To live within Earth's limits

AN AUSTRALIAN PLAN TO DEVELOP A SCIENCE OF THE WHOLE EARTH SYSTEM

Australian Academy of Science

To live within Earth's limits

AN AUSTRALIAN PLAN TO DEVELOP A SCIENCE OF THE WHOLE EARTH SYSTEM

Roger M. Gifford, Will Steffen, John J. Finnigan
and
fellow members of the National Committee for Earth System Science

Australian Academy of Science
2010

GPO Box 783
Canberra, ACT 2601
Australia
Email: aas@science.org.au

Also available online, with appendices, at
www.science.org.au/natcoms/nc-ess.html

Designed by Alexandra Chiragakis
Printed by New Millennium Print, Canberra
Complies with Good Environmental Choice labelling
standard GECA 20 (Printers and Printed Matter)

ISBN 978-0-85847-287-7

Abstract

This precious and beautiful blue planet on which we live is complex beyond measure, so complex, we argue here, that a whole new science – an integrative science of the Earth system (Earth System Science or ESS) – is needed to understand it. There is an imperative to predict its potential future states, particularly those influenced by human impacts on the atmosphere, oceans, land, and biosphere. The Earth is now entering an epoch that has been called the "Anthropocene", a time in which humans are profoundly changing the environment, even the stratigraphy, of the planet. Rising carbon dioxide levels and associated global warming is the iconic example of human-induced global change, but climate change is only the most prominent of a series of changes to the Earth that are ultimately driven by exponential growth in the world's population. These changes involve so many interconnecting factors that how they will unfold in the future is far from clear. We believe that ESS, as a body of fundamentally interdisciplinary knowledge, offers the understanding necessary to move us towards a sustainable occupation of the planet. Here we set out a systematic and coherent plan to create an Australian scientific enterprise – combining inputs from the natural and social sciences, economics, and the humanities – which is devoted to understanding the planet's life support systems. Its primary aim will be to discover the Earth's biophysical limits and how to live within them.

Foreword

To Live Within Earth's Limits presents an ambitious plan – one for advancing the science needed for Australia and the world to address the burgeoning globalisation of the impacts of human activities on the environment.

The extent of these environmental changes is partly a consequence of the sheer scale and rate of growth of human activities relative to the finite limits of our planet. The mixing of the fluid Earth – the atmosphere and the oceans – results in the transport of greenhouse gases, aerosols, soot, toxic substances, pollen grains, and organisms around the Earth. Thus, a multitude of local environmental changes have now merged into a set of global environmental changes.

The interacting processes underlying these changes require holistic examination. To do so calls for a science of the whole Earth system.

Internationally, ICSU (the International Council for Science) has conducted an open forum on "Earth system visioning" to decide how better to integrate its large portfolio of activities covering global change science. In mid 2010 it produced a document, *Grand Challenges for Global Sustainability Research*, as a "Framework for organising sustainability (or integrated Earth Systems) research over the next decade".

The Australian Academy of Science's National Committee for Earth System Science has developed a framework and approach to coordinate and integrate relevant Australian efforts in this important new area of science. Their position paper is one of a series of strategic plans for Australian Science produced by the Academy's National Committees. Plans for the Earth Sciences, Space Science, Astronomy, Mathematical Sciences, and Earth Observations from Space have already been developed and others are in preparation.

I commend the work of Earth System Science Committee, whose vision requires the drawing together not only of numerous disciplines in the natural sciences but also in economics, social sciences, humanities, and law.

Suzanne Cory
President
Australian Academy of Science

Earth system issues

Overarching global Earth system issue

How can we secure a well-functioning and resilient Earth system for the indefinite future? The challenge we face is to achieve a stable balance between the needs of the people on Earth and the physical and biological limits of our planet. The goal of Earth system science is to provide the knowledge needed to reach this balance.

Earth system issues

Australia-focused Earth system issues

1 How will Australia's regional climate change over the coming decades and what options are available for both adapting to inevitable changes and mitigating further changes?

2 To what extent can the large, human-induced changes in Australian biodiversity be arrested or reversed, and what are the associated costs and benefits of doing so?

3 How can we secure a well-functioning and resilient food and fibre production system in Australia for the indefinite future?

4 How can Australia meet the demand for freshwater and the need to maintain adequate "environmental flows" at the same time as climate changes are bringing changed rainfall patterns across the continent?

5 What institutional arrangements must be set in place to ensure long-term sustainable land use in the face of competing social and environmental requirements?

6 What long-term coastal occupancy and management issues need to be investigated for Australia to minimise the risks from rising sea levels?

7 What management options can Australia adopt to minimise the risks of damage from ocean acidification to its iconic coral reef systems and marine biodiversity?

8 What can Australians do, both institutionally and personally, to minimise the risks and impacts of pandemics in a "globalised" world?

9 As a complement to greenhouse gas emission mitigation, how can Australia engage in global considerations of responsible geo-engineering options?

10 What are the potential environmental, social, and economic consequences and practical timeframes for Australia's transition to a low-carbon economy?

11 What are the social, environmental, and economic implications of different trajectories for human population size and stabilisation in Australia?

Recommendations

To foster the emergence of an Australian Earth system science strategy, it is recommended that:

1 The Earth system research questions posed in this report be considered and evaluated by Australian ESS researchers and research funding agencies. This should be done in close collaboration with decision makers and other stakeholders, and the questions should be investigated as soon as possible. (Section 3.5)

2 An Australian Society for Earth System Science be established. (Section 4.1)

3 Discussions be initiated between the Australian learned Academies on collaboration and coordination of activities in Earth system science. (Section 4.1)

4 A series of Australian Earth System Outlook Conferences be initiated. (Section 4.2)

5 An Australian Earth system science journal be established. This journal would be of international standing and would publish highly interdisciplinary contributions, covering both research and opinion, relating to the Earth system state and its functioning. (Section 4.2)

6 As a means to further the development of an effective Earth system community in Australia, a tertiary-level textbook on Earth system science be prepared. It would have associated popular versions and a dynamically interactive web presence for keeping the information up to date and relevant to users. (Section 4.2)

7 National supercomputing infrastructure investment is kept up to date with the computing and observational data handling needs of Earth system science. (Section 4.3)

8 Australian research funding agencies explicitly create ways of competitively evaluating highly interdisciplinary Earth system research proposals. (Section 4.3)

9 The National Committee for Earth System Science explore the means to establish a National Office for Earth System Science. The function of the Office would be to champion the Recommendations of this report, to support and link existing relevant research activities and agencies as they move towards establishing a coordinated institutional structure for Australian Earth system science activities, and to foster communications between the Earth system research community and the general community, including education, government, and business. (Section 4.4)

Contents

▸ Diverse human influences on the global environment are now so pervasive as to justify referring to a new geological epoch, the "Anthropocene". ▸ The major environmental issues that Australia faces in the 21st century are expressions of human-induced global environmental changes, and the management of them requires objective scientific understanding, which ESS provides. ▸ The research questions needed to address these global change issues are motivated by the principal challenge humanity faces in the 21st century: how to secure a well-functioning and resilient Earth system as human population and its demands meets the biophysical limits of the planet. ▸ These limits are expressions of the size of the planetary spheres, like the atmosphere and biosphere, and the interactive cycles and processes that link them together.

Overview

Major aims

The aim of this document is to set out a plan for establishing a coherent, vibrant, and effective community of Earth system scientists in Australia. Such a community will form a source of sound, nationally relevant information that will help our nation anticipate, mitigate, and adapt to current and future global changes.

But what exactly is an Earth system scientist? The science of the whole Earth system is a developing, highly interdisciplinary field that treats the Earth as a single, complex dynamic system – and which considers humans as active agents within that system. The field sets out to document and analyse the Earth in its newest epoch, the "Anthropocene", and predict its future. The rationale of Earth system science is to address an overarching question, which we frame as:

> *How can we secure a well-functioning and resilient Earth system for the indefinite future? The challenge we face is to achieve a stable balance between the needs of the people on Earth and the physical and biological limits of our planet. The goal of Earth system science is to provide the knowledge needed to reach this balance.*

The question is not an easy one. We will need to rapidly find ways, within assuredly finite planetary boundaries, to feed, water, clothe, house, and stabilise the presently expanding human population. We will need to manage their waste streams while preserving the biological carrying capacity of the planet. And we would also like to bring billions out of poverty, and accommodate an ageing population profile, while coping with the human-induced global environmental changes that have already been set in train.

The core question has been brewing for some decades. Others have discussed related ideas: the "noosphere" of Teilhard de Chardin, the "spaceship Earth" of Buckminster Fuller ("there are no passengers, only crew"), the "Gaia hypothesis" of James Lovelock, cybernetics (the science of control of closed systems) from Norbert Wiener, consilience and resilience of Edward Wilson, global change science, and, via the United Nations, the Millennium Ecosystem Assessment and the Millennium Development Goals. These diverse considerations have flowed together into the concept of Earth system science (ESS). Earth system science reflects many of these disparate views but in a systematic, analytical way.

Most Earth system scientists do not regard the Earth as equivalent to Lovelock's "living organism" analogy. Nevertheless, they are fascinated by how the web of interactions and relationships between Earth's components, including the biosphere, somehow manages to keep it functioning – so far – within a more or less stable band of variability, even though far from thermodynamic equilibrium.

Earth system scientists are vitally engaged in predicting what conditions might cause the Earth to evolve in a new direction – physically, biogeochemically, and ecologically – as a result of human activity. Within just two centuries we have released into the atmosphere quantities of carbon that took tens or hundreds of millions of years to accumulate. Will the associated global "greenhouse" warming drive the Earth system into a new, much warmer, stable state, one that is much less conducive to the human enterprise?

Will the collective impact of a burgeoning human population – in the context of fast-growing per capita consumption and transformation of natural resources – disturb the long-evolved checks and balances in the Earth system? Will the "balance of nature", which seemed relatively stable pre-industrially, become so disturbed that we cannot comfortably move to a steady-state population that lives within a functionally intact and resilient environment?

Already we have some stark evidence in front of us. Consider these examples.

- The release of chlorofluorocarbons into the atmosphere has depleted stratospheric ozone concentrations.
- The planet's surface is warming.
- A direct effect of changing atmospheric CO_2 concentration on ocean pH has the potential to change the formation and dissolution of carbonates in sea shells.
- Plant and animal species are becoming extinct at an accelerating rate.

Rather than abandoning the problems as too hard, the intent of the plan we set out here is to blaze a trail forward. Repair of the "ozone hole" is happening from concerted action agreed on by international treaty, and this shows that big problems can be solved by global consensus and action. Similarly, with Earth system science the hope is that there can be a coming together of pertinent social science, economics, and humanities research on the one hand with relevant parts of the natural sciences on the other. The hybrid that results is what we see as comprising a new predictive science of the whole Earth system. Our goal is to achieve this merger by the end of the decade.

The social science strand is absolutely necessary because (i) the dominant drivers of global environmental change – human population pressure, consumption, behaviour, and responses to biophysical changes – are major areas of uncertainty in predicting future whole-system responses, and (ii) a much deeper knowledge of how humans interact with the biophysical world is required to enhance our social well-being.

ESS began from a quantitative natural science base, but over the last few years its scope has been expanding rapidly. It has come to recognise that, in order to effectively address global environmental changes, the human element in the Earth system must be treated as an *interactive* part of the whole system, rather than just an add-on, an external causal agent and affected party. By 2020 we expect to see a balanced mix of the natural sciences with socio-economic disciplines and related humanities (such as aspects of ethics, law, and history). In essence, we need to expand from considering just "global environmental changes" to interactive global changes in general.

While that important nexus is developing, natural scientists will remain busy. Much needs to be done to identify, document, and understand the biophysical changes that are happening to the global environment. We need to reduce the uncertainties about their immediate causes, ultimate drivers, and their geographic expression, particularly where predictions of human-induced effects are involved.

The Australian Academy of Science's current ESS planning process has emerged from the natural science side. It therefore builds from a base of interdisciplinary natural science as applied to global environmental change. This heritage is inevitably reflected in the emphasis of this document. However, in Chapter 3 we do raise several important questions and issues involving the human dimensions of ESS, issues that are urgently in need of research. This part is necessarily sketchy and incomplete because, as natural scientists, we lack the expertise to take it further.

Despite these gaps and limitations, our plan for the future is set out with a broad brush in the following section. The rest of the document, starting from Chapter 1, then fills in details.

The science of the Earth system: why, what, how, and who?

Why?

The Industrial Revolution was a revolution indeed, changing human activities so profoundly and pervasively that they now affect the functioning of the entire planet. Our species is changing the composition of the atmosphere, waters, soils, and energy balance at the Earth's surface; it is modifying climate patterns, acidifying land and sea, reducing the diversity of the biosphere, raising sea levels, and melting ice. Collectively, these impacts are altering the ecosystem services that in turn support human economic activity. A growing view is that the Earth is entering a new epoch in which humans have become a global biogeophysical force: the "Anthropocene".

The "Anthropocene" carries risks of abrupt and potentially irreversible environmental change, such as deglaciation of the Arctic and parts of the Antarctic, which would have serious and even catastrophic repercussions for current and future human civilisation. Major human impacts on the Earth system are now in train, meaning that wise, well-informed, and integrated management of the whole system is an enormous challenge for global governance in the 21st century. Earth system science (ESS) is an emerging, highly interdisciplinary, quantitative, and strongly analytical research area that aims to provide the knowledge base on which to build a wise approach to planetary stewardship.

ESS aims to (i) understand how the whole contemporary Earth system works, including the role of humans as an integral part of the system; and (ii) provide the knowledge required for humanity to thrive in the 21st century and beyond by maintaining a well-functioning and resilient whole Earth system as human population size, and its consumption demands, approach the planet's biophysical limits.

Importance for Australia. Australia comprises a large part of the Earth system. It is the only nation-continent, has the third-largest marine jurisdiction, and has territorial responsibilities from the tropics to the Antarctic. Changes in the Earth system have immense implications for Australia, including for ultraviolet radiation, rainfall, freshwater, biodiversity, and habitable and productive landscapes. Changes in the human sphere of the Earth system, such as the profound economic and technological transformation sweeping across Asia, also have considerable implications for us. Understanding how and why the whole Earth system is changing, and how it will change in response to human decisions, is of strategic national importance.

Specifically Australian challenges to framing ESS research questions include:

- How will Australia's regional climates change over the coming decades, and what feasible options are available to the Australian community for adapting to inevitable changes and mitigating further changes?

- What are the potential environmental, social, and economic consequences of Australia converting to various alternative greenhouse gas–neutral sources of energy, and what is a reasonable time-line for implementation?
- What are prudent, manageable trajectories for human population size and its stabilisation in Australia, given the limitations, pressures, and uncertainties provided by water resource scarcity and variability, predicted climate changes, native biodiversity loss and exotic species proliferation, increasing energy cost and carbon-emission cost of non-renewable resource acquisition, the ageing population, and refugee pressure?

What?

As its name implies, ESS is concerned with the planet as a whole. It focuses on the Earth as a single, complex dynamic system in which humans are active agents. It considers diverse time scales, from when humans were an insignificant part of the Earth system, through to the Anthropocene, and into the future. ESS focuses on the interface between the human and biophysical parts of the Earth system, a domain that requires a new range of approaches at diverse spatial and temporal scales.

At one level, ESS partitions the Earth into its largest biophysical units – continents, ocean basins, biosphere, cryosphere, and atmosphere – but also into several human spheres such as the money-based economy, cyberspace, socio-politics, and the national or regional domains relevant to decision makers and human communities. It is the interactions and feedbacks between these various spheres or domains that rapidly produce a complexity, a whole system dynamic, which calls for an integrated ESS approach. At a finer level, of course, traditional disciplinary research will continue to focus on individual parts of the Earth system, although we always need to remind ourselves that the whole is more than the sum of its parts. It is research based on integration and synthesis across many levels and scales which plays the core role in ESS.

How?

ESS takes a two-pronged approach: at the fine scale, it builds up knowledge from the wealth of existing detail, and at the large scale it develops new approaches to address the "big picture" gaps in understanding. For example, the vast body of work on climate change forms an excellent knowledge base on which to build understanding of the changing Earth system. It forms a platform for incrementally increasing our understanding of how biophysical systems function under human influence. At the same time, exploratory research is developing rapidly on how the human enterprise is dynamically coupled to global biogeophysical changes, and it promises to deliver major insights. Both the incremental approach, and what we call the exploratory integrative approach, are essential. The interactions and synergies between them will enhance the power and usefulness of ESS.

Our plan aims to include different approaches to ESS, but at the same time it also wants to be clear and coherent enough to guide a national research effort. To do this, we support both incremental developments of Earth system understanding, as well as the more integrated, exploratory approaches. An example of an incremental approach is the progressive addition of marine, cryospheric, land surface, ecological, and socio-economic feedbacks to atmospheric general circulation models of the climate system. A more exploratory approach might be one in which the impacts on the Earth system of the human enterprise are studied in a case where humans are considered from the outset as a fully coupled, co-evolving component.

We suggest that implementation of ESS be done using a conceptual framework in which global and regional social dynamics are but one element of the framework. The emerging science of complex systems is beginning to provide tools to address social factors and their interactions. Models will be important, ranging from the evolving family of global climate models to the exploratory genre of integrated global models that dynamically incorporate the human enterprise. Earth observations need to be greatly enhanced: more remotely sensed data streams, more *in situ* measurements to calibrate and extend satellite measurements (particularly time series at certain critical points), re-analysis of old data (taking advantage of advances in modelling and

model-data assimilation), and reconstructions of past Earth system dynamics from palaeo-data. Extensive global economic and trade data are already collected on a regular basis, but these need to be supplemented by census data and research on human behavioural responses to unfamiliar changes in the whole Earth system.

