Global Change – The IGBP Series

Springer

Berlin
Heidelberg
New York
Hong Kong
London
Milan
Paris
Tokyo

W. Steffen · A. Sanderson · P. D. Tyson · J. Jäger · P. A. Matson · B. Moore III
F. Oldfield · K. Richardson · H. J. Schellnhuber · B. L. Turner II · R. J. Wasson

Global Change and the Earth System

A Planet Under Pressure

With 258 Figures

Springer

Authors

Steffen, Will

IGBP Secretariat,
Royal Swedish Academy of Sciences, Stockholm

Sanderson, Angelina

IGBP Secretariat,
Royal Swedish Academy of Sciences, Stockholm

Tyson, Peter

Climatology Research Group,
University of the Witwatersrand, Johannesburg, South Africa

Jäger, Jill

Coordinator,
Initiative on Science and Technology for Sustainability

Matson, Pamela

School of Earth Sciences
Stanford University, CA, USA

Moore III, Berrien

Institute for the Study of Earth, Oceans and Space (EOS),
University of New Hampshire, Durham, NH, USA

Oldfield, Frank

Department of Geography,
University of Liverpool, UK

Richardson, Katherine

Department of Marine Ecology,
Århus University, Denmark

Schellnhuber, H. John

Tyndall Centre for Climate Change Research,
University of East Anglia, Norwich, UK,
and
Potsdam Institute for Climate Impact Research, Germany

Turner, B. L. II

Graduate School of Geography
& George Perkins Marsh Institute,
Clark University, MA, USA

Wasson, Robert J.

Centre for Resource and Environmental Studies
The Australian National University, Canberra

Library of Congress Control Number: 2005927608

ISBN-10 3-540-26594-5 **Springer Berlin Heidelberg New York**
ISBN-13 978-3-540-26594-8 **Springer Berlin Heidelberg New York**

First ed. 2004, 2nd printing 2005
3-540-40800-2 1st printing 2004

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitations, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media
springeronline.com
© Springer-Verlag Berlin Heidelberg 2005
Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Erich Kirchner, Heidelberg
Typesetting: Büro Stasch · Bayreuth (stasch@stasch.com)
Production: Luisa Tonarelli
Printing: Stürtz AG, Würzburg
Binding: Stürtz AG, Würzburg

Printed on acid-free paper 32/2132/LT – 5 4 3 2 1 0

Preface

The relationship of humans with the Earth's environment has changed throughout the evolution of *Homo sapiens* and the development of societies. For virtually all of human existence on the planet, interaction with the environment has taken place at the local, or at most the regional, scale, except perhaps for one example in which regional-scale human activities were repeated to create global consequences in concert with climate change – the Holocene megafauna extinction. Apart from this possible example, the environment at the scale of the Earth as a whole – the passing of the seasons, the vagaries of weather and climate, the ebbing and flowing of river systems and glaciers, the rich diversity of life in all its forms – has been a framework within which humans have been able to evolve and develop social structures, subject only to the great forces of nature and the occasional perturbations of extraterrestrial origin. The Earth's environment has been a bountiful source of resources as well as a remarkably accommodating life support system that has allowed human civilisations to develop and flourish.

This book focuses on the profound transformation of Earth's environment that is now apparent, a transformation owing not to the great forces of nature or to extraterrestrial sources but to the numbers and activities of people – the phenomenon of *global change*. Begun centuries ago, this transformation has undergone a profound acceleration during the second half of the twentieth century. During the last 100 years the population of humans soared from little more than one to six billion and economic activity increased nearly 10-fold between 1950 and 2000. The world's population is more tightly connected than ever before via globalisation of economies and information flows. Half of Earth's land surface has been domesticated for direct human use and nearly all of it is managed by humans in one way or another. Most of the world's fisheries are fully or over-exploited and little pristine coastline exists outside of the high latitudes. The composition of the atmosphere – greenhouse gases, reactive gases, aerosol particles – is now significantly different from what it was a century ago. The Earth's biota is now experiencing the sixth great extinction event, but the first caused by another species: *Homo sapiens*. The evidence that these changes are affecting the basic functioning of the Earth System, particularly the climate, grows stronger every year. Evidence from several millenia shows that the magnitude and rates of human-driven changes to the global environment are in many cases unprecedented. There is no previous analogue for the current operation of the Earth System.

This book sets out what is known about global change and the nature of the Earth System. It addresses a number of important but difficult questions. How did the Earth System operate in the absence of significant human influence? How can human-driven effects be discerned from those due to natural variability? What are the implications of global change for human well-being? How robust is the Earth System in the face of these new internal forces of change? Can human activities trigger abrupt and potentially irreversible changes to which adaptation would be impossible? How serious is this inadvertant human experiment with its own life support system? By raising and attempting to address these questions in this volume, the authors hope to give some direction to the future of Earth System science and to challenge the global change research community to find answers to these questions.

Such an undertaking as this volume could not have been possible without the active involvement of a large number of people. The book's production has truly been a community effort. The project began as a synthesis of a decade of research undertaken under the auspices of the International Geosphere-Biosphere Programme (IGBP) but quickly grew to encompass contributions from the global change research community more generally, particularly IGBP's partner international programmes: DIVERSITAS, an international programme of biodiversity science; the International Human Dimensions Programme on Global Environmental Change (IHDP); and the World Climate Research Programme (WCRP). The acknowledgements section at the end of this volume is thus unusually long. The authors hope that the many contributions to the book have been properly acknowledged; any inadvertant oversights are the responsibility of the authors and are regretted.

Finally, this volume stands as one contribution of the many required to build the knowledge base to support the long-term, sustainable existence of the human enterprise on planet Earth. It argues that a truly global system of science is needed for coping with the challenges that lie ahead.

Will Steffen, *Angelina Sanderson*, *Peter Tyson*, *Jill Jäger*, *Pamela Matson*,
Berrien Moore III, *Frank Oldfield*, *Katherine Richardson*, *H. John Schellnhuber*,
B. L. Turner II, *Robert Wasson*

Stockholm, August 2003

Contents

Contributors to Expert Boxes

Alverson, Keith

PAGES (Past Global Changes) International Project Office,
Bern, Switzerland

Anisimov, Oleg

State Hydrological Institute,
St. Petersburg, Russia

Betts, Richard

Hadley Centre for Climate Prediction and Research,
UK Meteorological Office

Blunier, T.

Climate & Environmental Physics, Physics Institute,
University of Bern, Switzerland

Brasseur, Guy P.

Max Planck Institute for Meteorology,
Hamburg, Germany

Clark, William C.

Belfer Center for Science and International Affairs,
Harvard University, USA

Claussen, Martin

Potsdam Institute for Climate Impact Research,
Germany

Cole, Julia

Department of Geosciences,
University of Arizona, Tucson, USA

Crossland, Chris

Land-Ocean Interactions in the Coastal Zone (LOICZ)
International Project Office,
Texel, The Netherlands

Crutzen, Paul

Max Planck Institute for Chemistry,
Mainz, Germany

DeFries, R.

Department of Geography and Earth System Science
Interdisciplinary Center, University of Maryland, USA

Ehleringer, Jim

Department of Biology,
University of Utah, USA

Farquhar, Graham D.

Cooperative Research Centre for Greenhouse Accounting,
Research School of Biological Sciences,
The Australian National University, Canberra

Folke, Carl

Center for Transdisciplinary Environmental Studies (CTM) and
Department of Systems Ecology, Stockholm University, Sweden

Fu, Congbin

Institute of Atmospheric Physics,
Chinese Academy of Sciences, Beijing

Galloway, James

Department of Environmental Sciences,
University of Virginia, USA

Goodwin, Ian

The University of Newcastle,
Australia

Hanson, Roger B.

Joint Global Ocean Flux Study (JGOFS)
International Project Office, Bergen, Norway

Harvey, Nick

The University of Adelaide,
Australia

Heintzenberg, Jost

Leibniz-Institute for Tropospheric Research,
Leipzig, Germany

Held, H.

Potsdam Institute for Climate Impact Research,
Germany

Jansson, Åsa

The Centre for Research on Natural Resources and the
Environment, Stockholm University, Sweden

Jayaraman, A.

Physical Research Laboratory,
Ahmedabad, India

Kates, Robert W.

Independent Scholar, USA

Kaye, Jack A.

Research Division, Office of Earth Science,
NASA Headquarters, Washington, DC, USA

Lavorel, Sandra

Laboratoire d'Ecologie Alpine, CNRS,
Université Joseph Fourier, Grenoble, France

Leemans, Rik

Office for Environmental Assessment,
Bilthoven, The Netherlands

Leichenko, Robin

Department of Geography,
Rutgers University, USA

Lenton, Tim

Centre for Ecology and Hydrology,
Edinburgh, UK

Lohmann, Ulrike

Department of Physics and Atmospheric Science,
Dalhousie University, Canada

Messerli, Bruno

Institute of Geography,
University of Bern, Switzerland

Meybeck, Michel

Laboratoire de Géologie Appliquée,
Université de Paris, France

Mitra, A. P.

National Physical Laboratory,
New Delhi, India

Nobre, Carlos A.

Center for Weather Forecasting and Climate Research – CPTEC,
Cachoeira Paulista, SP, Brazil

Norby, Richard J.

Oak Ridge National Laboratory, USA

O'Brien, Karen

Center for International Climate and Environment Research,
Oslo, Norway

Pataki, Diane

Department of Biology,
University of Utah, USA

Petschel-Held, Gerhard

Potsdam Institute for Climate Impact Research,
Germany

Rahmstorf, Stefan

Potsdam Institute for Climate Impact Research,
Germany

Raynaud, D.

Laboratoire de Glaciologie et Géophysique de l'Environnement,
Centre National de la Recherche Scientifique and Université
Joseph Fourier, Saint-Martin-d'Hères, France

Richey, Jeffrey E.

School of Oceanography,
University of Washington, Seattle, USA

Roderick, Michael L.

Cooperative Research Centre for Greenhouse Accounting,
Research School of Biological Sciences,
The Australian National University, Canberra

Scholes, R. J.

Council for Scientific and Industrial Research,
South Africa

Serneels, Suzanne

University of Louvain, Belgium;
currently at the
International Livestock Research Institute, Kenya

Stocker, Thomas F.

Climate and Environmental Physics,
University of Bern, Switzerland

Vörösmarty, Charles

Complex Systems Research Center,
University of New Hampshire, USA

Watson, Andrew J.

School of Environmental Sciences,
University of East Anglia, Norwich, UK

Chapter 1

An Integrated Earth System

The interactions between environmental change and human societies have a long and complex history spanning many millennia. They vary greatly through time and from place to place. Despite this spatial and temporal variability, a global perspective has begun to emerge in recent years and to form the framework for a growing body of research within the environmental sciences. Crucial to the emergence of this perspective has been the dawning awareness of two aspects of Earth System functioning. First, that the Earth itself is a single system within which the biosphere is an active, essential component. Secondly, that human activities are now so pervasive and profound in their consequences that they affect the Earth at a global scale in complex, interactive and apparently accelerating ways; humans now have the capacity to alter the Earth System in ways that threaten the very processes and components, both biotic and abiotic, upon which the human species depends. This book describes what is known about the Earth System and the nature of the human-driven changes impacting it. It also considers the responses of the System, the consequences of these responses for the stability of the System and for human well-being, and some of the ways forward towards an Earth System science that can contribute to the goal of global sustainability.

1.1 A Research Agenda to Meet the Challenge of the Future

The urge to deepen the scientific understanding of the environment derives from a number of motivations whose relative importance has changed through time. Among the more readily discernible of these has been the wish to reveal more clearly the nature of what has been perceived to be divine order, the compulsion to satisfy simple curiosity and the need to solve, or at least respond to, problems that have already arisen from human interactions with the environment. Over the last two decades a new imperative has come to dominate environmental concerns with the growing awareness that human activities have an increasing influence on Earth System functioning, upon which human welfare and the future of human societies depend.

The most familiar and dramatic illustration of this awareness is the impact humans have had on the atmospheric concentration of greenhouse gases (Fig. 1.1). The heat-absorbing property of these gases and the empirical demonstration that their changing atmospheric concentrations been closely linked to climate change over the last 400 000 years combine to pose urgent questions about the future. A wide range of additional human impacts on the Earth System have had, and continue to have, dramatic and far-reaching cumulative effects. The ever-growing combined effects and implications of human activities bring into focus the nature of the problems currently facing environmental and other scientists.

