Understanding the Earth System

Global Change Science for Application

Earth system science has been described as 'a science struggling with problems too large for its participants, but too important to ignore'. This exciting new book provides an overview of this enormous, rapidly growing field, tackling current scientific debates and policy-relevant questions on the global environment.

The multi-disciplinary author team explains the what, the how and the why of climate science, providing a review of research from the last decade, illustrated with cutting-edge data and observations. A key focus is the development of analysis tools that can be used to demonstrate society's options for mitigating and adapting to increasing climate risks. Emphasis is given to the importance of Earth system feedback mechanisms and the role of the biosphere. The book explains advances in modelling, process understanding and observations, and the development of consistent and coherent studies of past, present and 'possible' climates.

This highly illustrated, data-rich book is written both for those who use Earth system model outputs and need to know more about the science behind them, and those who develop Earth system models and need to know more about the broader context of their research. The author team is made up of leading scientists involved in QUEST, a major, recently completed, UK-led research programme. The book forms a concise and up-to-date reference for academic researchers or students in the fields of climatology, Earth system science and ecology. By highlighting the application of scientific results to contemporary policy issues, the book is also a vital resource for professionals and policy-makers working on any aspect of global change.

'This beautifully organized and written book connects the fundamental natural sciences – meteorology, oceanography, ecology and many others – to provide the most complete understanding yet of how our planet works. But it doesn't stop there. It lays out a seamless storyline from the deep past through the present and into the future that contextualises the current phenomenon of global change. Critically, the book brings humanity fully into the picture, from the impacts of environmental change to potential stewardship of the planet, while always maintaining the rigour that good Earth System research demands.'

– **Professor Will Steffen**, *Executive Director, ANU Climate Change Institute, Australian National University*

'With a scope extending across paleoclimate, current climate, feedbacks, human dimensions impacts, adaptation, and mitigation, this ambitious book succeeds in providing a deep yet comprehensive view of the earth system in all its facets. Particularly impressive and novel is its rich set of clear and original figures to illustrate each issue in vibrant ways that will be especially useful for educators and students.'

– **Professor Susan Solomon**, *Ellen Swallow Richards Professor of Atmospheric Chemistry and Climate Science, Massachusetts Institute of Technology*

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Global Change Science for Application

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Foreword

In 1999, as the new chief executive of the UK Natural Environment Research Council (NERC), I was struggling to find a simple, high-level description of what the NERC did, to use in discussions with our political masters. A conversation with Professor Chris Rapley (then the director of the British Antarctic Survey, part of the NERC) struck a chord; the Medical Research Council is about understanding how the human body works, NERC is about understanding how the planet works. The NERC does Earth system science. Simple, but was it actually true? Certainly, NERC-funded scientists studied all the components that make up the Earth system, but by and large what we were not doing was studying the interactions *between* these key components – between the biosphere and the atmosphere for example – and whilst "NERC strives to understand how the planet works" was a convincing argument to use in negotiations with government, in reality we needed to do better. So QUEST was born.

I don't remember who first suggested a NERC-directed programme in Earth system science (it wasn't me), but once the idea was floated it seemed blindingly obvious, and *Quantifying and Understanding the Earth System* emerged from some intense and scientifically exciting discussions among the members of the research community in 2002. I had the privilege of appointing Colin Prentice to be the scientific leader and chair of the QUEST research programme, and the programme itself started in 2003. I retired from NERC in 2005, and lost touch with what the NERC was doing in general, and with QUEST in particular. So it was with pleasure and surprise that I received Sarah Cornell's e-mail out of the blue in December last year, asking me to write the foreword to this book.

It is an amazing piece of work. When I was running the NERC I was in the fortunate position of being surrounded by colleagues working on all aspects of environmental science. If I wanted to know something, all I had to do was ask the experts, which I frequently did. One of the things I missed most when I retired was losing touch with major developments in environmental research outside my own immediate areas of expertise. Earth system science is a good example. But now here is the next best thing! A truly wonderful, up-to-date synthesis of the major links that exist between our climate system and the biosphere. The contributing authors and the scientific editorial team read like Europe's 'who's who' of Earth system science, writing with great clarity about not only what we know about the scale of the impacts of the human enterprise on our planet, but also what we don't know.

