GLOBAL IGBP CHANGE

Executive Summary

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Global Change and the Earth System

A Planet
Under Pressure




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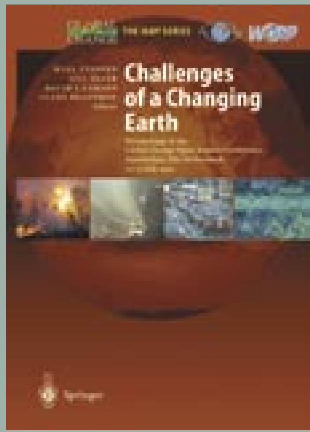

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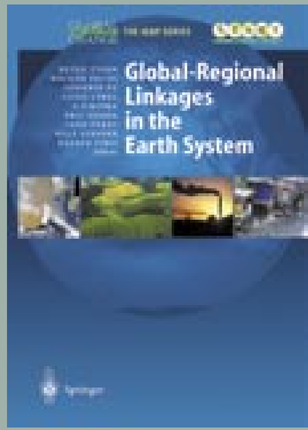

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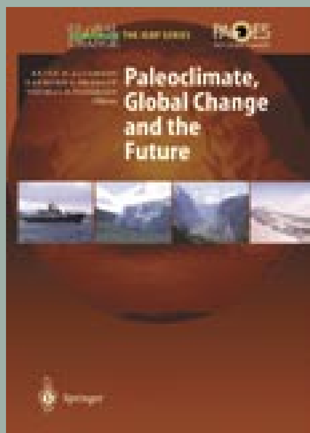

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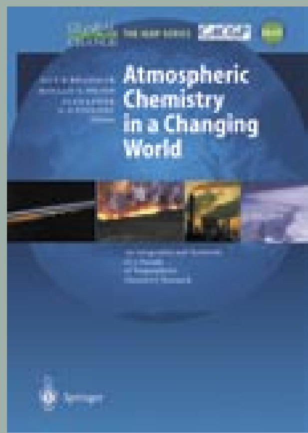

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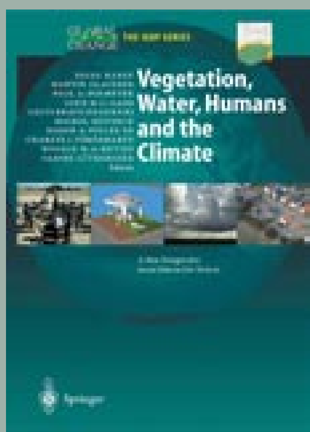

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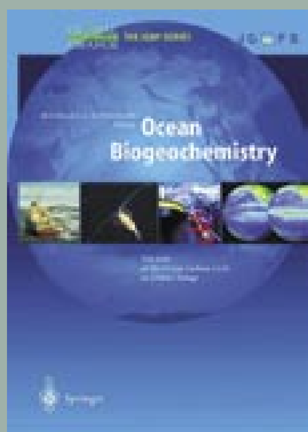

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Global Change and the Earth System: A Planet Under Pressure

Executive Summary

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Foreword

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. 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 something within which people have had to operate, subject only to the great forces of nature and the occasional perturbations of extraterrestrial origin. Earth's environment has been a bountiful source of resources as well as a remarkably stable life support system that has allowed human civilisations to develop and flourish.

A profound transformation of Earth's environment is now apparent, 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 20th century. During the last 100 years human population 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. Most of the world's fisheries are fully or over-exploited. The composition of the atmosphere - greenhouse gases, reactive gases, aerosol particles - is now significantly different than it was a century ago. The Earth is now in the midst of its sixth great extinction event. The evidence that these changes are affecting the basic functioning of the Earth System, particularly the climate, grows stronger every year. The magnitude and rates of human-driven changes to the global environment are in many cases unprecedented for at least the last half-million years.

This executive summary describes a book that 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 does 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 this new internal force of change? Can human activities trigger abrupt and potentially irreversible changes to which adaptation would be impossible? How serious is this inadvertent human experiment with its own life support system?

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

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Science Highlights

Somewhat more than a decade ago it was recognised that the Earth behaves as a system in which the oceans, atmosphere and land, and the living and non-living parts therein, were all connected. While accepted by many, this working hypothesis seldom formed the basis for global change research. Little understanding existed of how the Earth worked as a system, how the parts were connected, or even about the importance of the various component parts of the system. Feedback mechanisms were not always clearly understood, nor were the dynamics controlling the system.

Over the intervening years much has been learned. Global change research has confirmed many of the hypotheses and much of the sketchy understanding of that time, adding a wealth of quantitative detail and process-level understanding at all scales. It is now clear that global change is one of the paramount environmental issues facing humankind at the beginning of the new millennium.

The task of synthesising a decade or more of global change research has been daunting, but the rewards have been great. Detailed results and individual references can be found in the IGBP synthesis volume 'Global Change and the Earth System: A Planet Under Pressure', published by Springer Verlag in the IGBP book series. In this executive summary only generalised highlights are presented, the so-called big-picture findings:

- **The Earth is a system that life itself helps to control**. Biological processes interact strongly with physical and chemical processes to create the planetary environment, but biology plays a much stronger role than previously thought in keeping Earth's environment within habitable limits.

- **Global change is more than climate change. It is real, it is happening now and in many ways it is accelerating**. Human activities are significantly influencing the functioning of the Earth System in many areas; anthropogenic changes are clearly identifiable beyond natural variability and are equal to some of the great forces of nature in their extent and impact.

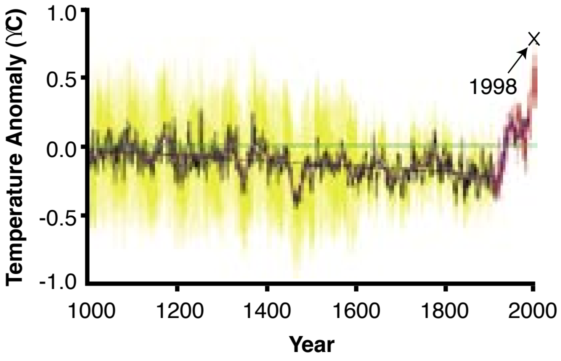
- **The human enterprise drives multiple, interacting effects that cascade through the Earth System in complex ways.** Global change cannot be understood in terms of a simple cause-effect paradigm. Cascading effects of human activities interact with each other and with local- and regional-scale changes in multidimensional ways.

- **The Earth's dynamics are characterised by critical thresholds and abrupt changes. Human activities could inadvertently trigger changes with catastrophic consequences for the Earth System**. Indeed, it appears that such a change was narrowly avoided in the case of depletion of the stratospheric ozone layer. The Earth System has operated in different quasi-stable states, with abrupt changes occurring between them over the last half million years. Human activities clearly have the potential to switch the Earth System to alternative modes of operation that may prove much less amenable to human life.

- **The Earth is currently operating in a no-analogue state**. In terms of key environmental parameters, the Earth System has recently moved well outside the range of the natural variability exhibited over at least the last half million years. The nature of changes now occurring simultaneously in the Earth System, their magnitudes and rates of change are unprecedented in human history and perhaps in the history of the Earth.

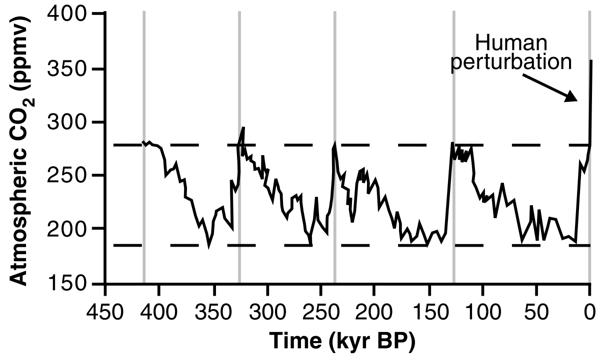
The Earth System is currently operating in a no-analogue state. Human activities are significantly altering the environment at the global scale:

Climate: Mean temperature



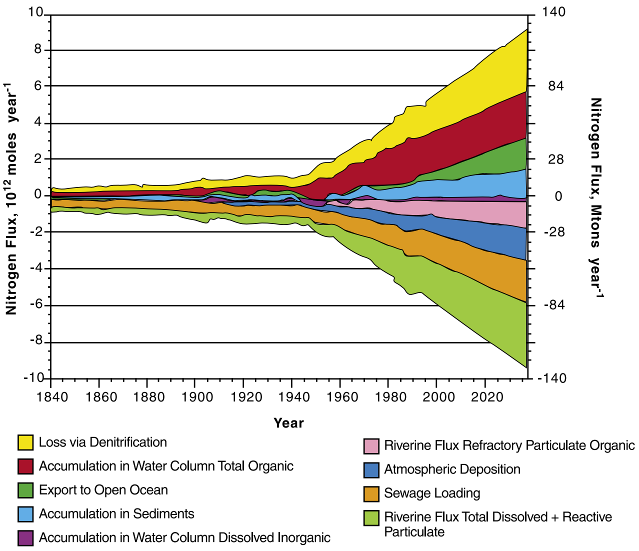
Source: Mann et al (1999) Geophys Res Lett 26, 759-762

Atmosphere: CO_2 concentration



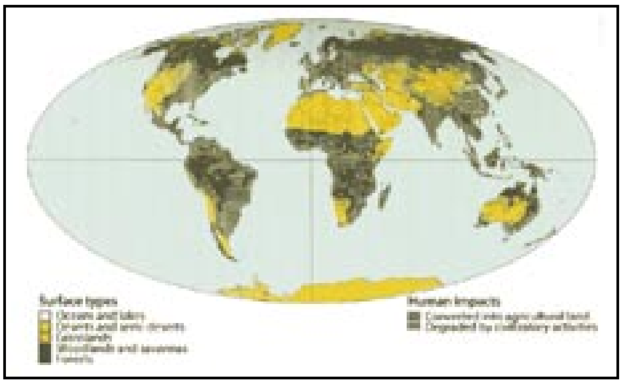
Sources: Petit et al (1999) Nature 399, 429-436; Keeling and Whorf (2000), In: Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Centre.

Coastal Zone: Nitrogen flux



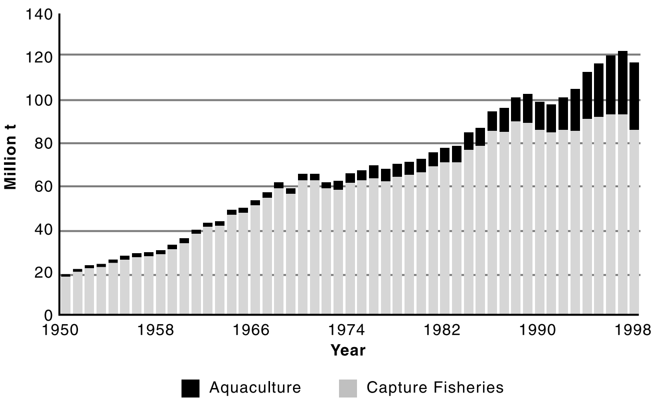
Source: Mackenzie et al. (2002) Chem Geol, 190, 13-32

Land: Land cover



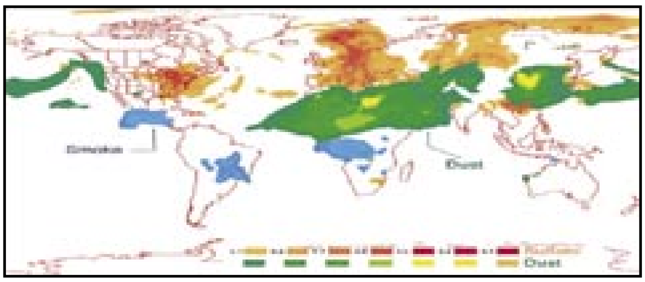
Source: Schellnhuber (1998), In: Earth System Analysis, Springer-Verlag, pp 3-195

Ocean: Fisheries



Source: FAO (2000) The State of World Fisheries and Aquaculture. Food and Agricultural Organisation of the United Nations.

Atmosphere: Aerosols



Source: (http://www.nrlmry.navy.mil/aerosol/ and Heintzenberg et al. (2003), In: Brasseur et al. "The changing atmosphere", Springer- Verlag, pp. 125-156

An Integrated Earth System

Over the last two decades a new imperative has come to dominate environmental concerns. With a rapidly increasing understanding of the nature of Earth's life support system, a growing awareness has emerged that human activities are exerting an ever-accelerating influence on aspects of Earth System functioning upon which the welfare and the future of human societies depend.

The human-environment relationship

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 these spatial and temporal differences, in recent years a global perspective has begun to emerge that forms 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 fundamental aspects of the nature of the planet. The first is that the Earth itself is a single system, within which the biosphere is an active, essential component. In terms of a sporting analogy, life is a player, not a spectator. Second, human activities are now so pervasive and profound in their consequences that they affect the Earth at a global scale in complex, interactive and 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 humans depend.

Systems thinking and its application to the environment are not new. However, until very recently, much of the understanding about how the Earth operates was applied to only pieces (subcomponents) of the Earth. What is really new about the understanding of the Earth System over the last 10 - 15 years is a perspective that embraces the System *as a whole*. Several developments have led to this significant change in perception:

- 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;
- Global observation systems allow the application of *concepts* that were only previously applicable at subsystem level, or regional or local scales, to the Earth as a whole;
- Global databases allow global scale phenomena to be addressed with consistently acquired *data* that have the potential for harmonisation and comparison at a global scale;
- Dramatic advances in the power to infer characteristics of Earth System processes in the past allow contemporary observations to be viewed in a coherent *time continuum*;
- Enhanced computing power makes possible not only essential data assimilation, but increasingly sophisticated *models* improve understanding of functional interactions and system sensitivities.

Science has crossed the threshold of a 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.

The Earth as a system

The fact that the Earth behaves as a single, interlinked, self-regulating system was put into dramatic focus in 1999 with the publication of the 420,000-year record from the Vostok ice core (Fig. 1). These data, arguably among the most important produced by the scientific community in the 20th century, provide a powerful temporal context and dramatic visual evidence for an integrated planetary environmental system.

The Vostok ice core data give a wealth of insights into the Earth System. Three striking characteristics demonstrate beyond any doubt that the Earth IS a system, with properties and behaviour that are characteristic of the System as a whole.

- The temporal dynamics of global temperature and of the global carbon cycle, as represented by the atmospheric concentration of the trace gases carbon dioxide (CO_2) and methane (CH_4), are tightly coupled and show very similar patterns throughout the record.

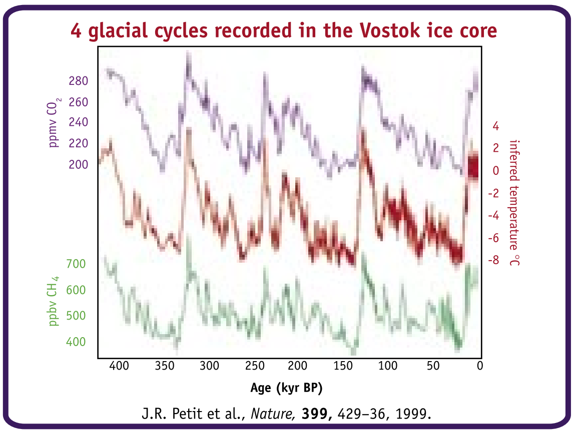


Figure 1. The 420,000 year Vostok ice core record, showing the regular pattern of atmosphere CO_2 and CO_4 concentrations and inferred temperature through four glacial-interglacial cycles. The upper and lower bounds of all three variables are tightly constrained. These features are typical of a self-regulating system.

Adapted from Petit et al. (1999) Nature 399, 429-436 by the PAGES (Past Global Changes) International Project Office.

- The main maxima and minima of temperature and atmospheric trace gas concentration follow a regular pattern through time, each cycle spanning approximately100,000 years;
- The range over which temperature and trace gas concentrations varied is bounded at upper and lower limits; the values fall recurrently within the same envelope through four cycles of the Earth System over the last half million years.

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. The internal dynamics of the System, rather than external forcings, undoubtedly keep the planet habitable for life. For example, without the thin layer of ozone in the upper atmosphere, much more harmful ultraviolet radiation would penetrate to the Earth's surface; and without the thin layer of heat-absorbing greenhouse gases in the lower atmosphere, the planet's mean surface temperature would be about 33 °C lower than it is now.