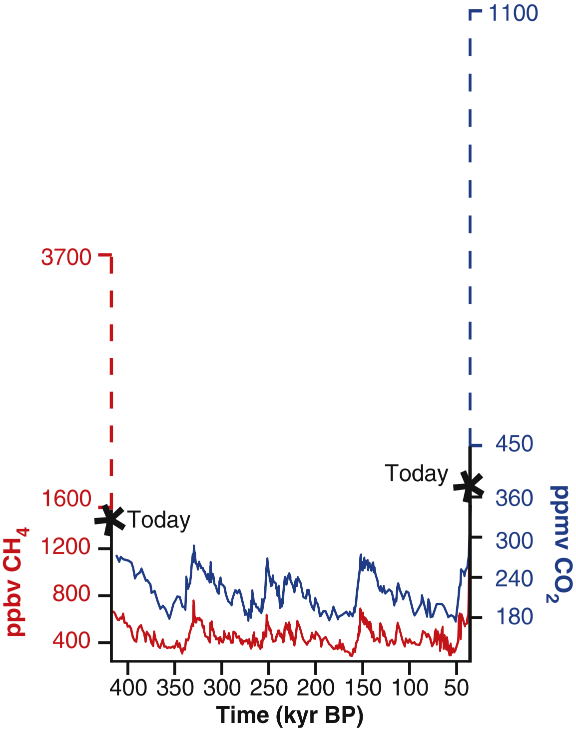

Fig. 1.1. Measurements of the atmospheric concentrations of the greenhouse gases CO_2 and CH_4 over the last four glacial-interglacial cycles from the Vostok ice core record, combined with current measurements and projections of future CO_2 and CH_4 levels based on IPCC 2000 scenarios (Petit et al. 1999; IPCC 2001). *Dashed lines* along the *y*-axis indicate the IPCC range of projections for CO_2 and CH_4 concentrations in 2100

The science required to address this future-oriented research agenda must transcend disciplinary boundaries, for it is concerned with issues that lie beyond any single field of study. All complex systems defy purely mechanistic analysis. The systems-level approach required to achieve an understanding of those aspects of Earth System functioning upon which human survival, and life in general, depend must encompass complex interactions, synergies between system components, non-linear responses and multiple feedbacks. It must also embrace both biophysical and anthropogenic drivers of change, not as separate influences but as closely interwoven and interactive processes.

Classical analytical science in which individual variables are isolated and their separate effects determined individually cannot cope with the challenges posed by Earth System science. This is often most clearly seen where responses to environmental problems have been designed to address specific, narrowly defined problems within a framework that fails to consider the full range of consequences inherent in a complex, interactive system. More generally, the emergent behaviour that often results from interactions among components of the system cannot be understood by studying the components of the system in isolation. The identification of cause-effect relationships is still useful, but they are embedded in complex systems in which synergies, interactions and non-linearities defy the classic, analytical approach.

Systems thinking and its application to the environment are not new. Ecosystem concepts go back to the 1930s (Tansley 1935), and systems formulations gained prominence in some fields (e.g., fluvial geomorphology) three decades ago (Chorley and Kennedy 1971). More general systems thinking was well expounded by the 1970s (Laszlo 1972), and the idea of global biogeochemistry, a major theme in this volume, was also discussed and described in broad outline some 50 years ago (Hutchinson 1944, 1954). However, each of these examples considers only a part of Earth System functioning. What is really new about perceptions of the Earth System over the last 10–15 years is the development of a perspective that embraces the Earth System *as a whole*. Several developments have led to this fundamental and accelerating change in scientific perception. These are that:

- the view of Earth from a spaceship, a blue-green sphere floating in blackness, triggers emotional *feelings* of a home teeming with life set in a lifeless void, as well as more analytical *perceptions* of a materially limited and self-contained entity (Fig. 1.2);

Fig. 1.2.
Earth viewed from space (*image:* NASA Online Photo Gallery)

- global observation systems allow scientists to apply *concepts* that were only previously applicable at subsystem, regional or local scale to the Earth as a whole. The Earth itself *is* a system;
- global databases address global scale phenomena with consistently acquired *data* that have the potential for harmonisation and comparison at a global scale;
- dramatic advances in the power to infer properties indicative of Earth processes in the past set contemporary observational snapshots in a *time continuum*; and
- enhanced computing power makes possible not only essential data assimilation, but increasingly sophisticated *models* that improve understanding of functional interactions and system sensitivities.

Science is at the threshold of a potentially profound shift in the perception of the human-environment relationship, operating across humanity as a whole and at the scale of the Earth as a single system.

1.2 The Earth as a System

The notion that global-scale cycles operate as systems is, again, not new. The fact that the hydrological and the carbon cycles, for example, each operate as planetary systems has been known for well over a century. However, the fact that these planetary cycles themselves are closely interlinked and the suggestion that life itself is an active and necessary player in planetary dynamics (e.g., the Gaia hypothesis; Lovelock 1979) are much more recent.

The extent to which, over the geologically recent past, the Earth behaves as a single, interlinked, self-regulating system was put into sharp focus in 1999 with the publication of the 420 000-year record from the Vostok ice core (Petit et al. 1999) (Figs. 1.1 and 1.3). These data, arguably among the most important produced by the global change scientific community in the twentieth century, provide a powerful temporal context and dramatic visual evidence for an integrated planetary environmental system.

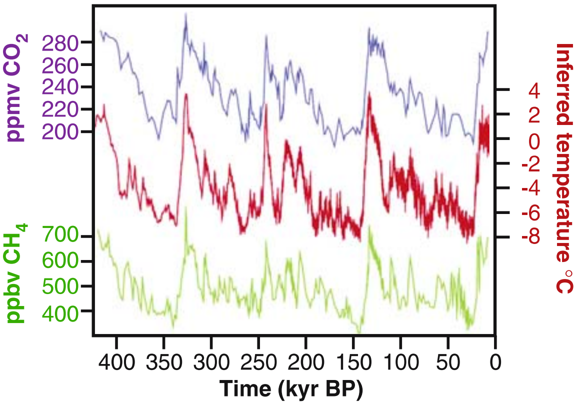

Fig. 1.3. The 420 000-year Vostok (Antarctica) ice core record, showing the regular pattern of atmospheric CO_2 and CH_4 concentration and inferred temperature through four glacial-interglacial cycles (adapted from Petit et al. 1999)

The Vostok ice core data give a wealth of insights into the Earth System, and they will be used at several points throughout this volume to examine aspects of system dynamics in more detail. For now, three striking characteristics are immediately apparent. Together, they demonstrate beyond any doubt that the Earth is a system, with properties and behaviour that are characteristic of the system as a whole. In particular:

- The evidence for climate variability, as represented by a proxy for local temperature ($\delta^{18}O$) and the record of changes in the global carbon cycle, as represented by the atmospheric concentration of the trace gases carbon dioxide (CO_2) and methane (CH_4) trapped in air bubbles in the ice, show largely parallel temporal variations throughout (Fig. 1.3). In fact, the record from Vostok confirms that there has been a close coupling between the climate proxies and both trace gas and aerosol (dust and sulphate) concentrations, all of which are linked in part to biological processes.
- The main maxima and minima of temperature and trace gas concentrations, which mark the alternation between glacial and interglacial conditions, follow a regular, cyclic beat through time, each cycle spanning approximately 100 000 years. The smooth changes in the eccentricity of the Earth's orbit that are believed to be the primary forcing mechanism for this dominant periodicity are too slight and too smooth to generate the changes recorded without strong modulation by internal feedbacks. This is especially so when the abrupt shifts to interglacial conditions at the end of each glacial period are considered. This highly non-linear response of the Earth System to external forcing must involve interactions among biological, chemical and physical components.
- The range over which isotopically inferred temperature and trace gas concentrations vary is limited. Throughout all four cycles, each interglacial gives rise to similar peak values; each glacial culminates in comparable minima. This points to a high degree of self-regulation within the Earth System over the whole of the time interval recorded in the Vostok ice core.

As Chap. 2 will show, this systemic behaviour of Earth's environment is due to a combination of external forcing – primarily variations in solar radiation levels near the Earth's surface – and a large and complex array of feedbacks and forcings within Earth's environment itself. In fact, it is undoubtedly the internal dynamics that keep the planet habitable for life. Without the thin layer of ozone in the upper atmosphere, for example, much more harmful ultraviolet radiation would penetrate to the Earth's surface; and without the thin layer of heat-absorbing trace gases in the lower atmosphere, the planet's mean surface temperature would be about 30 °C lower than it is now.

Over the past few decades, evidence has been mounting that planetary-scale changes are occurring rapidly in response to the forcings and feedbacks that characterise the internal dynamics of the Earth System. As indicated in Fig. 1.1, key indicators, such as the concentrations of trace gases in the atmosphere, are changing dramatically, and in many cases the linkages of these changes to human activities are strong. It is clear that the Earth System is being subjected to an ever-increasing diversity of new planetary-scale forces that originate in human activities. Primarily, it is these activities that give rise to the phenomenon of *global change* that is considered in this volume.

1.3 The Nature of Global Change

Global change is more than climate change and its full extent and complexity has been realised only very recently. The origins of the concept are largely derived from the careful and consistent measurement of atmospheric CO_2 concentration at the Mauna Loa Observatory in Hawaii (Keeling et al. 1995; Keeling and Whorf 2000). These observations first demonstrated beyond doubt that human activities can have direct global-scale consequences for the environment (Fig. 1.4). The Mauna Loa record shows a steady increase in CO_2 concentration in the atmosphere over the past three decades and forms the link between the natural variability provided by the Vostok ice core data and the projections of future values in Fig. 1.1. Coupled with other lines of evidence, such as the isotopic composition of the carbon in atmospheric CO_2 and the latitudinal distribution of CO_2 (Prentice et al. 2001), the record points to fossil fuel combustion as the main source of the additional CO_2. Startling though it is, the Mauna Loa record on its own gives little hint of its implications for the functioning of the Earth System. Two other pieces of evidence are required to understand this.

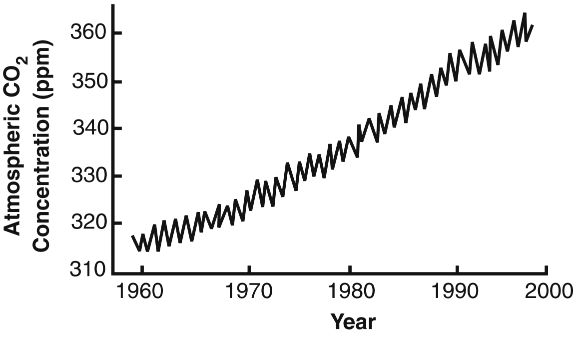

Fig. 1.4. Increase in atmospheric CO_2 concentration over the last 40 years as measured at the Mauna Loa Observatory, Hawaii (adapted from Keeling and Whorf 2000)

As Fig. 1.1 shows, the Vostok ice core record of atmospheric CO_2 concentration over the past 420 000 years shows a normal operating range of about 180 to 280 ppmV (parts per million by volume). The addition of the Mauna Loa record to bring the Vostok data up to the present shows immediately that the scale of change in the composition of Earth's atmosphere is of the same order of magnitude as the full range of natural variability. The long palaeo-record places modern instrumental observations into a time continuum and thereby provides a much clearer perspective on the magnitude of recent human perturbations to the Earth System.

Secondly, the detailed Vostok ice core record, as shown more fully in Fig. 1.3, also points to a relationship between the atmospheric concentrations of CO_2 and CH_4 and the climate, at least as represented by temperatures in the neighbouring part of Antarctica. However, many records from both marine and continental sediments (Alverson et al. 2000, 2003) confirm that the sequence of major climate changes – the oscillations between glacial and interglacial conditions – on the Vostok time-scale was broadly synchronous over the whole globe. Moreover, recent data from ice core records with higher temporal resolution (Alverson et al. 2003) reinforce the view that there is a close coupling between atmospheric greenhouse gas concentrations and climate change even during the intervals of rapid warming at each glacial termination. Although the phasing and likely lags are still not precisely determined for each glacial-interglacial transition, careful analysis shows that increases in the atmospheric concentrations of CO_2 and CH_4 closely followed solar radiation changes associated with changes in the eccentricity of the Earth's orbit that appear to have initiated the transition to interglacial conditions, but preceded by several thousand years the onset of intense deglaciation (Petit et al. 1999; Pépin et al. 2002). This is consistent with the proposition that there was an early and recurrently crucial feedback role for greenhouse gases in the transition from glacial to interglacial conditions.

