Plant Growth and Climate Change

Edited by

JAMES I.L. MORISON
Department of Biological Sciences
University of Essex
Colchester, UK

and

MICHAEL D. MORECROFT
Centre for Ecology & Hydrology
Maclean Building
Wallingford, UK

Blackwell
Publishing

Plant Growth and Climate Change

Biological Sciences Series

A series which provides an accessible source of information at research and professional level in chosen sectors of the biological sciences.

Series Editor:

Professor Jeremy A. Roberts, Plant Sciences Division, School of Biosciences, University of Nottingham. UK.

Titles in the series:

Biology of Farmed Fish Edited by K.D. Black and A.D. Pickering

Stress Physiology in Animals Edited by P.H.M. Balm

Seed Technology and its Biological Basis Edited by M. Black and J.D. Bewley

Leaf Development and Canopy Growth Edited by B. Marshall and J.A. Roberts

Environmental Impacts of Aquaculture Edited by K.D. Black

Herbicides and their Mechanisms of Action Edited by A.H. Cobb and R.C. Kirkwood

The Plant Cell Cycle and its Interfaces Edited by D. Francis

Meristematic Tissues in Plant Growth and Development Edited by M.T. McManus and B.E. Veit

Fruit Quality and its Biological Basis Edited by M. Knee

Pectins and their Manipulation Edited by Graham B. Seymour and J. Paul Knox

Wood Quality and its Biological Basis Edited by J.R. Barnett and G. Jeronimidis

Plant Molecular Breeding Edited by H.J. Newbury

Biogeochemistry of Marine Systems Edited by K.D. Black and G. Shimmield

Programmed Cell Death in Plants Edited by J. Gray

Water Use Efficiency in Plant Biology Edited by M.A. Bacon

Plant Lipids – Biology, Utilisation and Manipulation Edited by D.J. Murphy

Plant Nutritional Genomics Edited by M.R. Broadley and P.J. White

Plant Abiotic Stress Edited by M.A. Jenks and P.M. Hasegawa

Gene Flow from GM Plants Edited by G.M. Poppy and M.J. Wilkinson

Antioxidants and Reactive Oxygen Species in Plants Edited by N. Smirnoff

Plant Growth and Climate Change Edited by J.I.L. Morison and M.D. Morecroft

Plant Growth and Climate Change

Edited by

JAMES I.L. MORISON
Department of Biological Sciences
University of Essex
Colchester, UK

and

MICHAEL D. MORECROFT
Centre for Ecology & Hydrology
Maclean Building
Wallingford, UK

Blackwell
Publishing

Editorial Offices:
Blackwell Publishing Ltd, 9600 Garsington Road, Oxford OX4 2DQ, UK
Tel: +44 (0)1865 776868
Blackwell Publishing Professional, 2121 State Avenue, Ames, Iowa 50014-8300, USA
Tel: +1 515 292 0140
Blackwell Publishing Asia Pty Ltd, 550 Swanston Street, Carlton, Victoria 3053, Australia
Tel: +61 (0)3 8359 1011

First published 2006 by Blackwell Publishing Ltd

ISBN-13: 978-14051-3192-6
ISBN-10: 1-4051-3192-6

Library of Congress Cataloging-in-Publication Data

Plant growth and climate change / edited by James I.L. Morison and Michael D. Morecroft.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4051-3192-6 (hardback : alk. paper)
ISBN-10: 1-4051-3192-6 (hardback : alk. paper) 1. Climate changes. 2. Crops and climate. 3. Growth (Plants) I. Morison, James I.L. II. Morecroft, Michael D.
S600.7.C54P52 2006
632′.1—dc22
2006009717

A catalogue record for this title is available from the British Library

Set in 10/12 pt Times
by TechBooks
Printed and bound in India
by Replika Press Pvt, Ltd, Kundli

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp processed using acid-free and elementary chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

For further information on Blackwell Publishing, visit our website:
www.blackwellpublishing.com