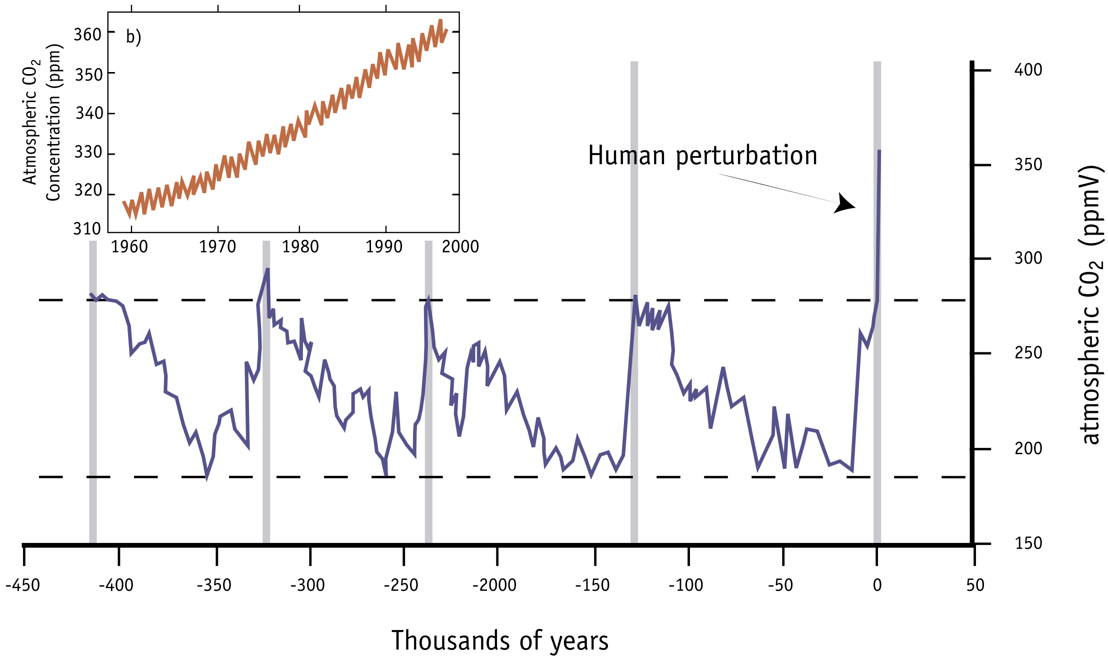


Figure 2. Atmospheric CO_2 concentration from the Vostok ice core record with the recent human perturbation superimposed. The inset shows the observed contemporary increase in atmospheric CO_2 concentration from the Mauna Loa (Hawaii) Observatory.

Sources: Petit et al. (1999) Nature 399, 429-436 and National Oceanic and Atmospheric Administration (NOAA), USA

Global change

Over the past few decades, evidence has mounted that planetary-scale changes are occurring rapidly. These are, in turn, changing the patterns of forcings and feedbacks that characterise the internal dynamics of the Earth System (Figs. 2, 3). Key indicators, such as the concentration of CO_2 in the atmosphere, are changing dramatically, and in many cases the linkages of these changes to human activities are strong. It is increasingly clear that the Earth System is being subjected to a wide range of new planetary-scale forces that originate in human activities, ranging from the artificial fixation of nitrogen and the emission of greenhouse gases to the conversion and fragmentation of natural vegetation and the loss of biological species. It is these activities and others like them that give rise to the phenomenon of *global change* (Box 1).

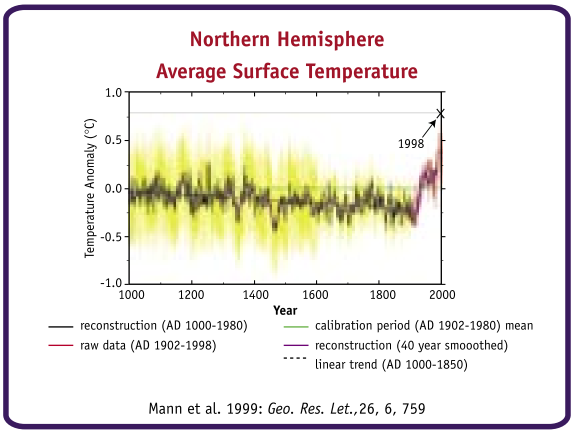


Figure 3. Mean annual surface temperature variations over the northern hemisphere for the last 1000 years.

Source: Mann et al. (1999) Geophys. Res. Lett. 26, 759-762.

Box 1: The Earth System, Climate and Global Change

The term Earth System refers to the suite of interacting physical, chemical, and biological processes that transport and transform materials and energy and thus provide the conditions necessary for life on the planet. Climate refers to the aggregation of all components of weather – precipitation, temperature, cloudiness, for example – but the climate system includes processes involving ocean, land and sea ice in addition to the atmosphere. The Earth System encompasses the climate system, and many changes in Earth System functioning directly involve changes in climate. However, the Earth System includes other components and processes, biophysical and human, important for its functioning. Some Earth System changes, natural or human-driven, can have significant consequences without involving any changes in climate. Global change should thus not be confused with climate change; it is significantly more.

Planetary Machinery

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. Rapid, abrupt changes can occur as the Earth System reorganises into a new state.

Temporal variability

Variability and change are realities of the Earth System, and static, so-called equilibrium conditions are unlikely to be a part of the System on almost any time scale. The record shows that the functioning of the Earth System has varied continuously on all time-scales (Fig. 4). A careful examination of evidence from the past shows that:

- Variability is reflected not only in temperature – variability in the hydrological cycle, which is often of much greater importance to human populations, has been quite extreme on all time-scales in the past;
- No single variable or region truly reflects global variability – global mean conditions mask immense variations in regional responses;
- During the late Holocene, when the natural forcings and boundary conditions were similar to those operating today, there is strong evidence that the range of variability significantly exceeded that captured by instrumental records. Reliance on the very short period of instrumental records gives a false sense of the true variability of the Earth System.

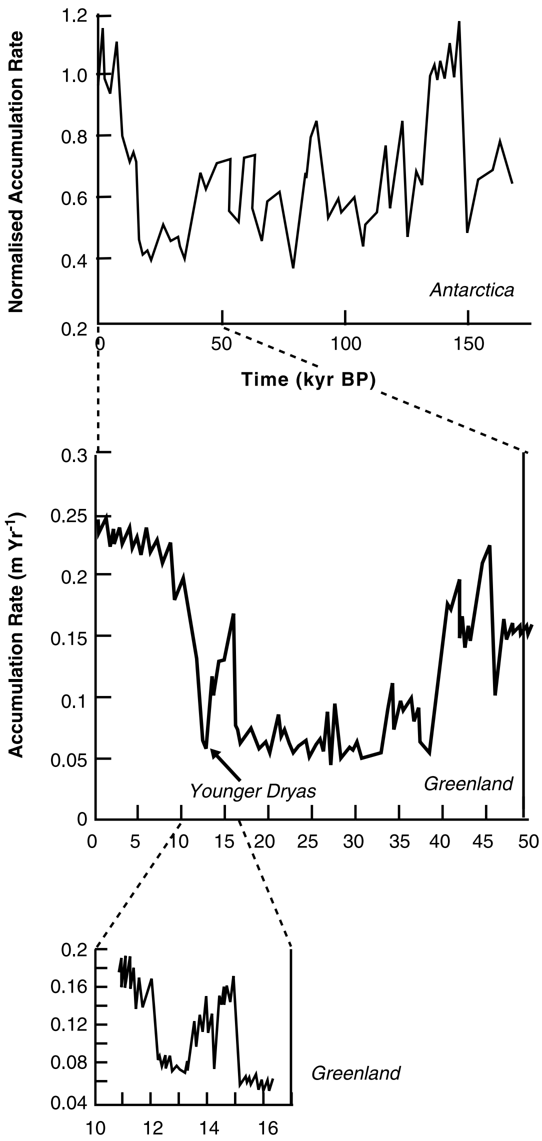


Figure 4. Natural variability in Earth System functioning: ice accumulation rate history at three different time scales. Data from Antarctica (top panel) and Greenland (bottom two panels).

Adapted from Jacobson et al. (eds.) (2000) Earth System Science, Academic Press, p. 479.

Role of biology in Earth System functioning

Biological processes interact strongly with physical and chemical processes to create the environment that keeps Earth habitable for life. The more that the functioning of the Earth System is examined in detail, the greater is the realisation of the role played by life itself in helping to control the System. For example, biological processes contribute significantly to the absorption of atmospheric CO_2 by the oceans, which in turn controls atmospheric CO_2 concentration on long time scales (Fig 5a). Photo-a)

b)

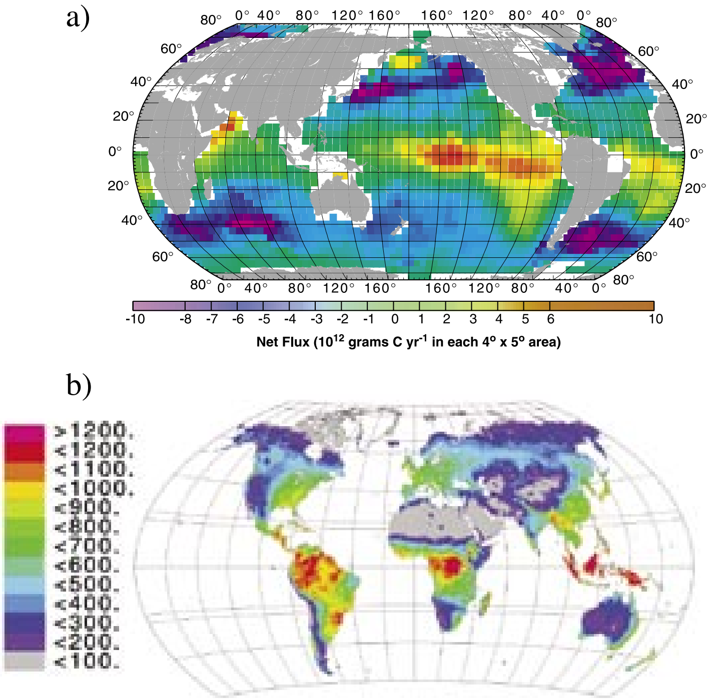


Figure 5. (a) Mean annual exchange of CO_2 across the sea surface. Blue and purple colours denote regions in which the ocean takes up large amounts of CO_2 while orange and yellow colours denote areas where significant outgassing of CO_2 occurs. (b) Annual terrestrial net primary production (g C m^{-2}) estimated as the averaged output of 17 terrestrial biogeochemical models.

Sources: (a) Takahashi et al. (1997) Proceedings of the National Academy of Science (USA) 94:8292-8299. (b) Cramer et al. (1999) Global Change Biology 5 (Suppl.1):1-15.

synthesis by phytoplankton reduces the amount of CO_2 in the surface layer of the ocean, thereby allowing more CO_2 to dissolve from the atmosphere. About 25% of the carbon fixed by phytoplankton in the upper layers sinks to the interior, where it is stored away from contact with the atmosphere for hundreds or thousands of years. This biological pump, along with physico-chemical constraints on the solubility of CO_2, controls the pattern of CO_2 exchange between the oceans and the atmosphere. Intriguingly, the nature of the phytoplankton species involved in the biological pump may hold a key to the rate of and potential for carbon storage (Fig. 6).

The terrestrial biosphere also plays an important role in helping to control the atmospheric concentration of CO_2 (Fig. 5b). Plants remove CO_2 from the atmosphere and convert it to carbohydrates through the process of photosynthesis. However, plant parts eventually die and decay, are eaten by herbivores, or are consumed by fire, all of which lead to the decomposition of the carbohydrates and the return of CO_2 to the atmosphere. Terrestrial cycling of carbon is generally much faster than that of the ocean, and much of the short-term variability in the contemporary CO_2 growth rate in the atmosphere is due to variability in terrestrial uptake or loss.

Terrestrial biota are an important component in Earth System functioning in other ways. For example, the type of vegetation present on the land surface influences the amount of water transpired back to the atmosphere and the absorption or reflection of the sun's radiation. The vegetation's rooting patterns and activity are also important controllers of both carbon and water storage and of fluxes between the land and the atmosphere. The biological diversity of terrestrial ecosystems affects the magnitude of key ecosystem processes such as productivity, and plays a role in the long-term stability of ecosystem functioning in the face of a changing environment.

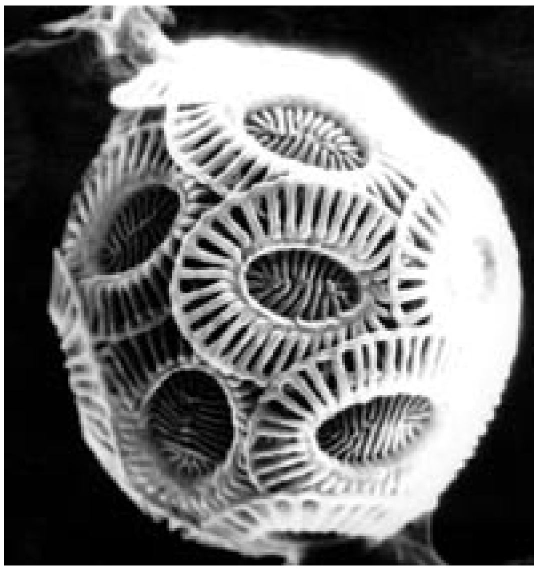
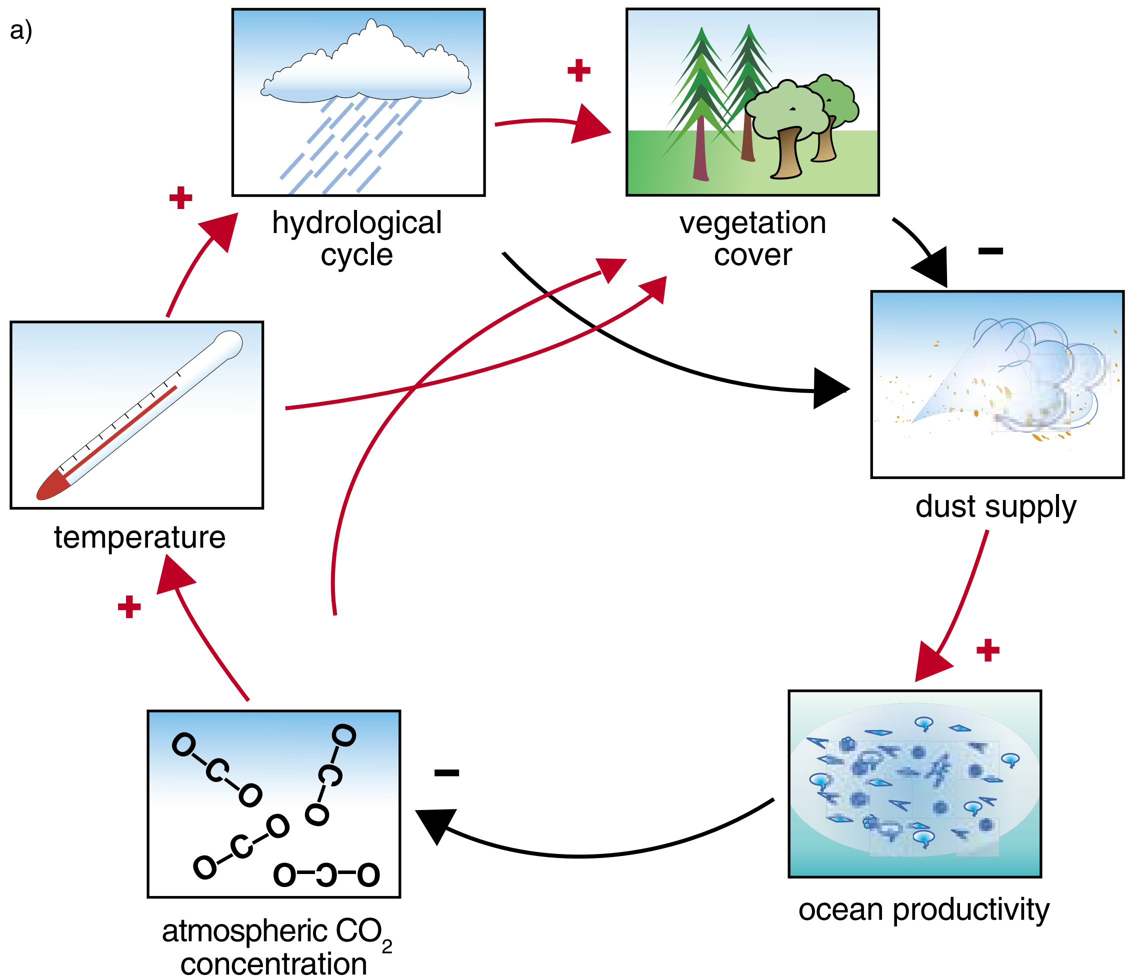


Figure 6. Life in the oceans plays an important role in maintaining geochemical balance in the Earth System and the fate of the carbon that is fixed by the ocean's phytoplankton is very much a function of the size and taxonomy of the species present. For example, in addition to fixing carbon via photosynthesis, one group of phytoplankton, the coccolithophorids, such as *Emiliania huxleyi* (shown above) produces calcium carbonate platelets (liths). Each lith is only about 2.5 μm in length but many are produced every year. It is estimated that blooms of *E. huxleyi* cover about 1.4 million km^2 of the ocean every year. Thus, over geological time, tremendous accumulations of carbon fixed by coccolithophorids develop. The white cliffs of Dover are, for example, largely comprised of platelets from coccolithophorids.