Turning to the most recent past, evidence is now mounting that the Earth's climate is changing rapidly (Fig. 1.5) and that the increasing concentrations of CO_2, CH_4 and other greenhouse gases due to human activities are an important causal factor in this change (Mann et al. 1999; Crowley 2000; IPCC 2001).

The changes in the relationship between natural and human-induced variability that have occurred over the last few centuries, and that are giving rise to global change, are complex and profound. They are almost certainly unprecedented in the history of the Earth. The expansion of humankind, both in numbers and per capita exploitation of the Earth's resources, has been re-

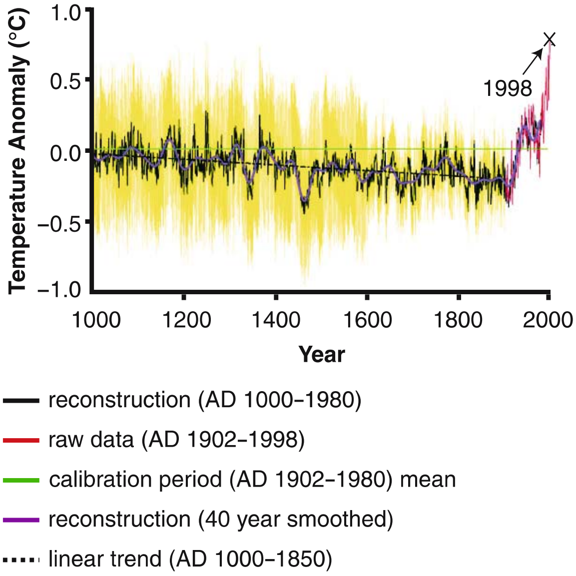

Fig. 1.5. Mean annual surface temperature over the northern hemisphere for the last thousand years (Mann et al. 1999)

markable. During the past three centuries human population increased 10-fold to 6 000 million. Concomitant with this population increase, the rate of consumption has risen even more sharply. Just as rapid and profound are other changes sweeping across human societies, many through the process often termed *globalisation* (Fig. 1.6). During the last 50 years alone, the increase in virtually every sphere of human activity has been considerable, such that:

- the world's population, currently 6 100 million, has doubled since 1960, tripled since 1930 and is projected to rise to over 9 000 million by 2050 (UNFPA 2001);
- since 1950 the global economy has increased by more than a factor of 15; real world Gross Domestic Product (GDP) grew from USD 2 trillion in 1965 to USD 28 trillion in 1995 (UNDP 2000; UNEP 2000);
- economic inequality is increasing. The richest nations have 15% of the global population but generate 50% of world GDP; between 1960 and 1994 the ratio of income of the richest 20% to the poorest 20% increased from 30:1 to 78:1 (World Bank 2002; UNDP 2000);
- world petroleum consumption has increased by a factor of 3.5 since 1960; global use of fuel wood has doubled in the last 50 years (EIA 2002; UNFPA 2001);
- transport accounts for 25% of world energy use, with motor vehicles accounting for 80% of the use. The number of motor vehicles has increased from 40 million in the late 1940s to 676.2 million in 1996 (IRF 1997);
- global communication has exploded with the development of the internet. In just six years, from 1993 to 1999, the number of people globally connected to the internet increased from three million to over 200 million (Internet Economy Indicators 2002);

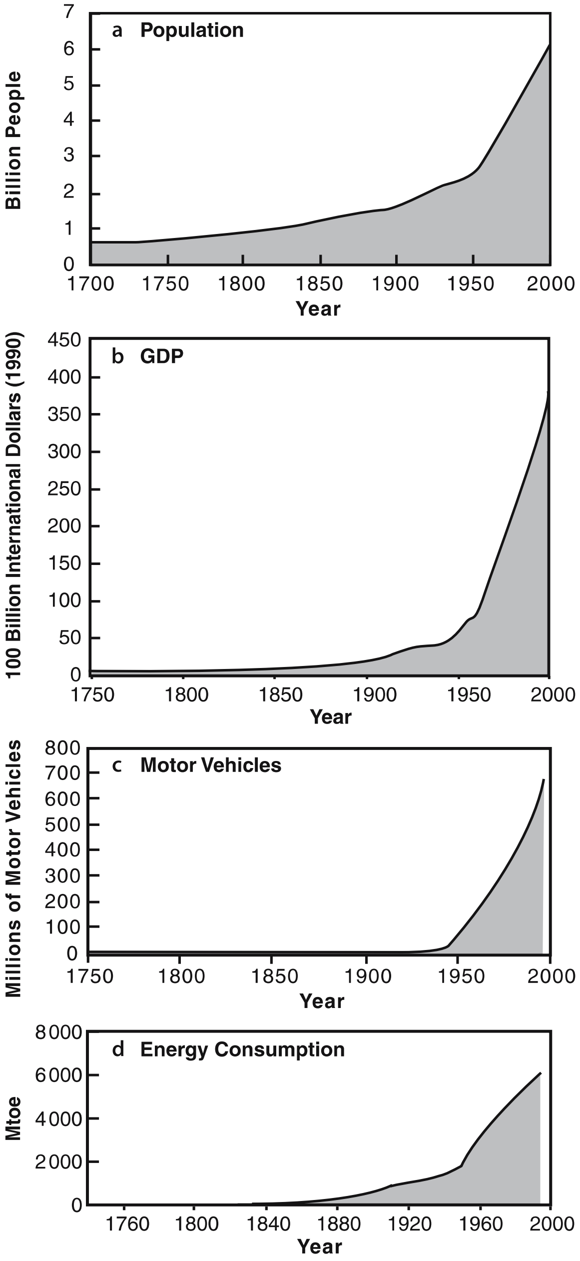

Fig. 1.6. Rate of increase in many spheres of human activity for the last 300 years: **a** population (US Bureau of the Census 2000); **b** world economy (Nordhaus 1997); **c** motor vehicles (UNEP 2000); and **d** energy consumption (Klein Goldewijk and Battjes 1997)

- urbanisation increased 10-fold in the twentieth century. From 1950 to 2000 the percentage of the world's population living in urban areas increased from 30% to 47% and is projected to increase to 56% by 2020. The number of megacities (10 million or more inhabitants) increased from five in 1975 to 19 in 2000. (FAOSTAT 2002; UNFPA 2001); and
- the interconnectedness of the cultures of the world is increasing rapidly with the increase in communication, travel and the globalisation of economies.

The pressure on Earth's resources and on the planet's capability to assimilate wastes from increasing human activities is intensifying sharply (Crutzen 2002; McNeill 2001) (Fig. 1.7). The manner in which human activities are bringing about change include the facts that:

- while petroleum was only discovered in the last 150 years, humankind has already exhausted almost 40% of known oil reserves that took over several hundred million years to generate (USGS 2000);
- nearly 50% of the land surface has been transformed by direct human action, with significant consequences for biodiversity, nutrient cycling, soil structure, soil biology and climate (Vitousek et al. 1986; Turner et al. 1990; Daily 1995);
- more nitrogen is now fixed into available forms through the production of fertilisers and burning of fossil fuels than is fixed naturally in all terrestrial systems (Kaiser 2001);
- more than half of all accessible freshwater is appropriated for human purposes (Postel et al. 1996);
- concentrations of several climatically important greenhouse gases, in addition to CO_2 and CH_4, have substantially increased in the atmosphere (IPCC 2001);
- coastal wetlands have been significantly affected by human activities, with the loss of 50% of the world's mangrove ecosystems (WRI 1996);
- 47–50% of marine fish stocks for which information is available are fully exploited, 15–18% are over-exploited and 9–10% have been depleted or are recovering from depletion (FAO 2000); and
- extinction rates are increasing sharply in marine and terrestrial ecosystems around the world, with the present sixth great extinction event in the Earth's history being the first one caused by the activities of a biological species, in this case *Homo sapiens* (Lawton and May 1995; Pimm et al. 1995).

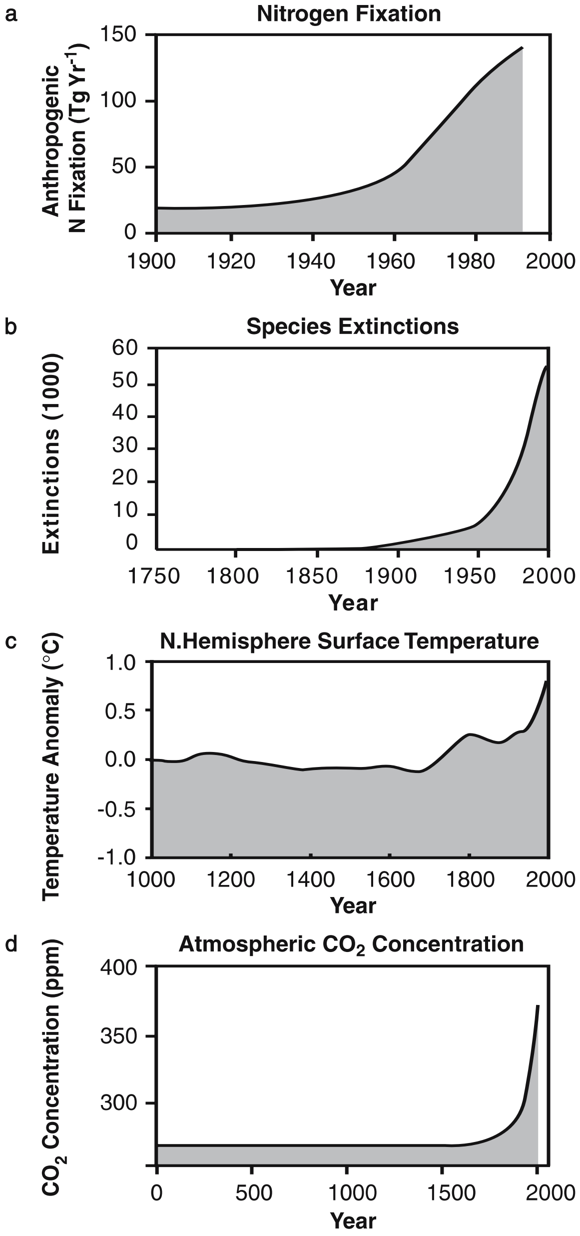

Fig. 1.7. Responses of the Earth System to increasing pressure from human activities: **a** nitrogen fixation (Vitousek 1994); **b** species extinctions (Smith 2002); **c** northern hemisphere surface temperature (Mann et al. 1999); and **d** atmospheric CO_2 concentration (adapted from Keeling and Whorf 2000)

The extent to which human activities are influencing or even dominating many aspects of Earth's environment and its functioning has led to suggestions that a new geological era, the *Anthropocene* (Crutzen and Stoermer 2001), has begun.

Listing the broad suite of biophysical and socio-economic changes that is taking place fails to capture the complexity and connectivity of global change since the many linkages and interactions among the individual changes are not included. For example, most of the rapid urbanisation is occurring in the coastal zone, leading both to direct conversion of natural coastal ecosystems to urban areas and increasing demand for marine resources, which in turn leads to further conversion of natural coastal ecosystems. These changes are compounded by land-use changes upstream, altering the mix and amount of suspended and dissolved material entering the coastal zone. Both within-coastal zone ecosystem modification/conversion and land-use change upstream are impacting on biological diversity. The potential synergies between biophysical and socio-economic trends becomes startlingly apparent when the effects of land-use change upstream combine with probable sea-level rise and changes in the frequency of storm events to increase the vulnerability of coastal settlements and infrastructure. Similar webs of connectivity can be found for other clusters of global changes, leading to *syndromes* of change characteristic of particular regions (Petschel-Held et al. 1999).