In addition to these quantitative approaches, the social sciences and humanities will need to increasingly provide qualitative analyses and insightful narratives to enhance understanding of the human enterprise and how it interacts with the rest of nature. Ultimately, natural and social scientists and humanities scholars will need to work together on the co-production of knowledge about the Earth system.

Who?

We are proposing that, by consensus, an Australian Earth System Science Strategy be set up. Such an internationally linked strategy will create a knowledgeable research community in Australia, one that will integrate relevant parts of the natural, socio-economic, and humanities disciplines and which will focus international progress in ESS on Australian concerns.

To build an Australian ESS community, we suggest capacity-building for early career scholars and regular events such as an Earth System Outlook Conference. Ultimately, an Australian Earth System Science Institute or Office could become a focal point for two-way research coordination and stakeholder liaison. A joint approach by the learned Academies would assist the implementation of this plan, given the interdisciplinary nature of ESS.

An essential element of the strategy is to engage Australian policy makers at all levels of government and business in the development and direction-setting of the Australian ESS effort. This will help to ensure the usefulness of ESS for strategic analysis, make sure it has an international context, and its inclusion in decision making throughout society. It is important to communicate ESS results beyond research communities to ensure that research outcomes are made use of by educational institutions, community groups, business communities, agricultural extension and advisory agencies, consultancies, other service providers, and by governments.

The Earth is complex far beyond our ability to fully grasp, but as scientists we are fired to understand it as best we can. The rest of our text spells out a plan for working towards answers to the core question on page 1 on which our very survival may depend.

Chapter 1

Rationale for Earth system science

1.1 The challenge of global change and origins of the idea of Earth system science

The term "Earth system" refers to a broad range of things. In specifics, it means the suite of interacting physical, chemical, biological, and socio-economic global-scale processes and cycles, driven by energy fluxes, which provide the conditions needed for sustainable life – including human society – on the planet. One recent definition of the Earth system is:

> *the unified set of physical, chemical, biological, and social components, processes, and interactions that together determine the state and dynamics of the Earth, including its biota and its human occupants. Earth system research includes global environmental change research.* (ICSU 2009)

In these terms, Earth system science (ESS) is the science of the integrated functioning of the planet, taking the major human influence in the contemporary period explicitly into account. Simply put, how everything is connected to everything else.

The scale of human influence on the global environment is now so large that earlier we introduced the term "Anthropocene" to describe it. The word is due to Nobel Laureate Paul Crutzen (Crutzen and Stoermer 2000, Crutzen 2002, Steffen et al. 2007) who used it in 2000 to describe the new geological epoch in which human activities have come to rival the "forces of nature" in their effect on the Earth. The Stratigraphic Commission of the Geological Society of London has evaluated the notion (Zalasiewicz et al. 2008, 2010) and concluded that a sufficient stratigraphic change had indeed occurred during the last couple of centuries to recognise the Anthropocene as a new epoch distinct from the Holocene. The Commission thought it justified formal consideration by the International Commission on Stratigraphy as a new Epoch of the Quaternary Period. Whereas for nearly all of human existence we have been the recipients of impacts caused by the natural variability of the planetary environment, now human influences are rivaling natural ones, and the term "Anthropocene" underlines that fact. We have come to play a major role in the ecology, biological evolution, climatology, biogeochemistry, and possibly even the geology, of the planet.

The scope and complexity of phenomena affected by human impacts is so broad that the phrase "Earth system science" has conveyed quite different things to different people. The term is still emerging, and its precise meaning depends on the interest of the investigator. Recorded impacts include biodiversity loss, atmospheric and oceanic temperature rise, enhanced soil and mineral transfer to the ocean, global toxification, sea-level rise, nitrogen deposition, freshwater diversion, stratospheric ozone depletion, land-surface alterations, and ocean acidification, among others. These phenomena encompass most of the traditional disciplines that scientists are trained in – climatology, oceanography, polar studies, biology, ecology, physics, geology, hydrology, toxicology, or, increasingly, one of the many social sciences or areas of humanities. The common theme is that it is the burgeoning human impact on the planetary environment that prompts new, integrated, inter-disciplinary investigations and understanding. Earth system science brings together knowledge and research from all sources that can assist understanding and deal with the human-induced changes that are sweeping the planet, changes which raise doubts that the seemingly endless growth in the consumption of ecosystem services and non-renewable resources can continue much longer.

Driving the environmental changes to the planet is a combination of rapid human population growth, rising per capita consumption of limited natural resources, a desire among nearly everyone to obtain a better life, and continuing economic prosperity. But as Buckminster Fuller, and Malthus before him, pointed out, exponential curves like these cannot persist. These issues of the 21st century have become the overarching Earth system issue around which ESS research questions are framed. That is, How can we secure a well-functioning and resilient Earth system for the indefinite future? The challenge we face is to achieve a stable balance between the needs of the people on Earth and the physical and biological limits of our planet. The goal of Earth system science is to provide the knowledge needed to reach this balance.

1.2 Treating the Earth as a unified system

Humans now have an impact on all the biological and physical systems of the planet. Almost no species, land area, or part of the ocean has remained unaffected. We have evidence today that the major components of the Earth system now operate well outside the range of variation over the last 500,000 years and that human activity is behind the change.

Since everything is ultimately connected, we need to find a way to understand how human activity percolates down through all the Earth subsystems. Our starting point is to see where the joints in the systems are so that we can start to map out the connections.

The key elements behind the concept of the Earth system are that:

- The Earth system must be treated as a closed, finite system for materials and stored energy sources. It has one dominant primary energy source that is external – the Sun.
- The major dynamic components of the Earth system are a suite of interlinked physical, chemical, biological, and socio-economic processes that cycle (i.e. transport and transform) materials and energy in complicated ways.
- Interactions and feedbacks (potentially destabilising "positive feedbacks" as well as stabilising "negative feedbacks") play crucial roles; they are as important as the primary drivers in determining overall system behaviour.
- Biological and ecological processes are an integral part of the functioning of the Earth system, and they are not just the recipients of changes in a physico-chemical system. Hence living organisms are treated as active, interactive participants in the behaviour and evolution of the Earth system.
- Human beings, their societies, and their activities are integral to the Earth system; they have co-evolved with it, contributed to it, and helped make it the way it is. They are not an outside force perturbing an otherwise "natural system".

- As well as human-driven changes, there are many sources of non-human-driven variability and instability within the system. Both types of variability are part of the dynamics of the Earth system. They are often impossible to separate completely, and they interact in complex and sometimes mutually reinforcing ways.
- Time scales considered in Earth system science vary according to the questions being asked. Many issues of global change occur on time scales of decades to centuries. However, a basic understanding of Earth system dynamics demands consideration of much longer time scales in order to capture longer term variability, to understand the fundamental dynamics of the system, and to place into context the current suite of rapid global-scale changes. Thus palaeo-environmental studies and prognostic modelling are both central to Earth system science.
- Many important changes in biogeochemical cycles can have appreciable direct impacts on the Earth system rather than via changes in the climate system. Examples include:
  - The direct effects of changing atmospheric CO_2 concentration on ocean pH can cause changes

in the formation and dissolution of carbonates in sea shells.

- Stimulation of plant photosynthesis (and reduction in stomatal conductance) directly affects the terrestrial carbon and hydrologic cycles and rate of rock weathering.
- The release of chlorofluorocarbons into the atmosphere has depleted stratospheric ozone concentrations.
- The global nitrogen cycle has been enhanced by the spread of phosphorus-fertilised leguminous crops and pastures, and fixation of inert nitrogen from the atmosphere into fertiliser. Effects have also come from leaching of reactive nitrogen compounds into freshwater systems and coastal seas, and the deposition of reactive nitrogen compounds from air pollution.
- The evolution of angiosperms has had an impact on rock weathering, increasing the transfer of calcium from the lithosphere to the oceans. Similarly, agriculture has had an impact on the rate of transfer of soil and soluble mineral nutrients to the oceans.

Chapter 2

Why we need an ESS perspective: Risks and opportunities for Australia as the Earth system changes

Of the many risks and opportunities for Australia in the future, some major ones are briefly highlighted here. They illustrate issues about which research questions might be posed, questions that will require a better understanding than we have now of how the Earth system functions. The list of issues is heavily skewed towards environmental risks, some of them recognisable as long-standing environmental problems in Australia. However, as ESS evolves through the decade to include more social science and humanities expertise, the object of study will increasingly become social-ecological systems rather than the environment as traditionally understood.

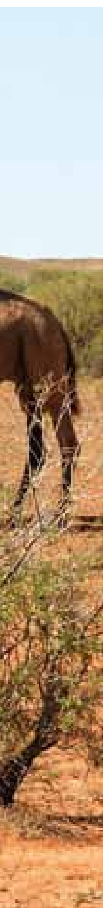
Global air quality and induced climate change. Global warming and changing rainfall patterns in Australia – attributable, at least in part, to increasing atmospheric greenhouse gas concentrations and aerosols (the "atmospheric brown cloud") – may put pressure on Australia's environmental and economic well-being. In coming decades, probable continuing changes to rainfall patterns, climate variability, risks of abrupt climate changes, and increasingly rapid sea level rises, pose a credible threat to national security.

We expect both winners and losers from global climate change. One potential gain is an increased crop and pasture yield from the fertilising effect of higher atmospheric CO_2 levels. Identifying ways of capitalising on such opportunities can minimise the net risks from atmospheric composition change to which the Earth is already committed. ESS can contribute by improving the spatial resolution of climate change predictions with better Earth system models, and by better understanding the response of human systems, such as annual crops, to the interacting effects of atmospheric composition and climate change.

Australia-focused Earth system issue 1

How will Australia's regional climate change over the coming decades and what options are available for both adapting to inevitable changes and mitigating further changes?

Changes in biodiversity. Over recent decades we have seen extremely rapid losses in terrestrial and marine biodiversity and gains in exotic biodiversity – a global phenomenon that is especially marked in Australia. These effects are a direct result of altered land use, habitat destruction, deliberate introduction and unintended escape of non-native species, hunting and fishing, and synthetic chemicals in the environment. Climate change is, on balance, unlikely to make things better, and



could make them worse. Although the purposeful introduction of exotic biodiversity – such as crop, tree, and pasture species and cultivars – and the successful use of biological control agents have provided major opportunities for human advantage, changes to the amount and spatial distribution of biodiversity pose real concerns for Earth system functioning in Australia, and involve issues of environmental, food, and economic security.

Australia-focused Earth system issue 2

To what extent can the large, human-induced changes in Australian biodiversity be arrested or reversed, and what are the associated costs and benefits of doing so?

Agricultural and forest production. Our land resource, already under considerable pressure from long-standing stressors – such as topsoil loss, compaction, subsoil acidification, salinisation, woody species thickening and encroachment in tropical rangelands, and exotic weed invasion – is now experiencing added pressure from climate change. There is the potential for global warming to have a deleterious effect on the stock of soil carbon and to make rainfall events heavier, increasing soil erosion. Both these issues affect food and environmental security. ESS can assist by evaluating the full spectrum of possible changes and how production will respond; it could also investigate how proposed remedial measures might interact with each other.

Australia-focused Earth system issue 3

How can we secure a well-functioning and resilient food and fibre production system in Australia for the indefinite future?

Freshwater availability and quality. Like many other places around the world, Australia is facing serious freshwater supply problems. The difficulties are due to high and growing demands on both surface flows and groundwater, combined with a better appreciation of the need to maintain "environmental flows" for ecosystem health. Changes in rainfall patterns, at least partly attributable to human-induced climate change, also aggravate the problem. In the most heavily inhabited regions of Australia, in parts of the south-east and south-west, some models predict reduced rainfall and runoff this century as a result of human-induced climate change, trends that have already appeared over the past few decades. In the Murray–Darling Basin, however, the model results are equivocal, and more research is needed (Roderick and Farquhar 2009, Chiew et al. 2009). If continued, these trends would exacerbate water shortages. In addition, our use of the land has led to salinisation of several waterways, producing poor biodiversity outcomes.

Australia-focused Earth system issue 4

How can Australia meet the demand for freshwater and the need to maintain adequate "environmental flows" at the same time as climate changes are bringing changed rainfall patterns across the continent?

Availability of uncommitted land. Conflicts of alternative land use are becoming a major 21st century issue in Australia and globally. The pressure to find land for growing bio-fuel crops, for carbon biosequestration, for renewable electricity production, and for biodiversity protection – as well as the continuing requirements for agricultural and forestry production, water catchment and storage, mining, urban development, and transport – pose challenges for managing the Earth system.

Australia-focused Earth system issue 5

What institutional arrangements must be set in place to ensure long-term sustainable land use in the face of competing social and environmental requirements?

Rising sea level. In the last decade global sea levels have been rising at about 3 mm per year (Rahmstorf et al. 2007), driven by thermal expansion of the ocean and by retreating glaciers and ice sheets (although uncertainties remain about the response of polar ice sheets

to warming). Australia has a special interest and responsibility for research into Antarctic ice sheets. Given that our population tends to live near the coast, sea level rises this century have implications for Australia's economic and environmental security.

Australia-focused Earth system issue 6

What long-term coastal occupancy and management issues need to be investigated for Australia to minimise the risks from rising sea levels?

Ocean acidification. When the ocean takes up CO_2 it becomes more acidic. Although the repercussions for the formation and dissolution of various forms of solid calcium carbonate are complex, there are potential major problems for coral reefs, with attendant risks for marine biodiversity. It also affects the ocean's capacity to remain a major net CO_2 sink.

Australia-focused Earth system issue 7

What management options can Australia adopt to minimise the risks of damage from ocean acidification to its iconic coral reef systems and marine biodiversity?

Increasing risk of major human pandemics. Humanity may find itself afflicted by serious pandemics due to the coming together of several factors. One is climate change, which is changing the distribution of disease organisms and vectors. Other factors are the

rapidly increasing urbanisation of the world (which means closer living), high international mobility (promoting interpersonal disease transmission), the emergence of multiple antibiotic resistance ("superbugs"), risky animal husbandry techniques in some countries, some risky human behaviours, and an ageing population profile (meaning a general weakening of immunity levels). Although more sparsely populated than most countries (but with a population highly concentrated in a few urban areas), Australia will inevitably be impacted by any pandemic both directly via international travel and indirectly via the global economic consequences.

Australia-focused Earth system issue 8

What can Australians do, both institutionally and personally, to minimise the risks and impacts of pandemics in a "globalised" world?

Geo-engineering of global climate. There has been broad scientific (Keihl 2006, Robock 2008) and public (Connor and Green 2009) discussion on "geo-engineering" – bold proposals such as fertilising the oceans with iron, injecting sulfur compounds into the stratosphere to enhance planetary albedo (Crutzen 2006), or placing orbiting mirrors above the Earth. The idea is to augment, or mitigate, the climate change we have already committed ourselves to through greenhouse gas emissions. The American Meteorological Society has developed a cautionary policy statement on large-scale geo-engineering of global climate (AMS 2009). The scope of geo-engineering options is still not clear (Schelling 1996), but the strategies mentioned above have as yet unproven efficacy, and they carry potential environmental risks of their own. Since research into some options is currently underway and is expected to continue (e.g. Cicerone 2006), it is essential that Australian scientists involved in Earth system studies keep technically abreast of the developments. In this way, they can engage fully and responsibly in the international dialogue, and be part of negotiations and regulations that must occur in relation to it. Indeed, geo-sequestration of CO_2, which is subject to Australian government policy and special research funding, is a geo-engineering approach that should be scrutinised by Earth system science to identify, quantify, and put in context any interactive repercussion that might ensue.

Australia-focused Earth system issue 9

As a complement to greenhouse gas emission mitigation, how can Australia engage in global considerations of responsible geo-engineering options?

Primary energy sources. Australia has an abundance of traditional, non-renewable fossil fuel resources, renewable energy resources of several types (solar, geothermal, wind, hydro, and others), and uranium. Earth system science can provide tools for exploring the environmental and social implications of a variety of alternative energy pathways, including varying mixes of energy from renewable and non-renewable sources and from greenhouse gas emitting and non-emitting sources.