Source: Helge Thomsen, Danish Fisheries Research Institute

Linkages and connectivities

Much global change research focuses strongly on the vertical links between the atmosphere and the Earth's surface. However, components of the global environment, such as ecosystems on land and in the sea, are also connected to each other laterally through the dynamics of the Earth System - through the horizontal movement of water and materials through it, through atmospheric transport and deposition, and through the movement of plants and animals. Moreover, they are connected through energy transfers and through chemical and biological legacies that linger over time. One of the greatest challenges of global change research is to establish the role played by internal forcings and feedbacks within the



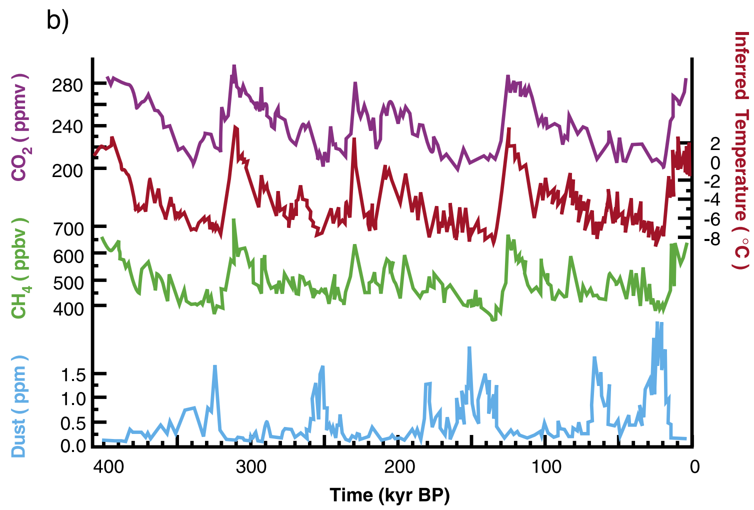


Figure 7. a) Feedbacks in the Earth System: a simplified system involving land cover, dust, atmospheric transport, the ocean biological pump, atmospheric CO_2 concentration, and climate.

b) The pattern of dust deposition through four glacial-interglacial cycles from the Vostok record.

Sources: a) Adapted from Ridgwell and Watson (2002) Paleoceanography 17: 10.1029/2001PA000729. b) From Petit et al. (1999) Nature 399, 429-436.

Earth System, mediated by such connectivities, in the long-term functioning of the System.

An example is the linkage of the terrestrial and marine biospheres through the generation, atmospheric transport, and deposition of dust (Fig. 7). A cooler and drier climate leads to less vegetation cover on the land surface, which in turn leads to an increase in bare soil and thus dustiness. Iron-containing dust from the land is transported by wind over the oceans, where it acts as a fertiliser to phytoplankton (iron is a micro-nutrient) when it is deposited on the ocean surface. This causes a phytoplankton bloom, which increases the productivity of the ocean biota and consequently draws down CO_2 from the atmosphere. Decreasing atmospheric CO_2 concentration leads to a cooler and drier climate, completing the positive feedback loop.

The record of dust deposition from the Vostok ice core (Fig. 7b) hints at the importance of this feedback loop for the functioning of the Earth System in terms of the pattern of glacial-interglacial cycling (Fig. 1). Recent work shows that a simulated dust field for the Last Glacial Maximum, consistent with the Vostok data, can provide enough iron to the Southern Ocean to stimulate a diatom bloom, drawing down CO_2 substantially. The simulated CO_2 drawdown is also consistent with data from a range of marine sediment proxies. In the simulation several factors are found to contribute to higher atmospheric dust content at Last Glacial Maximum - increased atmospheric transport as a result of stronger winds; a reduced hydrological cycle, especially lowered precipitation linked to cold ocean conditions; and reduced plant growth linked to both lower atmospheric CO_2 and drier climatic conditions.

In this example, the synergy between the state of the terrestrial biosphere and changed atmospheric processes is crucial for generating greater dust entrainment, while the enhanced primary productivity of marine diatoms provides the fuel for the biological pump sequestering carbon in the deep ocean. Both terrestrial and marine biota are vital components of the system of interactions that comprise this intriguing feedback loop in the Earth System.

Non-linearities, surprises and thresholds

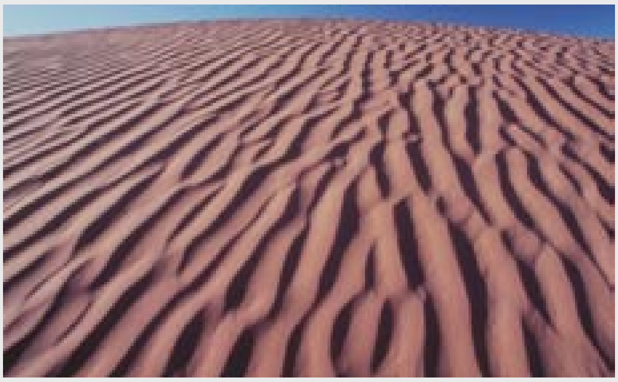
Because human societies have developed and flourished over a very short period of time from an Earth System perspective, and because the period of instrumental observation and modern scientific enquiry is even shorter, a narrow view of the Earth's environment has developed. The notion that a single stable equilibrium is the natural state of Earth's environment is not supported by observations of past global changes. The behaviour of the Earth System is typified not by stable equilibria, but by strong nonlinearities, where relatively small changes in a forcing function can push the system across a threshold and lead to abrupt changes in key aspects of System functioning. Examples include the rapidity of glacial terminations, the exceptionally rapid warming and cooling events in the North Atlantic region, mega-droughts and other extreme events, and the 'browning of the Sahara' (Box 2).

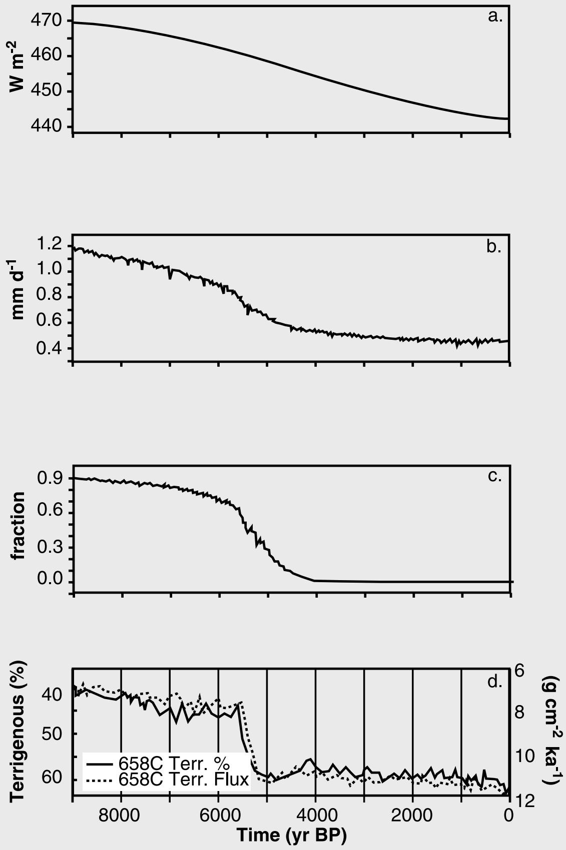
More specifically, the palaeo-record shows that:

- Major switches in Earth System functioning occurred on much shorter timescales than the glacial/interglacial cycles;
- The recorded changes were often rapid and of high amplitude; in some cases temperature over large regions changed by up to 10 °C in a decade or less;
- Although major, abrupt transitions, reflecting reorganisation of the Earth System, are most evident in predominantly cold, glacial periods, they are not absent in the last 12,000 years, especially in lower latitudes;
- The changes demonstrate widespread spatial coherence, but are not always globally synchronous;
- Complex inter-hemispheric leads and lags occur that require feedback mechanisms for amplifying and propagating changes in both space and time.

The potential for abrupt change is a characteristic that is extremely important for understanding the nature of the Earth System. The existence of such changes has been convincingly demonstrated by palaeo-evidence accumulated during the past decade. Unravelling the triggers of such changes and the internal dynamics of the Earth System that connect the trigger to the outcome is one of the most pressing challenges to improving understanding of the planetary machinery.

Box 2: The Browning of the Sahara





The dramatic desertification of the Sahelian region in prehistoric times demonstrates several important features of Earth System functioning. About 6000 years ago the climate in the Sahel-Sahara region was much more humid than today, with vegetation cover resembling that of a modern-day African savanna. About 5500 years ago, an abrupt change in the regional climate occurred, triggering a rapid conversion of the Sahara into its present desert condition.

The ultimate cause was a small, subtle change in Earth's orbit, leading to a small change in the distribution of solar radiation on Earth's surface (part a of figure). Model simulations suggest that this small change nudged the Earth System across a threshold that triggered a series of biophysical feedbacks that led, in turn, to a drying climate (part b). Vegetation changed more sharply in response to changing rainfall (part c), and the region became the present-day desert. Model predictions of the resulting increase in wind erosion and deposition of sand off the West African coast agree remarkably well with observations (part d).

The model simulations suggest that it was an interplay of atmosphere, ocean, vegetation and sea ice changes in widely separated parts of the planet that amplified the original orbital forcing. The abrupt change from savanna to desert in North Africa demonstrates that (i) abrupt changes can occur when thresholds are crossed, (ii) the biosphere plays a critical role in Earth System functioning, and (iii) teleconnections are an essential feature of the planetary machinery.

Photos: D. Parsons. Figure: Claussen et al. (1999) 24, 2037-2040 and deMenocal et al. (2000) Quat. Sci. Rev. 19, 347-361.

The Anthropocene Era

The planet is now dominated by human activities. Human changes to the Earth System are multiple, complex, interacting, often exponential in rate and globally significant in magnitude. They affect every Earth System component – land, coastal zone, atmosphere and oceans. The human driving forces for these changes – both proximate and ultimate – are equally complex, interactive and frequently teleconnected across the globe. The magnitude, spatial scale, and pace of human-induced change are unprecedented in human history and perhaps in the history of the Earth; the Earth System is now operating in a 'no-analogue state'.

The nature of global change

Until very recently in the history of Earth, humans and their activities have been an insignificant force in the dynamics of the Earth System. Today, humankind has begun to match and even exceed nature in terms of changing the biosphere and impacting other facets of Earth System functioning. The magnitude, spatial scale, and pace of human-induced change are unprecedented. Human activity now equals or surpasses nature in several biogeochemical cycles. The spatial reach of the impacts is global, either through the flows of the Earth's cycles or the cumulative changes in its states. The speed of these changes is on the order of decades to centuries, not the centuries to millennia pace of comparable change in the natural dynamics of the Earth System.

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 another geological epoch, the *Anthropocene Era* (a term coined by Paul Crutzen and Eugene Stoermer), has begun:

- In the last 150 years humankind has exhausted 40% of the known oil reserves that took several hundred million years to generate;
- 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;
- More nitrogen is now fixed synthetically for fertilisers and through fossil fuel combustion than is fixed naturally in all terrestrial ecosystems;
- More than half of all accessible freshwater is appropriated for human purposes, and underground water resources are being depleted rapidly in many areas;
- The concentrations of several climatically important greenhouse gases, in addition to CO_2 and CH_4, have substantially increased in the atmosphere;
- Coastal and marine habitats are being dramatically altered; 50% of mangroves have been removed and wetlands have shrunk by one-half;
- About 22% of recognised marine fisheries are overexploited or already depleted, and 44% more are at their limit of exploitation;
- Extinction rates are increasing sharply in marine and terrestrial ecosystems around the world; the Earth is now in the midst of its first great extinction event caused by the activities of a single biological species (humankind).

Drivers of change

Over the past two centuries, both the human population and the economic wealth of the world have grown rapidly. These two factors have increased resource consumption significantly, registered in agriculture and food production, forestry, industrial development, transport and international commerce, energy production, urbanisation and even recreational activities.

Somewhat more than 6 billion people inhabit the globe at present. All share basic human needs, such as the demand for water, food, shelter, community health and employment. The ways in which these needs are met are critical determinants of the environmental consequences at all scales (Table 1). In the developed world, affluence, and more importantly the demand for a broad range of goods and services such as entertainment, mobility, and communication, is placing significant demands on global resources. Between 1970 and 1997, the global consumption of energy increased by 84%, and consumption of materials also increased dramatically. While

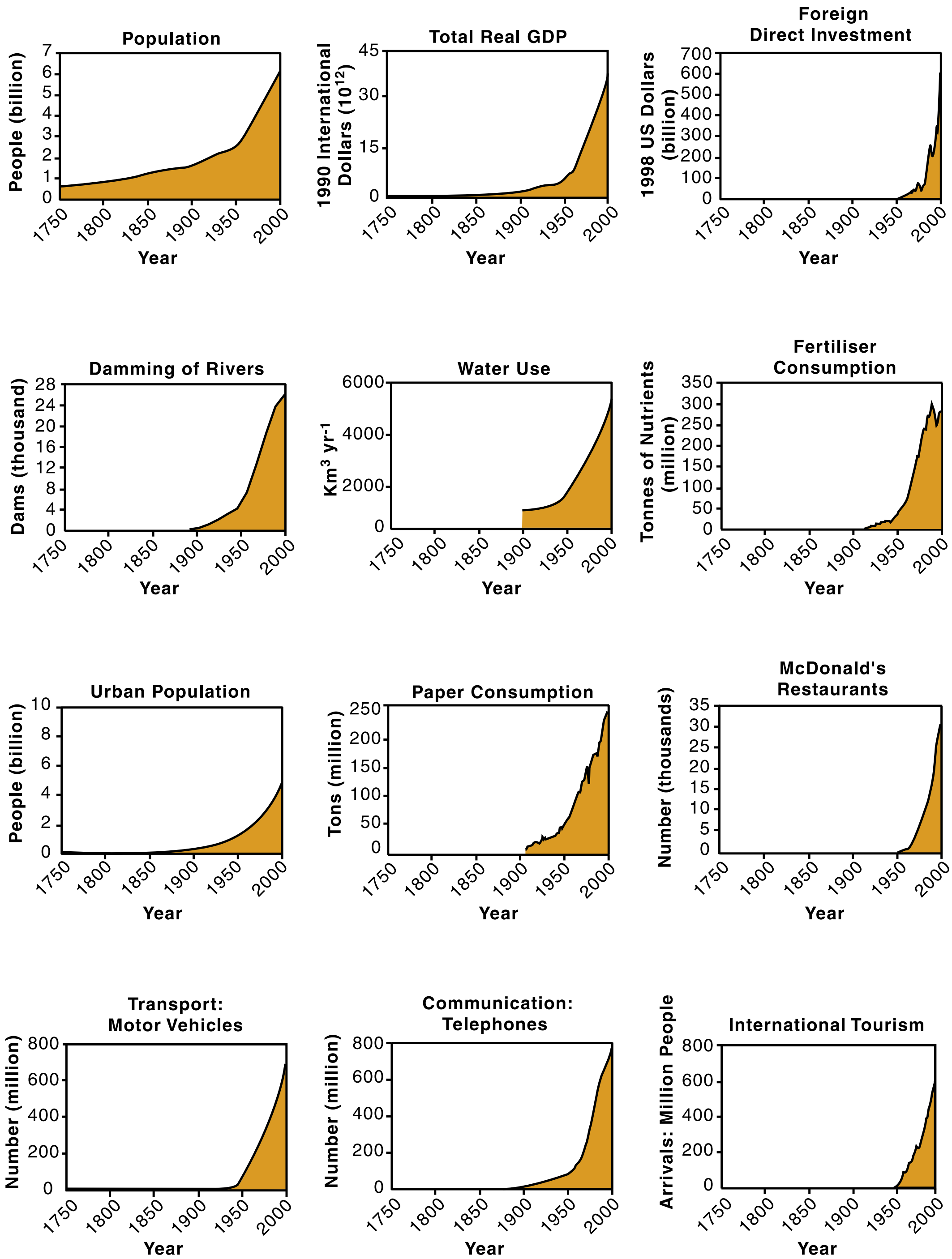
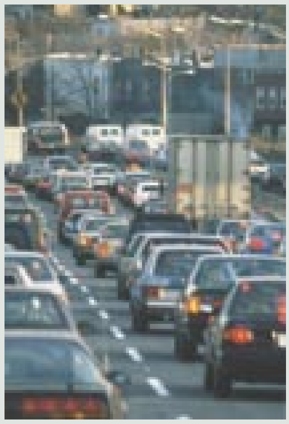


Figure 8. The increasing rates of change in human activity since the beginning of the Industrial Revolution. Significant increases in rates of change occur around the1950s in each case and illustrate how the past 50 years have been a period of dramatic and unprecedented change in human history.

Sources: US Bureau of the Census (2000) International database; Nordhaus (1997) In: The economics of new goods. University of Chicago Press; World Bank (2002) Data and statistics; World Commission on Dams (2000) The report of the World Commission on Dams; Shiklomanov (1990) Global water resources; International Fertilizer Industry Association (2002) Fertilizer indicators; UN Centre for Human Settlements (2001); The state of the world's cities, (2001); Pulp and Paper International (1993) PPI's international fact and price book; MacDonalds (2002) http://www.mcdonalds.com; UNEP (2000) Global environmental outlook 2000; Canning (2001) A database of world infrastructure stocks, 1950–95 World Bank; World Tourism Organization (2001) Tourism industry trends.



Compartment/ Cycle transformed	Proximate Driver	Underlying Driver
Land	Clearing (cutting forest, + burning), agricultural practices (e.g. tillage, fertilisation, irrigation, pest control, high-yeilding crops etc.), abandonment	Demand for food (+ dietary preferences), recreation, other ecosystem goods and services
Atmosphere	Fossil fuel burning, land-use change (e.g., agricultural practices), biomass burning, industrial technology	Demand for mobility, consumer products, food
Water	Dams, impoundments, reticulation systems, waste disposal techniques, management practices	Demand for water (direct human use), food (irrigation), consumer products (water usage in industrial processes)
Coastal/Marine	Land-cover conversion, groundwater removal, fishing intensity and technique, coastal building patterns, sewage treatment technology, urbanisation	Demand for recreation, lifestyle, food, employment
Biodiversity	Clearing of forest/natural ecosystems; introduction of alien species	Demand for food, safety, comfort, landscape amenity

Table 1. Proximate drivers are the immediate human activities that drive a particular environmental change; underlying drivers are related to the fundamental needs and desires of individuals and groups. Proximate and underlying drivers are the end points in a linked sequence with numerous intermediate linkages – markets, institutions, infrastructure, policy, political systems, cultural values.

the global population more than doubled in the second half of the last century, grain production tripled, energy consumption quadrupled, and economic activity quintupled. Although much of this accelerating economic activity and energy consumption occurred in developed countries, the developing world is beginning to play a larger role in the global economy and hence is having increasing impacts on resources and environment.