Furthermore, many changes do not occur in a linear fashion, but rather, thresholds are passed and rapid, non-linear changes ensue. For example, the initial pockets of deforestation in a large tropical forest may have little or no impact on the number of species of animals and birds. However, as the forest becomes increasingly fragmented, the rate of species loss can increase sharply (Hobbs 1989; Noss 1996). Similar effects have been shown to occur in the responses of insects to changing climate. In Sweden the tick species which carries encephalitis normally requires two seasons to complete its life cycle. However, with a warming climate in the high latitudes, at a certain point in the warming trend the tick can complete its life cycle in a single season, causing an apparently unpredicted outbreak of tick populations (Lindgren 2000). The pattern of little or no change until a critical threshold followed by a sharp response is common in Earth System dynamics, and may be the rule rather than the exception, especially as global change intensifies. In addition, many effects of global change are cumulative; for example, slow addition over time to the atmosphere of seemingly innocent chemicals in the form of chlorofluorocarbons led eventually to a rapid and significant disruption of the atmospheric chemical system in the stratosphere with the production of the so-called ozone hole.

Finally, global change is being played out in contrasting ways at different locations, each with its own set of characteristics being impacted by a location-specific mix of interacting changes. The global environment and the phenomenon of global change are both heterogeneous, and the variety of human-environment relationships is vast. The potential for an almost infinite range of interactions is large. To cope with or adapt to global change requires analyses that couple the particular characteristics of a location or region with the nature of the systemic, globally connected changes to Earth's environment as they interact with other factors affecting the location or region. Any attempt at achieving sustainability at any scale requires that this is done and that human societies learn to live with global change.

1.4 Objectives and Structure of the Book

The intent of this book is to explore what has been learned about the fundamental workings of the Earth System (see Box 1.1 for a definition of the Earth System),

Box 1.1. The Earth System

Frank Oldfield · Will Steffen

In the context of global change, the *Earth System* has come to mean the suite of interacting physical, chemical, and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes which provide the conditions necessary for life on the planet. More specifically, this definition of the Earth System has the following features:

- It deals with a materially closed system that has a primary external energy source, the sun.
- The major dynamic components of the Earth System are a suite of interlinked physical, chemical and biological processes that cycle (transport and transform) materials and energy in complex dynamic ways within the System. The forcings and feedbacks *within* the System are at least as important to the functioning of the System as are the external drivers.
- Biological/ecological processes are an integral part of the functioning of the Earth System, and not just the recipients of changes in the dynamics of a physico-chemical system. Living organisms are active participants, not simply passive respondents.
- Human beings, their societies and their activities are an integral component of the Earth System, and are not an outside force perturbing an otherwise natural system. There are many modes of natural variability and instabilities within the System as well as anthropogenically driven changes. By definition, both types of variability are part of the dynamics of the Earth System. They are often impossible to separate completely and they interact in complex and sometimes mutually reinforcing ways.
- Time scales considered in Earth System science vary according to the questions being asked. Many global environmental change issues consider time scales of decades to a century or two. However, a basic understanding of Earth System dynamics demands consideration of much longer time scales in order to capture longer-term variability of the System, to understand the fundamental dynamics of the System, and to place into context the current suite of rapid global-scale changes occurring within the System. Thus palaeo-environmental and prognostic modelling approaches are both central to Earth System science.

The term *climate system* is also used in connection with global change, and is encompassed within the Earth System. Climate usually refers to the aggregation of all components of weather – precipitation, temperature, cloudiness, for example – averaged over a long period of time, usually decades, centuries, or longer. The processes which contribute to climate comprise the climate system, and they are closely connected to biogeochemical cycles. However, there are some important differences between climate change and global change:

- Many important features of biogeochemical cycles can have significant impacts on Earth System functioning without any direct change in the climate system. Examples include the direct effects of changing atmospheric CO_2 concentration on carbonate chemistry and hence on calcification rates in the ocean and also the sharp depletion of stratospheric ozone from the injection of chlorofluorocarbons in the atmosphere.
- Many interactions between biology and chemistry can have profound impacts on ecological systems, and hence feedbacks to Earth System functioning, without any change in the climate system. Examples include the impact of nitrogen deposition on the biological diversity of terrestrial ecosystems and the effect of non-climate driven changes in terrestrial and marine biospheric emission of trace gases and hence to the chemistry of the atmosphere.
- Human societies and their activities are usually not considered to be a direct part of the climate system, although their activities certainly impact on important processes in the climate system (e.g., greenhouse gas emissions).

and the responses of that system to myriad anthropogenic changes as they interact with each other and with the patterns and processes of natural variability. In doing this, global change research over the past decade has been used, but not exclusively limited to this period. The results of research carried out in the International Geosphere-Biosphere Programme (IGBP, see Appendix), together with significant contributions from the IGBP's partner global change programmes (the World Climate Research Programme (WCRP), the International Human Dimensions Programme on Global Environmental Change (IHDP) and DIVERSITAS, an international programme of biodiversity science) are included and acknowledged. In addition, the book draws on the work of those not directly linked to any of the international programmes *per se*, but working within the numerous national and regional global change programmes around the world.

The theme of this book is the nature of Earth as a system, the evolving role of anthropogenic activities as an ever-increasing planetary-scale force in the System, and the consequences of rapid change for the future of the Earth's environment and for the well-being of human societies. As much of the research on global change has, until very recently, focused on components of the Earth System rather than on the System as a whole, this book continually attempts to balance reductionist, analytical approaches to the science with integrative, systems-level approaches. However, the book also acknowledges the fact that complete knowledge of the complex consequences of anthropogenic change has thus far proved to be elusive. In addition, the book attempts to put some solid scientific analyses into integrative systems approaches, which may otherwise lapse into vague generalities and lose the essential virtues of deductive science and especially hypothesis testing. This dual approach gives an indication of the type of science required for Earth System analysis in future.

The book takes the reader on a journey through time, beginning with a consideration of natural changes occurring over a half-million year time-frame, including glacial-interglacial cycle dynamics. It then passes through to the contemporary period of accelerating human dominance of many planetary processes. Following on from this come more speculative approaches to analysing and simulating the dynamics of the Earth System into the future. Figure 1.8 gives a visual representation of the structure of the book. The structural outline of the work may be summarised as follows:

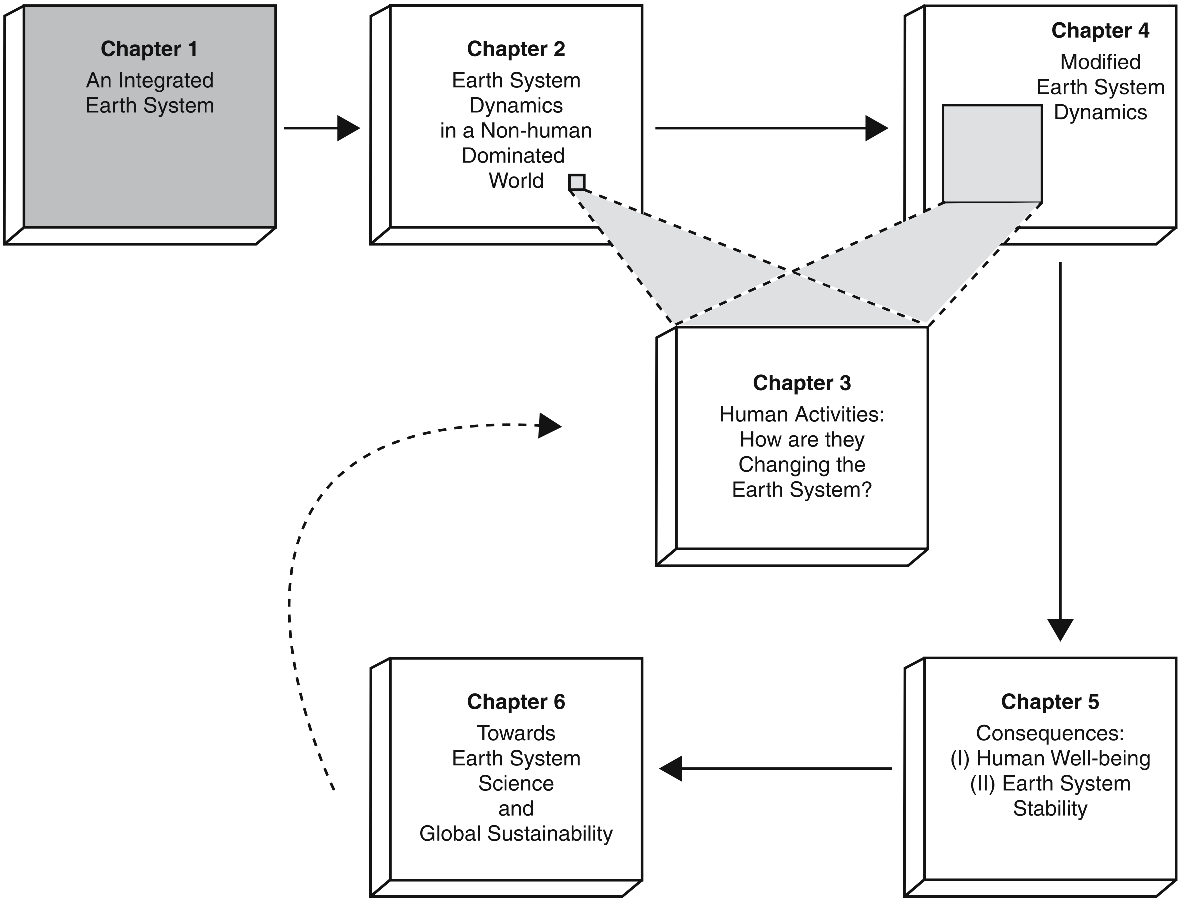

Fig. 1.8. Structural outline of the book

- Chapter 2 begins by examining Earth System dynamics as they functioned prior to significant human influence. In it the question of how the Earth's environment operated in the period before human numbers and activities became a planetary-scale force is considered. In addition, thought is given to how those natural processes least impacted by human activities operate at present.
- Chapter 3 focuses only on the human component of the Earth System and examines the nature of human alterations of the Earth System, the types and rates of anthropogenic changes, their interrelationships and teleconnections, and the direct and underlying human driving forces for these changes. It shows how human society has grown from insignificance to a force equal to or exceeding many of the great forces of nature.
- The much-expanded human enterprise is placed back into the Earth System in Chap. 4, which examines the responses of the Earth System to this new force. It deals mainly with how the major human driving forces associated with the burning of fossil fuels, on the one hand, and how deforestation and subsequent intensification of agriculture, on the other, affect the Earth System and how the Earth System responds. A central theme is how initial responses reverberate through the Earth System, sometimes damping the initial forcing and sometimes amplifying it. A related theme is how the complex webs of internal forcings and feedbacks that characterise the functioning of the Earth System are affected by the expanding human enterprise.
- The consequences of accelerating global change for human well-being and the stability of the Earth System are explored in Chap. 5. The main question addressed is how global change is likely to affect the goal of feeding, housing, clothing, educating and employing the expanding human population of the twenty-first century without compromising the sustainability of the Earth's life support system.
- The final chapter considers a new scientific approach aimed at a fully developed Earth System science. It points the way towards reducing the dichotomy between isolated empiricism and overarching theory; to linking skills and disciplines both biophysical and socio-cultural in exciting new combinations; and to treating biospheric functioning in complex, interactive, quantitative and trajectory terms. It seeks to identify key Earth System switches and triggers, to redefine creatively but rigorously the interaction between deductive and inductive scientific modes, as well as between model-based and empirically based research. It explores the ways in which this new approach can advance understanding of the dynamics of the planet, operationalise the growing knowledge base and use the resulting wisdom to help human societies develop in ways increasingly compatible with the natural dynamics of the Earth System.