Australia-focused Earth system issue 10

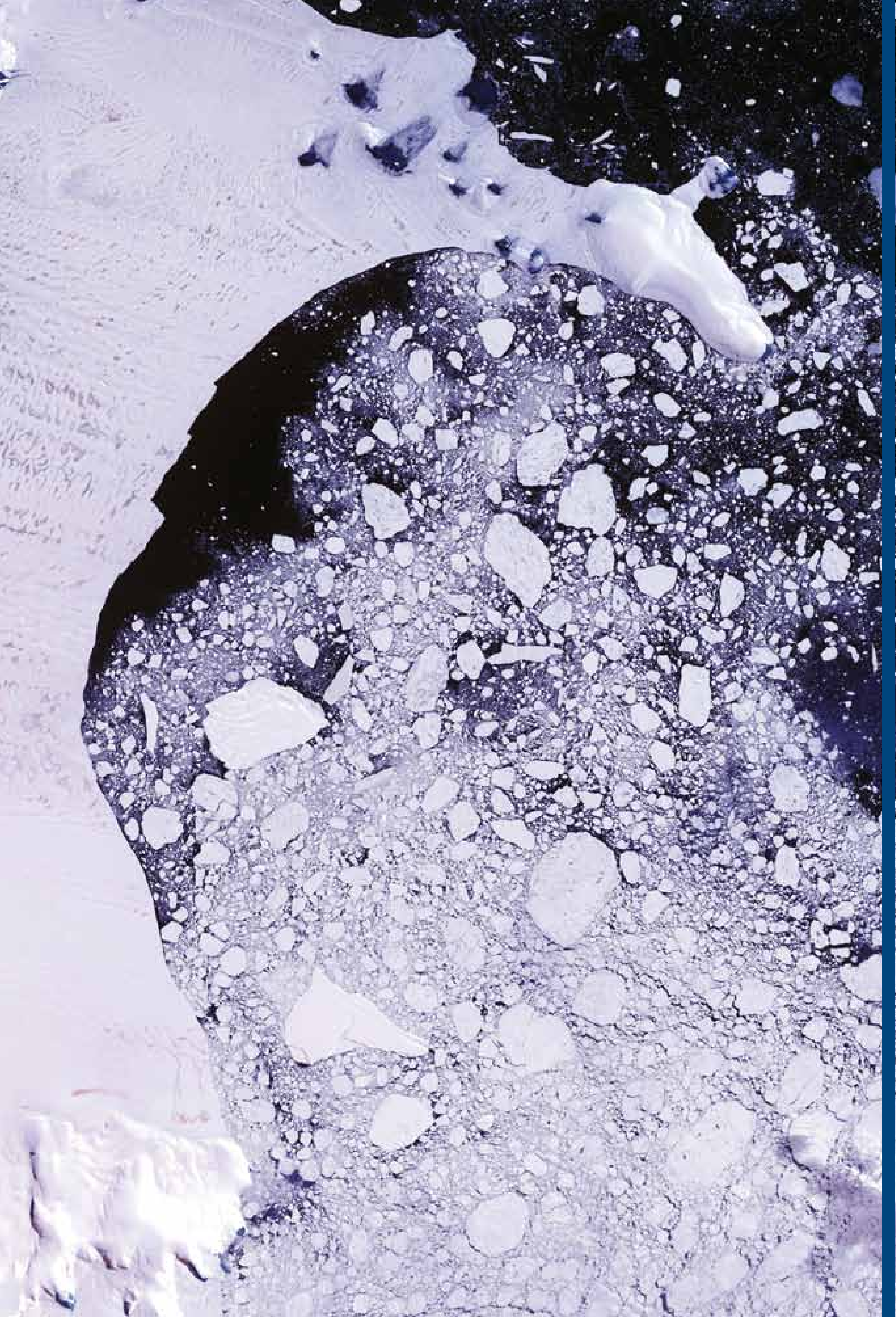
What are the potential environmental, social, and economic consequences and practical timeframes for Australia's transition to a low-carbon economy?

National population size and growth. The human impacts on ecosystem services are a product of a number of factors: the number of people, their per capita consumption of (or pressure on) resources, and the intensity of the impact of that consumption, or pressure, on ecosystem services. The impacts of population size (and its rate of growth) in Australia on ecosystem services is an important theme for Earth system science.

Australia-focused Earth system issue 11

What are the social, environmental, and economic implications of different trajectories for human population size and stabilisation in Australia?

Improved understanding of the science of the Earth system would undoubtedly help to resolve the above issues, at least in part. They are challenges that are subsets of similar global challenges – atmospheric composition change, sea-level rise, coral reef decline, and biodiversity losses – and they are not confined to jurisdictional boundaries. Earth system science needs to be conducted not only to determine the nature of the interacting environmental-social problems but also to maximise the range of options available to address them, be they technical or socio-economic. Australian research efforts will provide the technical backing for participation in the necessary international negotiations and plans to address the transnational environmental challenges.



Chapter 3

Scope and major characteristics of the changing Earth system

The Earth system is the panoply of interacting physical, chemical, biological, and socio-economic processes and cycles, driven by energy fluxes, which provide conditions necessary to sustain life on the planet. Thus Earth system science has an emphasis on observing, understanding, and predicting global changes involving interactions between land, atmosphere, water, ice, biosphere, societies, technologies, and economies.

3.1 Component spheres of the biophysical Earth system and Australian research roles

The ESS approach considers the actual and potential roles that life – human as well as non-human – plays in modulating the world's biophysical processes. It sees the composition of the global physical "spheres" – atmosphere, hydrosphere, lithosphere, cryosphere, and so on – as crucial in determining whether they will be suitable for sustaining life, as well as how they are, in turn, influenced and modified by life.

Atmosphere

The atmosphere, being the most well-mixed of the global spheres, is the fastest to respond to human-induced changes. Atmospheric composition is far from chemical equilibrium (Lovelock and Margulis 1974), a result of aeons of living forms fixing and exchanging oxygen, carbon dioxide, and nitrogen, and of emitting trace amounts of radiatively active and chemically reactive constituents such as methane, nitrous oxide, and volatile organic compounds. Dimethyl sulfide, produced by marine microorganisms, creates cloud condensation nuclei (Bates et al. 1987), thereby affecting the planetary albedo via cloud cover and reducing the loss to space of terrestrial long-wave radiation. Airborne black carbon (smoke and soot) from wildfires is also radiatively active (Ramanathan and Carmichael 2008). Such biological changes to the composition of the atmosphere powerfully influence the Earth's energy budget and hence its climate. In turn, the climate and the composition of the atmosphere profoundly affect the character and distribution of species and ecosystems. In this way, the atmosphere and the biosphere have been co-evolving for billions of years.

In the Anthropocene, humans are modifying the geosphere and the biosphere in numerous ways (Crutzen and Stoermer 2000), including the release of radiatively active greenhouse gases into the atmosphere. This is but the latest major step in the dynamic co-evolution of atmosphere and biosphere. The continuing feedback between the two is likely to have major effects on both, including of course on humans.

The capacity of humankind to measure, analyse, and interpret the state and rate of change of the Earth system, to predict what might happen in the future and how it might affect the species, and to exert concerted collective action to modify the time-course of change, is a dramatically new feature. It distinguishes the Anthropocene from all other periods. Humans have banded together to address the issue of stratospheric ozone depletion, and have implemented globally coordinated actions, through the UN Environment Program and the Montreal Protocol, to reduce the use of ozone-depleting substances.

In addition, humans are attempting to coordinate global actions to reduce anthropogenic greenhouse gas emissions through agreements under the UN Framework Convention on Climate Change, and through a range of other approaches. Whether that global collaboration will be sufficient to modify the future evolution of the planetary atmosphere and associated climate to human advantage is unknown, but an important part of the process is the continuing improvement in scientific understanding and quantification of the relationship between greenhouse gas concentrations in the atmosphere and global warming.

Many scientific uncertainties remain about human-induced tropospheric warming and consequential changes in climate patterns. The uncertainties arise from three sources. First, the emissions of greenhouse gases over future decades can only be sketched as possible scenarios; accurate future emission figures are beyond reach. Second, there are gaps in knowledge, simplifications of complex reality, uncertainties in process representation, and omissions in the global climate models used to estimate future climate states. Again, only likely scenarios of future atmospheric greenhouse gas concentrations can be brought to bear. Finally, the non-linearity of the climate system means the system is chaotic, implying that there will be fundamental uncertainties in climate predictions even if the models are perfect.

Given that international political agreement is now aimed at containing global warming to 2°C above pre-industrial levels (Ramanathan and Xu 2010), there is an imperative to gain a better estimate of the emission quantities that will achieve that objective. One tricky area requiring concerted effort is the likelihood of delayed positive feedback processes, including between the atmosphere and the other global spheres, which means that warming might "take off" at some point after a warming trend has begun. The processes envisaged here have time scales of up to millennia, beyond the prediction ability of current global climate models.

Earth system research question 1

What is the temperature sensitivity of the Earth system (including vertical profiles of temperature) to changes in greenhouse gas and ozone concentrations and to aerosol composition of the atmosphere over a range of time scales up to millennia, having in mind that feedbacks operate over a range of relaxation times?

The document *Australian Climate Change Science: A National Framework* (Commonwealth of Australia 2009) identified several areas of core scientific uncertainty requiring further research commitment to resolve. These included:

- radiative transfer,
- atmospheric composition and chemistry,
- atmospheric convection,
- cloud physics and dynamics,
- natural and human produced atmospheric aerosol effects, and
- changing character of teleconnections.

In such areas, improvements in both observation and modelling of the climate system are urgently needed.

In measurements of atmospheric composition, the atmosphere's water content – its humidity – is an important factor, given that in greenhouse-effect theory there is a strong positive feedback involving water vapour. Measurements of water vapour in the upper troposphere, from satellites and *in situ* observations, show inconsistencies in longer term trends (Paltridge et al. 2009) that require evaluation and targeted long term measurement programs, including in the Southern Hemisphere.

Improved understanding of atmospheric chemistry is critical for assessing the climate impacts of the stratospheric ozone recovery, for predictions of regional and urban air quality, for evaluating the atmosphere's contribution to biogeochemical cycles, and for satellite-based estimates of carbon sources and sinks in the terrestrial biosphere and in the oceans.

Insofar as atmospheric circulation is concerned, reconciliation of conflicting information is needed. The conflicts involve methods for deducing windspeed, one finding a change in surface windspeeds during recent decades over mid-latitudinal land masses (Roderick et al. 2007, McVicar et al. 2008), while another finding that changes in windspeeds reported over oceans differ from those reported over land (Wentz et al. 2007).

A major enduring problem is understanding the role of clouds, since these drifting ephemera make climate change prediction difficult and uncertain. How can we predict feedbacks between global warming processes and cloud formation? What drives cloud creation and dissolution, and why do cloud types differ so much with altitude? The subject requires continuing strong efforts.

With regard to aerosols, the sources, chemistry, fate, and radiative and climatic impacts of atmospheric aerosols from all sources is an area of considerable uncertainty and requires increased attention. For Australia, the impact of the "atmospheric brown cloud" on Australian climate, perhaps underlying the increasing rainfall in the north-west of the continent, requires resolution (Rotstayn et al. 2009).

As a final point, the significance of teleconnections in the atmosphere and the repercussions of global warming on Australian climate, particularly of regionally important atmospheric phenomena such as ENSO, the Hadley circulation, the Southern Annular Mode, and the Indian Ocean Dipole, require better understanding.

Earth system research question 2

What are the consequences of greenhouse gas-induced changes in Earth system dynamics for key drivers of Australian climate variability such as ENSO, the Southern Annular Mode, and the Indian Ocean Dipole?

A further area at the forefront of climate change research is the development of a quantitative understanding of the feedbacks between the atmosphere and the vegetated land surface in terms of atmospheric composition, radiative exchange, and momentum exchange. There is a strategic plan (see Appendix A.8 for details and further research questions) for developing the capacity in Australia to construct high-resolution vegetation models for the purposes of climate change impact analysis, and for coupling the vegetated land to physical climate change models.

Earth system research question 3

What are the important feedbacks between atmospheric dynamics, atmospheric composition, and the land surface?

Oceans

The Earth receives a surplus of heat from the Sun in equatorial regions and loses this heat from regions near the Poles. The fluid parts of the Earth's surface – the atmosphere and the oceans – play almost equal roles in transporting this excess heat from the Equator to the Poles. More understanding is needed in how the oceans transport this heat flux. This will require the continued support of research vessel voyages, robotic Argo floats, and moored instruments. It will also need supercomputers to process the data and test new models that can resolve fine details, such as eddies. Matching the fine details to the broad geographical picture will provide a way of exposing weaknesses in current models.

About 90% of the additional heat that the planet has received as a result of the anthropogenic greenhouse effect resides in the oceans. This is because water has a large heat capacity compared with the atmosphere and because oceans cover 71% of the Earth's surface. In absorbing heat so well, the oceans act as a "flywheel" in the climate system and slow down the rate of global increase of temperature in the atmosphere. Hence temperature measurements of the ocean play a major role in the detection of global warming, especially since there is no "heat island" effect in the ocean and in many parts of the ocean the signal-to-noise ratio of the global warming signature is favourable. Accurate mapping of future ocean warming will provide a valuable constraint on the accuracy of ocean models.

Because of the large thermal inertia of the oceans, there is an appreciable time lag between the warming of the sea surface and the eventual rise of the sea level; it takes a long time for thermal expansion to occur at all depths of the oceans. This tends to give us a false sense of security about sea level rises as it puts it off into a distant future. (This issue of the lagged response of the thermal expansion of the oceans is a separate issue from that of the possible melting of the Greenland ice sheet, which is a surface phenomenon, but one which also occurs over several centuries.)

There are several aspects of ocean models that are known to be uncertain and to which the models are sensitive. These are topics on which further observations and process studies would pay dividends. These processes generally operate at a spatial scale smaller than the resolution of the models. Some uncertainties include the rate of vertical mixing, the intensity of mesoscale (~100 km lateral scale) stirring and mixing, the processes that form the very densest water under ice shelves (Jacobs 2004), and the dynamic balances that work to regulate the strength of the Antarctic Circumpolar Current.

The oceans are an important sink of carbon dioxide, which readily dissolves in surface waters. The result is ocean acidification, which has probably already begun to inhibit the formation of the shells in some marine

organisms on the Great Barrier Reef and in the Southern Ocean (Moy et al. 2009, De'Ath et al. 2009). This will lead to appreciable but unknown species changes in the ocean with uncertain changes to the habitat of larger forms of marine life (e.g. Howard et al. 2009).

Australia, more than any other continent, is subject to inter-seasonal climate variations such as the El Niño Southern Oscillation (ENSO) phenomenon. On a time scale of several years, there are similar patterns of climate variability that affect Australia's regional climate. Among such patterns of coupled atmosphere–ocean climate variability are the IOD (Indian Ocean Dipole) and the SAM (Southern Annular Mode). The dynamical understanding of these coupled modes of climate variability is sketchy and much more fundamental research is warranted (see Earth system question 2). There are indications that the frequency and intensity of ENSO events have been increasing in the past two decades, although it is not yet possible to say whether this is an expression of human-induced climate change. We need to do research to find out, as this is important for Australia's economy, farmers, food security, and for Earth system science in general.

Earth system research question 4
What future sea-level rise are we committed to from recent global warming as a result of time-delayed effects on thermal expansion of the deep ocean?

Cryosphere

The cryosphere (where water exists as ice, at least in winter) plays an important role in the climate system, modifying the surface energy balance and affecting atmospheric and oceanic dynamics. Australian cryospheric studies focus on the Antarctic ice sheet and the surrounding sea-ice. However, the global nature of the issues in polar research means that there is also strong cross-over with research into Arctic sea-ice and Greenland glaciers. The cryosphere also includes seasonal snow-covered land and alpine glaciers, but these are a relatively minor component of Australian cryospheric research. The only Australian glaciers, on Heard Island, are a subject of study because glacier changes there are a useful indicator of climate changes in a region where climate data are sparse.

There is concern over uncertainties in predictions of sea-level rise, basically because we lack good understanding of the dynamics of ice sheets. Models fail to incorporate key processes realistically, particularly those relating to basal lubrication of ice sheets. The possibility of accelerated or abrupt change, especially where the base of the ice sheet is wet, is highlighted by the recent accelerated mass loss in parts of West Antarctica around Pine Island and Thwaites Glaciers. Areas of particular concern are those where the ice sheet has a marine terminus and is standing on land below sea-level. Research is now revealing free water and active drainage under much of the ice sheet, even in areas that are not below sea level. The implications of this for more rapid dynamical responses to change, in areas previously thought to be capable only of slow responses, are not well understood (Vaughan and Arthern 2007).

The major concern of rapid ice loss is already stimulating plans for greater research effort towards the next generation of ice-sheet models. These models will incorporate processes beneath floating ice shelves (at the ocean interface) and beneath glaciers, and incorporate more realistic physics for ice flow. This will require several years and will need to be accompanied by observations to provide boundary conditions, model validation, and process studies.

This observational work will include satellite and airborne remote sensing to survey ice-sheet changes. Additional research to access and monitor ocean cavities beneath ice shelves is required to understand the processes involved. Fundamental data such as detailed sub-glacial bedrock topography, ice sheet internal structure, and ice thickness are missing across large regions, although major airborne surveys, some underway and some planned, will partly address this.

Earth system research question 5

What will be the response of major ice sheets to the warming climate, and in particular what is the potential for accelerated ice loss due to poorly understood processes at the base of the ice sheets and at the ocean interface?

Climate observations across the ice sheets are also needed to detect regional changes and calibrate models. In addition, climate histories are required which match the "memory" of the ice sheets themselves to provide information on past accumulation of mass from snowfall.

This information can be derived from ice cores. Ice core records provide an "observational stream" that augments the short instrumental records and assists in detecting climate impacts. International plans, in which Australian research plays a role, call for development of two networks of ice core climate histories: one providing a 2000-year highly resolved record, and a sparser network extending out to around 40,000 years (Brook 2006). Together these networks will allow the ice-sheet response to past snowfall accumulation to be probed, including major changes during emergence from the last glacial period. This information directly feeds model studies of overall ice sheet dynamics. Plans are also in place to recover ice that should give a record of greenhouse gas changes that occurred around 1 million years ago when there was a major shift in the length of ice age cycles from 41,000 years to 100,000 years.

The sea-ice zone is also an area of priority research. At its seasonal maximum the area of sea-ice cover exceeds the area of the Antarctic continent and it dramatically modifies the Earth's energy balance because of its high albedo and its hindrance to air–sea fluxes. Sea-ice processes are strongly coupled to oceanic circulation via the freshwater cycle and changes to total water mass.