Energy is needed for almost all activities in all countries, industrialised and industrialising. Much is derived from the combustion of fossil fuels, which leads to emissions of CO_2, other trace gases and aerosols. Industrialisation has led to considerable air and water pollution associated with the extraction, production, consumption and disposal of goods. Over the past three centuries, the amount of land used for agriculture has increased five-fold. Furthermore,

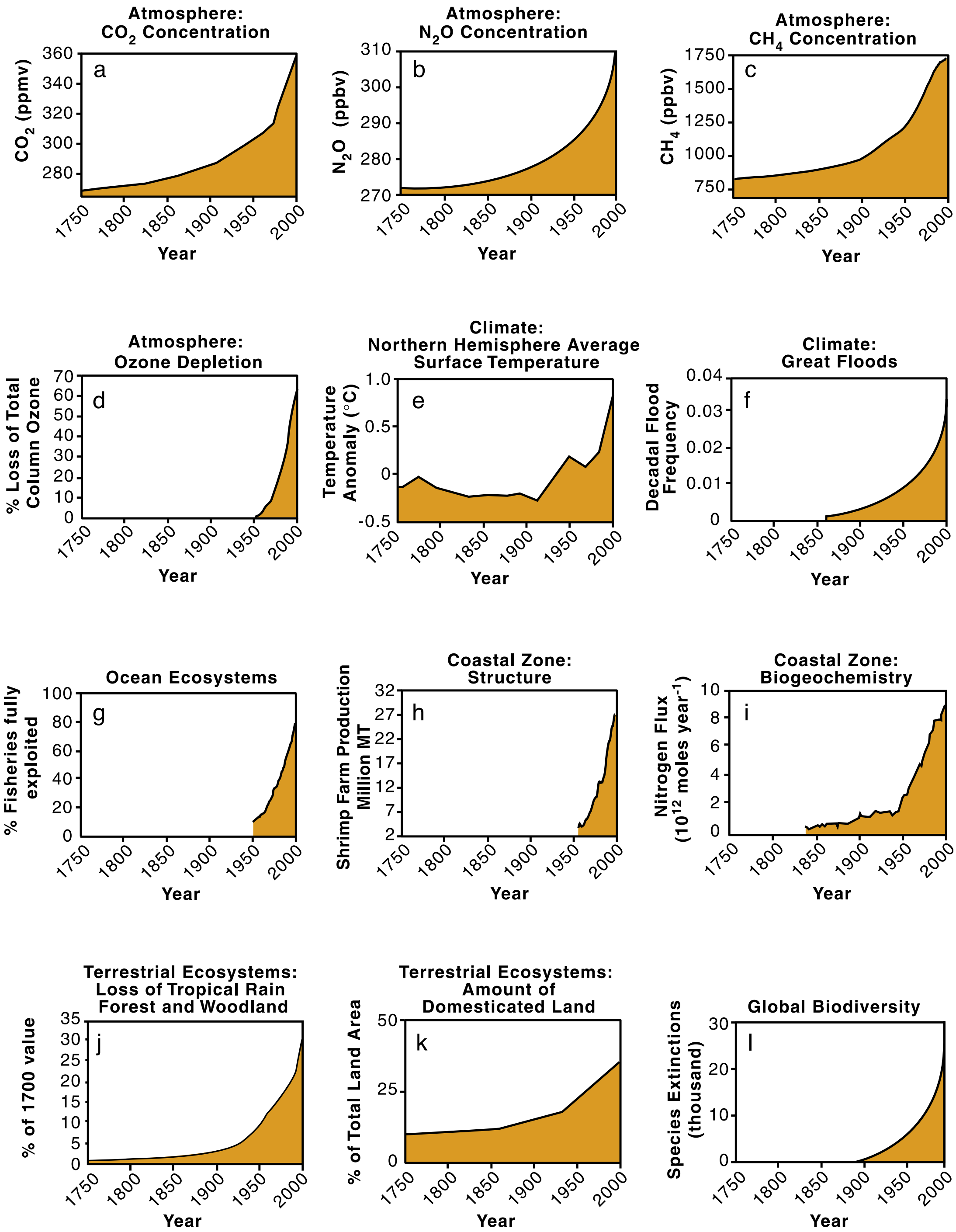


Figure 9. Global-scale changes in the Earth System as a result of the dramatic increase in human activity: (a) atmospheric CO_2 concentration. *Source: Etheridge et al. (1996) J. Geophys. Res. 101:4115-4128;* (b) atmospheric N_2O concentration. *Source: Machida et al. (1995) Geophys. Res. Lett. 22:2921-2924;* (c) atmospheric CH_4 concentration. *Source: Blunier et al. (1993) J. Geophys. Res. 20:2219-2222;* (d) percentage total column ozone loss over Antarctica, using the average annual total column ozone, 330, as a base. *Image: J.D. Shanklin, British Antarctic Survey;* (e) northern hemisphere average surface temperature anomalies. *Source: Mann et al. (1999) Geophys. Res. Lett. 26(6):759-762;* (f) decadal frequency of great floods (one-in-100-year events) after 1860 for basins larger than 200 000 km^2 with observations that span at least 30 years. *Source: Milly et al. (2002) Nature 415:514-517;* (g) percentage of global fisheries either fully exploited, overfished or collapsed. *Source: FAOSTAT (2002) Statistical databases;* (h) annual shrimp production as a proxy for coastal zone alteration. *Sources: WRI (2003) A guide to world resources, 2002-2004; FAOSTAT (2002) Statistical databases;* (i) model-calculated partitioning of the human-induced nitrogen perturbation fluxes in the global coastal margin for the period since 1850. *Source: Mackenzie et al. (2002) Chem. Geology 190:13-32;* (j) loss of tropical rainforest and woodland, as estimated for tropical Africa, Latin America and South and Southeast Asia. *Sources: Richards (1990) In: The Earth as transformed by human action, Cambridge University Press; WRI (1990) Forest and rangelands;* (k) amount of land converted to pasture and cropland. *Source: Klein Goldewijk and Battjes (1997) National Institute for Public Health and the Environment (RIVM). Bilthoven, Netherlands; and* (l) mathematically calculated rate of extinction. *Source: Wilson (1992) The diversity of life, the Penguin Press.*

large areas of land area have been lost to degradation, due, for example, to soil erosion, chemical contamination and salinisation. Changes in marine ecosystems as a result of human activities are no less significant.

An Earth System perspective

What is the ultimate significance for the functioning of the Earth System of the complex, interacting drivers of change originating in the burgeoning human enterprise? Figure 8 shows examples of changes in the Anthroposphere over the past few hundred years; it is an attempt to define a few key indicators that capture the changing nature of human societies at this pivotal time in the development of the human-environment relationship. All of the trends shown are global and mask important regional differences. Nevertheless, at the level of the Earth System, global-scale indicators are appropriate and important.

One feature stands out as remarkable. The second half of the 20th century is unique in the entire history of human existence on Earth. Many human activities reached take-off points sometime in the 20th century and have accelerated sharply towards the end of the century. The last 50 years have without doubt seen the most rapid transformation of the human relationship with the natural world in the history of humankind.

Figure 9 shows that the impacts of these accelerating human changes are now clearly discernible at the level of the Earth System as a whole. Many key indicators of the functioning of the Earth System are now showing responses that are, at least in part, driven by the changing human imprint on the planet. All components of the global environment - oceans, coastal zone, atmosphere, and land - are being influenced. Dramatic though these human-driven impacts appear to be, their rates and magnitudes must be compared to the natural patterns of variability in the Earth System to begin to understand their significance.

The increase in atmospheric CO_2 concentration provides a useful measure with which to evaluate the rate and magnitude of human-driven change compared to natural variability (Fig 2). The human imprint on CO_2 is unmistakable. Atmospheric CO_2 concentration now stands at 370 ppmV, almost 100 ppmV above the previous maximum level of ca. 280 ppmV recorded in the Vostok ice core. Within the current limits of resolution of the ice-core records, the present concentration has been reached at a rate at least 10 and possibly 100 times faster than increases of CO_2 concentration at any other time during the previous 420 000 years. Thus, in this case human-driven changes are well outside the range of natural variability exhibited by the Earth System for the last half-million years at least.

Over just the past few hundred years, human activities have clearly evolved from insignificance in terms of Earth System functioning to the creation of global-scale impacts that:

- are approaching or exceeding in *magnitude* some of the great forces of nature;
- operate on much faster time scales than *rates* of natural variability, often by an order of magnitude or more;
- taken together in terms of extent, magnitude, rate and simultaneity, have produced a *no-analogue* state in the dynamics and functioning of the Earth System.

Reverberations of Change

Human impacts on the Earth System do not operate in separate, simple cause-effect responses. A single type of human-driven change triggers a large number of responses in the Earth System, which themselves reverberate or cascade through the system, often merging with patterns of natural variability. The responses seldom follow linear chains, but more often interact with each other, sometimes damping the effects of the original human forcing and at other times amplifying them. Responses become feedbacks, which in turn can lead to further forcings that can alter the functioning of the Earth System.

Cascading impacts

The nature of the Earth System's responses to the increasing anthropogenic forcing is more complex than simple cause-effect relationships, such as greenhouse gas emissions causing global warming. Fossil fuel combustion produces a range of gases that have a large number of cascading effects. For example, CO_2 not only affects climate but also directly affects how vegetation grows. It also changes the carbonate chemistry in the ocean, which in turn affects marine organisms. Changing carbonate chemistry is a major factor in the widespread decline of coral reefs around the world.

Fossil fuel combustion also produces oxidising gases such as nitric oxide and sulphur dioxide that have well-known effects such as acidification and eutrophication of ecosystems. However, these gases can eventually contribute to changes in fundamental Earth System functioning, such as their indirect effects on the radiative properties of the atmosphere, and hence climate, through reactions with other gases and their impacts on the ability of the atmosphere to cleanse itself through oxidation and the removal of a wide range of substances. Aerosols produced by fossil fuel combustion can fertilise or reduce plant growth, depending on the circumstances, and directly affect human health. They also lead to large-scale direct or indirect modifications of climate.

Even more subtle effects can ultimately be traced back to fossil fuel combustion. Through the effect of increasing CO_2 concentration on the stomatal opening of terrestrial vegetation, the loss of water vapour through the stomates is reduced, resulting in increased water use efficiency. This effect is especially pronounced in semi-arid vegetation, and can lead to increased productivity through enhanced soil moisture. More generally, no two species react in an identical way to elevated atmospheric CO_2 concentration, leading to changes in the competitive abilities of plants and hence to changes in species abundances and community composition. Fossil fuel combustion reverberates through the Earth System to become even a biodiversity issue!

Like fossil fuel combustion, land-cover and land-use change also trigger widespread cascading effects at local, regional and global scales. Box 3 (page 20) shows a few of the pathways by which initial local effects of land-use change cascade through regional to global scales.

Multiple, interacting stresses

Global change does not operate in isolation but rather interacts with an almost bewildering array of natural variability modes and also with other human-driven effects at many scales. Especially important are those cases where interacting stresses cause a threshold to be crossed and a rapid change in state or functioning to occur.

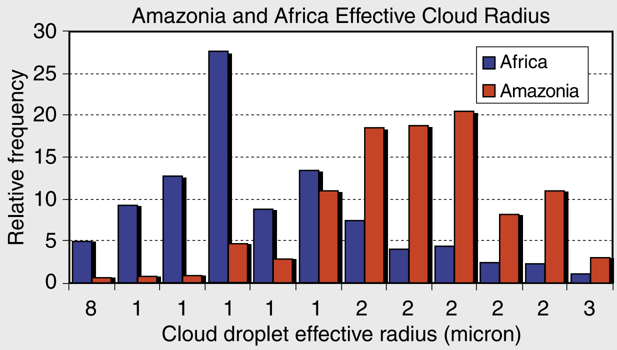
Coral reefs are a good example of threshold and step-change behaviour. Reefs are subject to a wide variety of natural disturbances, from hurricanes to episodic outbreaks of crown-of-thorns starfish. Over the last several decades human stresses - nutrient and sediment loadings from adjacent coastal areas, fishing and tourism - have begun to interact with natural disturbances to put reefs under increasing stress. Global change is adding even more stresses of a quite different nature. Increasing atmospheric CO_2 is changing the carbonate chemistry in the surface waters of the ocean, making it more difficult for reef organisms to form their hard shells. At the same time, warming of the upper ocean is leading to widespread bleaching events. These new, global-scale stresses operate everywhere, and are both persistent and inexorably increasing in severity. Given sufficient pressure from these interacting local to global stresses, coral reefs can cross a threshold with widespread death of the coral and a rapid change to colourless algal beds.

Box 3: Cascading Effects of Land-use Change

The impacts of land-use change reverberate through the Earth System at various scales and in various ways. The initial land-use change is normally the conversion of a natural ecosystem, such as a forest, to a managed agricultural system, with immediate consequences such as the loss of carbon to the atmosphere through the burning of the slash. Land use follows various trajectories after the initial conversion. A common pathway is for less intensive agriculture to be practiced initially, followed some years later by intensification - the use of fertilisers, irrigation and pest control, for example - to increase yields. Intensification modifies the cascading effects of land-cover conversion, damping some but intensifying others, such as the addition and mobilisation of nitrogen compounds and their loss to the atmosphere and to waterways.

Photos: IGBP image archive

Local Effects. Burning of biomass associated with the clearing of forests in Amazonia can affect local and regional rainfall. Biomass burning, like fossil fuel combustion, produces aerosols of a variety of sizes. Larger particles act as nuclei for condensation and cloud droplet growth to form rain. Production of larger numbers of smaller particles that form more but smaller cloud droplets, however, inhibit rainfall. This appears to be happening over Amazonia; a similar cascading impact of land-use change may be altering rainfall elsewhere, notably over southern Africa.

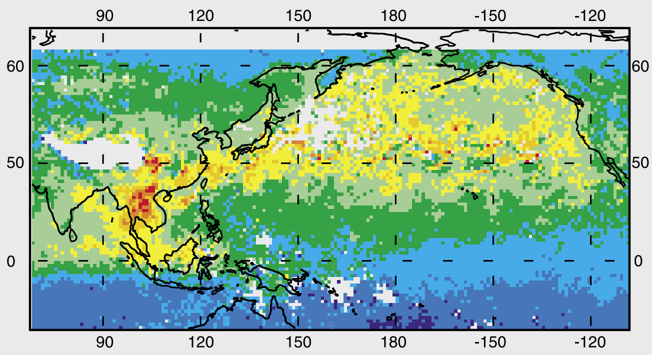


Source: Daniel Rosenfeld AVHRR Analysis

Regional Effects. Many of Africa's large herbivores rely on migration pathways to track seasonal changes in climate, water availability and grasses. Recently some areas of the Serengeti in Kenya, which are in the traditional migratory pathway of wildebeest, have been converted to intensive wheat farming as a response to global market forces. Their conversion has disrupted annual migration to the point where the wildebeest population has declined sharply. On the Tanzanian side of the Serengeti, with different economic forces operating, fewer land-use changes have occurred, and wildebeest migration patterns and numbers have been maintained.

Sources: Remote Sensing and Regional Analysis Laboratory, UCLovain, Belgium; Suzanne Serneels.

Global Effects. Biomass burning associated with land clearing and agricultural practices in Southeast Asia leads to global environmental effects. Satellite remote sensing in February 2001 showed strong production of carbon monoxide centred in Thailand, a result of seasonal burning as part of the normal agricultural practices. The carbon monoxide, an oxidising gas that has a number of implications for Earth System functioning, on this occasion formed a plume that extended all the way across the Pacific Ocean to the west coast of North America.



Source: J. Gille and L. Emmons, National Center for Atmospheric Research, USA; J. Drummond, University of Toronto, Canada; National Aeronautics and Space Administration (NASA), USA.

The extreme fires that raged through parts of Southeast Asia in 1997/98 and the Canberra bushfire disaster of 2003 (Box 4) are classic examples of the non-linear response of an ecosystem to multiple, interacting stresses. The 1997/98 fire episode in Southeast Asia was undoubtedly the result of the interplay of land-use change and an unusually strong ENSO event. The fires were associated with land management following conversion of tropical forest to oil palm plantation (deforestation). Normally the slash from the clearing operation is burned during the relatively dry southern monsoon period from June to October. As the wetter northern monsoon phase is established in October/November, the burning activities cease and the fires are extinguished. However, strong ENSO years lead to drought conditions in Southeast Asia during the July-September period, with abnormally low rainfall persisting later in the year. Under these conditions the vegetation is more susceptible to burning and the risk of uncontrolled fires increases sharply.

Responses of the Earth System

At the global scale, the responses of the Earth System to contemporary human forcings can clearly be seen in biogeochemical cycles, in the hydrological cycle and now in climate. The carbon cycle is now significantly out of balance. Although the oceans and land are absorbing some of the CO_2 emitted by human activities from fossil fuel combustion and land-cover change, these responses are insufficient to prevent a rapid build-up of CO_2 in the atmosphere. Similarly, the Earth System cannot assimilate fast enough the large amounts of reactive nitrogen compounds created by humans, largely for fertilisers. Significant amounts of nitrogen are accumulating in vegetation, soils and groundwater, with leakage to the coastal zone and to the atmosphere.