References

Alverson K, Oldfield F, Bradley R (2000) Past global changes and their significance for the future. Quarternary Sci Rev 19:1–5

Alverson K, Bradley R, Pedersen T (2003) Paleoclimate, global change and the future. IGBP Global Change Series. Springer-Verlag, Berlin Heidelberg New York

Chorley R, Kennedy BA (1971) Physical geography: A systems approach. Prentice Hall, New Jersey

Crowley TJ (2000) Causes of climate change over the past 1000 years. Science 289:270–277

Crutzen PJ (2002) Geology of mankind – the Anthropocene. Nature 415:23

Crutzen PJ, Stoermer E (2001) The "Anthropocene". International Geosphere Biosphere Programme, Global Change NewsLetter 41:12-13

Daily GC (1995) Restoring value to the world's degraded lands. Science 269:350–354

EIA (2002) Historical international data online database. Energy Information Administration. *http://www.eia.doe.gov/neic/historic/hinternational.htm*, 10 April 2002

FAO (2000) State of world fisheries and aquaculture 2000. Wijkstrom U, Gumy A, Grainger R (eds) Food and Agriculture Organization of the United Nations, Rome. *http://www.fao.org/DOCREP/003/X8002E00.htm*, 10 April 2002

FAOSTAT (2002) Statistical databases online. Food and Agriculture Organization of the United Nations, Rome. *http://www.apps.fao.org*, 10 April 2002

Hobbs RJ (1989) The nature and effects of disturbance relative to invasions. In: Drake JA, Mooney HA, di Castri F, Groves RH, Kruger FJ, Rejmanek M, Williamson M (eds) Biological invasions: A global perspective. John Wiley & Sons, Chichester, UK, pp 389–401

Hutchinson GE (1944) Nitrogen and the biogeochemistry of the atmosphere. Am Sci 32:284–306

Hutchinson GE (1954) The biogeochemistry of the terrestrial atmosphere. In: Kuiper GP (ed) The Earth as a planet. University of Chicago Press, Chicago, pp 371–433

Internet Economy Indicators (2002) Facts and figures. *http://www.internetindicators.com/factfigure.html*, 10 April 2002

IPCC (2001) Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge New York

IRF (1997) World road statistics, 1997 edition. International Road Federation, Geneva Washington DC

Kaiser J (2001) The other global pollutant: Nitrogen proves tough to curb. Science 294:1268–1269

Keeling CD, Whorf TP (2000) Atmospheric CO_2 records from sites in the SIO air sampling network. In: US Department of Energy (ed) Trends: A compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, USA

Keeling CD, Whorf TP, Wahlen M, van der Plicht J (1995) Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. Nature 375:666–670

Klein Goldewijk CGM, Battjes JJ (1997) One hundred year database for integrated environmental assessments. National Institute for Public Health and the Environment (RIVM), Bilthoven, Netherlands

Laszlo E (1972) The systems view of the world. Basil Blackwell, Oxford

Lawton JH, May RM (eds) (1995) Extinction rates. Oxford University Press, Oxford

Lindgren E (2000) The new environmental context for disease transmission, with case studies on climate change and tick-borne encephalitis. PhD Thesis. Natural Resources Management, Department of Systems Ecology, Stockholm University, Sweden

Lovelock JE (1979) Gaia: A new look at life on Earth. Oxford University Press, Oxford

Mann ME, Bradley RS, Hughes MK (1999) Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. Geophys Res Lett 26:759–762

McNeill JR (2001) Something new under the sun. WW Norton, New York, London

Nordhaus WD (1997) Do real wage and output series capture reality? The history of lighting suggests not. In: Bresnahan T, Gordon R (eds) The economics of new goods. University of Chicago Press, Chicago

Noss RF (1996) Conservation of biodiversity at the landscape scale. In: Szaro RC, Johnston DW (eds) Biodiversity in managed landscapes: Theory and practice. Oxford University Press, New York, pp 574–589

Pépin L, Raynaud D, Barnola J-M, Loutre MF (2002) Hemispheric roles of climate forcings during glacial-interglacial transitions as deduced from the Vostok record and LLN-2D model experiments. J Geophys Res 106:31885–31892

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pépin L, Ritz C, Saltzman E, Stievenard M (1999) Climate and atmospheric history of the past 420 000 years from the Vostok ice core, Antarctica. Nature 399:429–436

Petschel-Held G, Block A, Cassel-Gintz M, Kropp J, Lüdecke MKB, Moldenhauer O, Reusswig F, Schellnhuber HJ (1999) Syndromes of global change – a qualitative modelling approach to assist global environmental management. Environ Model Assess 4:295–314

Pimm SL, Russell GJ, Gittleman JL, Brooks TM (1995) The future of biodiversity. Science 269:347–350

Postel S, Daily GC, Ehrlich P (1996) Human appropriation of renewable fresh water. Science 271:785–788

Prentice IC, Farquhar GD, Fasham MJR, Goulden ML, Heimann M, Jaramillo VJ, Khesghi HS, Le Quéré C, Scholes RJ, Wallace DWR (2001) The carbon cycle and atmospheric carbon dioxide. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge New York

Smith N (2002) Species extinction. *http://www.whole-systems.org/extinctions.html*, 24 Jan 2003

Tansley AG (1935) The use and abuse of vegetational concepts and forms. Ecology 16:284–307

Turner II BL, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB (1990) The Earth as transformed by human action: Global and regional changes in the biosphere over the past 300 years. Cambridge University Press, Cambridge

UNDP (2000) Economic reforms, globalization, poverty and the environment. Reed D, Rosa H (eds) United Nations Development Programme

UNEP (2000) Global environmental outlook 2000. Clarke R (ed) United Nations Environment Programme

UNFPA (2001) The state of world population 2001. Marshall A (ed) United Nations Population Fund

US Bureau of the Census (2000) International database. *http://www.census.gov/ipc/www/worldpop.htm*, data updated 10 May 2000

USGS (2000) U.S. Geological Survey world petroleum assessment 2000. U.S. Geological Survey World Energy Assessment Team, United States Geological Survey. *http://greenwood.cr.usgs.gov/energy/WorldEnergy/DDS-60/*, 2 April 2002

Vitousek PM (1994) Beyond global warming: Ecology and global change. Ecology 75:1861–1876

Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA (1986) Human appropriation of the products of photosynthesis. Bioscience 36:368–373

World Bank (2002) Economic growth research. *http://www.worldbank.org/research/growth*, 10 April 2002

WRI (1996) World resources 1996–1997. World Resources Institute. Oxford University Press, New York

Chapter 2

Planetary Machinery: The Dynamics of the Earth System Prior to Significant Human Influence

The properties and processes of the non-human dominated Earth System vary across a wide range of space and time scales. Nevertheless, the Earth System has functioned within domains characterised by well-defined limits and periodic patterns. Interconnections among physical, chemical and biological processes and between land, ocean and atmosphere, across both space and time, are ubiquitous and critical for the functioning of the System. Forcings and feedbacks are difficult to distinguish as one becomes the other in the cyclical dynamics of the System. Rapid, abrupt changes can occur as the Earth System reorganises into a new state.

2.1 The Natural Dynamics of the Earth System

This chapter focuses on the nature of the Earth System before human activities became an important feature of the system, that is, prior to the beginning of the Industrial Revolution (Fig. 2.1). Much of the Earth System research that has been carried out in recent decades has sought to understand the backdrop of biogeochemical cycling and climate processes against which all current and future anthropogenic changes must be evaluated. Central to this analysis is the evaluation of the response of biological systems to physical and chemical changes in the Earth System and the role of biological systems in biogeochemical and biophysical processes within the Earth System. Global change research over the past decade has demonstrated that the biosphere is an active and important contributor to the functioning of the Earth System. The persistent notion that the Earth System, especially the climate, is driven largely by the physics of coupled ocean-atmospheric dynamics, with very little role for biology, has been effectively dispelled by the discovery of many concrete mechanisms by which both the marine and terrestrial biospheres interact with physical and chemical processes, and indeed, even help to control some critical Earth System functions.

In this chapter attention is drawn to the ways in which the biogeochemical and biological systems interact with the hydrological cycle and climate over space and time. The examination of biogeochemical systems assumes familiarity with the global cycles of carbon, nitrogen, phosphorus and sulphur. These are not dealt with in detail here. Complete descriptions of these cycles and their most critical processes are available in a number of recent texts (e.g., Schlesinger 1999; Jacobson et al. 2000), in review articles (e.g., Schimel et al. 1995; Vitousek et al. 1997; Smil 2001), and in syntheses in the IGBP series of books (Tyson et al. 2002; Brasseur et al. 2003; Fasham 2003; Kabat et al. 2004; Pedersen et al. 2003). Here, rather, the focus is on examples of some of the most exciting and critical recent findings that give insight into how Earth works as an integrated whole.

Studying the dynamics of the Earth System in a non-human dominated state is not straightforward. As will be made clear later in Chap. 3, many critical processes in Earth System functioning are now significantly influenced by human actions, and observing them directly now could give an incorrect or misleading picture of how the Earth functioned prior to being significantly influenced by human activities. Consequently, this chapter relies heavily on two sources of information: (*i*) palaeo-records, which provide data from time periods where human activities had no or only minimal impact on global-scale processes and which provide the opportunity to evaluate the natural dynamics and variability of the System, and (*ii*) contemporary research in those areas of Earth System functioning where human influences are still thought to be relatively small. The timeframe considered here is the last one million years of the evolution of the Earth System, as this is the period against which the very recent era of significant human influence is most appropriately considered. At a few points in the chapter events earlier than one million years ago are mentioned, but only to help place more recent events in context.

In addition, this chapter introduces a style of analysis that is used throughout this volume. Initially, attention is focused on individual aspects of the Earth System. The functioning of these is described in some detail leaving aside, for the moment, the systems-level perspective. In essence, the reader is asked to take a magnifying lens and examine various segments of the Earth System individually. Then, at the end of each chapter, the reader is asked to put the magnifying glass down and look at the entire object – the Earth System – as a whole, in order to see how the individual segments examined contribute to the functioning of the System.

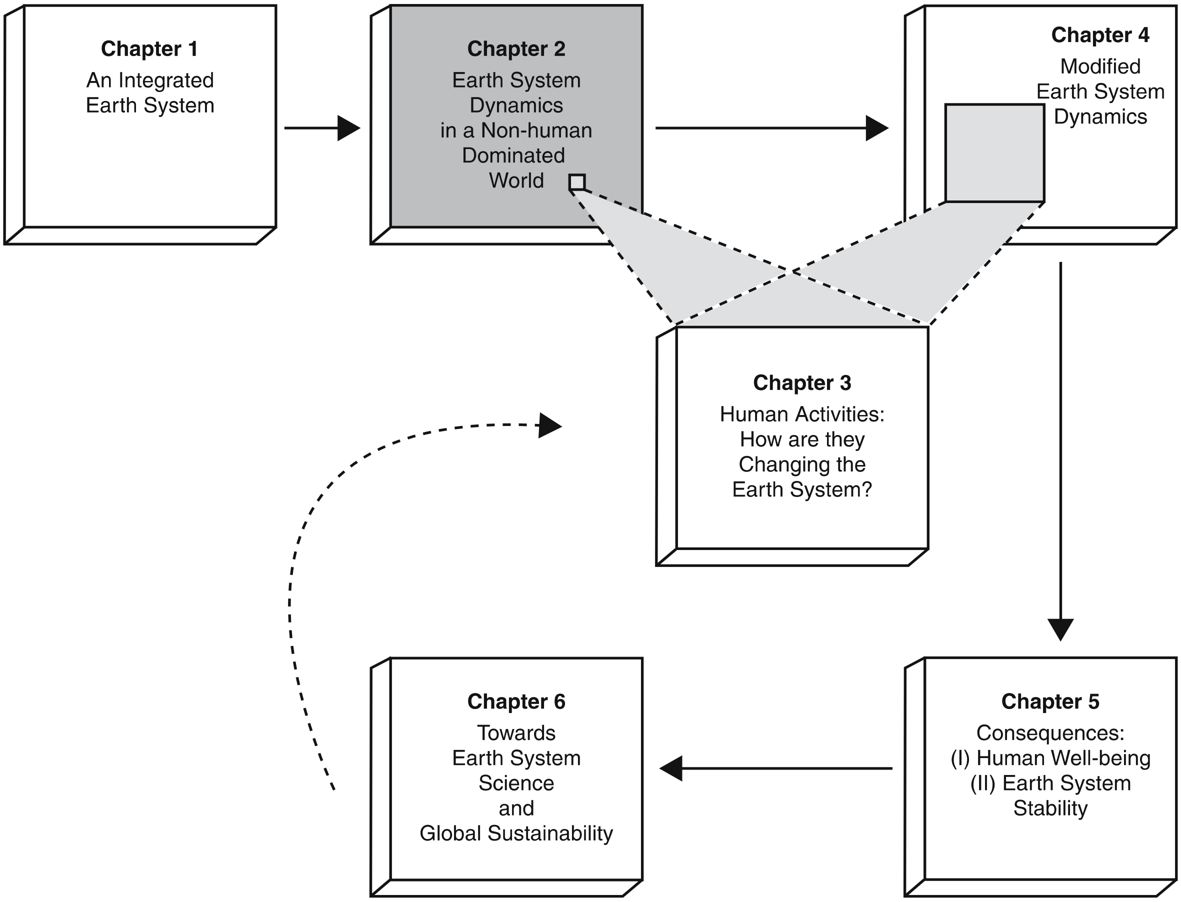

Fig. 2.1. Chapter 2 focus: Earth System functioning prior to significant human influence

2.2 New Insights in Temporal Variability of the Earth System

Recent research has illustrated the considerable natural variability and temporal dynamics of the Earth System. It has made clear that temporal change is a reality of the Earth System, and that static equilibria are unlikely to be a part of the System on almost any time scale and certainly not over the last 400 000 years. In the following sections, some of the insights gained by the great variety of palaeo-records that have been collected and evaluated over the past decade are considered.