There can be no more important scientific endeavour than to show policy-makers what we are doing to the planet, and what it means for our future. I am under no illusion that explaining to policy-makers what the science says will necessarily get them to 'do the right thing'; the translation of science into policy is a messy, iterative, slow process, fraught with difficulties and frustrations. But a work of this quality must make a difference, and I feel privileged to have been in at the beginning.

Professor Sir John Lawton
York
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Preface

Why have we written this book?

In 2001, the former chief executive of the UK Natural Environment Research Council (NERC), Sir John Lawton (Lawton, 2001), wrote:

> One of the great scientific challenges of the 21st century is to forecast the future of planet Earth. …We find ourselves, literally, in uncharted territory, performing an uncontrolled experiment with planet Earth that is terrifying in its scale and complexity.

In the year that followed, the research council consulted widely among its scientists, policy stakeholders and the international research community about how to address that challenge. By the autumn of 2002, a plan of action was in place. The research council had earmarked a very substantial research budget for 'Quantifying and Understanding the Earth System', matched by an ambitious vision for the science that this research programme – QUEST – would address:

> QUEST will seek to provide a more robust understanding of the global carbon cycle. QUEST will require partnerships, both within the UK, and between colleagues in Europe and the USA. NERC's planned investment in QUEST is substantial. It has to be if we are really to make a difference. It is difficult to think of a more important thing to search for (NERC, 2002).

We, the authors of this book, have worked together over several years under the auspices of QUEST (Box 1). QUEST ran from 2003 to 2011, as one of several initiatives worldwide aligned with the internationally developed Earth system science agenda for collaborative research. The research programme sought to do more than 'just' provide a more robust understanding of the global carbon cycle, although interactions between biogeochemical cycles and climate have been at the heart of the programme.

Box 1– About QUEST

Quantifying and Understanding the Earth System (QUEST), the UK Natural Environment Research Council's directed research programme for Earth system science, ran from 2003 until 2011. Nearly 300 scientists from over 50 institutions were involved in QUEST through its collaborative research projects and related activities. Their mission was to quantify Earth system processes and feedbacks for better-informed assessments of alternative futures of the global environment. The programme's research objectives were to make substantial progress in resolving the following scientific questions:

How important are biotic feedbacks to contemporary climate change?

QUEST investigated the contemporary carbon cycle and its interactions with climate and atmospheric chemistry. New modelling and data analysis tools were developed, incorporating a broader suite of the biogeochemical processes that occur on land and in the oceans. This new breadth enables Earth system models to be used to assess the feedbacks among physical, chemical and biological processes that have contributed to determining the contemporary atmospheric greenhouse-gas content.

How are climate and atmospheric composition naturally regulated?

Palaeoclimate records compiled from diverse marine and terrestrial data sets give a richer picture of landscapes, ecosystems and environmental changes in the past. These reconstructions of past climates have been compared with simulations made using climate and biogeochemistry models, to improve understanding of the interactions between atmospheric composition and climate, primarily on timescales of up to a million years.

How much climate change is 'dangerous'? And how much difference could managing the biosphere make?

Climate change is likely to have serious consequences for ecosystems, and for the societies that depend on them. QUEST carried out interdisciplinary, multi-sectoral studies that provide information about potential global and regional impacts of different degrees of environmental change. QUEST has also assessed the potential for biosphere management to mitigate climate change in a way that accounts for the constraints of land availability and environmental change.

Addressing these 'big-picture' scientific questions about the Earth system presents new operational challenges for research. QUEST explicitly set out to tackle the problematic interfaces between diverse science areas, notably those between the land, atmospheric and marine domains; modelling and observations; palaeoclimate and the contemporary Earth; and the natural and human sciences. Making advances towards integrating knowledge across these component areas of the Earth system requires sustained cooperation by scientists from different specialist backgrounds, institutions and cultures. QUEST was set up explicitly to encourage such cooperation, operating a programme of collaborative interdisciplinary research, investing in carefully designed multi-institution consortium projects, and supporting cross-cutting synthesis activities to respond to today's scientific challenges. QUEST scientists were also active in international collaborative networks and agenda-shaping assessments. Notably, QUEST included a very strong international programme of collaboration, supported by the CNRS of France. Also, through the life of the programme, project scientists maintained active engagement with policy stakeholders, recognizing the societal significance of the research.

One major theme QUEST addressed was feedbacks between climate and the biosphere (see Box 2), with the development of new dynamic global models of land and marine ecosystems and atmospheric chemistry for coupling into climate models. Together with improved approaches to link them with observational data obtained from satellite remote sensing and field and laboratory experimental and empirical studies, these are the tools that allow Earth system interactions to be identified and explored in the contemporary world.