Contents

The colour plate section appears after page 50

List of Contributors

Dr James A. Bunce	Crops Systems and Global Change Laboratory, ARS, USDA, 10300 Baltimore Avenue, Bldg 046A BARC-West, Beltsville, MD 20705-2350, USA
Dr Maria-Conceição Caldeira	Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Tapada da Ajuda, 1399 Lisboa Codex, Portugal
Dr Maria-Manuela Chaves	Departamento de Botenica e Engenharia Biologica, Instituto Superior de Agronomia, Tapada da Ajuda, 1399 Lisboa Codex, Portugal
Dr Alexandre V. Correia	Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Tapada da Ajuda, 1399 Lisboa Codex, Portugal
Professor William J. Davies	Department of Biological Sciences, I.E.N.S., Lancaster University, Lancaster LA1 4YQ, UK
Professor John Grace	School of Geosciences, University of Edinburgh, Crew Building, Mayfield Road, Edinburgh EH9 3JN, UK
Professor Christian Körner	Institute of Botany, University of Basel, Schönbeinstrasse 6, CH-4056 Basel, Switzerland
Dr Ross McMurtrie	School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney 2052, New South Wales, Australia
Dr Belinda Medlyn	School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney 2052, New South Wales, Australia
Professor Annette Menzel	Lehrstuhl für Ökoklimatologie, Technical University of Munich, Am Hochanger 13, D-85354 Freising, Germany
Dr Michael D. Morecroft	Centre for Ecology & Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, OX10 8BB, UK

Dr James I.L. Morison	Department of Biological Sciences, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK
Mr James S. Paterson	Environmental Change Institute, Oxford University Centre for the Environment, Dyson Perrins Building, South Parks Road, Oxford, OX1 3QY, UK
Dr David Pepper	School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney 2052, New South Wales, Australia
Professor Joao Pereira	Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Tapada da Ajuda, 1399 Lisboa Codex, Portugal
Dr Tim Sparks	Centre for Ecology and Hydrology, Monks Wood, Abbots Ripton, Huntingdon, Cambridgeshire PE28 2LS, UK
Dr David Viner	Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK
Dr Craig Wallace	Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ, UK
Dr Ying-Ping Wang	CSIRO Marine and Atmospheric Research, PMB #1, Aspendale, Victoria 3195, Australia
Dr Rui Zhang	School of Geosciences, University of Edinburgh, Crew Building, Mayfield Road, Edinburgh EH9 3JN, UK
Dr Lewis H. Ziska	Crops Systems and Global Change Laboratory, ARS, USDA, 10300 Baltimore Avenue, Bldg 046A BARC-West, Beltsville, MD 20705-2350, USA

Preface

Evidence grows daily of the rapid changes in climate due to human activities and their impact on plants and animals. Plant function is inextricably linked to climate and atmospheric carbon dioxide concentration. On the shortest and smallest scales the climate affects the plant's immediate environment and thus directly influences physiological processes. On longer and larger time and space scales climate influences species distribution and community composition and determines what crops can be viably produced in managed agricultural, horticultural and forestry ecosystems. Plant growth also influences the local, regional and global climate through the exchanges of energy and gases between the plants and the air around them. This book examines the major aspects of how anthropogenic climate change is affecting plants, covering the wide range of scales molecular and cellular through organ and plant, up to biome and global.

Anthropogenic climate change poses major scientific challenges for plant scientists. Firstly, we need to expand and apply our understanding of plant responses to the environment so that we can predict the impacts of climate change on plant growth for crops and natural ecosystems. This understanding in turn needs to be built into assessments of the global climate system, in order to correctly quantify the numerous feedbacks between plants, the atmosphere and the climate. Understanding plant growth responses to climate change is also important to allow society to respond. Plant production has to be maximised, to overcome the new or altered climatic constraints on food and fibre production, in the face of the continuing population growth. The sustainability of agricultural and forestry production needs to be improved by reducing greenhouse gas emissions from land use and fossil fuel use and by reducing water and nutrient consumption. Conservation policies and the management of natural and seminatural areas have to be adjusted to conserve biodiversity in the changing environmental conditions. The contributions in this volume exemplify work that addresses many of these challenges.