2.2.1 The Long-Term Envelope of Natural Self-Regulation

The geological record shows that the functioning of the Earth System has varied continuously on all time-scales (Fig. 2.2). Changes in the Earth's orbit lead to changes in the latitudinal distribution of incoming solar radiation. The orbital parameters responsible for these changes have known periodicities, ~19 000 years and ~23 000 years for precession, ~40 000 years for obliquity and ~100 000 years for eccentricity. The changes in climate to which these orbital parameters give rise are far reaching and their periodicities can be detected in the record of climate variability contained in many environmental archives. As was pointed out in Chap. 1, climate changes are not linearly related to the external forcing. Interactions between biological, chemical and physical components of the Earth System, in response to subtle shifts in external forcing, have often given rise to non-linear changes that are abrupt and out of all proportion to the changes in incoming solar radiation. Nor are the climate changes necessarily synchronous with the orbital changes to which they ultimately respond, for the combination of internal thresholds, differing response times of Earth System components and strong, non-linear interactions can lead to lags between the onset of external changes and the responses of the Earth System.

Not all the past changes in climate that are detectable in the palaeo-record can be ascribed to orbitally driven changes. Many of the changes in temperature and

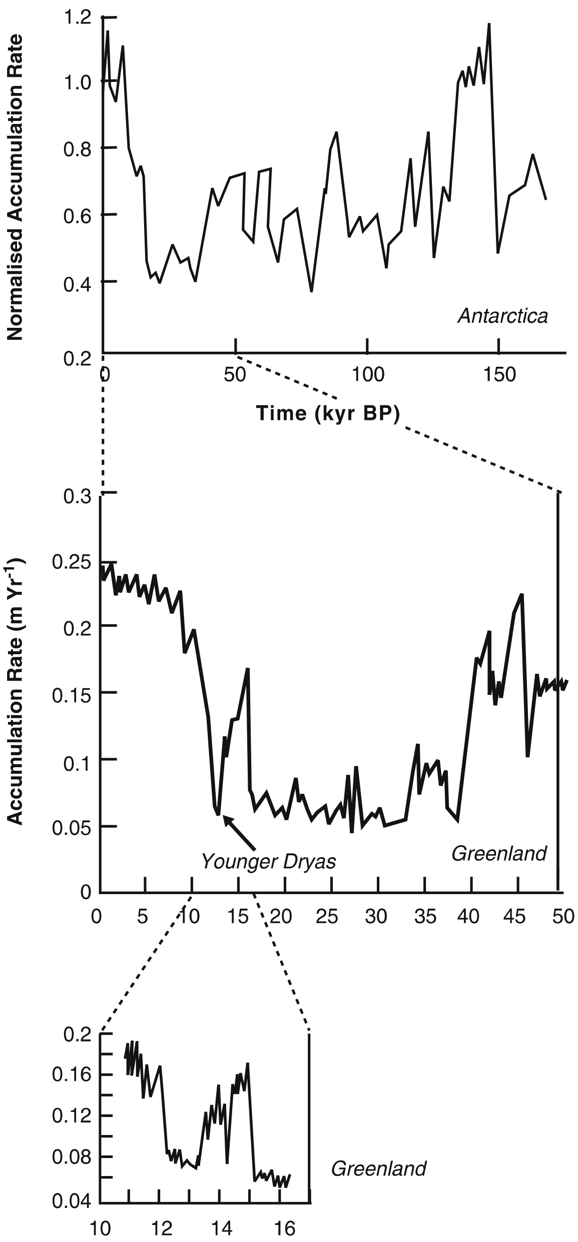

Fig. 2.2. Natural variability in Earth System functioning, from top to bottom: historic measurements of glacial ice accumulation rates, with insets focusing on the Younger Dryas cold interval and the very rapid termination of the last glaciation (adapted from Jacobson et al. 2000)

precipitation that are consistently recorded in environmental archives occur on shorter timescales, ranging from annual to millennial. Volcanicity influences climate on the shortest, mainly sub-decadal, timescales, but many other factors interact to drive the variability that has characterised the Earth's climate on sub-orbital forcing timescales, including short term changes in solar activity, ocean circulation and the terrestrial biosphere. The important point here is that regardless of the extent to which human activities may lead to changes in the Earth System, the functioning of the System will continue to vary in the future. Moreover, future changes, like those in the past, are likely to be characterised by highly non-linear responses to forcing, irrespective of the extent to which this is natural or anthropogenic. Documenting and understanding past variability, therefore, has a vital role to play in understanding present and predicting future change in Earth System functioning. This section focuses on the last 400 000 to 500 000 years, as this time period allows appraisal of four full glacial-interglacial cycles; these dynamics have been the normal operating mode of the Earth System throughout the later stages of human evolution.

The four-cycle Vostok ice core record from Antarctica, spanning the last 420 000 years (Fig. 1.3; Petit et al. 1999), provides the single most compelling template for multi-millennial scale natural variability in the geologically recent past. Of the many noteworthy features of the Vostok record, two provide an essential point of departure for any attempt to place contemporary trends into the longer-term context of natural variability. First, the atmospheric trace gas and isotopically inferred temperature records show that, over the whole of the last four glacial-interglacial cycles, values have oscillated within recurrently similar extreme values. Secondly, the changes in temperature and trace gas concentrations show a high degree of coherence throughout the sequence. Taken together, these observations demonstrate that the vast transformations involved in swings from interglacial to full glacial conditions have all taken place within a strongly self-limiting system; moreover, they show that the self-regulation of the system involves complex interactions in which atmospheric greenhouse gases play a significant part as climatic amplifiers and through essential feedback mechanisms. It is in the context of demonstrable self-regulation, involving maximum global atmospheric concentrations over almost half a million years of about 280 ppmv for CO_2 and 750 ppbv for methane, that any evaluation of contemporary values rising beyond 360 and 1 700, respectively, must be placed. These contemporary values are already significantly in excess of the peaks recorded in the Vostok series even when they are smoothed to replicate the processes affecting the trace gas record in the Vostok ice (Raynaud et al. 2003) (Box 2.1).

2.2.2 Millennial-Scale Oscillations and Abrupt Changes

While the Vostok record provides an essential long-term perspective, it fails to resolve the changes that have taken place on shorter time-scales. For these, archives that provide information with greater temporal resolution are

Box 2.1. The Ice Record of Atmospheric Greenhouse Trace Gases: Reliability and Dating

D. Raynaud · T. Blunier

Air trapped in glaciers and ice sheets is unique as it provides a clear record of the changes in greenhouse trace gas (CO_2, CH_4, N_2O) levels during the past. Not all glaciers and ice sheets provide an equally reliable record of greenhouse gas concentrations. Where melting occurs, gas content and gas composition may be altered by chemical reactions taking place in aquatic systems or by physical gas exchange between the gaseous and the aquatic sections.

Under dry and cold conditions of polar areas, essentially in Antarctica and Greenland, the top layer of the ice sheets (the first 50 to 130 m) results from the compaction of the surface snow through sintering. In this porous firn layer air readily enters the open spaces and records essentially the same composition as the atmosphere. Below this zone the air in the firn is static and mixes only by molecular diffusion. An equilibrium between molecular diffusion and gravitational settling is reached for each gas component (Craig et al. 1988; Schwander 1989). As a consequence, the air, just before being trapped at the base of the firn column, dates back several decades due to the slow diffusion through the firn pores and has a composition that departs slightly from the atmosphere because of the gravitational fractionation. The magnitude of this fractionation is well known, allowing an accurately corrected ice core record to be constructed.

Physi- or chemi-sorption of gases (especially CO_2) at the surface of the snow and firn grains, and subsequent expulsion of the attached gas molecules after recrystallisation of the grains in the ventilated top layer of firn may induce uncertainty into ice records of trace gases. Selective fractionation of the atmospheric ratios may also occur during the last stage of the closing of channels leading to the bubble close-off (Bender 2002). However, this effect does not significantly affect the concentrations of major trace gases. Despite these possibilities, no significant modifications of greenhouse trace gas concentrations during the trapping phase have been identified. This is demonstrated by the consistency between trace gas concentrations measured in air from the firn and the gas record directly measured in the atmosphere (Battle et al. 1996; Etheridge et al. 1996) and the generally good match of atmospheric and ice core data (Fig. 2.3).

Slow chemical reactions may alter CO_2 concentrations after the gas has been trapped in ice. This has been observed in Greenland where high concentrations of impurities in the ice may lead to significant *in situ* CO_2 production via acid-carbonate interactions and oxidation of organic material (Anklin et al. 1997; Delmas 1993; Haan and Raynaud 1998). Antarctic records provide the most reliable data of changes in global atmospheric CO_2 (Raynaud et al. 1993). Carbon dioxide measurements made several years apart on the same core show no significant changes. Antarctic results are consistent between sites to within a few parts per million by volume despite the coring sites having different ice accumulation rates, temperatures and concentrations of impurities.

At depth, air bubbles progressively disappear and air hydrates form as the ice molecular structure encapsulates the air molecules in the so-called brittle zone (in which recovered ice commonly contains a high density of cracks and fractures). Results obtained from the brittle zone of a single ice core have to be considered with caution as the presence of air hydrates in the deeper parts of long ice cores may induce artifacts in the record. However, multi-site data may be used with more confidence as the brittle zone usually does not have the same age in cores from different sites. Providing that appropriate extraction procedures are used, the agreement between records from different sites or measurements performed on the same core several years after the initial measurements confidently indicates that there are no significant artifacts linked with the air-hydrate occurrence in ice (Raynaud et al. 1993).

Bacterial activity has the potential to alter trace gas composition and its isotopic signature. In polar regions the bacterial concentration is low and bacterially induced alteration of the trace gas composition has yet to be confirmed. However, polar ice cores sporadically show high N_2O values that may originate from *in situ* bacterial production (Flückiger et al. 1999; Sowers 2001) but the significance of any resultant bacterial alteration of the record has yet to be demonstrated.

Dating ice-core records presents challenges. As a consequence of the air trapping process, the air bubbles found at the bottom of the firn column were closed off at different times. Consequently a given ice sample does not have an exact age reflecting its last contact with the atmosphere, but rather an age distribution. The width of the age distribution is as low as seven years at high accumulation/high temperature sites but can be several centuries for Antarctic low accumulation/low temperature sites (Schwander and Stauffer 1984). Furthermore, because the enclosure process occurs 50 to 130 m below surface, the gas is younger than the surrounding ice and the difference in age between ice and gas depends on the temperature and accumulation rate at the site. It can vary between a few hundred to a few thousand years under present day conditions and becomes larger under ice age conditions.