While the Antarctic has not yet exhibited the large losses in seasonal sea-ice cover that are occurring in the Arctic (and indeed has shown a recent increase; Turner et al. 2009), our knowledge of Antarctic sea-ice thickness is poor. Indications from the Arctic were that before the dramatic changes in extent occurred, a trend towards decreased ice thickness became evident. Methods for determining sea-ice thickness, using advanced technology, are now being developed, but considerable research into these new techniques (and ground-truthing of them) is required to establish baseline ice thickness records and to understand the inherent variability in the system. These technologies include satellite altimeter and radar missions, upward-looking sonar under the ice, and autonomous vehicles, and all have a role to play in detecting early changes in sea ice.

Climate models require improved representation of sea-ice physics, including processes of ice growth. The complex dynamics of pack ice – rafting of ice floes and rifting and ridging under the influence of currents, tides, and winds – also needs investigation. This requires research using in situ process studies, remote and airborne sensors, and model validation.

Earth system research question 6

What changes are occurring in the sea-ice zone and what are the impacts on ocean circulation and ecosystems?

Earth system research question 7

How has Antarctic climate varied on time scales from seasonal to glacial–interglacial, and what does this record tell us about climate variability, teleconnections, and global climate processes?

The terrestrial system

The role of the land in the Earth system is fundamental to understanding past and present observed global changes, and how the system may change in the future. The terrestrial system can be considered as an integrator of human-induced forcing, a contributor to the forcing, and an amplifier of the forcing. It may have the capacity to trigger abrupt changes in the Earth system (see Box 1). It is, of course, also the component of the physical Earth system that most directly affects humans and the ecosystem services on which societies depend.

As an integrator, the terrestrial system "feels" climate variability on many time scales. Agricultural productivity can be devastated by a single hot day. Seasonal droughts, and droughts persisting over several years, are closely linked to ocean processes such as ENSO and the IOD. Long droughts that may exist for a decade or more are probably related to large-scale reorganisation of circulation patterns. These changes can also induce near-permanent droughts in regions that were at one time productive (the Sahara and Middle East for example). Terrestrial feedbacks may amplify the intensity of drought, or extend the duration of droughts via feedbacks associated with vegetation degradation.

Terrestrial processes "force" changes to how the Earth system functions. Since the land cycles large quantities of carbon, small changes in the net balance can have profound impacts on atmospheric carbon dioxide levels on decadal, and longer, time scales. The land also emits biogenic volatile organic compounds to the atmosphere, which influence atmospheric chemistry, and possibly rainfall, and may have appreciable but largely unknown indirect impacts on climate (Peñuelas and Staudt 2010). The terrestrial system also cycles many other elements, such as nitrogen and phosphorus, which are important for the functioning of the Earth system.

Changes in the structure of the terrestrial system are important. An example is the internal allocation of carbon within a plant, which leads to changes in its cycling of water and nutrients. Another example is the interactions among individual trees in a forest (e.g. shading, competition) and, at a slightly larger scale, open patch dynamics in a forest during stages of recovery from a disturbance. All of these factors change how the landscape interacts with atmospheric and climatic processes. We also have to consider the direct human influences on the terrestrial system, which are usually expressed in a change to the entire composition and structure of an ecosystem (e.g. deforestation).

The terrestrial system modifies other human-induced climate drivers. Closure of stomata under higher CO_2 levels often reduces transpiration, leading to a positive feedback on surface temperature. Increase in photosynthesis rates under elevated CO_2 concentrations may be offset by down-regulation of CO_2 fixation. Large-scale loss of soil carbon under global warming could become an additional source of atmospheric CO_2, with the potential to trigger accelerated climate change (Cox et al. 2000), although research is needed into compensatory

feedbacks involving interaction between the carbon and nitrogen cycles (Gifford 1994) and into the time-frame effects of warming on decomposition (Kirschbaum 2010). A more likely scenario is the loss of permafrost and the release of stored methane, a potent greenhouse gas (Canadell et al. 2007). A particularly Australian issue may be the close coupling of some large ecosystems with groundwater, meaning there is the risk of an abrupt ecosystem loss if the sustaining groundwater is over-allocated for irrigation and the lowered water table "decouples" (cuts off) the ecosystem from water.

Changes in terrestrial structure can also amplify Earth system processes. If the Amazon forest were converted to a savanna (say if climate there dried), it would involve, over time, a massive release of CO_2 (Betts et al. 2008). However, the likelihood of this occurring is unknown. If, as a result of warming climate, boreal taiga forest expanded northwards, replacing tundra, this would decrease the albedo of the land surface (especially in winter snow conditions), contributing to further regional warming. This reinforcing feedback loop has been called the "taiga–tundra feedback" (Jahn 2005). Changes in root depth, leaf area, and vegetation height are all structural responses that may have regional, and conceivably global-scale, impacts on climate.

A major challenge is to include these functional and structural processes of the terrestrial system in Earth system models. Integration of land surface–atmosphere transfer schemes with dynamic global vegetation models

(DGVMs) is a key step, but very substantial challenges remain. The most important of these are:

- Simulation of terrestrial processes at local and regional scales (e.g. representation of land cover change, urban landscapes, irrigation, groundwater coupling).
- Appropriately configuring terrestrial models for different applications – weather forecasting, seasonal projection, decadal and century-scale projection.
- Assimilating observational data into terrestrial models.
- Improving hydrological modelling, including radiative transfer, surface–groundwater interactions, and stomatal response to various stresses.

Four terrestrial science challenges stand out as critical for ESS in the coming decade.

First, process-based understanding must be enhanced in many areas. These include (and it's a long list – see Appendix A.8) stomatal, leaf area, and productivity responses to higher CO_2 concentrations, leaf phenology, response of different vegetation types to different forcings, transpiration under nutrient limitation, impact of nitrogen deposition, representation of landscape heterogeneity, vegetation dynamics (especially disturbances), soil–vegetation interaction, and carbon allocation to leaves, stems, and roots.

Second, a concerted effort is required to improve understanding of long-term (multi-decadal) processes. This will involve a combination of on-going observation, palaeo-environmental analyses, manipulative experiments, and modelling studies.

Third, what are the implications of biodiversity loss for Earth system functioning? As the rates of biodiversity loss accelerate to 100 or 1000 times their background levels, there is growing concern that the terrestrial system's ability to play its part in the smooth functioning of the Earth system will be impaired. Beyond very simplified experiments on artificial ecosystems, little is known about the relationship between biodiversity and terrestrial system functioning.

Finally, non-linearities in the Earth system (thresholds or "tipping points") inferred from the palaeo-climate record raise the possibility of large, abrupt, and hemispherically significant changes on time scales of a few years. The role of the terrestrial system in triggering or amplifying these abrupt changes is unknown. An intensive research effort is required to understand the nature of these abrupt changes, to provide estimates of the likelihood of their occurrence, and to develop early warning systems.

Earth system research question 8

How do changes in the abiotic environment, especially those associated with atmospheric, radiative, and climatic changes, affect the structure and functioning of the terrestrial system, and what are the important feedbacks of physiological and structural change to the functioning of the Earth system?

Earth system research question 9

How important are feedbacks from terrestrial system changes (compared to changes in ocean–atmosphere dynamics) in affecting regional climates, particularly rainfall, evaporation and run-off?

Earth system research question 10

What levels of biodiversity – in terms of types of species and ecosystems, and in which biomes – are required to ensure that critical Earth system functions are not impaired?

Humans

Humans interact with the global biophysical environment in complex ways, and human activities drive many changes to the environment at the global scale. While climate change is the most well-known, there are many other important global-scale changes such as biodiversity loss, land clearing and erosion, global nitrogen enrichment, and overfishing.

Key attributes of the human presence on Earth as drivers of global environmental change are its large population, its continuing rapid population growth rate, the rapid rates of increase in per capita consumption of resources, and impacts on the "natural" environment. Humans also change the Earth through agriculture, industrial production, international commerce, recreation, urbanisation, globalisation, and a dominant economic paradigm that sees growth – in population and consumption – as good and important for society. The impact of the human enterprise on the functioning of the Earth system is often organised around proximate causes, which in turn are organised around compartments or cycles of the Earth system. This type of analysis would include the human imprint on (i) land systems (land-cover conversion, especially deforestation; co-option of net primary productivity); (ii) atmosphere (greenhouse gases, aerosols, photo-oxidants, trace metals); (iii) coastal and marine environments (pollution and sediment loading; overfishing); (iv) hydrological cycling (dams, inter-basin transfers, groundwater extraction); (v) biogeochemical cycles (carbon, nitrogen, phosphorus, sulfur cycles); (vi) biological diversity (extinctions, functional extinctions, introductions, invasive species, changes to the species composition of ecosystems). While these impacts are often treated distinctly, an objective of ESS is to integrate them and gain a fuller understanding of how they interact.

Earth system research question 11

What are appropriate measures or indicators to represent the magnitude and rate of change of the human imprint on the global environment and the functioning of the Earth system separate from non-human induced changes?

We address repercussions of global environmental changes on human well-being (impacts) and adaptive policy in Section 3.4.

3.2 Interactive global spheres and cycles

Before we can advance our understanding of how the Earth system functions, there are numerous interactions within and between the global spheres and cycles that need to be understood and quantified. Identification and quantification of important interactions between the spheres and cycles (which were traditionally studied by separate academic disciplines) characterises Earth system science as a distinct emerging field. Positive and negative feedbacks between Earth sub-systems can produce counterintuitive effects and surprises. Insight into these can only come from a holistic Earth system approach. If we are to manage the planet rationally in the Anthropocene, we need to be alert to such possibilities. Some areas of interaction, listed below, will yield useful results from concerted research. As the potential for interactions is so huge, the following examples are not intended to be comprehensive.

Besides causing warming of the troposphere, an increase in atmospheric CO_2 concentration has three other major effects on the functioning of the Earth system: acidification of water, stimulation of plant photosynthesis (the CO_2 fertilising effect), and increase in the resistance of leaves to water loss by evaporation (the stomatal closure or antitranspirant effect). Oceans are currently absorbing about one-quarter of the net emission of CO_2 to atmosphere by humans but that fraction may be gradually declining (Le Quéré et al. 2009). The absorption is acidifying the surface waters, which now have about 30% higher hydrogen ion concentration than pre-industrially. This acidification may tend to reduce the rate of shell formation by some, though not all marine organisms (e.g. Ries et al. 2009), with as yet poorly understood repercussions for marine biodiversity and biogeochemical cycles. Many reefs might become unsustainable. The subject is complex and unresolved, and more research is needed. Loss of coral reef habitat and other food webs based on shelled organisms may have adverse effects on marine biodiversity and fisheries (e.g. Cooley and Doney 2009). Concern about the ocean acidification issue was the subject of the *Monaco Declaration* (January 2009) and a *Summary for Policy Makers* (see http://ioc3.unesco.org/oanet/OAdocs/SPM-hirez.pdf) that was issued following the Second Symposium on Ocean Acidification (Orr and Turley 2009). These works highlight research and policy issues on ocean acidification.

Earth system research question 12
What chain of interactions and Earth system effects, over a range of time scales, including impacts on human affairs, are set in train by ocean acidification deriving from increasing atmospheric CO_2 concentration?

The land is absorbing about 30% of the anthropogenic release of CO_2 (be it with considerable year-to-year variability) and this fraction has shown a trend line of nearconstancy over several decades despite the increasing rates of anthropogenic CO_2 emission (Le Quéré et al. 2009). While the CO_2 fertilising effect on plant production and organic carbon stocks is almost certainly a contributor to this uptake of CO_2 emissions by the land, we still do not know what controls that 30% figure and what other possible mechanisms may be behind the terrestrial CO_2 sink. This is the long standing problem of the once-dubbed "missing carbon sink" and later "the unidentified terrestrial sink", but it remains critical to predicting the long-term effects of any scenario of atmospheric emissions. No matter what the mechanism or mechanisms are, ultimately saturation of such sinks seems inevitable. It is critical to know how soon saturation will set in because, once it occurs, the impact of anthropogenic emissions on atmospheric CO_2 concentration will accelerate. Right now we do not know whether such saturation will set in sooner or later, or whether it will happen gradually or suddenly.

Earth system research question 13

What is the explanation, significance, and sustainability of the apparent stability in the inter-decadal time trend of the fractional uptake by the land of anthropogenic CO_2 emissions?

In isolated plots, elevated atmospheric CO_2 concentrations lead to reduced stomatal conductance and hence, potentially, reduced transpiration. At larger spatial scales this effect may be offset by boundary layer feedbacks (Kruijt et al. 2008). The significance of this physiological transpiration effect at the Earth system level is not well understood. One ramification could be an increase in continental runoff (Gedney et al. 2006, Betts et al. 2007, but see also below on the interaction of the hydrological and carbon cycles). Another possible ramification is an increase in the surface temperature of the land (but not the ocean) and in the near-surface air temperature over the land by day but not by night (Sellers et al. 1996, Kleidon 2007). The transpiration effect could also contribute to the CO_2 fertilising effect via an increase in plant water use efficiency. Any temperature effects from transpiration will interact with the warming effects of greenhouse gases; they will also interact, in unknown ways, with a widespread weakening seen recently in mid-latitudinal winds, and might even affect the hydrologic cycle. Building such subtle interactions into climate models is yet to be done.

Earth system research question 14

Considering vegetation interactions with atmospheric CO_2 concentration and the climate system, how can we improve understanding of the terrestrial hydrologic cycle to improve global climate change prediction?

The carbon cycle of both the land and the ocean is tightly interconnected with the hydrological cycle and with other mineral cycles (especially nitrogen, phosphorus, sulfur, and iron). Understanding and quantifying those interactions is critical if carbon-cycle management is to have a lasting impact on global climate change. The interactions occur on a range of time scales and bridge the biosphere, the regolith, the ocean, the atmosphere, and, in the long term, the lithosphere. For example, root respiration and soil organic matter decomposition greatly increase the CO_2 concentration in soil water, which fosters the weathering of soil minerals which in turn solubilises minerals used by land plants and mobilises bicarbonate ions, which finally leach into the oceans. In the oceans the bicarbonate is converted into calcium carbonate shells by marine organisms which, ultimately, form limestone on geological time scales. A small fraction of the carbon cycling through land systems is also transported to the ocean primarily as dissolved or suspended organic carbon, where it can accumulate as ocean floor sediments. Another small fraction of carbon is converted during biomass burning to long-lived, inert carbon (black carbon) which has repercussions both for atmospheric and climatic processes and for soil fertility and long-term soil carbon storage.

Earth system research question 15

What are the details of the interactive network of mineral element and water interactions with the carbon cycle in marine and terrestrial ecosystems pertinent to improving the predictability of climate change under greenhouse forcing?

Land systems naturally fix large amounts of nitrogen from the atmosphere using both symbiotic and free-living microorganisms, which convert it to reactive nitrogen compounds essential for plant growth. This nitrogen fixation is energised by the products of plant photosynthesis and is facilitated by phosphorus (which is mobilised during rock weathering) and by low nitrogen status (relative to carbon) in the ecosystem. In driving increased photosynthesis, elevated atmospheric CO_2 concentration can increase the C:N ratio of plant litter and root growth, which may, in the long term, foster increased biological nitrogen fixation (Gifford 1994). Small amounts of this reactive nitrogen are returned to the atmosphere as nitrogen oxides and nitrous oxide, and to the groundwater and fresh water systems, and eventually to the ocean, primarily as nitrates.

The natural phosphorus cycle is largely controlled by slow rates of rock weathering, and so terrestrial ecosystems have developed ways to efficiently conserve and recycle P through the land ecosystem. Fertilisers in modern agriculture contain abundant nitrogen and phosphorus and are greatly enhancing and modifying the global N and P (and S) cycles (Rockström et al. 2009). Biosequestration of carbon into land systems, both above ground in long-lived trees and below ground in soil, is one option for reducing net CO_2 emissions by humans in the relatively short term. However, owing to the stoichiometry of mineral composition of organic matter, the stock of organic carbon in ecosystems can only increase if the stocks of organic N, P, and other minerals also increase. This fact has salutary

implications for the cost of biosequestration as a greenhouse mitigation option if it is to occur on the time scale of years to decades required for verifiable carbon accounting under international protocols. Quantifying our qualitative understanding of the complex interactions between cycles is a major challenge both for greenhouse gas mitigation procedures and for improving climate change modelling.

Earth system research question 16

To what degree is anthropogenic enhancement of the global N, P, and other mineral cycles driving the land-based global carbon sink that has, for many decades, been steady at about 30% of the exponentially increasing CO_2 *emissions?*

Interaction between the carbon cycle and the hydrologic cycle also has important gaps that urgently require improved understanding and quantification. Greenhouse effect theory assumes that the direct radiative effect of CO_2 in the atmosphere is strongly augmented by that of water vapour. This implies amplification of the hydrological cycle, because increased air temperature is matched by increased atmospheric humidity (producing near-constant relative humidity), largely via increased ocean evaporation. This theoretical intensification of the hydrological cycle involves increased global rainfall and river runoff. The observational evidence for an increase in globally averaged rainfall and river runoff over the last century (or half century) at the rate required by current theory is, however, equivocal (Dai et al. 2009). Increased and sustained empirical investigation is urgently required to resolve the conflict in published analyses: some show increasing continental runoff (Labat et al. 2004), whereas others show no change or decreasing runoff (Milliman et al. 2008).