In planning this book, we felt that the literature has often been rather divided between books on the effects of climate change on plants in agricultural and other managed systems and those examining effects on natural ecosystems. In addition, more fundamental aspects of plant physiology were often missing. It is clear that climate impacts research is informed by all aspects of plant physiology and ecology and we sought to organise a book that looked across the range of plant growth (although restricting the scope to terrestrial and vascular plants). We also wanted to show the range of scientific questions that exercise the wide variety of plant scientists involved in climate change research.

This book therefore tackles the main aspects of climate change and focuses on several key determinants of plant growth: atmospheric CO_2, temperature, water availability and their interaction. Although atmospheric CO_2 might not strictly be considered an aspect of climate, we felt it was essential that it was included as it is the main driver of climate change. The book demonstrates the plethora of techniques used across plant science: detailed physiology in controlled environments; observational studies based on long-term data sets; field manipulation experiments and modelling. Chapter 1 provides an overview of the processes in climate change, summarising the evidence for recent changes to temperature, precipitation and solar radiation and outlining the likely scenarios for change produced in the IPCC reports. In Chapter 2, Ziska and Bunce review what is known about plant responses to the increased atmospheric CO_2, looking across the spectrum of scales from gene expression to whole ecosystems. They draw attention to difficulties in understanding at the two extremes of this spectrum and emphasise the point that CO_2 change is not a single factor, but must be considered with other environmental variables.

The themes of timescales and the need for combining field and controlled environment work in order to understand the effects of temperature on plant growth is taken up by Körner in Chapter 3. He explores the paradoxes in plant short-term response and medium term acclimation to temperature and the very different issues of continuous effects of temperature compared to threshold responses. He shows us the difficulties in bridging from the single species physiological scale to ecosystems and the interactions with other variables such as soil nutrient and water supply and day length. In Chapter 4 Menzel and Sparks demonstrate the sensitivity of plant development to temperature and show many examples ranging from grapes and cereals to trees of how recent temperature changes have altered phenological development. Their examples emphasise the importance of long records, both from traditional observations and from newer technologies such as satellite NDVI remote sensing and they discuss some of the methodological problems in assessing phenological environmental relationships.

Warmer conditions and changed precipitation patterns will alter water availability for plants. In Chapter 5 Davies reviews cell and plant water relations and the signalling processes that coordinate the response of plants to water availability. He points out that exploitation of understanding of these physiological processes is already leading to improvements in crop production. This review is complemented by the larger scale examination of the relationship of plant productivity to water availability in Chapter 6 by Pereira and colleagues. They demonstrate the importance of considering the longer timescales for drought resistance and resilience in the response of perennial vegetation to drought. They discuss the interrelationship between productivity, drought and fires, especially in the Mediterranean environment. Temperature and water interactions are considered at the community scale in Chapter 7. Morecroft and Paterson assess the field experiments that have highlighted the sensitivity of plant community composition to climate changes, particularly temperature and precipitation. These changes often hinge on the interaction with soil and nutrients, although our information is dominated by studies in temperate and arctic or alpine environments.

The final two chapters illustrate the essential use of models to synthesise our understanding from the physiological and ecological experimental work, to test hypotheses and to make predictions on large spatial and temporal scales. Wang and colleagues (Chapter 8) demonstrate that increased CO_2 concentration cannot be considered alone in modelling plant productivity, because of the interaction with nutrients, especially nitrogen. Thus plant models have to be intimately linked to soil decomposition and mineral cycling models on longer timescales, which are also dependent on temperature and water availability. Chapter 9 examines the measurement and modelling of global plant productivity and the carbon cycle (Grace & Zhang). They demonstrate how the modelling of production depends on temperature responses of respiration and photosynthesis and thus highlight the importance of a full assessment of physiological responses of plants, on the correct timescales, to field conditions, as identified in the earlier chapters.

Much plant physiology has been founded on an experimental paradigm of investigating responses to one factor at a time, over short time periods, whereas much ecological work has been based in experimental manipulations in the field, over longer periods. Climate change impacts research has brought these two disciplines very closely together and the contributors to this volume admirably demonstrate the resulting synergies. We thank them for all their time and efforts in responding to our challenge.