A critical question in global change science is the establishment of the extent to which anthropogenic atmospheric changes over the last few centuries have been unprecedented

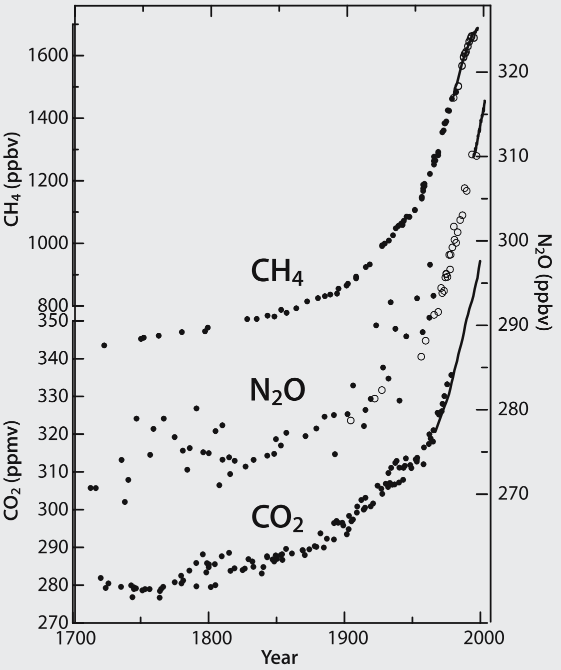

Fig. 2.3. Greenhouse trace gas records since AD 1700 (adapted from Raynaud et al. 2003). The ice core measurements overlap with direct atmospheric measurements in the contemporary period (*solid lines*)

over the last 400 000 years. The record of atmospheric gas composition is smoothed during the air trapping process. Since in the case of the Vostok record this smoothing averages over centuries, it may be questioned whether an anthropogenic signal can be observed in the Vostok data. A simulation to obtain a smoothed Vostok-like record of the present anthropogenic CO_2 increase (Raynaud et al. 2003) shows that such an increase would be imprinted in the record through a CO_2 peak reaching concentrations higher than 315 ppmv with a very slow return toward the pre-industrial level. Such a CO_2 signal is not visible in the Vostok record (Fig. 2.4), although the time resolution of the record does not exclude a pulse-like atmospheric CO_2 signal of a few decades duration with concentrations as high as today. However, this would require both a large carbon release within a few decades (of the order of 200 Gt C) and an equally large and rapid uptake. Such an oscillation is not compatible with the present understanding of the global carbon cycle.

An important question is whether the time resolution of the ice record is precise enough to resolve the leads or lags between greenhouse gases and climate signals. The main uncertainties in this respect arise in connection with the age differences between enclosed air and the surrounding ice. In regard to the onsets of the last two glacial-interglacial transitions, the best-resolved records indicate an uncertainty of about hundred to a few hundred years and an Antarctic warming leading the CO_2 increase by a few hundred years (Monnin et al. 2001; Caillon et al. 2003). In the case of rapid signals like those of the Dansgaard/Oeschger events (cf. Sect. 2.2.2), the uncertainty in age difference is reduced to 10–20 years (Leuenberger et al. 1999; Severinghaus et al. 1998).

Despite the uncertainties and caveats discussed above, ice-core data provide an excellent record of past changes; the record can be used with confidence and provides the most direct and accurate evidence for past atmospheric change yet obtained. The atmospheric greenhouse gas record measured in ice cores is a smoothed temporal record whose accuracy is currently of the order of ±5 ppmv for CO_2 and ±10 ppbv for CH_4.

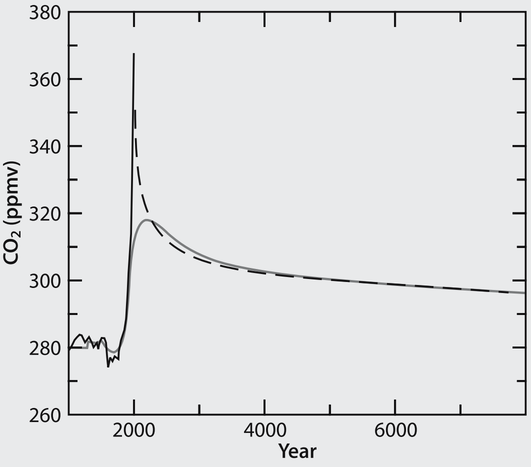

Fig. 2.4. Simulation of the minimum smoothed Vostok-like CO_2 record (in *grey*) that would result from the hypothetical incorporation of the present anthropogenic CO_2 increase (in *black*) in an ice core record (Raynaud et al. 2003)

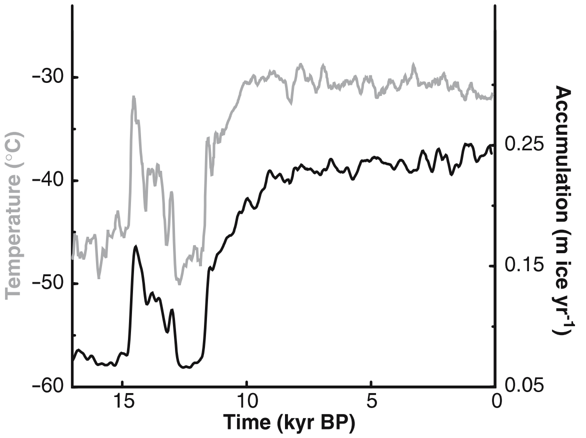

Fig. 2.5. Ice accumulation and oxygen isotope (interpreted as temperature) records from the GISP2 (central Greenland) ice core for the period between the present and 18 000 years ago (Alley et al. 1993; Alverson and Oldfield 2000), showing the abrupt climate shift at the termination of the Younger Dryas cold event some 11 600 years ago. In this record the event is manifested as a warming estimated to be as much as 15 °C, accompanied by a doubling in annual precipitation volume, that occurred in less than a decade

required. The ice cores from central Greenland provide a detailed, well-substantiated and repeatable record spanning the last glacial cycle of around 100 000 years. The rapid oscillations in inferred temperature (Dansgaard/Oeschger Cycles, see Fig. 2.5) recorded during the glacial part of the record often show over half the amplitude of the full glacial/interglacial cycle (Grootes et al. 1993). Apparently synchronous palaeo-oceanographic changes have been widely detected in the northern hemisphere (e.g., Behl and Kennett 1996; McManus et al. 1999; van Kreveld et al. 2000; see Fig. 2.6) and there are an increasing number of continental archives demonstrating parallel patterns of variability on land (e.g., Chen et al. 1997; Allen et al. 2000; Wang et al. 2001; Fang et al. 1999).

In Antarctica relatively high resolution records covering significant parts of the same time interval are, or will soon become, available from the Byrd Station, Taylor Dome, Law Dome (Indermuhle et al. 1999; Raynaud et al. 2000) (Fig. 2.7) and the first stages of analysis of the Dome C (Concordia) core (Flückiger et al. 2002). Now that data from the two hemispheres have been synchronised using common variations in the methane records (Blunier et al. 1998; Raynaud et al. 2000, 2003), several new insights have emerged. Although both sets of polar records show strong evidence for millennial-scale oscillations during the last glacial period in almost every parameter measured, the record from the opposite poles is often out of phase and, for some of the major oscillations, it is in antiphase. Moreover, during the glacial termination, the main warming trend in Antarctica precedes any rapid temperature increase in the northern hemisphere.

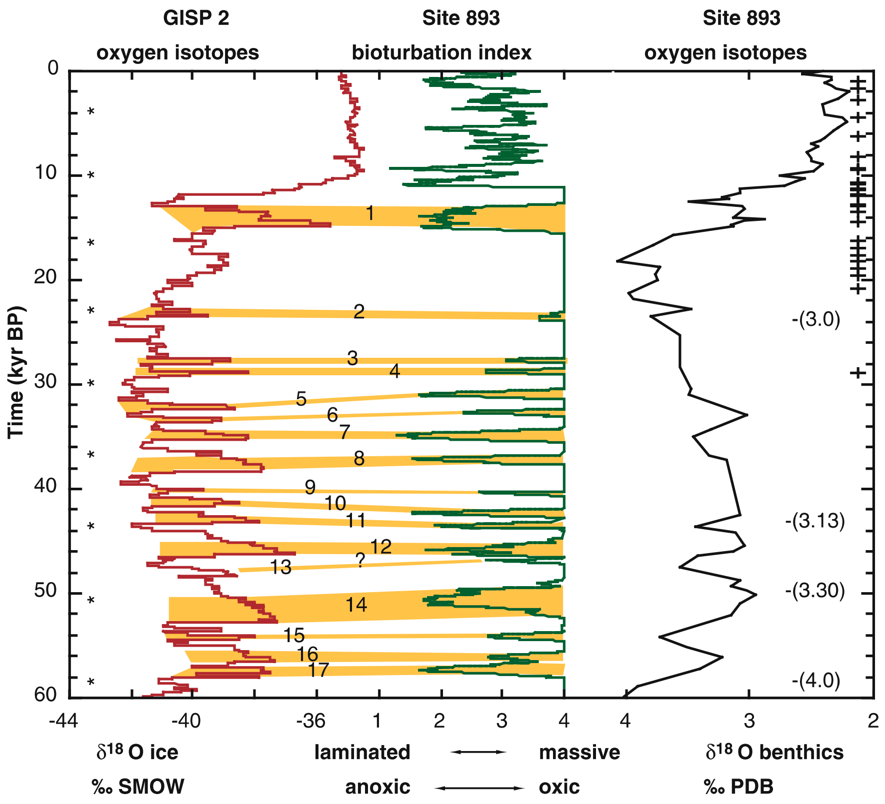

Fig. 2.6.
Low latitude expression of millennial scale climate oscillations taken from GISP2 oxygen isotopes, Santa Barbara basin (Site 893) bioturbation index and high-frequency variations in the CaCO$_3$ record of 70KL (Behl and Kennett 1996). Comparison of site 893 bioturbation index and benthic foraminiferal δ^{18}O records with $\delta^{18}\text{O}_{\text{ice}}$ time series from GISP2, showing the excellent correlation of site 893 anoxia (lamination) events to 16 of 17 of the warm interstadials of GISP2. Bioturbation index is presented as a 49 cm (ca. 300–400 years) running average to dampen high-frequency variation and to match the resolution of the GISP2 record. Chronologies for GISP2 and site 893 were independently derived. Radiocarbon age control points (+) and SPECMAP data used for the site 893 age model are shown to the right. Numbers in () refer to standard data of the SPECMAP stratigraphy. The base of each core interval in Hole 893A is indicated by *arrows* to the left

These observations further refine the perspective on past global changes, for they show that:

- major switches in the earth's climate system occurred on much shorter time scales than the glacial/interglacial cycles;
- the recorded changes were often rapid and of high amplitude;
- the changes demonstrate widespread spatial coherence, but, when characterised with sufficient temporal resolution, they are not globally synchronous; and
- complex inter-hemispheric leads and lags occur that require feedback mechanisms for amplifying and propagating changes.

In terms of present day and future implications, these observations are especially important, for they raise the possibility of anthropogenically induced global changes triggering positive feedbacks capable of provoking sudden, dramatic switches in climate comparable to those that have occurred in the past.

Aspects of the broad pattern of change presented above call for closer attention, specifically the rapidity with which the Earth's climate system may undergo major rearrangement. The best-documented period of rapid major change falls at the end of the glacial period, some 11 600 years ago. At mid to high latitudes in the northern hemisphere, the rapid warming at the opening of the Holocene is the final, decisive step in a sequence of oscillations. It represents the culmination of a suite of changes that appear to begin with the first clearly detectable warming trend in the record from Antarctica some 6 000 years earlier. Many lines of evidence point to a rapid warming at the opening of the Holocene, with records from central Greenland indicating that dramatic changes occurred within only a few decades at most (Alley et al. 1993; Alley 2000; Fig. 2.8). Studies of the opening of the Holocene from a wider range of sites may well provide the strongest empirical evidence available for the speed with which the Earth's climate system can respond given a sufficiently powerful combination of external forcing and internal amplification. They may also shed light on the rate at which ecological systems can respond to such rapid changes (Amman and Oldfield 2000; Birks et al. 2000).