The hydrological cycle is the lifeblood of the biosphere and, in many ways, the engine of the climate system. The responses of the Earth System to human influences reverberate through the hydrological cycle and go well beyond the direct human appropriation of freshwater for drinking, agriculture and industry. These responses include changes in precipitation patterns, especially increases over the high latitudes; changes in the intensity and timing of precipitation, with more heavy rainfall events and consequent flooding but also more severe and extended droughts; diminished evapotranspiration and ultimately diminished precipitation through increased aerosol particle loading in the atmosphere; and changes in the partitioning of incoming solar radiation between evapotranspiration and sensible heat due to land-cover change, which in turn affects the amount of water that runs off into riverine systems or infiltrates into soil.

The Earth's climate system is responding to the various direct and indirect human forcings in many ways in addition to the modification of the hydrological cycle. Changes in the radiative properties of the atmosphere and in the Earth's heat balance are clearly discernible in response to human forcings. These forcings include not only CO_2 but also other greenhouse gases such as CH_4, N_2O and halocarbons (such as CFCs); reactive gases; and a wide range of aerosol particles, which influence the climate in complex ways in addition to their effects via the hydrological cycle. The climate system responds to human-driven land-cover change by changing the amounts of absorbed and reflected solar radiation owing to changes in the reflectance of the Earth's surface. Such effects are known to be important for climate locally and regionally and may be significant globally. It should not be surprising that the responses of climate to human perturbations are already significant and appear to be accelerating since the magnitude of human-driven radiative forcings of climate are large compared to changes in natural forcing due to variations in solar radiation or emissions from volcanoes.

Box 4: The Canberra Bushfire Disaster

On January 18 2003 a massive bushfire originating in the mountains west of Canberra, Australia's capital city, descended upon the city with extraordinary speed and intensity. Over 500 houses were totally destroyed, four people were killed and hundreds of others were taken to hospital with burns, one of the oldest astronomical observatories in Australia was burned beyond repair and the total damage approached 400 million Australian dollars. The disaster was no simple cause-effect event. Rather, the tragedy was the result of threshold-abrupt change behaviour, building on the interaction of land-use practices, extreme weather, and longer-term climate change.

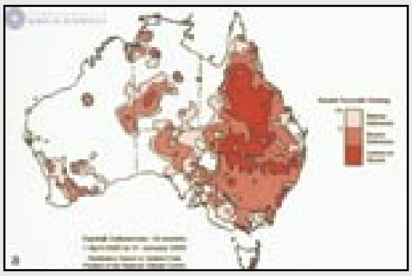
Land-use. Canberra is a planned city, built into a landscape of fire-prone ecosystems both within and around the urban area. In addition, extensive national parks to the west have been managed to follow a more natural fire regime, leading a build-up of fuel and thus fewer but more intense fires, compared to Aboriginal practices of regular burning.

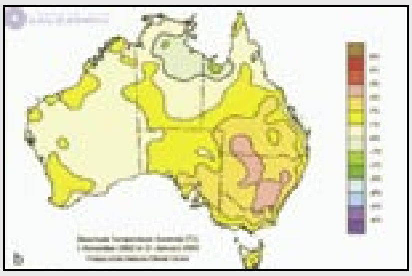
Extreme weather. Late on 17 January the weather conditions switched rapidly from the prevailing cool conditions. By 9 am the next morning the temperature was already 30 °C with northwesterly winds of 30 km hr^{-1}. By early afternoon the temperature had reached 38 °C, the relative humidity was only 2% and the winds were gusting at 70-80 km hr^{-1}. Such conditions quickly triggered a massive firestorm with flames leaping up to 100 m high and with the energy intensity (up to 50 000 kW m^{-2}) of a large bomb.

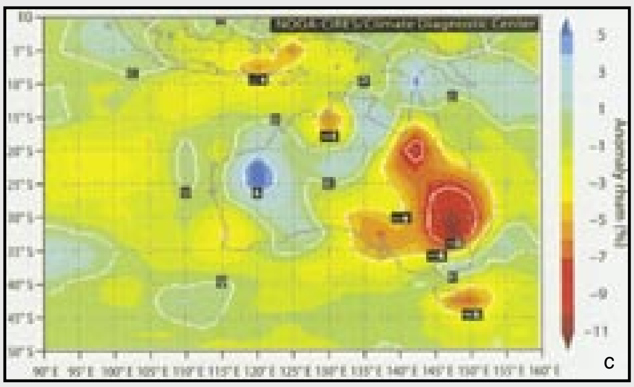
Photo: IGBP image archive

A satellite image of southeastern Australia on 19 January 2003 showing active fires (highlighted in red), including the fire that devastated parts of Canberra on 18 January.

Source: NASA







Pre-fire climatic conditions: (a) rainfall deficit (expressed as percentiles from the mean) for the period April 2002 - January 2003; (b) maximum temperature anomalies for the period November 2002 - January 2003; (c) relative humidity anomalies at 700 hPa (corresponding to 2 000 m above sea level) for the period November 2002 - January 2003.

Sources: Commonwealth Bureau of Meteorology, Australia; NOAA-CIRES Climate Diagnostic Center.

Climate change. Southeastern Australia had been experiencing a severe drought for several years leading up to the fires. In the three-four months leading up to the disaster, the relative humidity in the region was unusually low, about 12% below average. The forests were simultaneously subject to extreme heat; the temperature was nearly 3 °C higher than average, (see accompanying figures). Coupled with an almost complete lack of rainfall for the summer, these conditions meant that the forests were exceedingly dry and thus prone to a violent fire. The extreme climatic conditions that prevailed for the months and years leading up to the Canberra disaster appeared to be closely linked to systemic, global-scale climate change, in particular to a remarkably persistent pattern of high pressure systems, in turn due to cold Sea Surface Temperatures in the eastern tropical Pacific and warm SSTs in the western tropical Pacific and Indian Oceans. Such warm SSTs are beyond what is expected of natural variability and are due in part to increasing greenhouse gas concentrations in the atmosphere.

The Canberra bushfire disaster was due to the multiple, interacting effects of land-cover and land-use change, extreme weather conditions and longer-term climate change. This combination of factors pushed the forests of southeastern Australia across a critical threshold of fuel load and condition, ready for short-term weather conditions to trigger violent and uncontrollable wildfires.

Living with Global Change

The changes that are occurring in the functioning of the Earth System have implications for human well-being. Basic goods and services supplied by the planetary life support system, such as sufficiency and quality of food, water resources, air quality, and an environment conducive to human health, are all being affected by global change. At another level, global change poses potentially serious consequences for the stability of the Earth System itself. Catastrophic failures, such as the slow-down or collapse of the Gulf Stream circulation in the North Atlantic Ocean, are possible as the Earth System responds to an increasing suite of interacting human forcings.

Anticipating the consequences

There is now unequivocal evidence that human activities are affecting Earth's environment at the global scale. Increasingly strong evidence suggests that the functioning of the Earth System is changing in response. How can we anticipate the consequences of contemporary global change for human societies?

The scenario-driven approach for impact and consequence studies is the most common approach and has achieved considerable success. The approach is often to use a global change scenario, often a climate scenario, for 50 - 100 years to drive models of changes in the biophysical environment, for example, crop production. These impacts can then be further linked to simulate socio-economic consequences. More sophisticated approaches, such as integrated assessment techniques, allow both the interaction of a number of global change drivers and the feedbacks of impacts/consequences to the scenarios of change themselves. Despite their success, scenario-driven approaches suffer from a number of limitations, including propagation of uncertainties through model chains, problems in identifying and simulating threshold effects and nonlinearities, and difficulties in handling multiple, interacting stresses.

Vulnerability assessment differs from traditional approaches to impact assessment in a number of important ways (Table 2). In essence, impact assessment selects a particular environmental stress of concern (e.g. climate change) and seeks to identify its most important consequences for a variety of social or ecosystem properties. Vulnerability assessment, in contrast, selects a particular group or unit of concern (e.g. landless farmers, boreal forest ecosystems, coastal communities) and seeks to determine the risk of specific adverse outcomes for that unit in the face of a variety of stresses and identifies a range of factors that may reduce response capacity and adaptation to stressors. In principle, the same global change phenomena could be assessed from both perspectives. In practice, impact studies have been most helpful where they have been able to focus on a single stress that dominates system response. However, it is becoming clear that some of the greatest challenges arising from human-environment interactions entail complex system responses to multiple and interacting stresses originating in both the social and environmental realms. Vulnerability assessment offers a maturing strategy to provide guidance in such situations.

Another approach to vulnerability is based on the assessment of palaeo-data. Studies of the past give clues as to how earlier civilisations were impacted by natural variability in the Earth System, and the consequences for their resource base. The success or failure of past civilisations is undoubtedly due to a variety of factors, especially to cultural and social organisation. However, in some cases there is convincing evidence that climate variability, especially in the hydrological cycle, was an important factor, perhaps even a decisive factor, in determining the fate of a particular civilisation (Fig. 10). It is clear that human societies, including those of today, can be significantly affected by extreme events such as floods and droughts and can be seriously damaged by sequences of such events. Further development of palaeo-approaches to vulnerability analysis promises to deepen understanding of processes such as land degradation, soil erosion, eutrophication and pollution of both freshwater and marine aquatic systems, surface water acidification, salinisation, non-linear changes in ecosystem structure and functioning and a wide range of multiple stresses arising from the combination of climate variability and human actions.

Approach	Scenario	Vulnerability
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc.	Multiple stresses: climate (historical climate variability), land use and water use, altered disturbance regimes, invasive species, contaminants/pollutants, habitat loss, etc.
Usual timeframe of concern	Long-term, doubled CO_2, 30-100 years in the future	Short-term (0 to 30 years) and long-term research
Usual scale of concern	Global, sometimes regional, however, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales	Local, regional, national and global scales
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought	Potential extreme values in multiple parameters (temperature, precipitation, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.); measures of uncertainty
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses Results often show gradual ramping of climate change, limiting preparedness for extreme events Results represent only a limited subset of all likely future outcomes – usually unidirectional trends Results are accepted by many scientists, the media, and the public as actual predictions Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability	Approach requires detailed data on multiple stresses and their interactions at local, regional, national and global scales – and many areas lack adequate information Emphasis on short-term issues may limit preparedness for abrupt threshold changes in climate some time in the short- or long-term Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction – this is probably more realistic, yet difficult

Table 2. Comparison of vulnerability and scenario approaches to assessing human impacts of global change. Source: Pielke and de Guenni (2004). In Kabat et al. 'Vegetation, Water, Humans and the Climate', Springer.

Risks to key resources

There is little doubt that global change is impinging and will impinge on many activities and facets of life everywhere. Food systems, water resources, air quality and pests and diseases are four of the most important, and considerable research in all of these areas has provided many insights into what might lie ahead for societies under a rapidly changing global environment.

Over the next several decades food demand will rise in response to growth of population, growth of per capita income, and attempts to reduce the under-nutrition of the very poor. Further yield increases will be required along with additional growth in foods like meat as consumer preferences shift. Global change is adding further complications to this already challenging task. A recent analysis (Fig. 11) of the potential impact of climate change on food security in the 21st century highlights the importance of the current disparities in food production capability and of the differential impacts of climate change. In terms of individual countries, the analysis indicates there will be winners and losers; the developed countries of the world, which already have sufficient food and are net exporters, will likely gain from climate change while developing countries will likely suffer substantially from changing climate in terms of terrestrial food production.

The situation is strikingly similar in terms of water resources. The vulnerability of human societies to strongly variable or declining water resources is closely connected to the need to increase food production. About 70% of the world's current freshwater resource is used for agriculture, but that number approaches 90% in China and India, with extensive irrigation. An analysis of changing water resources based on population growth and climate change individually and in combination has been carried out recently (Fig. 12). Although climate change will have discernible impacts on freshwater availability by 2025, these changes will be overwhelmed by the increase in demand for water resources due to population growth and economic activity alone. In terms of absolute numbers, the current 2.2 billion people living under moderate or severe water stress will rise to 4.0 billion by 2025. The distribution of water stress by continent is even more striking. Africa, Asia and South America all show sharp increases of 73%, 60% and 93% respectively in the ratio of demand and supply. For Africa and South America, climate change is predicted to exacerbate water stress significantly.

While food security and access to reliable water resources are now recognised as global problems, air quality has traditionally been considered a local issue affecting urban areas and their adjacent rural areas only. Increasingly, however, it is being realised that intercontinental transport of gases and aerosol particles connects far distant parts of the globe. The emissions from intense point sources, such as megacities, have ramifications well beyond their own urban airsheds. With the growth of megacities through the first half of the 21st century, air quality is becoming a global change issue in its own right. The impacts of changing air quality are largely felt through photochemical smog, in which trophospheric ozone plays a key role, through the increasing concentration of aerosol particles and the potential impacts of increasing UV-B radiation caused by the loss of stratospheric ozone.

Sectoral impacts on food systems, water resources and air quality are of direct and obvious importance to human well-being. Human societies depend also on a wide range of ecosystem goods and services that in turn depend on the continued functioning of terrestrial, marine and coastal ecosystems. The impacts of global change on pests and diseases are a good example of the ways in which ecosystem goods and services are already being affected. Many changes are already evident, rang-

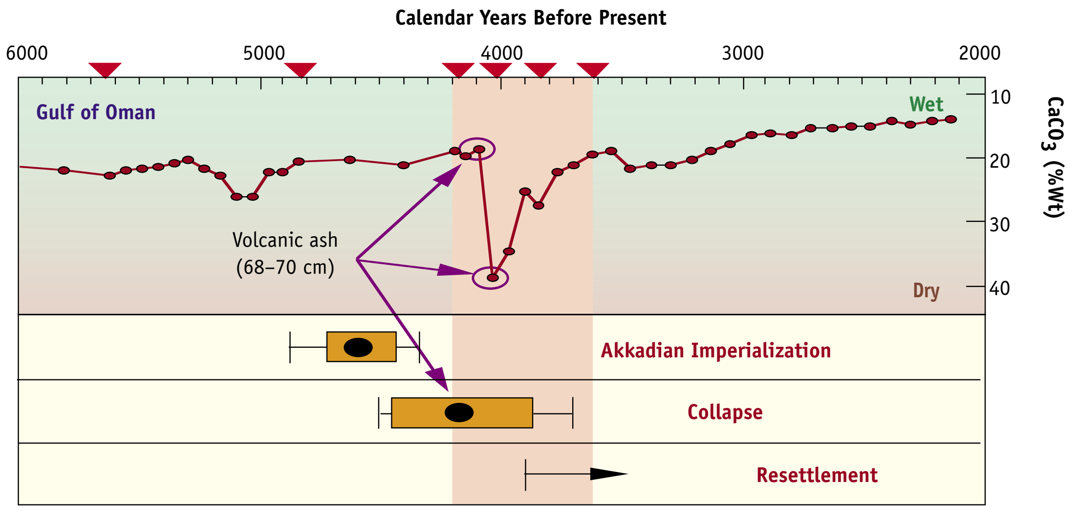


Figure 10. An example of the relationship between the incidence of drought and the collapse of human civilisations. Although many factors in addition to environmental change influence the success or failure of civilisations, the severe droughts in the region of the Akkadian empire about 4000 years ago were likely a significant factor in its demise.

Adapted from Cullen et al. (2000) Geology 28, 379-382 by the PAGES (Past Global Changes) International Project Office.

ing from massive outbreaks of spruce bark beetle in the boreal forests of North America, through the northwards spread and intensification of tick-borne encephalitis in Sweden, to projections of significant outbreaks of disease in South Africa from the pathogen *Escherichia coli* due to both land-use and climate change. Impacts of pests and diseases will likely increase sharply in the near future as these organisms have rapid life cycles and thus can adapt quickly to changing abiotic conditions.