The theoretical increased atmospheric humidity in the upper troposphere amplifies the "greenhouse" signal because water vapour is a powerful greenhouse gas, but the evidence to date for that upper atmosphere change is equivocal (Paltridge et al. 2009). Full understanding of the hydrologic cycle under climate change – including the control of evaporation from land and from ocean, control of atmospheric humidity at different heights, and cloud formation at different heights and its climatic feedbacks – are all major areas requiring intensive empirical research effort and theoretical development.

Earth system research question 17

Is the theoretically important hypothesis of intensification of the hydrological cycle – involving increased evaporation, rainfall, and river discharge under greenhouse forcing – true in reality?

Biogeochemical cycles influence the climate system in ways other than by the functioning of the carbon cycle. Understanding the multiple roles of biogeochemical cycles on the climate system, including the introduction of vegetation dynamics into global climate models, looks set to develop rapidly in the coming decade. A review of the decadal needs for vegetation dynamics research for climate change (see Appendix A.8) found there is a need in Australia for a coordinated program of ecosystem research which would develop a capacity to construct high-resolution vegetation models; these would be useful for analysing climate change impacts, and for introducing the vegetated land interactively into physical climate change models.

To support that objective it was proposed that a coordinated hierarchical network of several hundred permanent eco-hydrological observation sites be established as an integrated terrestrial observing system to cover the spectrum of Australian climates and ecosystems, including the full range of management intensities. A tentative start to the latter objective has been initiated in Australia with the Terrestrial Ecosystem Research Network (see Appendix A.9), but to meet the requirements needs considerable expansion in the coming decade.

At the heart of concerns about how humans affect the way the Earth system functions, lies a major research requirement - one that is at the interface between biophysics and socio-economics. As discussed, the ultimate driver behind the Earth system threats facing Australia (and the world as a whole) is an increasing human population, allied to rising per capita consumption of energy and materials, expanding environmental "footprints", and greater mobility and travel. Acting together, these factors may be compromising the "free" Earth system services faster than solutions can be found to counteract the growing impacts on those services.

Addressing the underlying socio-economic drivers of global environmental change, against a background of inequality in wealth distribution, are matters for social and economic research and policy. However, if these socio-economic factors could be incorporated into biophysical Earth system models, the resulting integrated global model might bring us closer to understanding and predicting changes in both the socio-economic and biophysical spheres of the Earth system.

Such highly interdisciplinary ESS is essential when human growth and consumption demands are moving inevitably towards a biologically determined peak in population numbers. How we make a smooth transition to a stabilisation, or peaking, of collective environmental demand is a major long-term challenge to society, one in which Earth system science can play a part.

After the peak is reached, managing the collective human demand on the environment in Australia will provide challenges and opportunities. The foundations of understanding need to be established now and in the decades leading up to the peak. It must start very soon.

An ESS-style approach to understanding and analysis of our situation is important. In particular, over the next several decades natural scientists and economists will need to work together to find ways to reconcile their viewpoints. One obvious difference relates to a prevailing paradigm that continuous, open-ended growth in aggregate wealth, and consumption, is necessary for the effective functioning of the existing financial system. On the other hand, from the natural science perspective (and considering the laws of thermodynamics), it is imperative that the aggregate environmental footprint of the community on a finite Earth stabilises over time, or even declines. Exponential growth can never continue indefinitely, and must be constrained if we are to extend the period of comfortable human existence on this planet for as long as possible.

The various national schemes to limit carbon emissions, already beginning or proposed in some countries, are intended to start reducing annual greenhouse gas emissions (market-based or otherwise) during the decade 2010 to 2020. They are attempts to address the "diabolical policy problem of climate change" (Garnaut 2008) by stabilising atmospheric greenhouse gas composition and climate during the subsequent eight decades of the century and beyond. Such schemes may be important early steps in addressing the much bigger diabolical policy problem: how to comprehensively internalise the environmental repercussions of traditional human activity into the mainstream economic paradigm. Understanding and insights from Earth system science will play an important role in coming to grips with that conundrum.

3.3 Earth system dynamics, past and present

Understanding the Earth system in the past

Past Earth system dynamics can be used to help inform understanding of present and future dynamics. Many knowledge gaps and questions related to past climates have been identified elsewhere, and they deal with climate forcings and palaeoclimate techniques as applied to large-scale global climate dynamics and regional climate dynamics. This section aims to identify broad themes and issues that are of particular importance for Australian palaeoclimate research in the coming decade. Further details on Australian palaeoclimate research may be found in Australian government reports (Harle et al. 2007, Tennant et al. 2008).

While palaeo studies have provided us with a detailed picture of past changes and insights into processes, there remain considerable knowledge gaps, major questions, and ongoing challenges. We know, for example, that during the late Quaternary the climate underwent periodic cycling between glacial and interglacial states, and that this was driven by orbital variations which modulated the seasonal and geographic distribution of solar radiation. We also know that strong feedbacks – involving albedo and greenhouse gases – played a key role in this cycling. Yet, even at this gross level, we still cannot simulate, from external forcing alone, the dynamics of the system. This has obvious implications for our ability to accurately determine whether the climate system has other states into which it can be forced by high greenhouse gas levels. It also underlines our inadequacy in estimating the sensitivity of the climate to greenhouse gas variations (e.g. Hansen et al. 2007, 2008) – see *Earth system research question 1*.

The IPCC Fourth Assessment Report (IPCC 2007) notes that the low density of Southern Hemisphere and tropical palaeoclimate data limits knowledge of climate variability in these regions over the last 1,000 years. This is a serious shortcoming which Australian research is geographically well-situated to address and can benefit from. The short and sparse instrumental records in the Australian region make high-resolution, well-dated palaeoclimate data highly important for understanding regional teleconnections and natural variability. In addition, advances in modelling are providing high spatial resolution series that demand corresponding well-dated, regional palaeoclimate data of high time resolution for model intercomparison and validation.

Australian palaeoclimate data derive from many sources, including tree rings, speleothems, corals, ice cores, and lake and marine sediments. On longer time scales, palaeoclimate evidence also derives from coastal sedimentary records, geomorphological research, and study of glacial deposits. For high-resolution studies, and comparing them with the Northern Hemisphere, our unique landscape and ecology, and the regional and hemispheric dominance of marine versus terrestrial environments, place severe constraints on available palaeoclimate approaches. This is particularly the case with regard to tree-ring records, since many Australian species do not have regular annual rings. Nevertheless, a number of long, well-controlled records have been derived, and the potential exists for extending them to other geographical places and times.

To obtain reconstructions at global and regional scales, we need to synthesise high-fidelity palaeoclimate data from multiple proxies across the Australian region and the Southern Hemisphere in general. For Australia, there is a clear need to derive longer term records of temperature and precipitation over time scales sufficiently long to probe decadal scale variability. Long-term regional effects and natural variability need to be established for climate modes such as ENSO, the Southern Annular Mode, Indian Ocean Dipole, Pacific Decadal Oscillation, and the Asian and Australian monsoons. This undertaking requires development of a denser network of well-calibrated proxies and analysis infrastructure to measure and date the individual records.

Earth system research question 18

What controls the maximum and minimum temperatures and CO_2 levels during glacial–interglacial cycles (i.e. why do temperature and CO_2 levels stop where they do as the Earth system comes out of, or into, a glacial state)?

Earth system research question 19

Will the current human-driven excursion of atmospheric composition beyond past interglacial levels drive the Earth system into another semi-stable state that does not involve glacial advances and retreats? Or will the Earth system relax to its two-phase late Quaternary state following the end of significant human perturbation?

Dynamics of the contemporary Earth system

In contrast to the Earth system in the past, the dynamics of the contemporary Earth system are characterised by responses to human forcing. This is sometimes expressed by the "IPAT identity" (Commoner 1972): that is, human **I**mpact on planetary systems = **P**opulation × **A**ffluence (per capita resource use) × the **T**echnology used to access those resources. External forcing over the last century, by changes in solar radiation or volcanism, has been relatively small compared with the pervasive effects of human activity. This forcing can be explored under three headings: physical, chemical, and biological.

Human changes to the state of the planet have directly changed the physical energy balance at the Earth's surface. First, changes in albedo result from changes in land use, such as deforestation, agriculture, reservoirs, and urbanisation. Second, changes in the surface water balance, and to a lesser extent in plant functioning, alter the partition of radiant energy between sensible heat and evaporation. We are seeing interception and redirection of water, with at least half the world's rivers now dammed and many aquifers subjected to unsustainable rates of extraction. Third, increases in global surface temperatures cause the melting of Arctic sea ice, decreasing the planetary albedo. However, the overall dynamics of Arctic and Antarctic ice extent are neither well understood nor well parameterised in global climate models (see Box 2).

Human manipulation of the biogeochemical cycles (C, N, P, and S), with effects on the atmosphere's chemical composition, has been substantial and accelerating since the start of the industrial revolution. Atmospheric composition affects the radiation balance, with planetary albedo altered through a change in cloud amount and through the injection of aerosols or their precursors, which reflect or absorb radiation depending on type and circumstance. Elevated atmospheric carbon dioxide levels tend to decrease ocean pH, affecting calcium carbonate chemistry. Biological and ecological processes are also directly modified by human activities. Overfishing has led to the collapse of many of the world's major fish stocks. Everywhere, the top layers in marine food chains are being replaced by humans, while in the bottom layers complex organisms are being replaced by simpler ones (Jackson et al. 2007). On land, we see a massive loss of biodiversity through direct impacts, habitat destruction, and habitat fragmentation, leading to assessments that we are currently in the sixth major extinction event of the geological record. From the point of view of Earth system dynamics, we urgently need better understanding of the functional role played by biodiversity in providing essential ecosystem services. This is one of the most glaring knowledge gaps we currently face in our understanding of planetary dynamics.

Earth system research question 20
When considering the Earth's surface radiation balance, what are the relative impacts (on a global scale and compared with the primary absorption of longwave back radiation) of rising atmospheric CO_2 on transpiration and plant cover, enhancement of the mineral cycles, land use change, and hydrological and cryosphere modifications?

Earth system research question 21
What ecosystem services have we lost as a result of human-induced loss of biodiversity, and what ecosystem services are being lost or at risk from continuing major biodiversity loss? How do these losses compare with gains of ecosystem services through plant and animal domestication and productive improvement?

Some aspects of the human drivers of these dynamical processes, as expressed in the IPAT identity, are well understood, at some scales at least, while our knowledge of others is very poor. We have human demographic models

with reasonable predictive ability at global or continental scale, but the detailed drivers of population change at national or local scale are contentious. The Affluence factor in the IPAT equation is strongly conditioned by human aspirations, human decisions, and political choices, although biophysical limits do impose the ultimate constraints. Technological change is notoriously hard to predict, but its rate of change is itself constrained by the time involved in replacing infrastructure. Such questions are the purview of the social sciences, but the lack of success of economics as a predictive science underlines the intractability of these questions. When we try to draw an integrated picture of human–Earth system dynamics, the greatest uncertainties lie in our descriptions of social dynamics.

It is the feedbacks and responses of the Earth system under this set of human forcings that needs study if we are to understand the dynamics of the contemporary Earth and how the Anthropocene differs from the late Holocene. Concerns about climate change have to date focused attention on planetary scale responses, even though there are many system-level questions to be addressed at smaller scales, particularly to do with hydrology and ecosystem services. Of most immediate concern is whether we are approaching virtually irreversible thresholds in the Earth system (see Box 1). Crossing these thresholds might cause the natural dynamics of the Earth system to move rapidly to a state that human civilisation has not encountered before, and at a rate that makes society-wide adjustment without catastrophes problematic.

Study of palaeo-climates give us clues as to how rapidly (without human forcing) the whole Earth system can adjust. Regionally, especially at high latitudes, this can be very rapid. The tools we use to study these system properties are global climate models or GCMs (see Box 2). Consensus is slowly building on which processes cause rapid (or slower) changes, usually through comparison studies with simpler models, but this kind of science is still in its infancy. We do not yet have enough confidence in these models to believe their predictions when they are forced with rapid changes in greenhouse gases and radiative forcing characteristic of the Anthropocene.

Confidence in prediction is much lower if we include human interactions with the biophysical system – both human forcing and human reaction. Human impacts can be fast and have consequences that are difficult to foresee. The intrinsic role of contingency in social dynamics means that when we couple models of social and biophysical dynamics, to build Integrated Assessment Models, the range of future possibilities expands dramatically. The question of what are the natural dynamical cycles in a coupled human–biophysical Earth system model is only now being asked, although its answer is critical to the development of the subject.

Given these daunting uncertainties, one approach to managing humanity's relationship with the rest of the Earth system is based on the concept of planetary boundaries (Rockström et al. 2009). The approach is to maintain – or more accurately, return – key aspects of the Earth system to the Holocene state, the 10,000-year-old epoch of relative biophysical stability in which agriculture and civilisations have arisen, developed, and thrived. The aim is to avoid crossing critical

thresholds in important Earth system processes or subsystems, such as irreversible loss of the Greenland or West Antarctic ice sheets (Box 1) which loom if we continue in the same way into the Anthropocene. To minimise the risk of crossing such thresholds, nine planetary boundaries have been identified which humanity should respect. The initial analysis suggests we have already transgressed three of the boundaries (climate, nitrogen cycle, biodiversity), although much more research in the realm of Earth system science is required to strengthen the planetary boundaries approach.

Earth system research question 22

From the perspective of a well-functioning Earth system (and its implications for human well-being), what should be the prudent limits on human perturbations to the physical, chemical, and biological spheres (globally and in Australia)?

Earth system research question 23

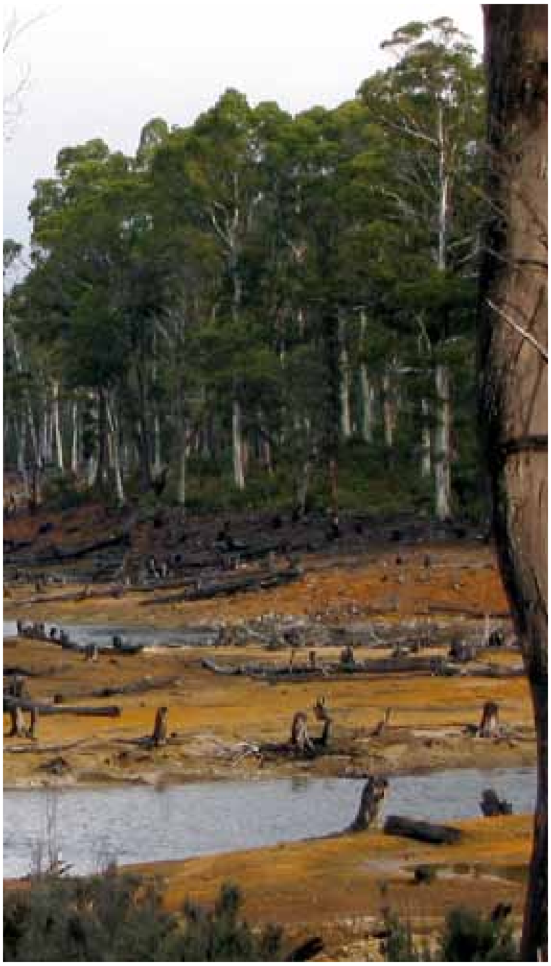
What are the most likely tipping elements in the contemporary Earth system and when might they reach their tipping points?

Earth system research question 24

How finely can we expect to usefully assess the time and space impacts of future human-induced warming?

Earth system research question 25

What are the important interactions among the physical, chemical, and biological spheres of the planet that have been significantly perturbed by human activities (noting that climate change focuses strongly on the physical)?



BOX 1 TIPPING POINTS IN THE WHOLE EARTH SYSTEM

Non-linearities and positive feedbacks can create instability in complex systems, which can lead to critical thresholds or "tipping points". Crossing these thresholds can result in a qualitative change in the state or development of the system. The idea derives from concepts of non-linear dynamics such as attractors or multiple stable states (Alley et al. 2003). Lenton et al. (2008) generalised this concept and introduced the term *"tipping element to describe subsystems of the Earth system that are at least sub-continental in scale and can be switched – under certain circumstances – into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point at which the future state of the system is qualitatively altered."* Lenton et al. (2008) focused on events that were close enough in time to pose policy dilemmas today.

Examples of potential tipping elements include:

- Arctic sea-ice melting, which can exert a positive feedback on climate via reduced albedo as the highly reflective sea-ice is replaced by much darker ocean.
- Greenland ice-sheet melting, which can be self-sustaining for the same reason.
- West Antarctic ice-sheet melting, which can be self-accelerating where the ice grounding line is below sea level, allowing water to undercut and further separate the ice from the bedrock.
- The Atlantic thermohaline circulation, which keeps western Europe warm, could be slowed and ultimately closed down, if sufficient fresh water from Arctic and Greenland ice-melt

layered over the top of the North Atlantic, reducing the surface water density and preventing deep water formation by down-welling of cold, dense saline water.

- Increased amplitude and changes in frequency of El Niño–Southern Oscillation events.
- Indian and West African Monsoons are thought to have exhibited bi-stable behaviour in the past and could be flipped into different modes by combinations of climate forcings.
- Dieback of the Amazon rainforest, and associated increased CO_2 emission, might occur under global warming as a result of regional drying that could lead to increased wildfire incidence and frequency, especially in the context of human land use changes.
- Mobilisation of boreal carbon stores as permafrost regions melt.

This is a rapidly growing area of research. It considers the probability of abrupt change in the whole Earth system as the climate moves rapidly into a different state at a rate driven by its internal dynamics once a threshold has been crossed. Current climate models (see Box 2) are not yet able to assign probabilities to these tipping points with any confidence.