Another key research question is: 'What are the natural controls that regulate Earth's climate and atmospheric composition over much longer timescales?' Society is concerned about human-induced, or anthropogenic, changes to climate, associated with accelerated emissions of greenhouse gases into the atmosphere and changes to the land surface. These changes are taking place in the context of a great deal of natural variability, particularly when set into the context of geological timescales. Understanding the drivers of these changes, and assessing the consequences to ecosystems and landscapes of warming and cooling events is a major challenge that QUEST has sought to address.

Improving our understanding of the interconnected physical, ecological and biogeochemical dimensions of climate change opens opportunities to 'forecast' planet Earth, or rather, to make robust predictions of what consequences would be likely to result from different climatic conditions. This understanding has implications for human society, which is increasingly recognizing the vital need to adapt to climate change and mitigate by reducing emissions of carbon dioxide (CO_2) and other greenhouse gases. Earth system science can be deployed in assessing the potential impact of different degrees of climate warming on key socio-economic sectors (such as agriculture, fisheries, water resources, biodiversity and human health). Improved understanding of the role of the biosphere in climate also offers the potential for managing land ecosystems (forests, farmlands and biomass for energy use) differently to optimize their mitigation potential.

Sir John Lawton was right in that this research effort has been an international enterprise. Nations recognize the strategic importance of research into the dynamic processes of planet Earth and, as concern about global change grows, more effort is being directed in many countries towards research that integrates knowledge about all the sub-systems of our world. With the UK investment in this area, QUEST was able to build strong collaborative relationships, particularly with a large team of Earth system scientists supported by the French Centre national de la recherche scientifique (CNRS), Swiss scientists at the University of Bern and Zürich's Eidgenössische Technische Hochschule (ETH Zürich) and with scientists from many nations who participated in QUEST's extensive programme of working groups. Overall, QUEST has been a major initiative in global-change research, so we draw substantially on our collective experience in this book.

Our motivation in writing this book is to provide an overview of the current state of knowledge of Earth system science, a very rapidly developing field of research. We have highlighted the areas where there is scientific consensus, but perhaps the more important motivation for us is our desire to explain the many areas where there are misconceptions, active debates and open questions still to be addressed. We are not making a detailed scientific assessment of global change; that enormous synthesis process is the domain of the Intergovernmental Panel on Climate Change (although several members of the author team are involved in the IPCC as authors or reviewers). The IPCC's in-depth worldwide peer-review and political-approval process means that it tends not to highlight debated and contested areas of the science. These contested areas are of particular interest to us, in fact, because a clear understanding of the issues, including the arguments and uncertainties, is needed by policy- and decision-makers.

The origins and evolution of Earth system science

The concept of Earth – the whole planet – as a complex interacting system was set out in the late 1960s by James Lovelock whose provocative ideas about planetary-scale feedbacks developed into the Gaia hypothesis (Lovelock, 1979). Although the idea of Earth operating like a living organism, with its dynamic processes acting in concert for self-stabilization, was and still is controversial, it has also been a fruitful source of new thinking.

The period from the late 1960s onwards saw remarkable technological developments in space exploration, new Earth observation technologies, and the development of computers capable of handling and storing very large data sets and running calculations at unprecedented rates. The Bretherton Report (Earth System Sciences Committee, 1988) was a landmark document setting out the scope for an Earth system research agenda that would make the most of these opportunities. This new field of study would integrate studies of Earth's 'spheres' (Box 2) – the atmosphere, oceans, ice sheets, land surfaces, and marine and terrestrial ecosystems, explicitly looking at the interactions between the spheres at various timescales.

Box 2– The 'spheres' of the Earth system

When we conceptualize Earth as a system, our analysis focuses on the characteristics and interactions of a set of interdependent components. These components are often referred to as 'spheres' (see Figure P1), which have different intrinsic rates and patterns of dynamic change:

- ***Atmosphere*** – the fluid layer of air that surrounds Earth, bound by gravity. The atmosphere plays a vital role in Earth's energy balance. It receives solar radiation, the energy that drives life on Earth. It is characterized by relatively rapid physical and chemical processes that shape heat transfer, weather patterns and the long-range transport of dust and aerosols on timescales of hours to seasons.
- ***Hydrosphere*** – all water on Earth, including the oceans, freshwater and groundwater as well as the water cycling through the atmosphere. Over 95% of the volume of water on Earth is found in the oceans, while the rest is split between ice, groundwater, lakes, soil moisture, the atmosphere, rivers and the biosphere. The hydrological cycle describes the processes associated with the movement of water through these different reservoirs, powered by solar radiation. Processes that affect the hydrosphere are generally slower than those of the atmosphere, but vary greatly in time and scale; the residence time of water can be thousands of years in the oceans but only 10 days for water vapour in the atmosphere. Because the heat capacity of water is greater than that of air, the hydrosphere is particularly important for the global redistribution of heat.
- ***Cryosphere*** – although often classed as part of the hydrosphere, Earth's areas of ice cover are climatically important for other reasons. Residence times for ice and snow vary much more than the hydrosphere, from seasonal up to one million years for the ancient ice in eastern Antarctica. The reflection of incoming solar radiation off ice surfaces has a cooling effect, so their high albedo makes them an important factor in geophysical feedback processes. Another key process that determines the extent of the cryosphere and its interaction with other spheres is the thermal diffusivity of snow and ice. This is much lower than air, meaning that it cannot transfer heat very quickly, and therefore any land or ocean covered with snow and ice are

decoupled from their normal interactions with the atmosphere.

- ***Lithosphere*** – the rocky component of Earth, usually extending from the crust to the upper mantle, although in the context of Earth system science it can also include the mantle and core. This provides the ultimate control on supply of essential elements to the biosphere, and the variations in topography and landscape are key physical controls on climate. With exceptions such as earthquakes and volcanic eruptions, the Earth system processes of the lithosphere are generally slow. Processes like erosion, tectonics and geological uplift operate on timescales of centuries to millions of years.

Together, these components comprise the ***geosphere***, or the physical climate system. Earth system science also is concerned with the processes of life itself:

- ***Biosphere*** – comprised of all of Earth's living organisms, on land and in water bodies, the ecosystem processes of this sphere operate at multiple timeframes, but diurnal and seasonal cyclic processes are particularly important features for the Earth system. Energy is obtained mainly through photosynthesis and is used by the organisms on Earth up through the trophic levels. Important processes include the cycling of nutrients such as carbon, nitrogen and phosphorus.

The interdependence of these spheres means that an event can trigger consequences through the whole system. Earth system analysis explores these causal chains of interactions, the patterns of effects in the different spheres, and the explanatory mechanisms for changes.

In an extension of the concept of Earth's spheres, the ***anthroposphere*** is seen as a distinctive subset of the biosphere, capable of disproportionate impacts on all the other spheres of the Earth system through the deployment of technology. The expansion of communication technologies has driven a much more rapid connectivity on a global scale. In earlier phases of human history, new discoveries or inventions that led to greater efficiency in human transformation of landscapes or appropriation of natural resources were spatially independent. Now, ideas can have global consequences within very short timescales, wherever they arise. Proponents of the idea of the anthroposphere, and the related concept of the cybersphere, argue that incorporating understanding of the dynamics of human activities – including information flows – is essential for explaining and predicting the behaviour of the Earth system.

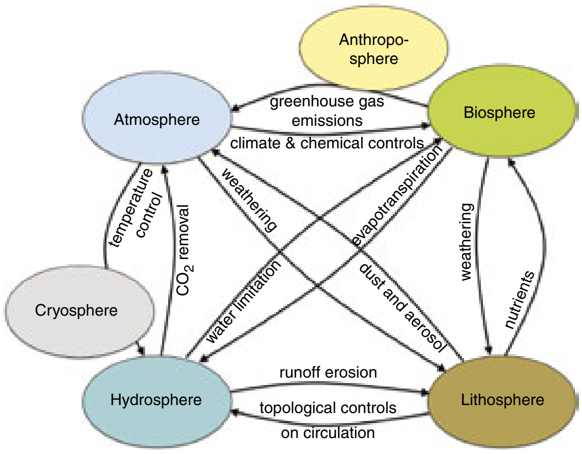

Figure P1 – The 'spheres' of the Earth system and examples of their exchanges.

The two vital strands to this work – Earth observation and global modelling – are both enormous enterprises, and right from the start it was recognized that international efforts would be needed to pull together the fundamental knowledge of Earth's processes and the infrastructure to support an Earth system research effort. Because these research networks, institutional structures and policy-dialogue mechanisms feature throughout this book, we describe them briefly here. Box 3 sets these developments in their historic context.