Risks to the Earth System

The palaeo-record shows that in the Earth System abrupt changes and surprises are a common feature, and that environmental extremes beyond those recorded during

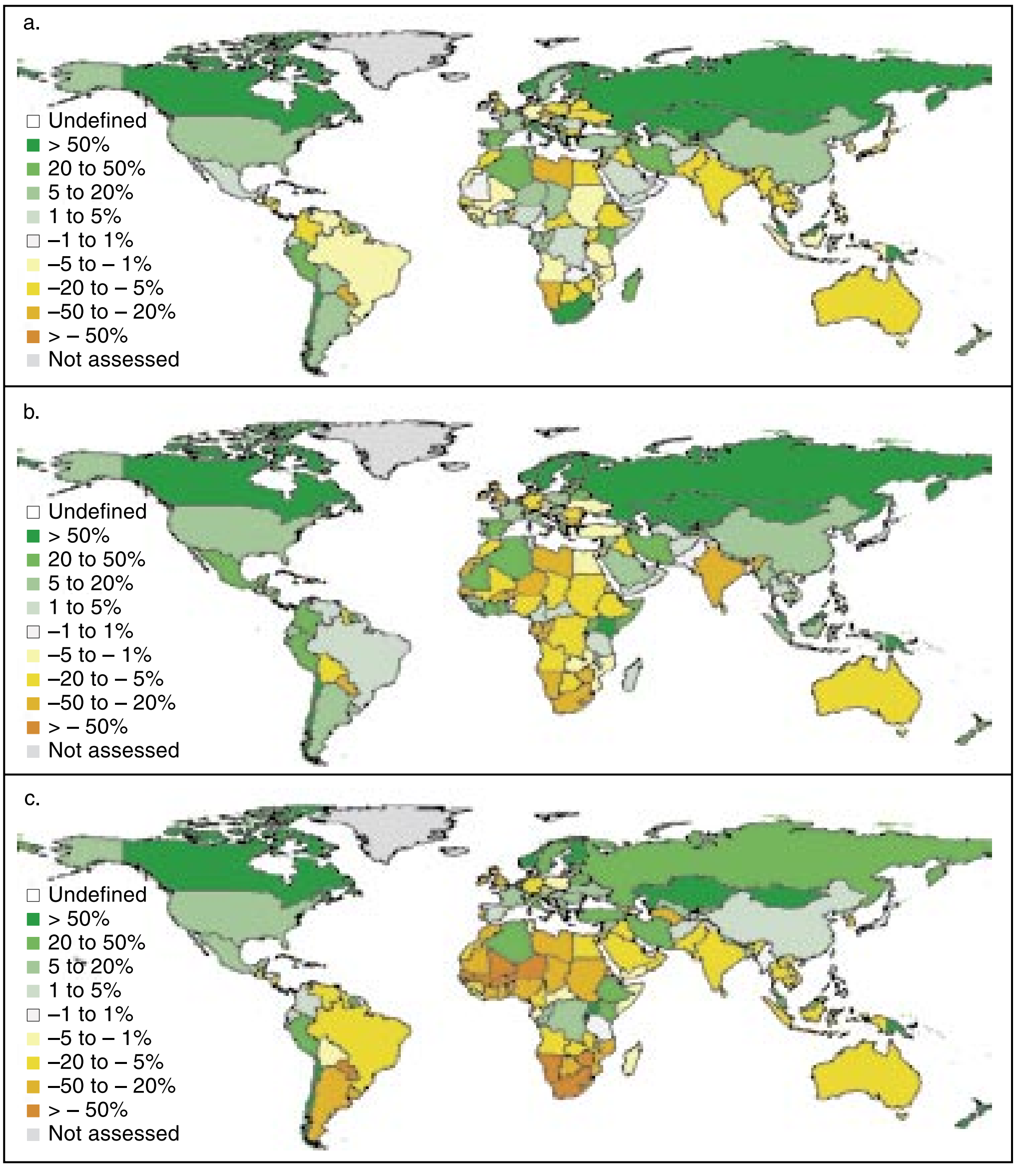


Figure 11. Country-level climate change impacts for the 2080s based on cereal production potential on currently cultivated land, based on three climate change scenarios: a Max Planck model; b Hadley Centre model; c Canadian model.
Source. Fischer et al.(2001) IIASA Land Use Project Report, Austria.

the period of instrumental record occur frequently. Especially large risks to the Earth System are associated with the 'threshold-abrupt change' behaviour that arises when a well-buffered system is forced beyond a certain limit. Until the time that the threshold is approached, it appears that the system is unresponsive to the forcing function. However, when the threshold is passed, the system can move to another state very quickly, a state that may prove to be difficult to reverse or may even be irreversible. Changes of this nature are especially dangerous in the context of global change. Societies can have little or no warning that a forcing factor is approaching such a threshold, and by the time that the change in Earth System functioning is observed, it will likely be too late to avert the major change.

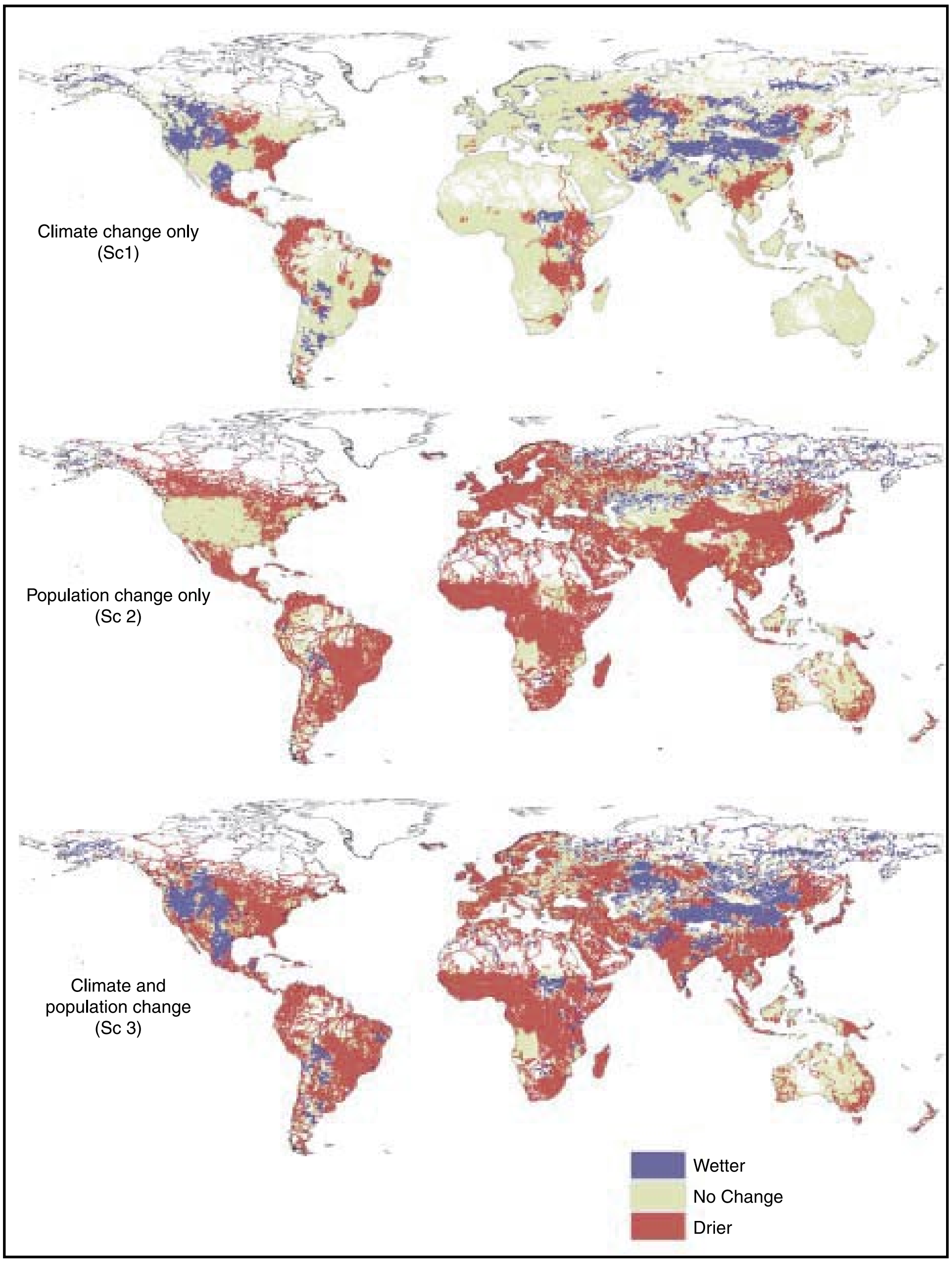


Figure 12. Maps of the change in water reuse index (defined as the quotient of the combination of domestic, industrial and agricultural sectors water demand to the mean annual surface and subsurface runoff accumulated as river discharge) as predicted by the CGCM1/WBM model with climate change alone (Scenario 1), population and economic development only (Scenario 2), and the effects of all drivers of change (Scenario 3). Changes relative to contemporary conditions are shown and a threshold of +/-20% is used to highlight areas of substantial change.

Source: Vörösmarty et al. (2000) Science 289:284-288.

Catastrophic failures resulting from abrupt changes are possible as the Earth System adjusts to an ever-accelerating suite of interacting human forcings. Perhaps the most well-known potential catastrophic perturbation in the Earth System is the slowing or shutting-down of the North Atlantic thermohaline circulation and an accompanying shift in the Gulf Stream (Box 5). However, the stratospheric ozone episode demonstrates that catastrophic failures of the Earth System are not only possible, but that humankind narrowly escaped one very recently.

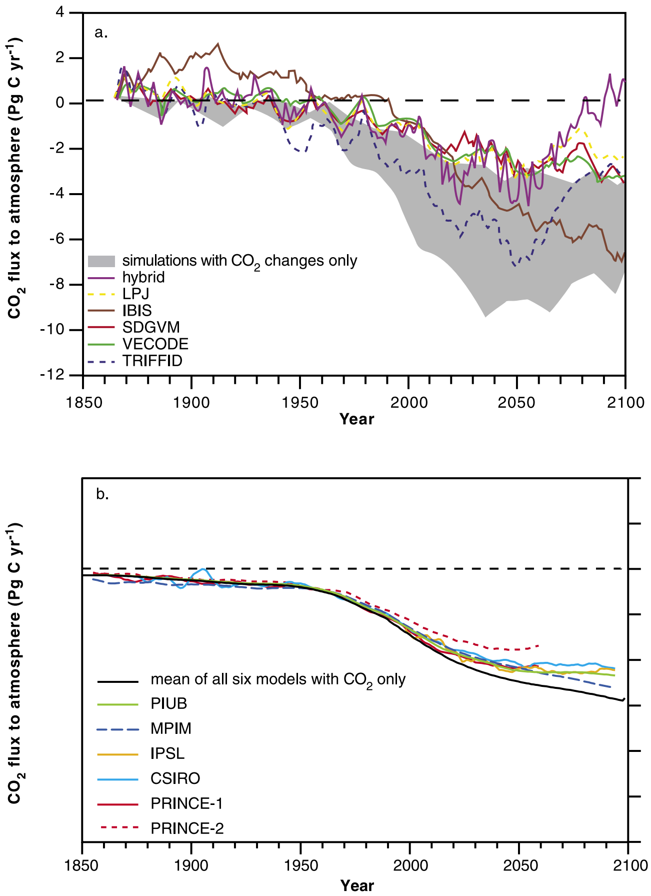


Figure 13. Projections of (a) terrestrial and (b) marine CO_2 uptake through the 21st century. In panel (a) six Dynamic Global Vegetation Models were driven by atmospheric CO_2 concentration projections of the IPCC SAR IS92a scenario and by simulated climate changes obtained from the Hadley Centre climate model with CO_2 and sulphate aerosol forcing from IS92a. The grey shaded area represents the response of the vegetation models to increasing atmospheric CO_2 alone, without any associated climate change. In panel (b) six ocean carbon models were used to estimate the combined impact of increasing atmospheric CO_2 and changing climate on marine CO_2 uptake.

Sources: Cramer et al. (2001) Global Change Biology 7: 357-373; IPCC (2001) Climate change 2001, IPCC Third Assessment Report, Cambridge University Press.

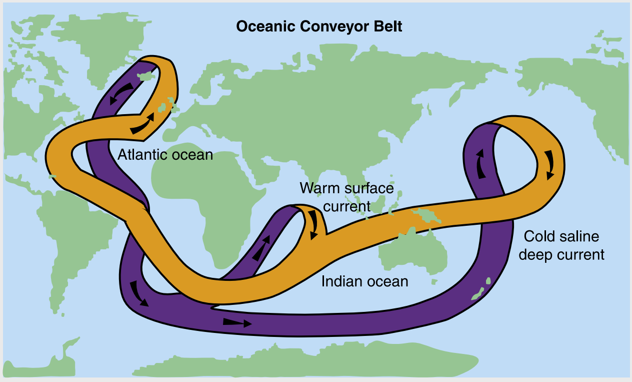
The development of the ozone hole was an unforeseen and unintended consequence of widespread use of chloroflurocarbons as aerosols in spray cans, solvents, refrigerants and as foaming agents. Had, inadvertently, bromofluorocarbons been used instead, the result could have been catastrophic. In terms of function as a refrigerant or insulator, bromofluorocarbons are as effective as chlorofluorocarbons. However, on an atom-for-atom basis, bromine is about 100 times more effective at destroying ozone than is chlorine. As Nobel Laureate Paul Crutzen has written "This brings up the nightmarish thought that if the chemical industry had developed organobromine compounds instead of the CFCs – or, alternatively, if chlorine chemistry would have run more like that of bromine – then without any preparedness, we would have been faced with a catastrophic ozone hole everywhere and at all seasons during the 1970s, probably before the atmospheric chemists had developed the necessary knowledge to identify the problem and the appropriate techniques for the necessary critical measurements. Noting that nobody had given any thought to the atmospheric consequences of the release of Cl or Br before 1974, I can only conclude that mankind has been extremely lucky." (Source: P. Crutzen (1995) My life with O_3, NO_x and other YZO_xs. Les Prix Nobel (The Nobel Prizes) 1995. Stockholm: Almqvist & Wiksell International. pp. 123-157).

Another example of a potentially catastrophic perturbation in the Earth System is a change in the capacity of the terrestrial and marine biospheres to slow the buildup of atmospheric CO_2. It is possible that this ability might weaken or fail later this century (Fig. 13). Currently land and ocean sinks remove, on average, over half of the CO_2 emitted to the atmosphere by fossil fuel combustion. The land sink is highly sensitive to climate variability, with the sink strength reduced in warm years. Models based on the processes controlling terrestrial sinks suggest that the sink strength will level off around the middle of the century and could drop thereafter. At the same time the build up of CO_2 will continue inexorably unless effectively abated.

Ocean uptake of CO_2 is also sensitive to temperature, as the solubility of CO_2 in seawater decreases as the water warms. Simulations of the processes that control the biological uptake of CO_2 in the oceans suggest that this sink, too, will weaken with projected climate change. With the major processes that sequester carbon from the atmosphere likely to weaken during this century, the

Box 5. Thermohaline Circulation: Past Changes and Future Surprises?

Thermohaline circulation (THC) consists of ocean currents driven by surface fluxes of heat and freshwater and subsequent interior mixing of heat and salt, and can be summarised as a global-scale deep overturning of water masses (see figure). A prominent feature of the THC is the sinking motion in the North Atlantic Ocean, which, as the water cools and sinks, releases vast amounts of heat to the atmosphere and makes northern Europe significantly warmer than other regions of the Earth at that latitude.



Schematic representation of the thermohaline circulation of the ocean.

Source: Broecker (1991) Oceanography 4:79-89.

The THC has proven to be a fragile system that can respond in a highly non-linear fashion to changes in surface climate. There is strong evidence that this has repeatedly occurred in the past, and reason for concern that it might happen again in the future. The best evidence for major past THC changes comes from the last glacial period (120 000 - 10 000 years before present - see figure). Two main types of abrupt and large climate shifts have occurred during that period, Dansgaard-Oeschger events and Heinrich events. The former typically start with an abrupt warming (by up to 10 °C in Greenland) within a few decades or less, followed by gradual cooling over several hundred or thousand years. Heinrich events were caused by a massive influx of freshwater from melting North American ice sheets and completely shut down or drastically reduced the overturning of water masses in the North Atlantic, which in turn led to a strong cooling in the North Atlantic region.

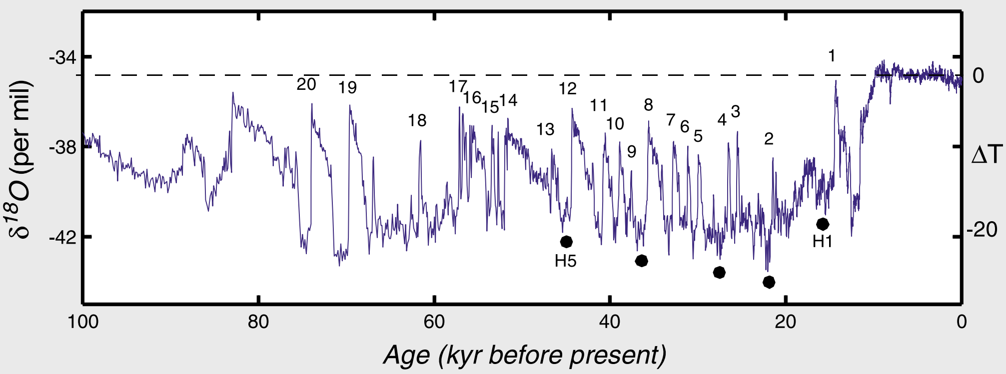
Climate change presents a number of new possibilities to alter substantially the freshwater balance of the North Atlantic in the future and thereby trigger THC variability or even collapse, thus triggering strong regional cooling in the midst of global warming. When air temperature rises, surface waters also tend to warm up, an effect which is enhanced in the high latitudes via the retreat of snow and sea ice with warming. In addition, the hydrological cycle may be accelerated in a warmer atmosphere; the observed increase in river runoff in the high latitudes may be due to this phenomenon. These effects tend to reduce the THC because heating and freshening both decrease surface water density.

The majority of global climate models indicate a reduction of the THC from 10% to 80% in response to increasing CO_2 concentrations in the atmosphere for the next 100 years (see figure). Significant uncertainties persist, illustrated by the large spread of simulated THC changes. Long-term simulations with different climate models suggest that the maximum projected CO_2 concentration may constitute a threshold for the Atlantic THC beyond which the circulation stops. In these early simulations a threshold was found between 2x and 4x pre-industrial CO_2 concentrations.

Model simulations indicate that the threshold may be crossed if the forcing is strong enough and applied for long enough. The threshold may well lie within the range of warming that is expected under business-as-usual in the next 100 years or less. The risk of major ocean circulation changes becomes significant for the more pessimistic warming scenarios, but can be greatly reduced if global warming is limited to the lower end of the IPCC range. The rate of increase in CO_2 matters: the ocean-atmosphere system appears less stable under faster perturbations.