James Morison and Mike Morecroft

1 Recent and future climate change and their implications for plant growth

David Viner, James I.L. Morison and Craig Wallace

1.1 Introduction

The geographic distribution of plant species, vegetation types and agricultural cropping patterns demonstrate the very strong control that climate has on plant growth. Solar radiation, temperature and precipitation values and seasonal patterns are key determinants of plant growth through a variety of direct and indirect mechanisms. Other climatic characteristics are also major influences, such as wind speed and storm frequency. There is a rapidly growing number of well-documented instances of change in ecosystems due to recent (and probably anthropogenic) climate change (Walther *et al.*, 2002). For example, there are several lines of evidence in the Arctic, ranging from indigenous people's knowledge to satellite images, that show that species distributions have changed, with growing shrub cover and increasing primary productivity (Callaghan *et al.*, 2004). Another example is that plant species composition in the mountains of central Norway has changed over a 70-year period, with lowland species coming in and snow-bed and high-altitude species disappearing (Klanderud & Birks, 2003). Meta-analyses of data for well-studied alpine herbs, birds and butterflies by Parmesan and Yohe (2003) found a mean range shift of approximately 6 km per decade towards the poles or 6 m per decade in elevation, and that the date of the start of spring has advanced by 2 days per decade. In agriculture, there are clear examples of recent climate change affecting plant growth and cropping potential or performance. For example, in Alberta (Canada) the potential maize-growing zone, defined by temperature limits, has shifted north by 200–300 km over the last century (Shen *et al.*, 2005). However, climate change is not just affecting temperate zones. For example, in some arid zones there have been increases in precipitation, leading to increased shrub density, and changes in the rest of the ecosystem (e.g. Brown *et al.*, 1997). Overall, the Intergovernmental Panel on Climate Change (IPCC, 2001b) concluded that 'from collective evidence, there is high confidence that recent regional changes in temperature have had discernible impacts on many physical and biological systems'. These recent climate changes are likely to accelerate as human activities continue to perturb the climate system, and many reviews have made predictions of serious consequences for ecosystems (e.g. Izaurralde *et al.*, 2005) and for food supplies and food security (e.g. Reilly *et al.*, 2003; Easterling & Apps, 2005). This chapter outlines recent past and future anthropogenic climate change. Much of the relevant research has already been drawn together, reviewed and summarised by the many contributors to the IPCC reports (IPCC, 2001a–c), and we have therefore relied heavily on that authoritative source of information.

1.2 The climate system

The recent and future anthropogenic changes to the climate have to be considered in the context of natural climate changes. The Earth's climate results from the complex interaction of many components: the ocean, atmosphere, geosphere, cryosphere and biosphere. Although the climate system is ultimately driven by the external solar energy, changes to any of the internal components, and how they interact with each other, as well as variability in the solar radiation received can lead to changes in climatic conditions. These influences are often considered as 'forcings', changes to the energy inputs and outputs that result in modifications in the climate. Therefore there are many causes of climate change that operate on a variety of timescales. On the longest timescales are mechanisms such as geological processes and the changes in the Earth's orbit around the sun (Milankovitch-Croll effect). The latter is believed to be the mechanism underlying the cycle of ice ages and interglacials. Geological processes resulting from the movement of tectonic plates and consequent major changes in physical relief, continental distributions and ocean basin shape and connectivity clearly have influenced global climate patterns. Geological processes can also work on a much shorter timescale through volcanism. Large, explosive volcanic eruptions can inject millions of tons of soot and ash into the middle atmosphere where they reflect solar radiation, creating a 'global soot veil'. The Tambora eruption in Southeast Asia in 1815 caused extensive global cooling and 'the year without a summer' in Europe (e.g. Engvild, 2003; Oppenheimer, 2003). The climate impacts of such volcanic events usually decay after 1 or 2 years (as in the Mt. Pinatubo eruption of June 1991, which caused 0.25–5°C drop in mean temperature for 1–2 years in several parts of the world; Hansen *et al.*, 1996). However, some research has suggested that very infrequent, regional so-called supereruptions can alter the climate for enough time to cause radical species loss (Rampino, 2002), although this is much debated.