2.2.3 Climate Variability in Interglacial Periods

Most of the high variability in inferred temperature outlined above is characteristic of glacial intervals and terminations, but the Earth is currently in a major interglacial that has lasted for over eleven millennia. It is, therefore, not surprising that an increasing amount of attention has been devoted to characterising climate during the last, Eemian interglacial (Marine Isotope Stage 5e). Depending somewhat on definition and on the chronology adopted, this interglacial spanned

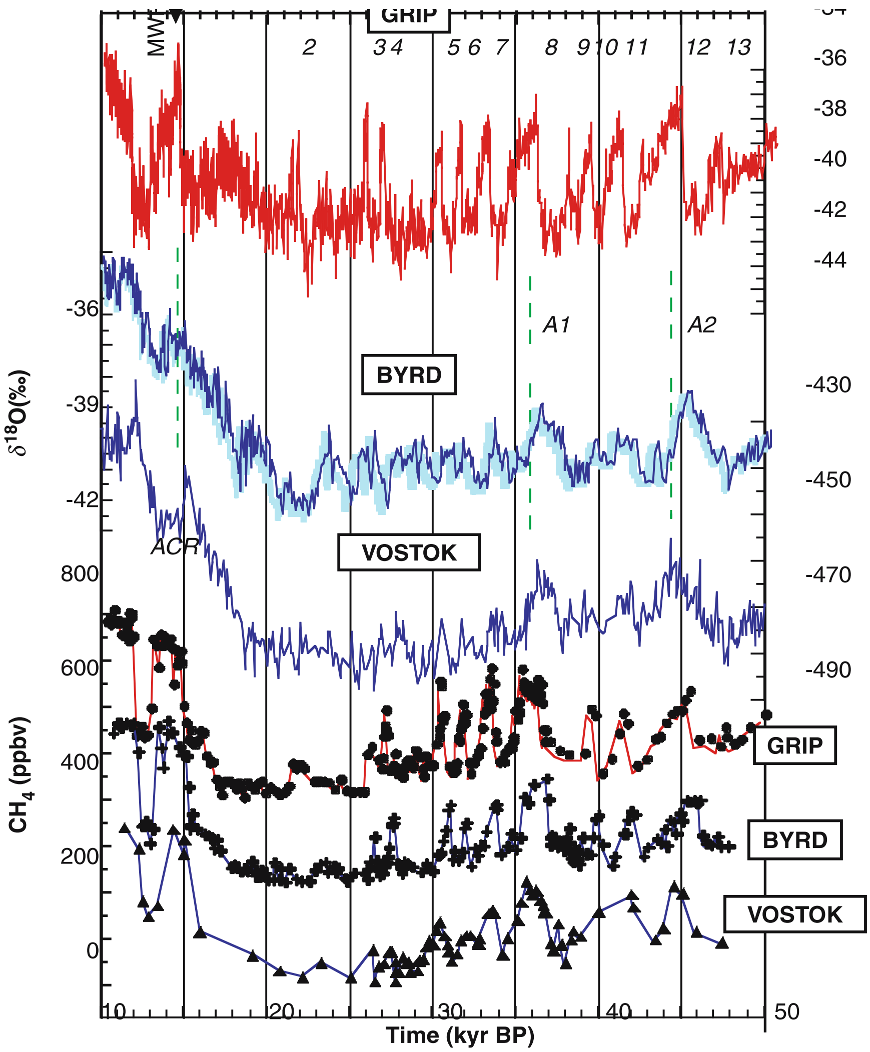

Fig. 2.7.
Inter-hemispheric phasing of the Antarctic Cold Reversal and the Younger Dryas and the timing of the Antarctic Cold Reversal and the atmospheric CO_2 increase with respect to the Younger Dryas event, as deduced from the CH_4 synchronisation, the isotopic records of the GRIP, Byrd and Vostok ice cores, together with the CO_2 record from Byrd (Blunier et al. 1998)

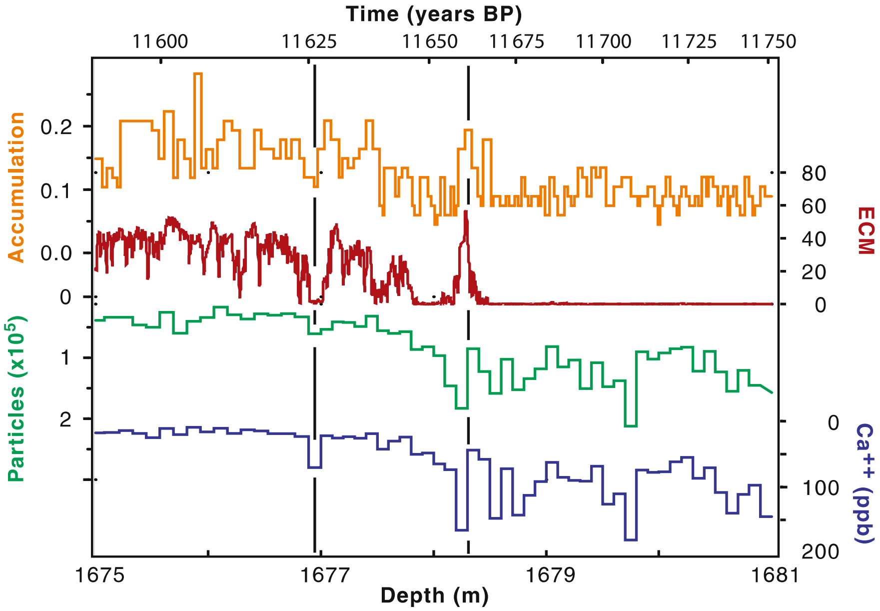

Fig. 2.8.
The end of the Younger Dryas in the GISP2 ice core from central Greenland (Alley 2000). Shown are selected curves illustrating the possible flickering behaviour near the transition: snow accumulation in m ice yr^{-1} (*orange*); electrical conductivity, ECM current in microamps (*red*); insoluble-particulate concentration in number ml^{-1} (*green*); soluble-calcium concentration in ppb (*blue*). The main step at the end of the Younger Dryas falls between 1677 and 1678 m depth, between the two probable flickers indicated by the *vertical lines* at 1676.9 and 1678.2 m depth

around 10 000–15 000 years between about 135 000 and 110 000 years ago. During the first half of the Eemian, summer insolation in the northern hemisphere reached an exceptionally high maximum from which it declined to an exceptionally low minimum by the end of the Eemian. Cortijo et al. (1999) have shown that in response to this, sea surface temperatures in the North Atlantic peaked during the early Eemian, declining steeply around 120 000 years ago. Using an Ocean-Atmosphere General Circulation Model forced by glacial inception conditions, Khodri et al. (2001) simulate a rapid southward shift in the site of North Atlantic Deep Water formation. Thus both the empirical findings and model simulations are in good agreement. Pollen records from Europe (e.g., Guiot et al. 1989) are also consistent with a marked cooling during the Eemian. These and other studies summarised in Labeyrie et al. (2003) confirm that the Eemian was not a period of uniform climate, thus countering the view that only glacial periods were marked by significant natural climate variability. It is important to realise, however, that external forcing during the Eemian differed significantly from that during the Holocene, the present interglacial period.

The isotopic record from central Greenland ice cores has sometimes been invoked as evidence that climate variability during the Holocene was an order of magnitude less than the variability during glacial periods and at the transition between glacial and interglacial intervals (Grootes et al. 1993). This view requires serious qualification. At the beginning of the Holocene, some 11 600 years ago, northern hemisphere summer insolation was at a maximum from which it has steadily declined. As a result, the early- to mid-Holocene was warmer than present in northern high latitudes, though the slow melting of the Laurentide Ice Sheet delayed the expression of this in parts of North America and Europe. At mid- to lower latitudes in the northern hemisphere, the contrast between high northern hemisphere summer insolation and low winter insolation, combined with the greater thermal inertia of the ocean compared with the land, led to increased temperature contrasts between land and sea and hence stronger monsoonal activity. Superimposed on these changes largely linked to external forcing is abundant evidence for climate variability on annual to millennial timescales. The central Greenland ice core record itself shows a rapid change in temperature and ice accumulation, correlated to a similar rapid temperature change in Germany and elsewhere, early in the Holocene some 8 200 years ago (Von Grafenstein et al. 1998) (Fig. 2.9). However, the most dramatic refutation of a relatively constant Holocene climate comes from low latitudes, where the Holocene is marked by major hydrological changes comparable to those accompanying the transition from glacial to interglacial periods (Gasse and Van Campo 1994) (Fig. 2.10). Even in temperate and higher latitudes, many lines of evidence point to Holocene changes in both temperature (Bradley 2000) and precipitation/evaporation balance (Bradbury et al. 2000) that lie outside the range of values captured by instrumental records (Fig. 2.11). There is some suggestion that Holocene variability in the North Atlantic region has included a damped continuation of that marked by Dansgaard/Oeschger Cycles during preceding glacial times (e.g., Bond et al. 1997).

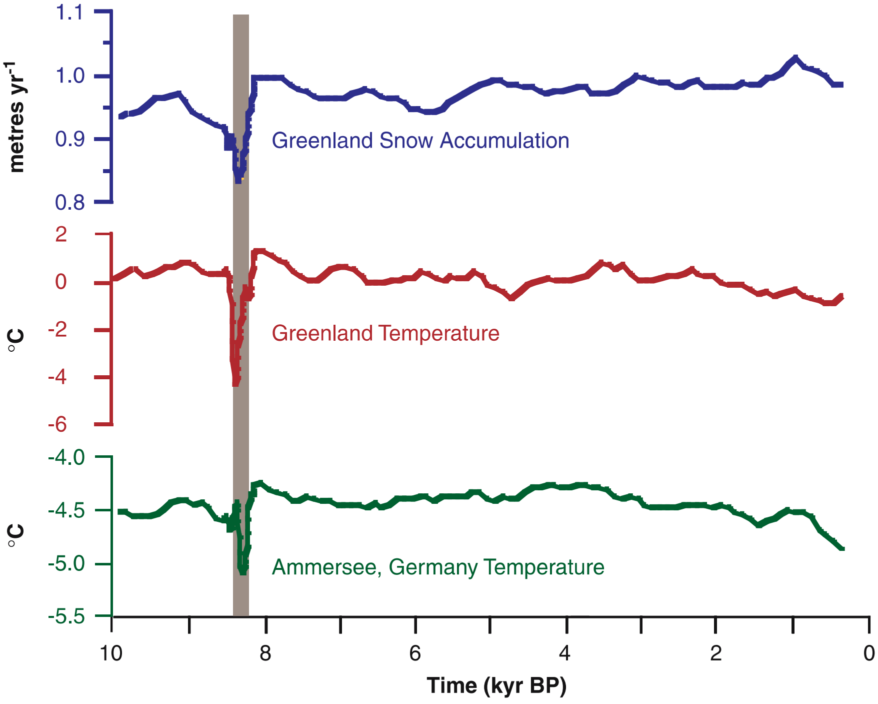

Fig. 2.9.
Snow accumulation and isotopically inferred temperature records in the Greenland GISP2 ice core and a temperature record derived from oxygen isotope measurements of fossil shells in the sediments of Lake Ammersee, southern Germany (Von Grafenstein et al. 1998), showing a major climatic instability event that occurred around 8 200 years ago, during the Holocene. The event was large both in magnitude, as reflected by a temperature signal in Greenland of order 5 °C, and in its geographical extent, as indicated by the close correlation of the signal in these two locations. The dramatic event is also seen in the methane record from Greenland, indicating possible major shifts in hydrology and land cover in lower latitudes

Palaeo-climatic evidence demonstrating that strong variability persisted into the second half of the Holocene is particularly important as this is the period that forms the baseline used to assess the significance of major anthropogenic perturbations. The amplitude and frequency of past hydrological variability (e.g., droughts) are especially important because human populations are concentrated in temperate and tropical latitudes. Moreover, in many of the populous areas of the globe, hydrological changes are much more crucial for human survival than are changes in temperature. One important implication of this part of the palaeo-record is that for many parts of the world, and even without any hypothesised anthropogenic greenhouse gas forcing, the future course of climate change is likely to include variability beyond any expectations based on an analysis of the short period of instrumental measurements alone.

Natural Late Holocene variability on sub-decadal to century timescales may be characterised in some cases as shifts in mean temperature that, despite regional differences of detail in timing and expression, appear to show a degree of coherence over a wide area (for example, the so-called Medieval Warm Epoch and Little Ice Age) (Bradley et al. 2003). Variability may also manifest itself as shifts in the spatial teleconnection patterns (teleconnections are defined here as the correlation between specific planetary processes in one region of the

Fig. 2.10.
Changes in lake level over the past 15 000 years in an east to west transect of lakes in the northern monsoon domain of Africa (Gasse 2000), showing lake level variations as much as 100 metres, an indication of large changes in the regional hydrological balance