Based on present knowledge of the climate system, the following results appear to be robust:

- The Atlantic THC can have multiple equilibria which implies thresholds;
- Reorganisations of the THC can be triggered

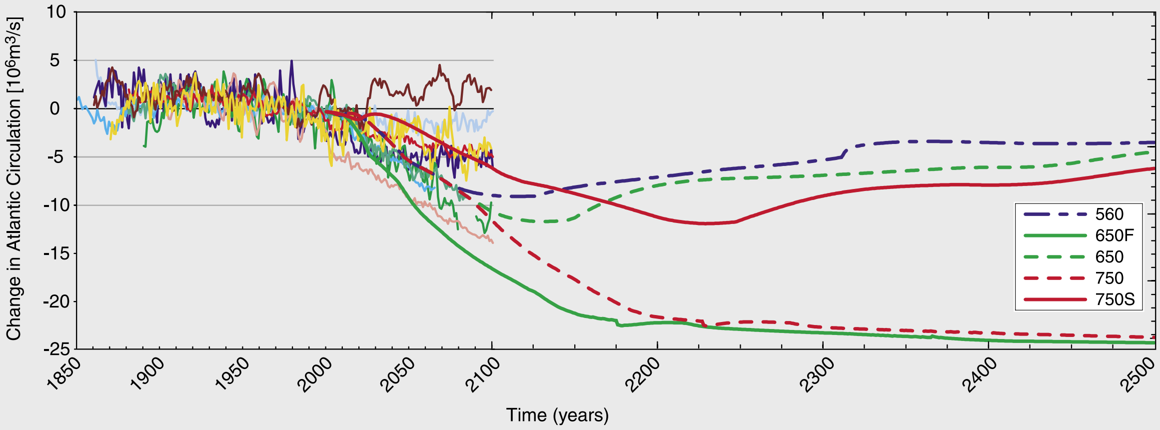


Record of $\delta^{18}O$ (per mil, scale on left) from the Greenland Ice Sheet Project (GRIP) ice core, a proxy for atmospheric temperature over Greenland (approximate temperature range, in °C relative to Holocene average, is given on the right), showing the relatively stable Holocene climate in Greenland during the past 10 000 years and Dansgaard-Oeschger (D/O) warm events (numbered) during the preceding colder glacial climate.

Source: Ganopolski and Rahmstorf (2001) Nature 409:153-158.

by changes in the surface heat and freshwater fluxes;

- Most models indicate a weakening of the THC in the next 100 years. This implies an approach towards possible thresholds;
- Crossing of thresholds and associated irreversible changes of ocean circulation *cannot be excluded* within the range of projected climate changes over the next century.



Composite of changes in meridional overturning in the Atlantic Ocean simulated to 2100 by a set of comprehensive coupled climate models (fine lines). To illustrate the possible long-term behaviour of the thermohaline circulation, simulations using a coupled model of reduced complexity are overlaid. They use artificial CO_2 emissions scenarios that are identified in the inset. Carbon dioxide increases by rates of 0.5, 1 and 2% per year up to maximum concentrations of 560, 650 and 750 ppm, and constant thereafter. Depending on the rate of CO_2 -increase and the maximum CO_2 concentration, and hence the warming, the THC crosses a threshold beyond which the circulation stops and remains collapsed.

Sources: Cubasch et al. (2001) IPCC TAR, Cambridge; Stocker and Schmittner (1997) Nature 388:862-865.

Earth System brake on human-driven CO_2 build-up in the atmosphere could fail and the concentration could surge strongly, leading to a chain of positive feedbacks in the Earth System that could propel it into another state.

Human perceptions of global change

Virtually all of the discussions on the consequences of global change for human well-being focus on the material and physical aspects of such change – provision of food and water, security of infrastructure, impacts on the economy, and so on. Virtually no analyses consider the psychological impacts or consequences of global change on individual humans and on their societies. Many in the scientific community may consider these aspects to be irrational and inconsequential. Yet, in the final analysis, it will be the human *perceptions* of global change and the risks associated with it that will determine societal responses. At the heart of these perceptions is the fundamental place of humanity in the natural world. Three examples illustrate the point.

- Snow at the equator is one of the geographical features of Earth that has fascinated humans for centuries. Yet in just a few generations the summit glaciers and snowfields of Kilimanjaro may disappear, probably due to anthropogenic climate change; at present rates, the mountain will be snow free by 2015 or 2020, within the lifetime of many people already on the planet. The most significant consequence will likely be the psychological one; the fact that through a myriad of daily activities far removed from tropical Africa humanity can so influence the global environment that such striking changes can occur so rapidly.

- The glaciers of the Swiss Alps are already retreating rapidly and may disappear altogether. Given the importance of Switzerland's mountainous landscapes for the psyche of its people, the effects of global change on the Swiss population's perception of its homeland will be profound and may 'destroy the soul of a nation'.

- The loss of biological diversity is an aspect of global change that may prove to be just as important as climate change. Ultimately the human perception that significant disruption of Earth's complex webs of life is an inherently dangerous pathway may be more important than scientific knowledge of the impacts of diversity change on ecosystem functioning. In southern China bees have disappeared from a region where the production of fruit is an important economic activity. The local population has responded by pollinating the trees themselves (Fig. 14). The economic losses of having to pollinate fruit trees manually can be calculated, but the image of humans climbing trees to pollinate flowers penetrates to the fundamental nature of the problem far more effectively.

These examples raise fundamental moral and ethical issues. Human civilisations around the world and all that they entail – accumulated wisdom, literature, art and music handed down over generations – have developed in the context of a naturally varying global environment, a planetary life support system with a pace and patterns of change within which civilisations could develop, grow and prosper. Now, however, human activities are changing the natural rhythms of Earth in ways that are only partly understood and onto trajectories that may lead to unknown states of the planetary environment, some possibly much less hospitable for human and other forms of life. After all of the scientific syntheses and assessments are done, after all of the economic analyses of global change consequences are laid out in cost-benefit terms, after all of the debates between sceptics and believers have generated even more heat, one basic ethical question lies at the heart of the global change debate. How should the generations of humans now inhabiting Earth respond to the fact that their activities are creating risks, possibly very big risks, for the future of Earth's life support system?

Figure 14. In Maoxian County, near the border between China and Nepal, people pollinate apple trees by hand because the bees, which were pollinating these trees, have become extinct. It takes 20-25 people to perform the work of two bee colonies.

Source: ICIMOD

Towards Earth System Science and Global Sustainability

Achieving global sustainability demands answers to several critical questions: What will be the nature of changes in the Earth System over the next decades? What are the implications of these changes for humankind? What type and scale of management responses – from prevention and adaptation to more proactive geo-engineering approaches – are consistent with the scientific knowledge base? How must science itself change to tackle the challenges that lie ahead? How can an innovative and integrative Earth System science be built? The interactions between the likely accelerating changes to the Earth System over the coming decades and the growing needs of a rapidly expanding human population give a sense of urgency to realising the goals of Earth System science and global sustainability.

Making Earth System science

The challenges of a rapidly changing Earth demand new strategies to generate scientific knowledge to support societal action. Much exciting new knowledge, insights and understanding are flowing from disciplinary research on parts of the Earth System. Even more is needed. However, the biggest challenge is to develop a substantive *science of integration*, putting the pieces together in innovative and incisive ways towards the goal of understanding the dynamics of the planetary life support system as a whole.

The research required to address the future-oriented research agenda of Earth System science must have new characteristics. It must:

- continue to support and facilitate the study of pieces of the planetary machinery in fine detail, but from a systems perspective;
- embed the insights of this classical analytical science – the identification of cause-effect relationships – into complex systems analysis which directly address the synergies, interactions and nonlinearities that defy the traditional approach on its own;
- complement the bottom-up approach to integration with the development of explicit systems-level research strategies, addressing directly the phenomena which emerge at larger scales in complex systems;
- above all, it must transcend disciplinary boundaries across the natural and social sciences, as Earth System science is ultimately concerned with issues that lie well beyond any single field of study.

An integrative Earth System science is already beginning to unfold. Observations of Earth from the surface and from space are yielding new insights almost daily, interdisciplinary research centres focused on global change are springing up around the world, and the international global change research programmes are building an interdisciplinary framework through the Earth System Science Partnership. What questions should guide this science? What new research strategies are required to deal with the complex nature of the Earth System? What tools are needed to do the work?

Questions at the frontier

The past decade of global change research has provided answers to many important questions, but in the process has generated new questions. Even more importantly, a level of understanding has now been achieved that allows the identification of *key questions* that can help set the agenda for systems-level research on Earth's environment and that must be addressed on the road to global sustainability. Table 3 gives examples of the types of questions currently under development, ranging from analytical and methodological research questions to normative and strategic questions that rely on value-based judgments.

Coping with complexity and irregularity

Most environmental systems are characterised by a multitude of non-linear internal interactions and external forcings. As a consequence, they do not often behave regularly and predictably, but rather exhibit chaotic dynamics or abrupt transitions to new modes of operation under appropriate forcing. These systems usually become even more complicated when human activities

Analytic Questions
1. What are the vital organs of the ecosphere in view of operation and evolution?
2. What are the major dynamical patterns, teleconnections and feedback loops in the planetary machinery?
3. What are the critical elements (thresholds, bottlenecks, switches) in the Earth System?
4. What are the characteristic regimes and time-scales of natural planetary variability?
5. What are the anthropogenic disturbance regimes and teleperturbations that matter at the Earth System level?
6. Which are the vital ecosphere organs and critical planetary elements that can actually be transformed by human action?
7. Which are the most vulnerable regions under global change?
8. How are abrupt and extreme events processed through nature-society interactions?
Operational Questions
9. What are the principles for constructing "macroscopes ", i.e., representations of the Earth System that aggregate away the details while retaining all systems-order items?
10. What levels of complexity and resolution have to be achieved in Earth System modelling?
11. Is it possible to describe the Earth System as a composition of weakly coupled organs and regions, and to reconstruct the planetary machinery from these parts?
12. What might be the most effective global strategy for generating, processing and integrating relevant Earth System data sets?
13. What are the best techniques for analysing and possibly predicting irregular events?
14. What are the most appropriate methodologies for integrating natural-science and social-science knowledge?
Normative Questions
15. What are the general criteria and principles for distinguishing non-sustainable and sustainable futures?
16. What is the carrying capacity of the Earth?
17. What are the accessible but intolerable domains in the co-evolution space of nature and humanity?
18. What kind of nature do modern societies want?
19. What are the equity principles that should govern global environmental management?
Strategic Questions
20. What is the optimal mix of adaptation and mitigation measures to respond to global change?
21. What is the optimal decomposition of the planetary surface into nature reserves and managed areas?
22. What are the options and caveats for technological fixes like geoengineering and genetic modification?
23. What is the structure of an effective and efficient system of global environment and development institutions?

Table 3. Research questions to help guide Earth System science in the future. Source: GAIM (Global Analysis, Integration and Modelling) Task Force of the IGBP.

are involved, which introduces a further element of indeterminacy. All these generic difficulties are reflected and severely amplified at the Earth System level, where the connections and feedbacks of millions of entangled local, regional and global processes have to be considered. Typical examples of Earth System complexity and irregularity are the intricate patterns in space and time of carbon fluxes between the Earth's surface and the atmosphere, and the very abrupt and seemingly erratic temperature oscillations documented in the Greenland ice-core records. Nature-society interactions also tend to come in complicated functional patterns that defy the power of standard scientific analysis.

In order to cope with these challenges, Earth System science can take advantage of the considerable progress recently made in fields outside the usual arena of global change research – like nonlinear dynamics, complex systems analysis, statistical physics, scientific computing or artificial intelligence research. By combining, for example, arguments from bifurcation theory and stochastic analysis, the wild temperature fluctuations during the last ice age can be explained in large measure. There are now methods developed in biophysics that try to anticipate when critical systems thresholds will be crossed by detecting warning signs of the imminent phase transition. The latter approach is particularly relevant to Earth System analysis that attempts to identify the switch and choke points in the planetary machinery that might be inadvertently activated by human activities. In fact, science can even benefit from the existence of strong non-linearities in the Earth System by devising an inverse sustainability strategy that calculates the critical anthropogenic perturbations to be avoided at all costs.

In addition to these more visionary tools, Earth System science will still need to build on many of those developed and used successfully during the previous decade of global change research. These tools will undoubtedly need to be developed further, as well as integrated into more powerful combinations of multi-technique approaches that tackle system complexities directly.

The Earth System science toolkit

Making Earth System science happen demands an extensive toolkit comprised of existing and developing techniques, such as fully coupled three-dimensional atmosphere-ocean general circulation models, and novel methods and approaches like those described above. The challenge is to deploy the toolkit not as a series of independent instruments that examine parts of the planetary machinery in isolation, but as an interlinked suite of probes and processors that sense and interpret Earth System behaviour in a holistic way.

Palaeo-science. The only way to investigate Earth System processes that operate on timescales longer than the period of contemporary instrumental records is through palaeo-environmental research. The Earth System leaves traces of and clues to its behaviour in a wide variety of archives – marine and lake sediments, ice caps, tree rings, long-lived corals and archeological remains and other historical records. Although palaeo-science has achieved remarkable success in shaping the present understanding of Earth System dynamics, significant challenges remain in building a more integrative global system of palaeo-observation and in recovering key archives of past change before they disappear in the current era of accelerating change.

Contemporary observation and monitoring. Observation of the Earth from space has revolutionised human perspectives and understanding of the planet, and the expanding array of sophisticated remote sensors promises a flood of valuable data, complementing observations made on the Earth's surface. Creative approaches for documenting the role of people in the Earth System can illuminate the human dimensions of planetary dynamics (Fig. 15). Well-conceived and -deployed global monitoring networks can provide powerful early warning systems for global change. Some innovative concepts have already been developed and first concrete steps taken towards developing a global macroscope, a truly integrated system for observing the most critical features of Earth System dynamics.

Earth System experimentation. Experimental simulation of future environmental conditions on Earth provides the means to study the structure and functioning of ecosystems under new combinations of atmosphere and climate. Addition and removal of species provide insights into the responses of biological systems as their complexity changes. Manipulation of element flows, such as the addition of iron to nutrient-poor areas of the oceans, mimics system responses to changes in biogeochemical cycling. Nature itself and human activities have both provided inadvertent experiments that can give important new insights into Earth System functioning. Natural disturbances, such as volcanic eruptions and the subsequent lava flows, can eliminate existing terrestrial ecosystems, thereby allowing the study of the change in functioning as ecosystems recolonise destroyed areas and slowly build up system complexity. Humans have inadvertently conducted many experiments by simplifying ecosystems through land-cover conversion, through the introduction of alien species into new ecosystems and by the fertilisation of large areas of land and coastal seas

Figure 15. Distribution of densely populated regions of the world as shown by night lights. Source: NASA, USA

through the alteration of biogeochemical cycles. In fact, the Earth as a whole is now a global test bed as humanity accelerates its unintended planetary-scale experiment with its own life support system.

Global networks. Scientific networks studying aspects of the global environment will continue to form the backbone of the emerging new science required to study Earth as a system. Planetary patterns emerge more clearly when small-scale or site-specific measurements and process studies are carried out in a consistent and comparative way across the globe. Major challenges of site representivity and stratification, scaling up and aggregation, and interpolation and interpretation stand between the individual studies and their application to Earth System questions. By meeting these challenges, global networks are becoming a powerful tool for sharing methodology, technology and experience; for enhancing the cost effectiveness of research; and for generating synthesised understanding beyond the reach of individual research groups (Fig. 16).

Integrated Regional Studies. Global change is evolving in very different ways in different regions of the world. Increasing and variable rates of population growth, rapid rates of land-cover conversion, dense human settlements, evolution of megacities, large-scale industrialisation and economic development are all leading to rapid changes in regional socioeconomic conditions and in terrestrial, marine and atmospheric systems, with implications for the regional environment and resource development as well as for the global environment. Because regions are normally defined by common biophysical characteristics (e.g., the Asian monsoon) and broadly common socio-economic characteristics, regional-scale studies of global change and sustainable development lend themselves to the undertaking of vulnerability analyses, identification of hotspots of risk and identification and simulation of syndromes of environmental degradation.