In addition to geological and orbital changes, the climate system is sensitive to inherent and periodic internal variability in any one of its components, such as ocean currents. These can be on decadal timescales, such as the Interdecadal Pacific Oscillation. Or the variations can be on near-interannual timescales, such as the well-documented El-Niño/Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). During ENSO events when the ocean upwelling in the eastern equatorial Pacific is weaker than normal, the resulting changes to sea surface temperatures and to the wind patterns dramatically affect climate and consequently impact the biosphere across the region. For example, in El Niño years, maize yields in China are decreased by 5% (Tao *et al.*, 2004) and in Australia wheat crop yields are closely related to the severity of rainfall reductions (e.g. Nicholls, 1985). The NAO has wide ecological effects (e.g. reviewed by Ottersen *et al.*, 2001), such as determining the length of the growing season in Europe, as evident in extensive phenological observations (see Chapter 4, Menzel, 2003). Also correlations of the NAO index have been found with crop yields in Europe and North America (e.g. Gimeno *et al.*, 2002). The overall effects of such internal changes on climate are difficult to predict, because of the feedbacks between the climate system components. For example, an ocean current change might warm a high-latitude region, leading to reduced snow cover, which in turn leads to more land surface exposure and more solar energy absorption which results in a positive feedback.

1.3 Mechanisms of anthropogenic climate change

Although most public discussion on climate change currently focuses on fossil fuel combustion, CO_2 emissions and the enhanced 'greenhouse effect', it must be noted that there are other components of human-induced climate change. Human activity has modified, and continues to modify, the Earth's surface on a very large scale, through deforestation, afforestation, cultivation, mineral extraction, irrigation, drainage and flooding. These large alterations in land cover change the surface shortwave reflectivity and hydrological and thermal properties of the land surface. Thus, replacing forest with pasture changes the surface energy balance and increases the proportion of radiant energy going into heating the air and reducing evaporation, as many studies have shown (e.g. von Randow *et al.*, 2004). Conversely, the very large expansion of irrigation in previously dry areas changes land cover and solar radiation absorption and increases energy partitioning into evaporation, as well as changing the seasonal pattern of surface–atmosphere exchanges (e.g. Adegoke *et al.*, 2003).

The crux of the enhanced greenhouse effect is that human modification of the atmospheric concentration of the key radiation-absorbing gases – CO_2, CH_4, N_2O and various halocarbons – has resulted in a radiative forcing of the climate system. These gases have been released primarily as a result of industrial, transport and domestic activities and to a lesser extent from agricultural activities and land use changes (IPCC, 2001a). Direct and indirect determination of CO_2, CH_4 and N_2O in the atmosphere over the past 1000 years show marked and unprecedented increases in concentrations in recent times (Figure 1.1). The start of these increases coincides with the rapid industrialisation of the Northern Hemisphere during the late eighteenth and nineteenth centuries, and so since 1750, the global mean atmospheric concentration of CO_2 has increased by 31%; approximately 75% of this increase has come from fossil fuel combustion and 25% from land use change (IPCC, 2001a). Analysis of extended data sets from ice cores indicates that the current atmospheric concentration of CO_2 is the highest for the past 420 000 years, and is likely to be the highest within the last 20 million years (IPCC, 2001a). The percentage increase in methane concentrations is greater, having risen by 151% since 1750, whilst the concentration of nitrous oxide has increased by 17% over the same period (IPCC, 2001a). The estimated radiative forcing associated with the increased concentrations