Scientific institutions in Earth system research

Scientific institutional developments to support the global Earth system research effort included the establishment by the International Council of Science Unions (ICSU) of a set of international collaborative global-change programmes. These have the remit to agree on scientific priorities and help coordinate collaborative international activities funded by national research agencies. The World Climate Research Programme was the first of these programmes to be set up by ICSU, in partnership with the World Meteorological Organisation (WMO) and later also with support from UNESCO's International Oceanographic Commission. The International Geosphere–Biosphere Programme (IGBP) followed in 1987, to address biogeochemical interactions on a global scale. Diversitas was set up in 1991 to address biodiversity and ecosystem change, with the support of UNESCO, the International Union of Biological Sciences and the Scientific Committee on Problems of the Environment. The International Human Dimensions Programme on Global Change was established in 1996 as a partnership of ICSU and the International Social Sciences Council. (It is now also sponsored by the United Nations University.) Together, these four programmes cover the key fields of global-change research, from the physical climate system, through biogeochemical cycles, ecosystems and human society. But even this level of integration of knowledge reached its limits. The challenges of bridging all these fields of knowledge are huge. In 2001, the four programmes collectively formed the Earth System Science Partnership,[1] to provide another level of international coordination and cooperation in research and societal engagement. This structure is still evolving[2] as society's needs, and the perceived opportunities for technological innovation, change.

It was evident from the start of these programmes that although there was excellent scientific understanding of environmental processes at a small scale, there was a dearth of basic information at the global scale. There was a need for long-term time-series studies so that the dynamics of key processes could be observed. Global budgets were needed for the major biogeochemical cycles of water, carbon, nitrogen, sulfur and other elements, with a better understanding of their environmental (and human) sources and sinks. Together with partner organizations at the national level, the programmes coordinated studies linking space and detailed in-situ process studies in land and marine environments, and of the atmosphere. Early examples include NASA's 'Mission to Planet Earth' (Wickland, 1991); 'Global Change and Terrestrial Ecosystems' (Walker and Steffen, 1996); 'Past Global Changes' (Alverson, 1998); and the 'Joint Global Ocean Flux Study' (Fasham *et al.*, 2001). As each project reached completion, the new data and models opened new vistas and raised new questions, so the process of international observation and collaborative networking has continued. QUEST was actively engaged in this process from its inception. Together, all this effort has combined to give unprecedented insight into workings of Earth as a system.

Institutions at the science–policy interface in Earth system research

Another area where institutional change has been required is in the interface between science and policy. The most visible of these interfaces is IPCC,[3] established in 1989 by the UN Environment Programme and the WMO to provide the world's governments with a consensus scientific view of climate change, its economic and social impacts, and a scientifically and technologically informed assessment of possible responses. At the time of writing, the IPCC is now working on its fifth comprehensive assessment report. Since its creation, it has expanded the range of climate-linked topics it addresses through special reports and technical guidelines. Yet even this is not enough for today's challenges of environmental change. Recognizing the global scale of ecosystem change, and the importance for human society of biodiversity and ecosystem health, another international body is being created using similar scientific assessment and worldwide policy engagement mechanisms to the IPCC: the newly approved Intergovernmental Platform on Biodiversity and Ecosystem Services,[4] which will provide synthesis reports targeted for policy-users in the area of conservation and sustainable use of natural resources. Alongside these global-scale activities, there are many mechanisms and processes for information exchange at the science–policy interface at both the national level (such as research centres linked to government departments, and forums linked to national academies of science) and the international level (notably the technical and scientific advisory bodies associated with global environmental conventions and treaties).

Box 3 – A history of Earth system science

The foundations of Earth system science lie in physical climate science, but the field has developed as a result of its particular focus on the nature of the interactions between the many components of the Earth system, the human controls of system processes, and of course the global scale of inquiry. As in many other fields of study, Earth system science began with the collection of empirical or observational data, shifting from the anecdotal towards more coordinated, systematic inquiry, coupled with the development of explanatory theory. These developments in the field of knowledge

[1] www.essp.org
[2] www.icsu.org/future-earth
[3] www.ipcc.ch
[4] www.ipbes.net

have taken place in the context of increasingly formalized scientific cooperation, and the creation of intergovernmental organizations to support research and science policy dialogues. Fuller treatments of the history of climate and Earth system science are given in Weart (2008), Liverman *et al.* (2002) and Cornell (2010).