From an Earth System perspective, regions manifest significantly different dynamics and thus changes in regional biophysical, biogeochemical and anthropogenic compo-

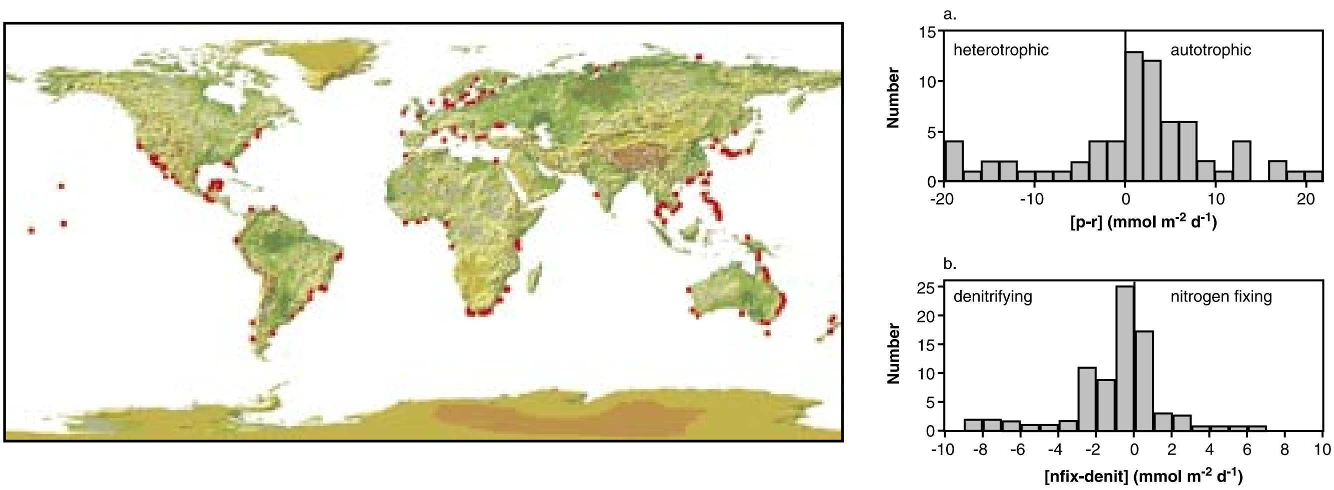


Figure 16. The global network of LOICZ biogeochemical budget sites, January 2002. Inset shows the frequency distributions of [p-r] and [nfix-denit] at the budget sites. [p-r] is primary production minus respiration and [nfix-denit] is nitrogen fixation minus denitrification.

Source: Smith et al. (2002), IGBP NewsLetter 49, pp. 7-11.

nents may produce considerably different consequences for the Earth System at the global scale. Regions are not closed systems and thus the linkages between regional change and the Earth System are critical. Regions may function as switch or choke points and small changes in regional systems may lead to profound changes in the ways that the Earth System operates (Fig. 17). Regional studies can contribute substantially to the reconstruction of global dynamics from regional patterns; in effect, integrated regional studies represent a unique way to reconstruct the Earth System from its components.

Simulating Earth System dynamics. Observations, experimental results and large regional studies must eventually be brought together in coherent ways to understand and simulate the dynamics of the Earth System as a whole. A vast array of mathematical models has already been designed to simulate the Earth System or parts of it. Simple, stylised Earth System models focus on description and understanding of the major features of the planetary machinery while comprehensive Earth System simulators are being assembled from the most sophisticated component modules. In between, Earth System models of intermediate complexity have already proven to be effective tools for both hindcasting and forecasting Earth System behaviour (Fig. 18). Even more innovative approaches will be required, however, to include the complexity of human and societal behaviour as an integral part of Earth System dynamics.

The range of Earth System modelling approaches can be classified in terms of their level of integration. Simple conceptual models, sometimes called tutorial models, are based on a small number of mechanistic processes, but nevertheless can exhibit complex behaviour when the processes are coupled. At the other end of the Earth System modelling spectrum are the well-known comprehensive general circulation models (GCMs) or, more recently, coupled general circulation models. GCMs have proven to be a very powerful tool in simulating and understanding climate variability and change. As more and more processes are included in the models, their ability to simulate correctly the contemporary variability in climate has improved significantly. Complemen-

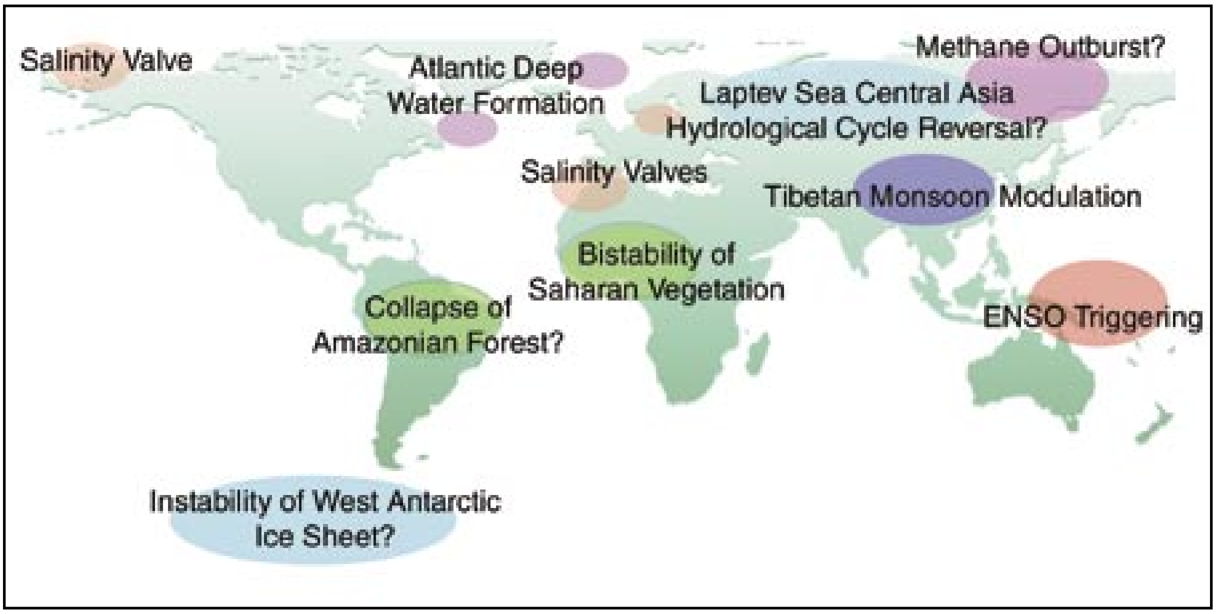


Figure 17. Critical region analysis of hot spots or switch and choke points: an early attempt at identifying parts of the Earth where changes at the regional scale can cause significant changes in the functioning of the Earth System as a whole.
Source: Schellnhuber (2002) In Steffen et al., Challenges of a Changing Earth, Springer.

tary to both simple models and GCMs, Earth System Models of Intermediate Complexity (EMICs) aim to simulate the dynamics of the natural Earth System (i.e., humans and their activities are prescribed as external driving forces) albeit at a reduced level of resolution and at a higher level of parameterisation compared to GCMs. One of the strengths of EMICs is that most of them emphasise the interactions among processes and thus capture many of the forcings and feedbacks between biogeochemical cycles and physical dynamics. In addition, their relative simplicity compared to fully comprehensive models allows simulations up to hundreds and thousands of years, so allowing EMICs to be tested against many of the long-term palaeo-records.

Global integration, synthesis and communication. The Earth System toolkit represents an exceptionally powerful approach to understanding the workings of the planet's life support system. Many new insights and novel conceptualisations of the Earth System will be proposed, debated and eventually accepted, refined or disproved. Knowledge of Earth System dynamics will expand at an accelerating rate. However, society expects that the scientific community will eventually address directly the simple yet profound questions that it asks about the global environment. Thus, no toolkit would be complete without explicit methodologies to synthesise, integrate and communicate the expanding knowledge base on the Earth System to underpin the evolution towards global sustainability.

Global change lies at the nexus between science and society, so efforts to transfer the expanding knowledge base to a wide variety of audiences - policymakers, resource managers, and the general public - must be intensified. Equally important is the need to equip the next generation of scientists with the tools required to undertake Earth System science. Courses focusing on global change and Earth's environment are already expanding rapidly in universities around the world, spawning younger scientists who are challenging their elders with their breadth of understanding of Earth System dynamics. Finally, the divide between the developed and the developing worlds also afflicts the scientific

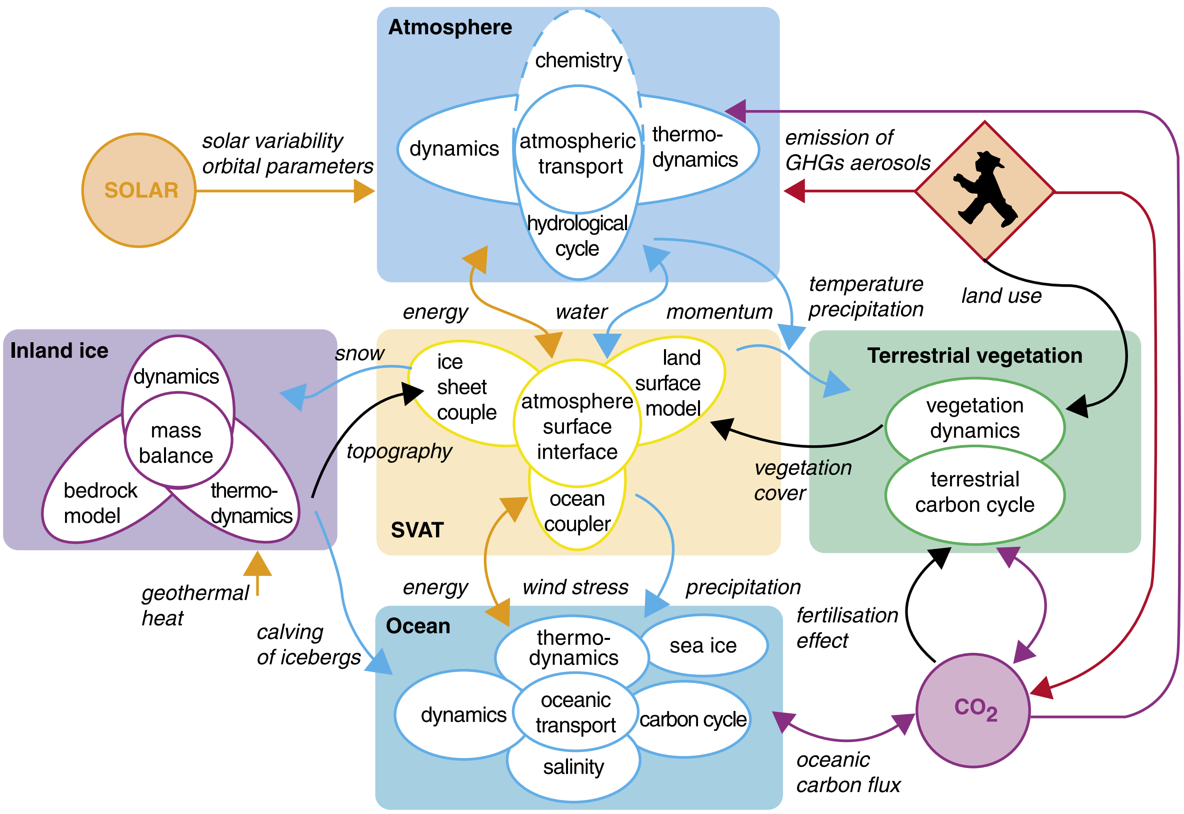


Figure 18. The structure of the CLIMBER model, an example of an Earth System model of intermediate complexity.
Source: Petoukhov et al. (2000) Clim. Dyn. 16, 1-17.

world in all aspects - research, education, facilities and communication. Special, dedicated efforts are required in all of these areas to ensure that Earth System science becomes truly global.

Stewardship of the Earth System

Humanity is already managing the planet, but in an unconnected and haphazard way driven ultimately by individual and group needs and desires. As a result of the innumerable human activities that perturb and transform the global environment, the Earth System is being pushed beyond its natural operating domain. Many of these global changes are accelerating as the consumption-based Western way of life becomes more widely adopted by a rapidly growing world population. The management challenges to achieve a sustainable future are unprecedented. Earth System science is the key to implementing any approach towards good planetary management, as it can provide critical insights into the feasibility, risks, trade-offs and timeliness of any proposed strategy.

Science is centrally important in advancing sectoral wisdom in order to deal with global change. Dramatic increases in energy efficiency, decarbonisation and the development and utilisation of new sustainable energy technologies, such as a hydrogen-based energy system, are needed. In agriculture, continued increases in food production and improvements in distribution and access are needed urgently as the world's human population continues to grow and dietary preferences change. Strategies for management of water must increasingly take integrative, regional approaches. Likewise, management of air quality recognises increasingly the multi-sectoral and regional, rather than local, determinants of air quality. In terms of sustaining ecosystem goods and services, the importance of overlapping sectoral activities has led to the development of more integrated landscape planning that reconciles ecosystem processes with human social and economic activities.

In addition to specific management approaches, an overall, comprehensive, internally consistent strategy for stewardship of the Earth System is required. A fundamental underpinning in Earth System science is even more important here to support the new paradigms for global sustainability that are beginning to appear:

Standardisation. The management objective is to maintain the evolution of the Earth System within a safe range of environmental qualities or aggregated functions defined as sustainability indicators.

Optimisation. In an ideal world the most attractive of all of the management approaches would aim to maximise generalised utility over a prescribed time period, where utility is defined in a broad, normative way through millions of acts and interactions by individuals around the world.

Pessimisation. The primary emphasis in this approach is placed on the precautionary principle of preventing the worst from happening, for example, abrupt changes with potentially catastrophic effects.

Equity. Management approaches focussing on equity aim to achieve a relative balance amongst the various participants who have a stake in global management (i.e., virtually the entire human population), but taking into account the nature of Earth System dynamics.

Status quo. The goal of this paradigm is to define and maintain a stable equilibrium in the global environment.

In reality human societies will not be able to adopt any one of these approaches in their pure forms. Even if they desired to do so, lack of complete scientific understanding and limits to predictability may prevent the full implementation of the paradigm. In this situation adaptive management is the only feasible way forward. In a broad sense adaptive management is an interactive process of learning by doing and of doing based on learning. In the context of global change and the Earth System, it implies that combinations of management approaches will be required. For example, the overall strategy must be to avoid catastrophic state changes, but within that overall strategy a number of the other approaches may also be applied. The climate system could be stabilised at some agreed level of change while also taking equity and economic and social cost considerations into account.

Earth System science is essential for any attempts at adaptive management at the planetary scale to succeed. There are already powerful tools to support management approaches. For example, integrated Earth System models allow many different scenarios of interacting natural and human-driven changes to be developed and evaluated. Such models, of course, need to be rigorously tested against empirical reality, both past and present, to increase confidence in their projections. In addition, the models and the scenario development that follows from them must evolve further through integrated interdisciplinary research, and in continuing dialogues between the scientific community and policymakers at a variety of levels. The most challenging scientific task of all is to build a common international framework for Earth System science that can harness the potential synergies that will arise from the interactions of tens of thousands of investigators, research groups and institutions around the world. The ultimate challenge, however, is directed towards the governance and management communities, as they must deal with the implications of Earth System science. How can a large group of independent nations with differing cultures, values, wealth, social organisation and world views come together to manage their own single, connected life support system in a coherent and effective way?

As global change assumes a more central place in human affairs, science must accept the responsibility of developing and communicating the essential knowledge base societies can use to debate, consider and ultimately decide on how to respond to global change. Ultimately, upon this science the preservation of the Earth's life support system depends. The challenge of ensuring a sustainable future is daunting. It can be met, but only with a new and even more vigorous approach to studying and managing an integrated Earth System.

Appendix

The International Geosphere-Biosphere Programme

IGBP is an international scientific research programme (sponsored by the International Council for Science, ICSU) built on inter-disciplinarity, networking and integration. The participation of most of the thousands of scientists worldwide who contribute to IGBP research is voluntary. IGBP aims to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions. It delivers scientific knowledge to help human societies develop in harmony with Earth's environment.

IGBP helps to:

- develop common international frameworks for collaborative research based on agreed agendas
- form research networks to tackle focused scientific questions and promote standard methods
- guide and facilitate construction of global databases
- undertake model inter-comparisons
- facilitate efficient resource allocation
- undertake analysis, synthesis and integration of broad Earth System themes

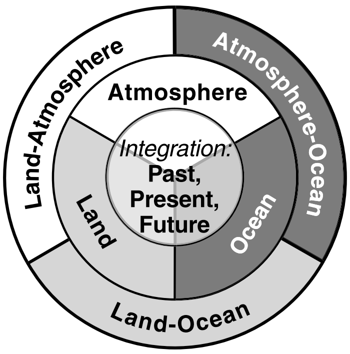
IGBP produces:

- data, models and research tools;
- refereed scientific literature (special journal editions, articles etc);
- syntheses of Earth System science (IGBP book series);
- policy-relevant information in an accessible format (IGBP Science Series).

IGBP's research effort

IGBP research is organised around eight projects that represent the Earth System - land, atmosphere, ocean and their interfaces (land-atmosphere, atmosphere-ocean and land-ocean); integration and modelling, focusing on the changing environment of the planet as a whole, from past through present and to the future.

The projects of IGBP are:



Atmosphere: International Global Atmospheric Chemistry (IGAC)

Ocean: Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and Global Ocean Ecosystem Dynamics (GLOBEC)

Land: Land-Use/Cover Change (LUCC) and Global Land Project (GLP)

Land-Atmosphere: Integrated Land Ecosystem-Atmosphere Process Study (iLEAPS)

Atmosphere-Ocean: Surface Ocean – Lower Atmosphere Study (SOLAS)

Land-Ocean: Land-Ocean Interactions in the Coastal Zone (LOICZ)

Integrating projects: Past Global Changes (PAGES) and Global Analysis, Integration and Modelling (GAIM)

Many IGBP projects are co-sponsored (see the IGBP website for details).

Earth System Science Partnership

IGBP works in close collaboration with the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP), and DIVERSITAS. The four international programmes have formed an Earth System Science Partnership (ESSP) for the integrated study of the Earth System, the changes that are occurring to the System and the implications of these changes for global sustainability (www.ess-p.org). ICSU is the common scientific sponsor of the four international global environmental change programmes.

To find out more about IGBP visit our website (www.igbp.kva.se).

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