the multimodel mean (*thick red line*) and individual simulations (*thin yellow lines*). Data in **b** are from 19 simulations produced by five models with natural forcings only showing the multimodel mean (*thick blue line*) and individual simulations (*thin blue lines*). (IPCC 2007a, Fig. 9.5)

from the deep oceans to warmer areas of Earth. The MOC effectively regulates Earth's temperature, especially in northern and southern latitudes, by redistributing energy received by the sun around the globe; anything that interferes with the MOC has potential to influence climate (IPCC 2007a).

Anthropogenic Processes The observed changes in average global temperatures since the 1950s cannot be explained by natural process alone (IPCC 2007a). In contrast to the observed global temperatures, Atmosphere–Ocean General Circulation Model simulations of global temperature change predict a slight cooling beyond 1960 (Fig. 7b). It is only when anthropogenic causes are included in these simulations that the results correspond to actual observations (Fig. 7a).

Production of GHG and depletion of stratospheric ozone have had the greatest impact on global temperature change since the mid 1900s, but land-use changes and the production of aerosols also have had significant impacts on global climate change (IPCC 2007a). Among the several GHG produced, CO_2 and CH_4 have had the greatest positive climate forcing effect, with CFC and N_2O also having significant contributions. In 2005, atmospheric concentration of CO_2, CH_4, and N_2O were 379 ppm, 1,774 ppm, and 319 ppb, respectively, which are the highest of any time in the past 20,000 years (IPCC 2007a). Since 1995, atmospheric concentration of CO_2 and N_2O has increased steadily, whereas CH_4 and CFC have decreased.

Fossil fuel use and cement production have likely contributed about three-fourths of the total CO_2 increase, and land-use changes have contributed the remaining one-fourth (IPCC 2007a). Land-use changes, primarily deforestation in the tropics to make room for agriculture, contribute to climate change both from increased CO_2 production as a result of biomass burning and decomposition of soil organic matter and greater reflectance (albedo) of the surface that results in positive radiative forcing.

Agriculture is a significant source of GHG that contributed about 10–12 % of total emissions in 2005, but about 52 % of CH_4 and 82 % of N_2O (Eaglesham and Hardy 2009; IPCC 2007a). Agricultural sources of CH_4 and N_2O mainly include wetlands, rice agriculture, ruminant animals, biomass burning, and nitrogen-based fertilizers (Desjardins 2009; Eaglesham and Hardy 2009; IPCC 2007a). Although agriculture has contributed significantly to CO_2 emissions in the past as a result of deforestation and intensive grassland cultivation, CO_2 fixed by plants now nearly balances the net output from other agricultural sources (Desjardins 2009; Ortiz-Monasterio et al. 2012).

Future Climate Change

There is considerable uncertainty about the rate and magnitude of future climate change. Predicting future change depends on how human society reacts to the causes of climate change, and specifically the issue of GHG emissions. Given that there is no globally agreed upon solution to the problem, it is impossible to predict how the future will unfold relative to climate change. Consequently, the IPCC produced the Special Report on Emissions Scenarios (SRES) that provides four "storylines" with possible outcomes based on the degree to which society adopts environmental versus economic and global versus regional solutions to the problem of GHG emissions (IPCC 2000). Population growth, economy, technology, energy, land-use, and agriculture were the driving forces behind these scenarios. The scenarios were developed as a tool to envision what might happen given certain assumptions and enable an analysis of potential actions to adapt to and mitigate climate change.

SRES Emission Scenarios The four SRES scenarios, labeled A1, A2, B1, and B2, each has a subset of scenarios constituting a "family" that projects potential global temperature increase, sea-level rise, GHG emissions, and other climate parameters out to 2,100. Six "marker scenarios" (A1F1, A1B, A1T, A2, B1, and B2) were selected to represent a wide range of possible responses for use by climate modelers to represent a range of outcomes (Arnell et al. 2004). For example, the A1 storyline family assumes a future with very rapid economic growth; within this family, A1F1 assumes fossil fuel-intensive energy, A1T nonfossil fuel energy, and A1B a balance across energy sources (IPCC 2000). The best estimates of global tempera-

Table 1 Projected global average surface warming at the end of the twenty-first century. (Adapted from IPCC 2007a)