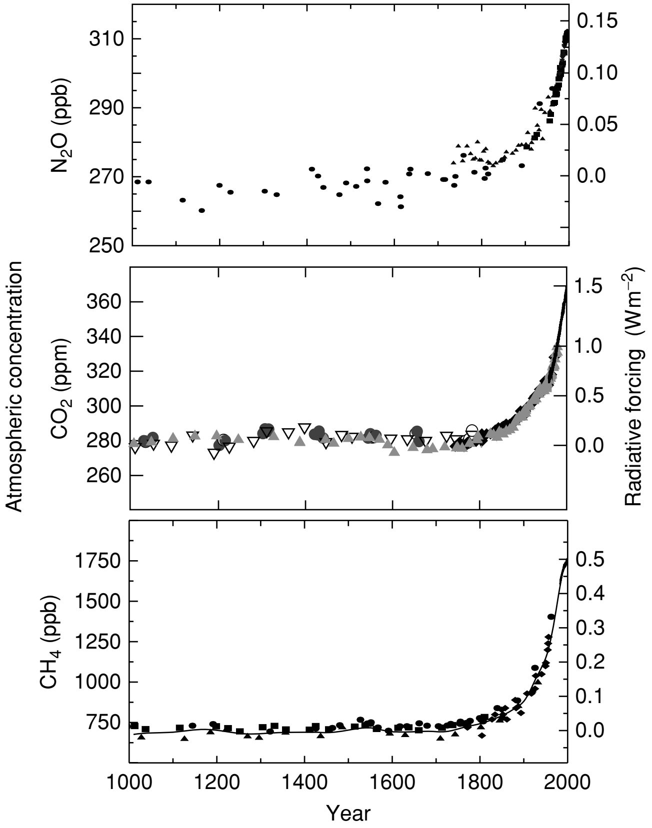

Figure 1.1 Changes in the atmospheric concentrations of CO_2, CH_4 and N_2O over the last 100 years. Data from Antarctic and Greenland ice cores and recent direct air samples. The estimated positive radiative forcing of the climate system is indicated on the right-hand scale. (From IPCC, 2001a.)

of the three main greenhouse gases is shown on the right-hand axis of Figure 1.1. In total, increased atmospheric concentrations of CO_2, CH_4, N_2O and halocarbons are estimated to have placed an additional 2.4 W m^{-2} of radiative forcing onto the climate system since 1750 (IPCC, 2001a). At the same time there have been other changes in radiative forcing, particularly from changes in carbon and sulphate aerosols, also produced by fossil fuel combustion and biomass burning. While there is still some uncertainty over their direct and indirect effects through cloud modification, it is widely agreed that sulphate aerosol pollution has had a net negative forcing, resulting in a cooling effect, particularly in source regions (IPCC, 2001a). Therefore, as aerosol pollution is now declining in some areas, e.g. Europe and North America, the effect of the positive forcing due to the increased greenhouse gases may become more marked in those regions (IPCC, 2001a). Clearly, future net forcing will be affected by the amount of sulphate emissions and what intensity and technology of fossil fuel combustion is adopted.

The change in temperature resulting from the various forcings is termed the climate sensitivity and clearly depends upon many components of the climate system, not all of which are well understood. 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 anthropogenic radiative forcing. It is this, and the geographical pattern of the observed warming, that led the IPCC to conclude in 2001 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' (IPCC, 2001a). The continuing huge international scientific efforts since that Third Assessment Report (TAR) have largely confirmed this work, and the forthcoming Fourth Assessment Report of the IPCC due in 2007 is likely to agree and strengthen this conclusion while providing further advances in our understanding of human influences on the climate system.

1.4 Recent climate changes

Clearly, the changes in the Earth's climate in the past have been well documented by palaeoclimatologists. Analysis of oceanic and lake sediment cores has established that during the course of the past 800 000 years Earth has experienced a number of warm interglacial and cold glacial periods, each of which lasted several (and maybe tens of) thousands of years. We are currently experiencing a warm interglacial period which began approximately 10 000–12 000 years ago and which marks the start of the current epoch, the Holocene (e.g. Lamb, 1977). The changes in temperature that accompanied the switch from the last glacial to the present interglacial period were not smooth and varied greatly over the planet. For example, work focusing on the British Isles has estimated that between 13 300 and 12 500 years before the present time, the mean temperature rose by 8°C in summer and approximately 20°C in winter (Atkinson *et al.*, 1987).

Historical records suggest some substantial changes over the past one or two millennia, with century-length colder and warmer periods (e.g. Lamb, 1977). Climate reconstructions based upon proxy records (particularly tree-ring widths) permit a quantitative examination of the last 1000 years (Colour Plate 1). The last millennium is generally accepted to have experienced three main climatic epochs. The 'Medieval Warm Period' (MWP) characterised the climate of the twelfth and thirteenth centuries, and was followed in the sixteenth and seventeenth centuries by the 'Little Ice Age'. The third, recent climatic event has been 'Post-industrial Warming'.