The difficulty of predicting tipping points and when they might occur poses substantial policy problems, particularly when the probabilities of the events occurring within a policy-relevant time frame are considered small but the human implications if or when they occur are huge.

BOX 2 GLOBAL CLIMATE MODELS OF DIFFERENT STRIPES

There are three classes of global climate model in common use: ocean–atmosphere global climate models (OAGCMs), Earth system models of intermediate complexity (EMICs), and simple climate models (SCMs). These three are potentially supported by integrated assessment models (IAMs).

Ocean–Atmosphere Global Climate Models. OAGCMs are the most complex models, expensive in computer time and with a basic structure similar to numerical weather prediction (NWP) models but driven by radiative forcing and boundary conditions. Spatial resolution is ~0.5° for the most highly resolved, but nesting for greater local detail is possible. Different dynamics impose different resolution requirements for ocean and atmosphere.

Research to improve OAGCMs is focused on:

- cloud processes,
- terrestrial ice and sea-ice dynamics,
- deep sea-water formation,
- ocean boundary currents,
- the carbon cycle,
- biogeochemistry (e.g. aerosols),
- hydrology,
- dynamic vegetation.

Dynamics that current OAGCMs simulate poorly include ocean–atmosphere modes like ENSO, Madden Julian Oscillation (MJO), Meridional Overturning Circulation (MOC), and North Atlantic Oscillation (NAO). Another focus of current research is how to bridge the gap in predictive ability between NWP models, which span daily to seasonal time scales, and OAGCMs, which predict from a few decades to centuries. Note that OAGCM predictions are driven by specified trajectories of land use change and greenhouse gas emissions or concentrations. These are usually obtained from Integrated Assessment models (IAMs).

Earth System Models of Intermediate Complexity. EMICs are not as complex as OAGCMs. They have lower resolution and simplified dynamics to enable long ensemble runs to explore climate dynamics.

- EMICs are the tool of choice for palaeoclimate analysis.
- They can be used to assess future possibilities like weakening of the MOC under warming.
- They allow investigation of natural modes of the climate system which might produce observed rapid regional climate shifts such as the Dansgaard–Oeschger events or the drying of the Sahara. Thus they are often used in the analysis of tipping elements (Box 1).

Simple Climate Models. SCMs are far simpler than OAGCMs or EMICs.

- SCMs treat the climate system as a set of coupled well-mixed boxes described by rate equations for globally averaged concentrations of greenhouse gases and temperature.
- Their parameters must be tuned to match the output of OAGCMs.
- They play a very important role in policy formation in areas like mitigation strategies.

Integrated Assessment Models (IAMs) include economic and social processes as well as biophysical processes. Given assumptions about how the world will develop, they produce trajectories of land use change, greenhouse gases, and aerosols used by the climate models. The output of IAMs is implicit in IPCC scenarios of future climate. Fundamental problems with IAMs relate to the fidelity of economic and social parameterisations.

3.4 Repercussions for human affairs

The dividing lines between global, regional, and local scale influences are arbitrary, but over time, as human population size and per capita consumption increase, the local scale influences of today become the global scale ones of tomorrow. That is an important reason for strengthening a whole-of-Earth system science.

Ecosystems services and human well-being

The concept of ecosystem services has gained prominence as a way to describe the ultimate dependence of human well-being on the natural world, from local to global scales. The concept of ecosystem services was largely popularised by the *Millennium Ecosystem Assessment* (2005), which defined four types: supporting services (e.g. primary production and nutrient cycling); provisioning services (e.g. food, fibre, and freshwater); regulating services (e.g. climate regulation and water purification); and cultural services (e.g. spiritual and recreational). These services contribute to many aspects of human well-being, such as security, basic materials for a good life, health, good social relations, and freedom of choice and action. Ultimately, ecosystem services (which themselves are based on a well-functioning Earth system) contribute significantly to the life support system that makes human existence possible. The Earth system provides "free" services, both abiotic and biotic: oxygen supply, absorption of ultraviolet by stratospheric ozone, stocks of mineral ores, rainfall, biotic and abiotic cleansing of pollutants, soil formation, nitrogen fixation, decomposition of organic wastes, and so on. Given this diversity, perhaps we should in the context of Earth system science refer to *Earth system services*, a term somewhat broader than the standard *ecosystem services*.

The *Millennium Ecosystem Assessment* presented a number of major findings, including:

- Over the past 50 years humans have changed ecosystems more rapidly and extensively than in any comparable period in human history.
- The changes made by humans to ecosystems have contributed to substantial gains in human well-being, but these gains have been achieved at a growing cost in the form of degradation of many ecosystem services.
- The degradation of ecosystem services could grow significantly worse during the first half of the 21st century.
- It may be possible to reverse the degradation of ecosystems while meeting increasing demands for their services, but that would require improved Earth system understanding to inform significant changes in policies, institutions, and practices.

Earth system research question 26

From the perspective of the Earth system, what are the most important ecosystem services (and, more generally, Earth system services) and how do human impacts on these services affect the functioning of the Earth system on different time scales?

Earth system research question 27

How can we better quantify the nature of land system change – types of change, rates, and locations? How can we incorporate human-driven land system change into predictive Earth system models?

Urbanisation

Cities have become the centres of power in terms of economy, technology, and decision-making. They propel the human enterprise and thus have a very large influence on the ways in which humans affect the functioning of the Earth system. Urban centres are also now the primary drivers of changes in culture, lifestyle, consumption patterns, economic policies and financial management, and politics, all of which ultimately determine the human impact on the Earth system.

In 2008, the world human population passed beyond the point of being 50% urban (UNFPA 2007), and urbanisation is still increasing. As a result, urban areas now play a key role in the biogeochemistry of the planet. They act as concentrators of nutrients, water (i.e. directly piped in or imported as food embodying water in its production, so-called "virtual water"), energy, and other materials that originally come from far away, and also as concentrated sources of effluents after the materials have been consumed or processed. Some of these flows (e.g. nitrogen, carbon) are of similar magnitude to the lateral flows of these elements by natural processes on the land.

Earth system research question 28
How will the continuing trend towards urbanisation and the changing form and structure of cities affect the flow of biogeochemically important elements, water, and energy into and out of urban areas, as well as their transformation within cities, and what repercussions can be identified?

"Urban footprints" have become a common way of quantifying the impact of an urban area on the surrounding hinterland (although, increasingly, goods and services are sourced from many parts of the world, much further away than the city's immediate vicinity). A related idea is to map the flows of materials from their source region into the urban area in which they are consumed – for example, the flow of food (including the embodied nutrients, water, carbon, and energy) into and out of a city. Taken together, these methods – footprints and element and material flows – provide a good way of quantifying an urban area's impact on the whole Earth system.

Earth system research question 29
How can the "footprints" and "material flow" concepts be refined to quantify better the human imprint on biogeochemical cycling?

Urban areas link to the atmosphere in fundamentally different ways from those of a natural landscape (Geiger 1965). They are commonly hotter and drier, with lower fluxes of latent heat to the atmosphere and a deeper boundary layer due to sensible heating and roughness-generated turbulence. Some very large cities may now dominate their regional climates (e.g. London, Tokyo, Los Angeles). Other big cities, including Sydney, Melbourne, and Perth, probably appreciably affect their own local weather and climate. Given that we predominantly live in cities, the questions become how do these interact with climate and climate change, and do they amplify or suppress large-scale climate change?

Earth system research question 30
How can urban landscapes and their interaction with the atmosphere be measured and incorporated into Earth system models?

3.5 Tools and approaches

Integrated observation and documentation of the Earth system

Accurate, objective, verifiable observations form the bedrock of all science. For Earth system science, combining observations from diverse sources is essential. There have been, and still are, numerous observational programs, both nationally and internationally, on the biophysical and socio-economic aspects of the Earth system. These exist for specific purposes and involve problems that need to be addressed.

First, the observational record of socio-economic attributes – for example those collected and managed by the Australian Bureau of Statistics (demographics, economic and financial attributes, land use, agricultural and forestry production, imports and exports) – are much more comprehensive and well-organised than routine observations on most of the biophysical environment. This is because such human-system data relate routinely to business and government decision-making and policies. Second, with the exception of weather data, most biophysical attributes measured do not have the necessary complete runs over many decades using a standardised collection method. Continuous, multi-decadal, coherent series of biophysical data are essential for understanding and distinguishing variability and longer term trends of the natural environment and Earth system characteristics. Third, there is not a national or global history of inter-jurisdictional collaboration for unifying observation methodologies, calibration systems, and standards. There have, however, been moves both internationally and nationally to achieve coherence in observational networks (see below). A motivation for this has been rapid developments in remote observation of the Earth from satellites, and in large computer systems that make it easier to process, store, retrieve, and disseminate vast bodies of data.

The Australian National Collaborative Research Infrastructure Strategy (NCRIS) has funded two important first steps for coordinating Australian biophysical observations of the Earth system. These are IMOS (the Integrated Marine Observation System) and TERN (the Terrestrial Ecosystem Research Network). IMOS is a coordination of several, relatively well-established, marine observation programs in the Australian region. TERN is younger, low budget, short duration, and less well-established. It is still developing its scope and structure and positioning itself to attract longer term and much more realistic levels of funding.

A recent Australian Strategic Plan for Earth Observations from Space (see Appendix A.11) has set out recommendations for Australian Earth observations from space (EOS), including the types of observation important to ESS. In that report it points out that Australia has in the past adopted a "free rider" approach to satellite observation: it uses other nations' data streams and does not put up any satellites of its own or contribute to the costs of others. The report recommends that national EOS policy should be to strengthen the national commitment to full Australian participation in the international EOS system by 2025. There is a strong need for ESS to develop *in situ* and remote observation programs in a way that create integrated and inter-calibrated data sets.

Internationally, the Committee on Earth Observation Satellites (CEOS) was established to coordinate government-funded satellite programs around the world. To that end, the Global Earth Observation System of Systems (GEOSS) has been set up. GEOSS is coordinated by GEO (the Group on Earth Observations) which has 80 countries, including Australia, as members and also 58 participating organisations (www.earthobservations.org/ag_partorg.shtml).

Our knowledge of the Earth system, including its climate system, derived from direct human observation, is short. Indirect "palaeo-data" provide the necessary means to explore a wider range of Earth system behaviour and are an essential tool for Earth system science (Section 3.3). Palaeo-data also provide the means to test models over long periods of time (palaeo and contemporary). Irrespective of models, palaeo-observations trigger new insights into, and hypotheses about, the functioning of the Earth system.

There is a need to differentiate between long-term routine observation (e.g. temperature, atmospheric CO_2, etc.) and data derived from short-term campaigns and experiments on particular processes.

Earth system experiments

To test hypotheses in science, designed manipulative experiments are of great value for advancing understanding of how things work. A successful experiment requires direct control by the experimenter of the influential factors of interest, independently of others, and replication to distinguish the effects of the varied factors from random variations. At the Earth system level there can be no replication – there is only one Earth – and variables generally cannot be independently varied, either for practical or ethical reasons. On the practical level, the spatial scale of the question is often too big to be able to vary relevant factors independently and then return them to the original condition (stratospheric ozone levels, for example). And ethically, it is unacceptable for scientists to fiddle with the environment on a large scale in ways that affect other people.

But progress can be made by doing small-scale experiments in model systems that attempt to isolate or mimic portions of the Earth system. Here, it is important to identify the correct boundaries by which an experimental domain or system can be defined, and which can then be interpreted in a whole Earth context. It is failure to do that adequately, or for scientists to recognise that it has not been done adequately, that is a major source of disagreement about the significance for the "real world" of various experiments. An example is where plants are exposed in growth cabinets to changed atmospheric composition or radiation regime, perhaps CO_2, SO_2, NO_x, O_3, UV radiation, or temperature. There are many problematic aspects that might confound interpretation of such experiments. One in particular relates to time scales. In experiments – funded by a short-term grant of typically 2 to 4 years – the imposed factor is varied by a step change from the control background. The change is made big enough to be able to distinguish the expected effect from typical random variation, based on the number of replicates that can be afforded under the grant. But in the real world, of course, all the pertinent factors may change very gradually over decades to centuries. Over such long time periods there is the possibility of unknown biochemical, physiological, genetic, or other system-level adjustments or adaptations occurring which might either counter or exacerbate responses observed over the few years of the experiment.

Put simply, there can be no absolute certainty when it comes to predicting the future of the Earth. Observations and experiments may give us clues about hypotheses and models (be they conceptual, mathematical, or computer simulation models), but we can only achieve best guesses. We have to deal with probabilities of future time courses and attempts at minimising unwanted risks. To give it our best shot, it is critical that our experiments be designed and interpreted in the context of all other information, understanding, and hypotheses. Here is where computer models can be helpful in bringing all of this together. Similarly, computer models need to be routinely updated in the light of new observations and the results of experiments.

As with observations of the Earth system, there is a pressing need in the coming decade for some experiments related to the Earth system to be funded on a much longer basis than has been usual – and we mean decades rather than years. In this way, we can advance the science of the Earth system on a time scale relevant to national and global planning.

Integrated global analysis and Earth system modelling

A key aspect of Earth system science is studying the interactions between spheres and cycles, in a best effort to anticipate future change. For that, computer models have become essential. They are an unparalleled tool for analysing and interpreting observational and experimental data. Many types of computer model exist: simple or complex, statistical or mechanistic, exploratory or predictive, and many shades in between. For most, a solid base of observational and experimental data is essential. The normal *modus operandi* is iterative: one moves from the model behaviour to a new hypothesis, then to new observations and experiments based on the hypothesis, then to a better model based on the improved data and knowledge and on criticism of past work by peers, and so on. The full diversity of modelling approaches has a role and it needs to continue.

For understanding climate change and predicting the future, the progressive improvement of GCMs (see Box 2) has been impressive. In the future, GCMs will need to work towards more realistic representations of the climate system, and to increase the spatial and temporal detail.

To include humans as dynamic, interactive parts of the Earth system, there is a wide range of tools being developed, some in their infancy but others more mature. These include the following:

Scenario development. There is now a formalised process for developing internally consistent projections of plausible futures. The Millennium Ecosystem Assessment (2005) suite is well known, but there are many others. For those who do not favour quantitative modelling of human activities, scenario development provides an alternative – and it can in some ways account for contingent (unpredictable) events.

Retrospective scenario development. Given the impossibility of predicting the future correctly, another approach to using knowledge of the past to help chart a way to the future is to work backwards: to propose a desired future objective (e.g. zero net CO_2 emissions to the atmosphere in 2100) and to investigate what steps need to be taken by society to achieve such an outcome. This is the approach taken by the greenhouse gas emission trading schemes which are intended to achieve a certain maximum atmospheric CO_2 equivalent concentration (like 450 ppm).

Integrated Assessment Models. These are the most well-known of the "humans in environment" models, and are often used to explore the consequences of plausible scenarios of climate change for society (see Box 2). Most of these models include modules on demography, energy, industry, trade, urbanisation, etc., and so have the capability to include the human enterprise in a dynamic, interactive way in the Earth system.

Integrated Global Models. IGMs aim to simulate the complex, dynamic history and future of the human–environment relationship. In general, the models are strongly skewed towards either the socio-economic or the biophysical parts of the Earth system. A challenge for ESS is to build more balanced IGMs.

Exploratory Earth/World System Models and Analysis Tools. These are new approaches that are being developed de novo to simulate the co-evolution of humanity and the biophysical world in which we are embedded. Examples include massive "agent based" modelling, social network theory, game theory, evolutionary psychology, and complex systems theory. These approaches are in contrast to the dynamical systems genre of model (e.g. GCM) that dominates modelling of the biophysical Earth system.

Earth system research question 31
How can the many ways that human activities affect the Earth system be included dynamically in Earth system models?