Scenario	Temperature Change (°C)	
	2090–2099 relative to 1980–1999	
	Best estimate	Likely range
Constant year 2000 GHG concentrations	0.6	0.3–0.9
B1	1.8	1.1–2.9
A1T	2.4	1.4–3.8
B2	2.4	1.4–3.8
A1B	2.8	1.7–4.4
A2	3.4	2.0–5.4
A1F1	4.0	2.4–6.4

GHG greenhouse gas

ture increases by 2090–2099 under these models range from 1.8 °C for B1 to 4.0 °C for A1F1 by the end of the twenty-first century compared with 0.6 °C if year 2000 GHG concentrations are held constant (Table 1). All of the models indicate that climate change will continue at the same rate for the next 15–20 years even with immediate efforts to mitigate GHG production (IPCC 2007a).

Agricultural Sustainability

The concept of sustainable agriculture has evolved over the past 30 years and consequently, means different things to different people. In the United States, sustainable agriculture was defined in the 1990 farm bill as “an integrated system of plant and animal production practices having a site-specific application that will, over the long term: satisfy human food and fiber needs; enhance environmental quality and the natural resource based upon which the agricultural economy depends; make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole.” This definition integrates concepts of ecology and environmental health, economic profitability, and social and economic equity to provide stable food production systems. This discussion will focus on the sustainability of satisfying human food and fiber needs in the context of northern hemisphere climate change.

Most climate change predictions are based on global circulation models and consequently, need to be downscaled to predict local or regional change to estimate the impact on agricultural production (Arnell et al. 2004; Jarvis et al. 2012; Parry et al. 2004). Climate change will affect agriculture globally, but not uniformly; the impact of climate change will vary geographically within regions and across latitudes depending on the magnitude of change and predominate crops grown in those regions. The impact of climate change will also vary economically with countries having the greatest Gross Domestic Product devoted to agriculture at the greatest risk for negative impacts (Jarvis et al. 2012). In general, the fertilization effect of increased atmospheric CO_2 concentration, reduced snow cover, longer growing seasons, and increased rainfall in the northern latitudes likely will have positive impacts on crop production in the short term, whereas increased temperature and reduced rainfall in low latitudes will negatively impact crop production. The IPCC FAR (2007a) concluded that global food production would continue to increase with temperature increases up to 3 °C, but decrease thereafter with increasing temperature.

Climate Change and Agriculture The impact of climate change on agricultural production will be mediated through the direct effects of temperature, CO_2 concentration, and other changes in the environment that influence plant growth (e.g., length of growing season), as well as through indirect effects on pests and diseases. In regions where crops are growing at or near their temperature optima, increasing average temperature likely will result in reduced yields and/or transition to other crops; however, for crops growing below their temperature optima, yields may increase (Lobell and Burke 2012). For example, wheat yields in the northern hemisphere likely will increase with increasing average temperature up to 2 °C (Fig. 8) and production will expand into previously unsuitable areas becoming suitable for crop production (IPCC 2007b). However, wheat yields in low latitudes will decrease with any increase in temperature. Similarly, yield of maize will decrease at both mid latitudes to high latitudes and low latitudes (Fig. 8).

Estimates of climate change impacts on agriculture include the fertilization effect of increased CO_2 concentration on crop productivity; however, most of the research on CO_2 and enhanced crop productivity is based on studies conducted under controlled environmental conditions where water and nutrients are not limiting (Jarvis et al. 2012). More studies in open-air chambers that better simulate field conditions are needed to determine whether and to what extent CO_2 may enhance plant productivity, especially under conditions where water and nutrients are not limiting (Long 2012). In addition, studies on the effect of other GHG and specifically elevated ozone concentration on crop productivity have not been considered in these controlled environment studies and may negatively impact crop yield (Long 2012). Another limitation in some estimates of climate change on agricultural productivity is the impact of pests and diseases. Parry et al. (2004) concluded that world agriculture would likely be able to continue feeding the planet for the rest of the twenty-first century. However, their projections assume that all pests and diseases are controlled and that soil conditions resulting from climate change will not be limiting. Lastly, the role and impact of severe weather events on agricultural productivity is unknown and impossible to predict. Given that the frequency and severity of heat waves, drought events, and heavy precipitation are expected to increase, it seems likely that there will be some negative impact on crop productivity.

Climate Change and Plant Diseases The plant disease triangle tells us that a susceptible plant and pathogen must be present in a favorable environment for a