The dates of the first two events are debated because much of the evidence varies 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. For example, Jones (2002) has questioned the validity of

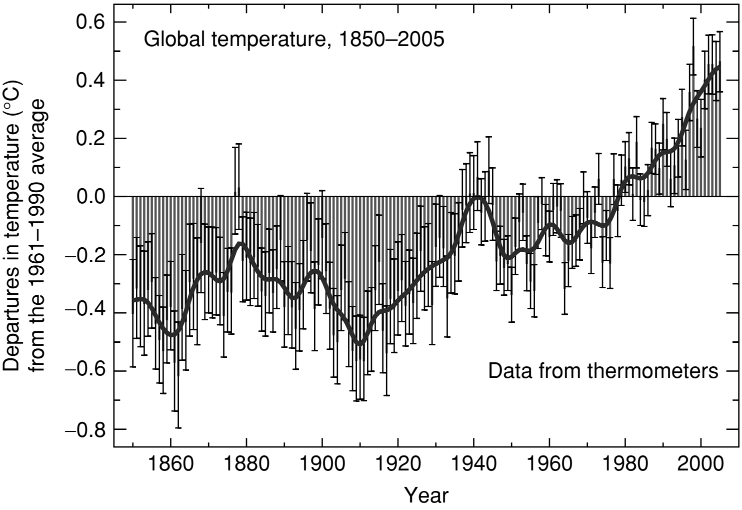

Figure 1.2 The global surface temperature record from 1850 to 2005, expressed as departures from the 1961–1990 mean. The solid line is a filtered curve to show interdecadal variations. (Source: The HadCRUT3 data set, the UK Meteorological Office; Brohan *et al.*, in press.)

the MWP, pointing to a lack of a distinct rise in the proxy temperature record for the Northern Hemisphere average at this time. What is evident from many of the curves in Colour Plate 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 many reconstructed climate records indicate that the coldest annual temperature for the Northern Hemisphere in the last 1000 years occurred in 1601 (Jones, 2002). Nonetheless, the validity of the Little Ice Age label 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 (Jones, 2002) and glacial advances occurred at different times during the supposed 'cold' centuries (Matthews & Briffa, 2005).

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 Colour Plate 1 and a more detailed curve in Figure 1.2) and is key evidence of human-induced climate change. Two warming events are apparent and these constitute the *only* statistically significant events of the instrumental record (Jones, 2002). The first warming period occurred between 1920 and 1945; the second since 1975. It is clear that globally the 1990s have been the warmest decade of the last 1000 years, and that 1998 was the warmest individual year. The global curve in Figure 1.2 shows that compared to temperatures representative of the late nineteenth century, 1998 was approximately 0.8°C warmer.

However, to understand effects of temperature on plant growth, we need more information than just data on changes to the mean global annual temperature highlighted by Colour Plate 1 and Figure 1.2. The instrumental record also shows (a) that the Post-industrial Warming has affected the mid to high latitudes of the Northern Hemisphere the most, (b) that winter months have warmed more rapidly than summer months and (c) that night-time temperatures are more affected than the day time temperatures (IPCC, 2001a). In addition, there has been a reduction in the frequency of extreme low monthly and seasonal average temperatures across much of the globe and a small increase in the frequency of extreme high temperatures (IPCC, 2001a). Other temperature changes that are probably of major importance to plant growth are 10–15% reductions in the number of days with air frosts (minimum air temperature $< 0^\circ$C) found across the Northern Hemisphere (e.g. Frich *et al.*, 2002), and reductions in the spring snow cover extent since the 1960s (IPCC, 2001a).

Although the dramatic recent changes in the mean global temperature are easy to depict (e.g. Colour Plate 1 and Figure 1.2), it is harder to generalise the overall changes in precipitation, as there is substantial temporal and spatial variation (IPCC, 2001a). In the mid to high latitudes of the Northern Hemisphere, precipitation increased by approximately 10% (30–85°N) over the twentieth century, and these increases correlate with various reports of increased stream flow and increased soil moisture in some areas within these latitudes (IPCC, 2001a). There is also compelling evidence that intense winter precipitation events in some mid-latitude areas are becoming more common already (Osborn and Hulme, 2002), which has serious consequences for erosion and flooding. In the tropics and subtropics, patterns of precipitation change have been much more regional and variable over decadal timescales (IPCC, 2001a). For example, in West Africa the rainfall during the last 30 years of the century was on average 15–40% lower than during the previous 30 years (Nicholson, 2001).