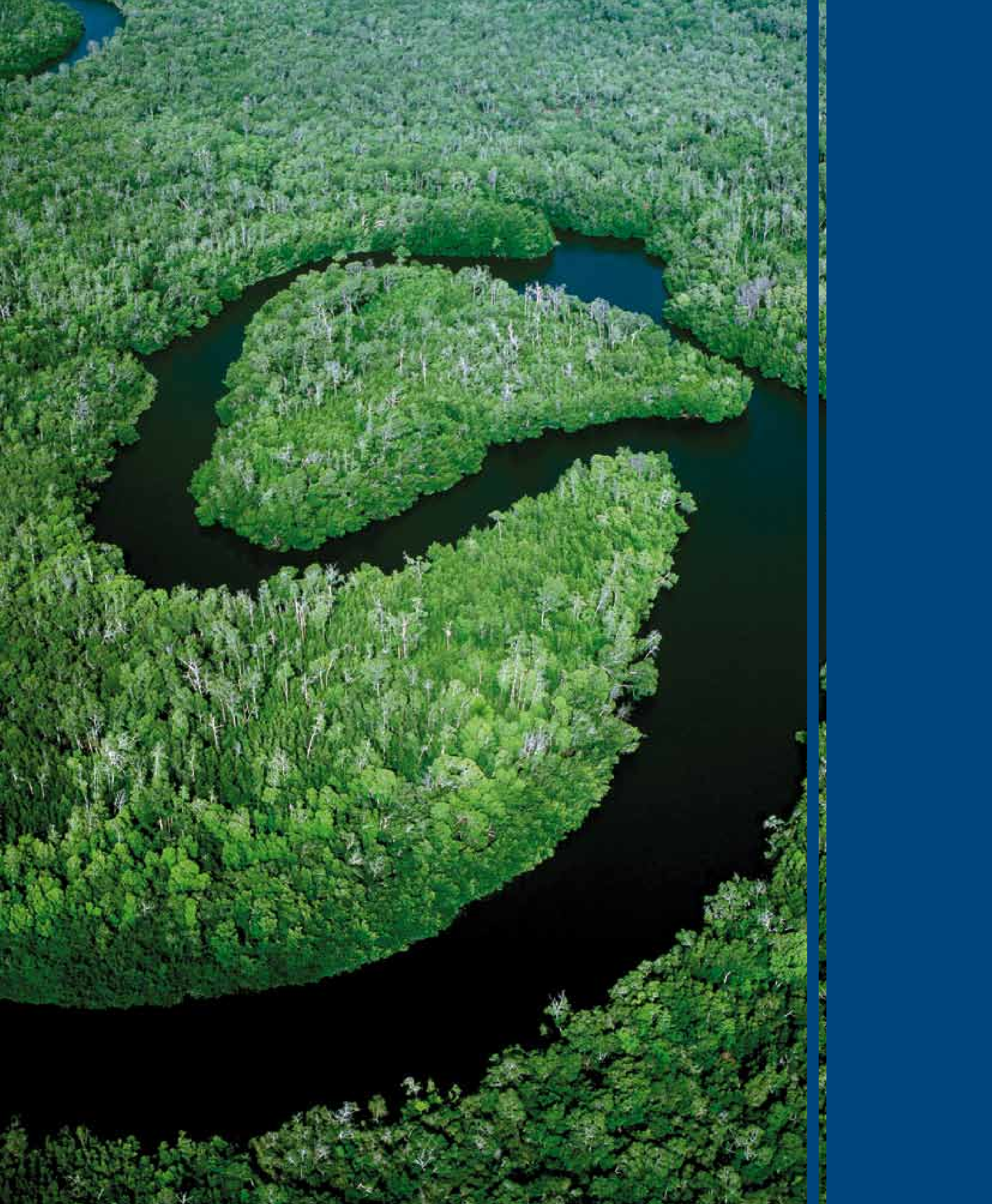
Earth system research question 32
How can the feedbacks from changes in human well-being, especially with regard to equity issues, be included in Earth system analysis and modelling?

Earth system research question 33
What types of contingent (unpredictable) events can cause abrupt changes in the current trajectory of the human enterprise?

Earth system research question 34
What can Earth system science contribute to the quest for sustainability of human societies?

The 34 Earth system research questions posed above, while by no means representing all pressing Earth system questions, do embrace a good cross-section of the more biophysical ones and urgently need attention.

Recommendation 1
The Earth system research questions posed in this report be considered and evaluated by Australian ESS researchers and research funding agencies. This should be done in close collaboration with decision makers and other stakeholders, and the questions should be investigated as soon as possible.



Chapter 4

Implementation strategies

We are facing looming and difficult global environmental and socio-economic problems and, to have a reasonable prospect of success, their resolution will require a focused, interdisciplinary, and integrated research effort. Unprecedented challenges require insightful and innovative responses, and here we set out some ways to help reach those goals.

4.1 Fostering an Australian community of Earth system scientists

An association for Earth system science. Since the rationale for ESS is to provide information and understanding in order that global management of the coupled human–environment system can be done better, it follows that there has to be close liaison between scientists, managers, policy makers, and the general community.

We therefore need to establish strong links between science, policy, management, and interested members of the community. In other words, policy and management experts and the general community should be kept well-informed of scientific findings and their implications; scientists, in turn, need to take policy and management needs and community opinion into account when framing research programs. Routine liaison between stakeholders and scientists means that science will closely reflect human needs and that Earth system policy makers and managers will keep up to date with the emerging science. To this end, the formation of an association for the advancement and application of Earth system science would have many advantages.

There are risks here that need to be understood and addressed. The risks relate to the immediacy and political complexion of many policy issues. If policy comes to dictate the research that is funded, then the science will become narrower and opportunities for genuine advances will be missed. Unfettered, objective, scientific enquiry must remain a strong component of the research mix.

Recommendation 2

An Australian Society for Earth System Science be established.

Inter-Academy links on Earth system science. Since Earth system science needs to establish stronger links between the natural and social sciences, economics, and the humanities disciplines, there needs to be top-level communication about Earth system issues between the learned Academies.

Recommendation 3

Discussions be initiated between the Australian learned Academies on collaboration and coordination of activities in Earth system science.

4.2 Communication and reporting of Earth system science

Earth system conferences. To present research results and discuss views on emerging problems and issues, we propose that a regular (perhaps biennial) Earth System Outlook Conference be established. Initially this could be under the auspices of the Australian Academy of Science. Later it could be run jointly under the auspices of the learned Academies or by the proposed Society for Earth System Science. Such a conference series would serve several purposes. One would be to foster the emergence, from the present range of diverse disciplines and interests, of a coherent body of researchers having a strong communication network. Second, the conference would provide opportunities for investigators, policy makers, system managers at all levels, communicators, and interested community members to inform each other about developments, issues, and opportunities – both formally via the programmed conference sessions and informally during conference social events and subsequently. Third, it would help identify further interdisciplinary links that are still needed to solve ESS problems. These Australian meetings, while focusing on issues of particular interest to Australia's long-term management, should involve international science and policy people to underline the global perspective implicit in the concept of ESS.

Recommendation 4

A series of Australian Earth System Outlook Conferences be initiated.

Earth system science journal. It is difficult to find a peer-reviewed journal that is both broad enough and of sufficient substance to publish ESS research findings. Over the course of the coming decade consideration needs to be given to establishing a high-quality journal for Earth system science. Internationally, the journal Global Change Biology has set an excellent precedent in covering biological aspects, but there is now a need for an equivalent journal to cover the full multidisciplinary scope of ESS, including positions and thoughts relating to management and policy.

Recommendation 5

An Australian Earth system journal be established. This journal would be of international standing and would publish highly interdisciplinary contributions, covering both research and opinion, relating to the Earth system state and its functioning.

Textbook on Earth system science. Over the coming decades, the primary intended outcome of a coherent Australian research effort on the Earth system will be a suite of wise planning decisions – regional, national, and global – that will make communities, the nation, and the world less-exposed to human-induced environmental risks and more resilient to unexpected environmental events. These decisions will be guided by a wide-ranging understanding of the repercussions of human actions on the comfortable and fair occupancy of the planet.

We have noted repeatedly that engagement of all stakeholders is crucial for identifying the full spectrum of research agendas; fully involved stakeholders also mean that research findings and improved understanding can be promptly put into action. Such engagement can take a range of forms. But one important approach would be the production of a new textbook or similar books giving a well-integrated account of what is known about the state and functioning of the Earth system. It will be initially a tertiary-level book, but also with versions available to the planning and decision-making communities, including politicians, public sector bureaucrats, business people, and secondary teachers and students. The textbook should link to a well-managed interactive web presence, permitting dialog between researchers and the community and providing information updates. In this way, Australia could play a role in the emerging global governance of the Earth system, quick to respond to changing conditions, and operating from local to global scales (Biermann et al. 2009). An operating manual for the planet, perhaps.

Recommendation 6

As a means to further the development of an effective Earth system community in Australia, a tertiary-level textbook on Earth system science be prepared. It would have associated popular versions and a dynamically interactive web presence for keeping the information up to date and relevant to users.

4.3 Funding

Research infrastructure. Progress in ESS depends on the field having a conceptual framework in which observations, experimental data, and analysis can be logically placed. A framework facilitates modelling the system and its parts, exploring whole system behaviour and properties, and making predictions. Infrastructure that allows ground-based and remotely sensed Earth system observation and experiment is necessary but expensive and, given its complexity, is not discussed here. Requirements for Earth observation from space have been documented in a recent report from the Australian Academy of Science (Australian Academy of Science 2009).

Both the observational programs and the modelling efforts required by Earth system science have huge computational requirements. Global climate modelling, in particular, requires supercomputers to run climate change simulations with high spatial resolution to evaluate what impacts climate change will have on specific areas. Thus it is essential that Australian Earth system science has adequate access to a national supercomputing facility that keeps up to date with available supercomputer technology.

Recommendation 7

National supercomputing infrastructure investment is kept up to date with the computing and observational data handling needs of Earth system science.

ESS is inherently interdisciplinary across a wide spectrum of objective enquiry. At the same time, science funding in Australia is strongly disciplinary and oriented to industry sectors, a situation that puts interdisciplinary proposals at a disadvantage. Funding agencies are not set up to evaluate and rank highly interdisciplinary proposals; it is nearly impossible to rank such proposals alongside the traditional ones – those that fit neatly into specific disciplines, tackle current industry problems, or only involve two or three disciplines at most. This difficulty needs to be addressed urgently.

Recommendation 8

Australian research funding agencies explicitly create ways of competitively evaluating highly interdisciplinary Earth system research proposals.

4.4 Championing the Earth system science agenda

The far-reaching scope envisaged in this research plan means that we want a broad range of researchers belonging to a large number of research institutions. Indeed, it should be acknowledged that some of the pieces of research identified in this plan are already under way or on the drawing board (see Appendix A for a list of some such programs). To implement the plan effectively, the challenge is to build a framework that facilitates and supports the necessary linkages between research communities and institutions. Over the course of a decade, it would be desirable to progressively work towards the establishment of a coherent, multi-institutional program.

Given the scope and magnitude of the issues involved, it will probably take some time before a single focal point for ESS research can be established in Australia. In addition, the above recommendations require a champion to foster the establishment of a society for Earth system science, a journal, authorship of a textbook and website, to argue the case with funding sources that they should find a way to fairly evaluate highly interdisciplinary proposals falling outside the standard categories, and to promote the regular updating of supercomputing and Earth system observational infrastructure in Australia. An Australian Office of Earth System Science is needed to perform these activities. Such an Office could also take on the role of organising a regular Earth System Outlook Conference. Depending on its funding level, this Office could perform, as part of its championing function, community educational activities such as arranging public lectures, workshops, and public forums, and helping school systems with curriculum development. It could also arrange meetings between researchers and users of Earth system information such as policy makers, managers, and politicians. The National Committee for Earth System Science should explore ways and means to establish such an Office in an appropriate institutional setting.

Recommendation 9

The National Committee for Earth System Science explore the means to establish a National Office for Earth System Science. The function of the Office would be to champion the Recommendations of this report, to support and link existing relevant research activities and agencies as they move towards establishing a coordinated institutional structure for Australian Earth system science activities, and to foster communications between the Earth system research community and the general community, including education, government, and business.

4.5 Connections to international ESS

Australia has good connections in the committee structures of the international agencies and research programs involved in ESS, such as ICSU, WMO, and off-shoot organisations such as IGBP, IHDP, WCRP, and ESSP. These agencies and programs are currently in a state of organisational flux as they come to grips with the same issue as is being dealt with in this research plan – how to organise the plethora of interests and activities that have developed, from diverse disciplinary beginnings, into a unified, functioning structure. Moreover, the core philosophy of that structure must fully recognise that the science of the Earth system involves much more than a mere collection of individual disciplines can contribute.

Chapter 5

Seeking the broadest picture

Researchers involved in Earth system science recognise that their work is based on a very different world view from that provided by the economic orthodoxy prevailing in most developed nations. In the orthodox view it is trusted that inter-human competition within a financial free-market mechanism will indefinitely provide the optimum solution to resource allocation for human well-being. Where that optimism is found wanting, the failure is marginalised as an "externality" or "market failure", as if it were not a fundamental error in the basic assumptions. A likely outcome of an effective Earth system science program would be progressive revaluation of how better to implement short-term market mechanisms for achieving a well-functioning, resilient Earth system in the long haul.

5.1 Scale and inertia

If we are to avert longer term resource-related and environment-related problems like climate change, the issue of scale – both temporal and spatial – needs to be considered. Ultimately, we need to translate concepts in Earth system science into human responses, and short-term market forces fail to address this adequately. The difficulty is that the processes causing concern globally have impacts on individuals, communities, and countries, and each of these can legitimately say that their contribution to the problem is minor or even infinitesimal: they can easily say they can't afford to damage their lifestyle or economy for the greater good of "the environment", or even of humanity, let alone of future generations.

Given degrees of inertia in all components of the Earth system – physicochemical, biological, socio-economic, political, and legal – there is a potential time-lag problem: even if a problem identified by Earth system science gains widespread acceptance, its realisation may come too late to avert major detrimental changes. While this lag will always work against us, it doesn't mean that all attempts to predict and forestall negative impacts are futile. Given the gravity of the situation, a sensible response is to give it our best efforts. The findings of Earth system science will at least give us a set of options for escaping our worst predicaments.

5.2 The human enterprise from an Earth system science perspective

From an ESS perspective, the suitability of the Earth as a habitat for life and civilisation is not something that can be taken for granted, an inevitable given. Even though the essential resources of air, water, ice, soil nutrients, soil structure, and a UV-absorbing and temperature-stabilising atmosphere are "free" and not amenable to bartering, this does not stop our habitat from deteriorating as a result of human economic activity. We are a dominant animal species that (from an ecological perspective) is growing in epidemic proportions, and is increasing its average per capita use of resources. We now need to realise that some far-sighted environmental stewardship is needed for our own long-term well-being, and that this may need to override our personal self-interest and market forces in deciding how resources are used. A more complete economic theory underpinning national planning and government would accommodate these features without resorting to *ad hoc* ideas of externalities and market failure. We hope that one outcome of an improved understanding of Earth dynamics will be the internalisation, in management and policy, of what is presently labelled "externalities".

5.3 One bridge, individual rivets

The potential subject matter of Earth system science is vast, covering many traditional disciplines in an interactive way. Given the limitations of individuals, and the disciplinary history of science and of science education, specialisation is inevitable. Scientists who are discipline specialists are essential to investigate specific phenomena at the forefront of science.

However, the intent of Earth system science is to transcend the disciplinary barriers; it aims to bring together integration and synthesis to reveal higher level interactions, feedbacks, and emergent properties of the Earth system. Thus, in this domain, non-specialisation is itself a speciality. Being a good generalist is a special skill. The word "good" is important here because, if the field is not careful, it will grow to embrace far too many things to be tractable and fall into chaos. Thus identification of focused activities is critical, calling for a long-term outlook. "Across the board" scientists are system conceptualisers, but computer simulation modelling is not the only route for gaining insights into whole Earth behaviour. Qualitative analyses, especially of the human components of the Earth system, and descriptive narratives are also valuable. Accordingly, an important part of a research plan for Earth system science needs to be explicit plans for fostering the integration of specialist findings into whole-system frameworks, concepts, and research that have targeted application. This is difficult, but it is an essential outcome of an effective ESS program.

5.4 Human involvement in the evolution of the Earth system from the past into the future

Because change is a fact of life, some people have dismissed concerns about human-induced climate change, arguing that climate has never been stable and that the world has experienced huge and rapid changes to climate in the past. Why worry?

Others counter that the world's climate has been remarkably stable and equable during the last 10 millennia (by the standards of the prior 2 million years). They note that this recent period of relative stability has been an important ingredient in the mix of factors that fostered the development by *Homo sapiens* of a highly organised civil society.

The science of the Earth system recognises the truth of both perspectives, and attempts to disentangle those causes of risky environmental changes that are human-induced (and therefore can be countered with appropriate actions) and those that are outside human control, for which preparedness and adaptation are the only options. Greenhouse gas–induced climate change is an example of the former, although it is now too late to avoid the need for adaptation to climate change already committed to. Examples of the latter would be appropriate urban location and design in order to minimise risk from, say, hurricanes in tropical areas or major earthquakes on tectonic plate margins.

The intent of the plan we have set out here has been to blaze a trail forward. The "ozone hole" is now under repair by concerted action arising from an international treaty, and this shows that big problems can be solved by global consensus and action. Similarly, with Earth system science the hope is that there can be a coming together of pertinent social science, economics, and humanities research with relevant parts of the natural sciences. The hybrid that results is what we see as comprising a new predictive science of the whole Earth system. The goal we set ourselves is to achieve such a merger by the end of the decade.

Literature

Alley, R. B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke, R.A. Jr., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D., Wallace, J.M. (2003) Abrupt climate change. *Science* 299: 2005–2010.

AMS [American Meteorological Society] (2009) "AMS Policy Statement on Geoengineering the Climate System." Available at http://www.ametsoc.org/policy/2009geoengineeringclimate_amsstatement.pdf, accessed 14 June 2010.

Australian Academy of Science and Australian Academy of Technological Sciences and Engineering (2009) *An Australian Strategic Plan for Earth Observations from Space*.

Bates, T. S., Charlson, R. J., Gammon, R. H. (1987) Evidence for the climatic role of marine biogenic sulphur. *Nature* 329: 319–321.

Betts, R. A., Boucher, O., Collins, M., Cox, P. M., Falloon, P. D., Gedney, N., Hemming, D. L., Huntingford, C., Jones, C. D., Sexton, D. M. H., Webb, M. J. (2007) Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* 448: 1037–1041.

Betts, R. A., Malhi, Y., Roberts, J. T. (2008) The future of the Amazon: new perspectives from climate, ecosystem and social sciences. *Philosophical Transactions of the Royal Society B* 363: 1729–1735.

Biermann, F., Betsill, M. M., Gupta, J., Kanie, N., Lebel, L., Liverman, D., Schroeder, H., Siebenhüner, B. and others. (2009) *Earth System Governance: People, Places and the Planet*. *Science and Implementation Plan of the Earth System Governance Project*. Earth System Governance Report 1, IHDP Report 20. IHDP, Bonn.