~1700s	The foundations were set for climate science in its 'parent disciplines' of meteorology and oceanography. These foundations included the development of observational data sets from around the world, such as surface temperature, ocean currents and atmospheric dynamics; a systematization of study; and the development of theory to explain climatic phenomena such as the tides, winds and monsoon systems.
~1800s	Many fundamentals of the climate system were determined: Earth's greenhouse effect was calculated by Joseph Fourier. The properties of greenhouse gases were identified by John Tyndall. Svante Arrhenius noted the anthropogenic greenhouse effect of CO_2, including projections for the extent of future warming. Structures were established for formalized scientific cooperation, including major oceanographic expeditions and the creation of organizations to support climate research. The International Meteorological Organization was formed as a specialist intergovernmental agency for scientific exchange and cooperation between national research bodies.
Early 1900s	The 'Great Acceleration' in human activity was enabled as oil fields were first exploited on a large – and rapidly expanding – scale. G. S. Callendar made early measurements of the warming trend, having calculated the 'artificial production of carbon dioxide' through fuel combustion. The natural controls were also being explained: Milutin Milanković explained the role of solar orbital changes on climate. The USA led a major post-war research investment in climate science and Earth observation technology.
1950s	Numerical modelling emerged as a powerful tool for global-change science, with the quantification of feedbacks, global atmospheric modelling (including the GCMs) and the explanation of the links between atmospheric structure, chemical composition and radiative forcing. The first observations of Earth were made from space.
1960s	Charles Keeling's high-precision measurements in Hawai'i showed that the atmospheric CO_2 concentration was increasing with time with a pronounced seasonal signal. Key concepts relating to climate as a system were explained and accepted, including positive and negative feedbacks, the role of ice and albedo changes, and the evidence of orbital changes in palaeorecords. Syukuro Manabe and Richard Wetherald made the first model calculations of climate sensitivity to a doubling of CO_2. The international Global Atmospheric Research Program (GARP) was established, linking governmental (UN) and scientific institutions in ways that set the pattern for subsequent international collaboration and science–policy interactions.
1970s	Key Earth system insights were obtained into episodes of comparatively rapid climate changes in the past, including feedback processes; the biosphere's effects on climate; and the role of atmospheric aerosols and dust. Space exploration gave information about the 'system behaviour' (and past climates) of other planets. The first weather satellite (NASA GOES, launched in 1975) provided data that could be used for model validation. The recognition that human-induced changes, including aerosol production and deforestation, have climate consequences fed into growing societal concern about the environment. A coherent environmental movement emerged and strengthened.
1980s	Essentially, this was a decade of consolidation of evidence addressing debates that had begun earlier: Greenland ice cores showed that very rapid (century-scale) climatic changes were possible; the Vostok ice core showed the very strong coupling of CO_2 and temperature over several glacial cycles; the strong warming trend over the previous decade was observed, and the cooling effect of anthropogenic aerosol that partially disguised the warming was determined. This was also a period of scientist mobilization, with the creation of the IPCC for the science–policy interface; and the evolution of GARP into the global-change programmes IGBP and WCRP, supporting strategic research cooperation. The Bretherton Diagram mapped out an international collaborative scientific agenda for Earth system science.

1990s	The UN Framework Convention on Climate Change was agreed. The first IPCC Assessment Reports were published, refining research questions and driving progressive improvements in global-change models and process-based research. Two new international, non-governmental global-change programmes were formed: Diversitas provided an umbrella programme for biodiversity research, and the IHDP addressed social science research on global environmental change. The Human Interaction Working Group's Social Process Diagram identified key research areas for the social sciences concerned with global environmental change.
2000s	A strong scientific consensus now exists on the anthropogenic control on climate. Stronger warming has been observed, increasing fairly steadily since the 1970s. The effects on ice sheets are a growing concern, because of sea-level rise and poorly understood physical feedbacks. Understanding biophysical and biogeochemical feedbacks is a research priority, because they shape the timeframes and scope for society's adaptive responses to climate change. A key focus remains in bridging and integrating the knowledge of the natural and social sciences in the Earth system context.

The aims of Earth system science

Earth's climate history has been subject to enormous changes, and our growing understanding of these changes indicates that the interactive Earth system is astonishingly complex and an exceedingly rich subject for research. By gaining a better understanding of the processes and control mechanisms that make up the climate system, the aim of today's research effort is to provide society with knowledge about how the system might respond to future perturbations.