In addition to these changes in temperature and precipitation, there have been substantial changes in solar irradiance. The pioneering work of Stanhill drew attention to these changes when he carefully analysed the rather few high-quality solar measurement records and found a gradual decline in solar irradiance of approximately 3% per decade over the period 1950–2000 (0.5 W m^{-2} $year^{-1}$; Stanhill & Cohen, 2001). Support for this also comes from several regional analyses of evaporation pan records in both the Northern and Southern hemispheres, which show annual reductions of 2–4 mm $year^{-1}$ (e.g. Roderick & Farquhar, 2002; Liu & Zeng, 2004). These solar radiation changes are probably because of increases in anthropogenic aerosols affecting atmospheric and cloud optical properties, and they could have substantial direct effects on plant growth (Stanhill & Cohen, 2001). However, recent work has questioned the persistence and magnitude of the ‘global dimming’ effect. One suggestion is that it may be due to the bias of measurement sites for densely populated locations (declines of 0.41 W m^{-2} $year^{-1}$), while sites in sparsely populated areas showed only 0.16 W m^{-2} $year^{-1}$ (Alpert *et al.*, 2005). More evidence comes from an analysis of global satellite data, which showed that there was a decrease from 1983 to 1990 followed by an increase up to 2001, amounting to an overall increase of 0.16 W m^{-2} $year^{-1}$ (Pinker *et al.*, 2005). Newly analysed surface observations also suggest an increase since the late 1980s (Wild *et al.*, 2005). Therefore, it is clear that solar radiation receipt at the surface has varied substantially over decadal timescales, and will change in the future with changes in cloud and aerosol load. The effect of this on plant growth is rarely directly considered.

1.5 Future changes in anthropogenic forcing of climate

Projections of future climate change can be developed by computer simulation of the Earth's climate system, given different scenarios of future changes to both natural and anthropogenic radiative forcing. In the Special Report on Emissions Scenarios (SRES; Nakicenovic & Swart, 2000), the IPCC devised six possible future scenarios of greenhouse gas emissions through to the year 2100 based upon changes that may occur in global population growth, degree of globalisation, technological change and use of sustainable energy sources. The six SRES scenarios ranged from those likely to produce high anthropogenic climate forcing because of heavy use of fossil fuels (e.g. scenario A1FI) to those with low forcing because of reduced consumption and introduction of resource-efficient technologies (e.g. B1; IPCC, 2001a).

1.5.1 Future global climate scenarios

The aforementioned SRES scenarios have been used in global circulation models (GCMs) to make projections of future climate change during the present century. GCMs are mathematical approximations of the real physical climate system and model the atmospheric circulation and the exchange of energy between the main climate system components. All GCMs used by the IPCC to develop climate change scenarios for the TAR had interactive atmospheric and oceanic components (atmosphere–ocean general circulation models, AOGCMs), including representation of seasonal sea ice, and most of the GCMs also had an interactive land surface scheme which simulated the moisture and energy fluxes between the ground and the atmosphere. However, the uncertainties associated with GCM results should be acknowledged. In particular, some real-world climate system components are poorly understood, and so their approximation by mathematical equations is difficult. A good example, and a major continuing debate in climate change, is the effect of changing cloud characteristics (altitude, water content, droplet or crystal size) as well as the scale at which they are considered in the models (IPCC, 2001a). Uncertainties in climate projections also arise because of the constraints of the current level of computing power, which can limit how realistically some physical processes can be incorporated at the large geographic scale required for model practicability. While specific regional climate models have been developed that simulate processes on a finer geographical scale, they are very costly to run and have more uncertainty in long-term predictions.

Because of the rapid and comparatively recent rise in atmospheric concentrations of greenhouse gases (some of which have very long lifetimes), the climate system is not in equilibrium, and thus temperature increases must be anticipated, even if