Developing this kind of predictive power means:

- **Bringing together the best available understanding of Earth's living and non-living components**, or – using the 'spheres' terminology, linking the biosphere (including the anthroposphere) with the geosphere, atmosphere and hydrosphere. This requires much improved understanding of physical, chemical and biological processes, which we have summarized in Chapter 2. It also requires many key gaps in climate models to be filled. We address those gaps and progress in Earth system modelling in Chapter 5.
- **Finding independent ways to verify or constrain this dynamic process understanding.** Chapters 3 and 4 describe how we use the palaeorecord (fossils and other measures from the past) together with contemporary science, and combine Earth observation from space with ground-level observations. Very often, the picture has to be pieced together from many strands of evidence, so we give particular attention to data synthesis and comparisons of models and data involving multiple data sources.
- **Bringing computer modellers, 'ground-up' field and laboratory experimentalists and 'top-down' Earth observational researchers together**. This has proved to be a surprisingly big challenge. As science has become ever more specialized, bigger differences have developed between different knowledge communities, who may have very different ideas of what counts as scientific evidence, what are the best ways to present research findings, how best to share and store data, and so on (described humorously in Randall and Wielicki, 1997). Moss and Schneider (2000) suggested that increasing confidence in a scientific finding requires coherence in the quality and amount of theoretical underpinning, observations, model results and expert consensus. Achieving 'joined-up' Earth system science requires careful meshing of very different gears across different physical scales. This integrative effort is a key theme throughout the remainder of this book, but is addressed particularly in Chapter 5.

In turn, these new insights demand new dialogues that are currently developing worldwide (these are summarized briefly here; research in these areas is addressed in more detail in Chapter 1):

- **Improved academic interaction between the natural and social sciences**. Many 'environmental issues' of the last few decades are now seen as *socio*-environmental issues, such as air and water pollution, the over-exploitation of land and natural resources, and even wildlife and natural-habitat conservation. The cross-disciplinary challenges of delivering integrated knowledge in this area are evidently even greater than linking across the different knowledge communities in the biogeochemical and physical sciences, but the need to do so is no less pressing. Chapters 6 and 7 show how Earth system science offers important tools for assessing and mitigating the impacts of changing climate on ecosystems and the human societal systems that depend on them.

- **Deeper, more responsive interaction between science and policy communities.** The whole history of Earth system science as a field of study has taken place in a context of awareness of the societal importance of its research findings and engagement with policy in the co-development of research priorities. In common with previous global environmental challenges, the trans-boundary and multicultural issues in Earth system science require societal engagement and response mechanisms that operate across the science–policy interface. However, as our knowledge develops more explanatory and predictive power, the nature of this interface changes, with different policy areas becoming engaged, and at different levels of governance. In other words, the deeper the scientific understanding, the more complex the policy terrain for engagement. And the dialogue is emphatically not a one-way provision of science for decision-makers. Many argue for more 'democratization of science', both in terms of scientists engaging directly in informing society's responses to environmental change challenges, and in terms of opening up more transparent deliberative processes about the science that is used in the policy process. Our final chapter sets the scientific issues described in the earlier chapters back in their social context.

The Editors on behalf of the Author Team

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Units

We have followed international scientifically agreed standards for the units in this book, most of which are defined by the International System of Units (SI). Many of the basic units are very familiar:

mass	gram	g
length	metre	m
temperature	kelvin	K
quantity of substance	mole	mol
time	second	s
	hour	h
	year	a

We also use scientific notation and exponents for quantities, so for example:

- cubic metres per second is denoted as $m^3\ s^{-1}$
- watts per square metre is denoted as $W\ m^{-2}$
- per year is denoted as a^{-1}

Many of these units require prefixes in order to avoid presenting very big numbers, which are taxing on the eye when reading! The prefixes we use are:

Name	Factor	Symbol
kilo	1000, or 10^3	k
mega	10^6	M
giga	10^9	G
tera	10^{12}	T
peta	10^{15}	P
exa	10^{18}	E

One petagram (Pg) is equivalent to a gigatonne, an alternative unit often used in global-change science because of the magnitudes of processes like the carbon cycle. A tonne is 1000 kg.

We also refer to atmospheric concentrations in terms of mixing ratios, as parts per million (ppm), and parts per billion (ppb, that is 10^{-9}).

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