Brook, E. J. (2006). The future of ice core science. *Eos* 87(4): 39.

Canadell, J. G., Pataki, D. E., Gifford, R., Houghton, R. A, Luo, Y., Raupach, M. R., Smith, P., Steffen, W. (2007) Saturation of the terrestrial carbon sink. Chapter 6 in Canadell, J. G., Pataki, D., Pitelka, L. (eds) *Terrestrial Ecosystems in a Changing World*. The IGBP Series, Springer-Verlag, Berlin.

Chiew F.H.S., Teng J., Vaze J., Kirono D.G.C. (2009) Influence of global climate model selection on runoff impact assessment. *Journal of Hydrology* 379: 172-180.

Cicerone, R. J. (2006) Geoengineering: encouraging research and overseeing implementation. *Climatic Change* 77: 221–226.

Commoner, B. (1972) The environmental cost of economic growth. In *Population, Resources and the Environment*. Government Printing Office, Washington, D.C., pp. 339–363.

Commonwealth of Australia, Department of Climate Change (2009) *Australian Climate Change Science: A National Framework*. 26 pp. Available at http://www.climatechange.gov.au/~/media/publications/science/national-framework-cc-science.ashx, accessed 21 June 2010.

Connor, S., Green, C. (2009) Climate scientists: it's time for 'Plan B'. *The Independent*, 2 January 2009. Available at http://www.independent.co.uk/environment/climate-change/climate-scientists-its-time-for-plan-b-1221092.html, accessed 14 June 2010.

Cooley, S. R., Doney, S. C. (2009) Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters* 4(2): 024007

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., Totterdell, I. J. (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408: 184–187.

Crutzen, P. J. (2002) The Anthropocene. *Journal de Physique* IV 12: 1–5.

Crutzen, P. J. (2006) Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change* 77: 211–219.

Crutzen, P. J., Stoermer, E. F. (2000) The "Anthropocene". *Global Change Newsletter* 41: 1.

Dai, A., Qian, T., Trenbarth, K. E. (2009) Changes in continental freshwater discharge from 1948–2004. *Journal of Climate* 22: 2773–2792.

De'Ath, G., Lough, J. M., Fabricius, K. E. (2009) Declining coral calcification on the Great Barrier Reef. *Science* 323(5910): 116–119.

Garnaut, R. (2008) *The Garnaut Climate Change Review*. Cambridge University Press, Cambridge, U.K., 634 pp.

Gedney, N., Cox, P. M., Betts, R. A., Boucher, O., Huntingford, C., Stott, P. A. (2006) Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* 439: 835–838.

Geiger, R. (1965) *The Climate Near the Ground*. Harvard University Press, Cambridge, MA, 611 pp.

Gifford, R. M. (1994) The global carbon cycle: a viewpoint on the missing sink. *Australian Journal of Plant Physiology* 21: 1–15.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M. E., Royer, D., Zachos, J. (2008) Target atmospheric CO_2: where should humanity aim? *The Open Atmospheric Science Journal* 2: 217–231.

Hansen, J., Sato, M., Kharecha, P., Russell, G., Lea, D. W., Siddall, M. (2007) Climate change and trace gases. *Philosophical Transactions of the Royal Society A* 365: 1925–1954.

Harle, K., Etheridge, D., Barbetti, M., Jones, R., Brooke, B., Whetton, P., van Ommen, T., Goodwin, I., Fink, D., Haberle, S. (2007) Building a future on knowledge from the past: what palaeo-science can reveal about climate change and its potential impacts in Australia. Australian Greenhouse Office, Department of the Environment and Water Resources: Canberra. Available at http://pandora.nla.gov.au/pan/102841/20090728-0000/www.climatechange.gov.au/science/publications/pubs/palaeo-science.pdf, accessed 14 June 2010.

Howard, W. R., Havenhand, J., Parker, L., Raftos, D., Ross, P., Williamson, J., Matear, R. (2009) Ocean acidification. In *Marine Climate Change in Australia: Impacts and Adaptation Responses, 2009 Report Card* (eds Poloczanska, E. S., Hobday, A. J., Richardson, A. J.) National Climate Change Adaptation Research Facility Publication 05/09. Available at http://www.oceanclimatechange.org.au/content/images/uploads/OceanAcidfication_2009.pdf, accessed 6 July 2010.

ICSU (2009) "Developing a New Vision and Strategic Framework for Earth System Research." Available at http://www.icsu.org/1_icsuinscience/PDF/ICSU_ES_visioning_process_paper.pdf, accessed 14 June 2010.

IPCC (2007) "Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment." Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, 104 pp.

Jacobs, S. S. (2004) Bottom water production and its links with the thermohaline circulation. *Antarctic Science* 16: 427–437.

Jackson, J. B. C., Kirby, M. X., Berger, W. B., Bjorndal, K. A., Botsford, L. W., Bourque, B. J., Bradbury, R. H., Cooke, R., Erlandson, J., Estes, J. A., Hughes, T. P., Kidwell, S., Lange, C. B., Lenihan, H. S., Pandolfi, J. M., Peterson, C. H., Steneck, R. S., Tegner, M. J., Warner, R. R. (2007) Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629–638.

Jahn, A., Claussen, M., Ganopolski, A., Brovkin, V. (2005) Quantifying the effect of vegetation dynamics on the climate of the last glacial maximum. *Climate of the Past* 1: 1–7.

Kiehl, J. T. (2006) Geoengineering climate change: treating the symptom over the cause? *Climatic Change* 77: 227–228.

Kirschbaum, M. U. F. (2010) The temperature dependence of organic matter decomposition: seasonal temperature variations turn a sharp short-term temperature response into a more moderate annually averaged response. *Global Change Biology* 16: 2117–2129.

Kleidon, A. (2007) Optimized stomatal conductance and the climate sensitivity to carbon dioxide. *Geophysical Research Letters* 34: L14709.

Kruijt, B., Witte, J. P. M., Jacobs, C. M. J., Kroon, T. (2008) Effects of rising atmospheric CO_2 on evapotranspiration and soil moisture: a practical approach for the Netherlands. *Journal of Hydrology* 349: 257–267.

Labat, D., Godderis, Y., Probst, J. L. (2004) Evidence for global runoff increase related to climate warming. *Advances in Water Resources* 27: 631–642.

Le Quéré, C. and 30 others (2009) Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* 2: 831–836.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., Schellnhuber, H. J. (2008) Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences USA* 105: 1786–1793.

Lovelock, J. E., Margulis, L. (1974) Atmospheric homeostasis by and for the biosphere: the Gaia Hypothesis. *Tellus* XXVI: I–10.

McVicar, T. R., van Niel, T. G., Li, L. T., Roderick, M. L., Rayner, D. P., Ricciardulli, L., Donohue, J. (2008) Windspeed climatology and trends for Australia 1975–2006: capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters* 35(20): L20403.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, D.C., 137 pp.

Milliman, J. D., Farnsworth, K. L., Jones, P. D., Xu, K. H., Smith, L. C. (2008) Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change* 62: 187–194.

Moy, A. D., Howard, W. R., Bray, S. G., Trull, T. W. (2009) Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience* 2: 276–280.

Orr, J. C., Turley, C. (2009) The ocean in a high-CO_2 world: the second symposium on ocean acidification. *Global Change Newsletter* 73: 22–23.

Paltridge, G., Arking, K., Pook, M. (2009) Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data. *Theoretical and Applied Climatology* 98: 351–359.

Peñuelas, J., Staudt, M. (2010) BVOCs and global change. *Trends in Plant Science* 15: 3133–3144.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J. E., Keeling, R. F., Parker, D. E., Somerville, R. C. J. (2007) Recent climate observations compared to projections. *Science* 316: 709.

Ramanathan, V., Carmichael, G. (2008) Global and regional climate changes due to black carbon. *Nature Geoscience* 1: 221–227.

Ramanathan, V., Xu, Y. Y. (2010) The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues. *Proceedings of the National Academy of Sciences* 107: 8055–8062.

Ries, J. B., Cohen, A. L., McCorkle, D. C. (2009) Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology* 37: 1131–1134.

Robock, A. (2008) 20 reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists* 64: 14–18.

Rockström, J. and 29 others (2009) A safe operating space for humanity. *Nature* 461: 472–475.

Roderick, M. L., Farquhar, G. D. (2009) *Water availability and evapotranspiration in the Murray–Darling Basin: A look at the past and a glimpse into the future*. A report commissioned by the Murray–Darling Basin Authority, 40 pp.

Roderick, M. L., Rotstayn, L. D., Farquhar, G. D., Hobbins, M. T. (2007) On the attribution of changing pan evaporation. *Geophysical Research Letters* 34: L17403.

Rotstayn, L. D., Keywood, M. D., Forgan, B. W., Gabric, A. J., Galbally, I. E., Gras, J. L., Luhar, A. K., McTainsh, G. H., Mitchell, R. M., Young, S. A. (2009) Possible impacts of anthropogenic and natural aerosols on Australian climate: a review. *International Journal of Climatology* 29: 461–479.

Schelling, T. C. (1996) The economic diplomacy of geoengineering. *Climatic Change* 33: 303–307.

Sellers, P. J., Bounoua, L., Collatz, G. J., Randall, D. A., Dazlich, D. A., Los, S. O., Berry, J. A., Fung, I., Tucker, C. J., Field, C. B., Jensen, T. G. (1996) Comparison of radiative and physiological effects of doubled atmospheric CO_2 on climate. *Science* 271: 1402–1406.

Steffen, W., Crutzen, P. J., McNeill, J. R. (2007) The Anthropocene: are humans now overwhelming the great forces of nature. *Ambio* 36: 614–621.

Tennant, S., Pearce, K., Turney, C., Harle K. (eds) (2008) How evidence from the past can help unravel the future: using palaeo-science to understand climate change science in Australia. Department of Climate Change, Canberra. Available at http://www.climatechange.gov.au/~/media/publications/science/palaeo-evidence.ashx, accessed 14 June 2010.

Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T., Maksym, T., Meredith, M. P., Wang, Z., Orr, A. (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. *Geophysical Research Letters* 36: L08502.

UNFPA [United Nations Population Fund] (2007) *State of World Population 2007: Unleashing the potential of urban growth*. http://www.unfpa.org/swp/2007/presskit/pdf/sowp2007_eng.pdf. Accessed 31 July 2010.

Vaughan, D. G, Arthern, R. (2007) Why is it hard to predict the future of ice sheets? *Science* 315: 1503–1504.

Wentz, F. J., Ricciardulli, L., Hilburn, K., Mears, C. (2007) How much more rain will global warming bring? *Science* 317: 233–235.

Zalasiewicz, J. and 19 others (2008) Are we now living in the Anthropocene? *GSA Today* 18(2): 4–8.

Zalasiewicz, J., Williams, M., Steffen, W., Crutzen, P. (2010) The new world of the Anthropocene. *Environmental Science & Technology* 44: 2228–2231.

Acknowledgements

On behalf of the National Committee for Earth System Science, I thank all those who contributed their expertise, foresight, energy, and patience for putting into words something which a few years ago was only a vague inkling. We all knew that this document was important to do, and how it all came together into a unity, despite the huge diversity in perspectives brought to bear, reflects the good will and forbearance of all the committee members, who are listed below.

In particular I thank co-authors, Will Steffen and John Finnigan, whose depth and breadth of knowledge and vision provided a constant reference point in winnowing the universe of information that our subject matter draws upon.

Also of considerable importance was the skilled work of our scientific editor, Andrew Bell, who quickly picked up the intent of the exercise and gave the document much improved readability, not only by detailed wordsmithing but also by effective suggestions for re-organising the text. His contribution has been invaluable and is much appreciated.

Members of the Reference Group, listed on page 84, provided valuable guidance and enthusiasm for the objectives both by a workshop in 2009 and subsequently. This work has been a collegiate exercise spanning several years.

The encouragement by members of the Academy of Science's Executive Committee to both start and complete this exercise has been of considerable importance to our not giving up on the arduous venture. I thank those committee members for their patience and encouragement.

The financial support of the Department of Climate Change and Energy Efficiency (and its predecessor organisations) is gratefully acknowledged. Without their commitment to supporting the work of the National Committee for Earth System Science, this plan could not have been developed.

On a personal note, I wish to thank Jeanette Mill and Connie Berridge of the Academy of Science administration office for both supporting us in many ways and keeping us all on track in a professional and good-natured fashion.

Roger M. Gifford

Chair, National Committee for Earth System Science

Contributors

National Committee for Earth System Science

Dr Roger Gifford (Chair)

Professor Amanda Lynch (Deputy Chair to Dec 2009)

Dr Tas van Ommen (member to Dec 2009, Deputy Chair from Jan 2010)

Dr John Finnigan FAA (observer 2009, member from Jan 2010)

Professor David Karoly (member from Jan 2008)

Professor Mike Manton (member to Dec 2007 then observer)

Dr Bruce Mapstone (member Jan 2009 – Apr 2010)

Dr Trevor McDougall FAA (member to Dec 2008)

Professor Andy Pitman (member)

Dr Neville Smith (member to Nov 2008)

Professor Will Steffen (member)

Dr Susan Wijffels (member from May 2009)

Plan Reference Group

Dr Ian Allison, Australian Antarctic Division

Professor Roger Bradbury, Resource Management in Asia–Pacific Program, Australian National University

Dr Pep Canadell, Global Carbon Project

Professor Michael Dopita FAA, Treasurer, Australian Academy of Science

Professor Matt England, Climate Change Research Centre, University of New South Wales

Professor Graham Farquhar FAA, Secretary Biological Sciences, Australian Academy of Science

Dr Paul Fraser, CSIRO Marine and Atmospheric Research

Professor David Griffith, Department of Chemistry, University of Wollongong

Professor Ann Henderson-Sellers, Department of Environment and Geography, Macquarie University

Dr Will Howard, University of Tasmania

Dr Mark Howden, CSIRO Sustainable Ecosystems

Professor Kurt Lambeck FAA, President (to May 2010), Australian Academy of Science

Dr Richard Matear, CSIRO Marine and Atmospheric Research

Dr Gary Meyers, Integrated Marine Observing System

Dr Tim Moltmann, Integrated Marine Observing System

Professor Pascal Perez, Resource Management in Asia–Pacific Program, Australian National University

Professor Stuart Phinn, Terrestrial Ecosystem Research Network, School of Geography, Planning and Environmental Management, University of Queensland

Professor Colin Prentice, Department of Biological Sciences, Macquarie University

Dr Kamal Puri, Bureau of Meteorology

Dr Michael Raupach FAA, CSIRO Marine and Atmospheric Research

Dr Steve Rintoul FAA, CSIRO Marine and Atmospheric Research

Mr Martin Rice, Department of Environment and Geology, Macquarie University

Dr Neville Smith, Bureau of Meteorology

Dr Mark Stafford Smith, CSIRO Climate Adaptation Flagship

Professor Mark Westoby FAA, Department of Biological Sciences, Macquarie University

Dr John Zillman FAA, Academy of Technological Sciences and Engineering

Scientific Editing

Dr Andrew Bell, Australian National University

Image captions

front cover The Earth by day and by night (composite). Human energy consumption visible from space. © Visible Earth, NASA (http://visibleearth.nasa.gov)

page vi Our home: Earth from space. © Visible Earth, NASA. Surrounding images © iStockphoto (www.istockphoto.com)

page xviii Intensively fertilised sugarcane farms near Cairns, Queensland. Photo by Ben Heys, © iStockphoto

page 6 Bondi beach, Sydney, NSW. Will it survive sea level rises? Photo by Jean-Paul Ferrero, © Hedgehog House (www.hedgehoghouse.com)

page 8 A phytoplankton bloom, covering hundreds of square kilometres, in the sea off the west coast of Tasmania. © NASA

page 12 Prolific energy expenditure by congested traffic. © Science Photo Library (www.sciencephoto.com)

page 13 Small shells make up the beach at Shell Beach, Shark Bay National Park, Western Australia. Shells of some marine organisms are vulnerable to ocean acidification. Photo by George Clerk, © iStockphoto

page 14 A wheat farm's top soil blowing away, near Renmark, South Australia. Photo by Jean-Paul Ferrero, © Hedgehog House

page 16 Feral camels are a major and increasing problem in outback Australia. Photo by Uros Ravbar, © iStockphoto

page 18 The Murray River meets the sea. Years of low flows have impacted badly on this fragile ecosystem. Photo by Jean-Paul Ferrero, © Hedgehog House

page 19 Urban infrastructure developed in recent decades close to sea-level at Surfers Paradise on the Gold Coast, Queensland. Photo by Jenny Bonner, © iStockphoto

page 20 Woman wearing a face mask against pollution or disease. Pandemics are an increasing risk. Photo by Barnaby Chambers, © iStockphoto

page 21 Wind turbines are becoming more common. But how quickly can alternative electricity supplies realistically replace carbon-based power generation? © iStockphoto

page 22 The Larsen ice shelf, Antarctica, breaking up in February 2000. © Visible Earth, NASA

page 26 Floating ephemera. The dynamics of clouds is poorly understood but they are a critical factor affecting climate. Photo by Phil Green, © Stock.xchng (www.sxc.hu)

page 28 Bulldozers repairing a beach at Burleigh Heads, Queensland, October 2010. Rising sea-level will necessitate more attention to beach management. Photo by Mike Batterham, © Newspix (newspix.com.au)

page 30 The Antarctic in 2003. Ice sheet dynamics under global warming is ill-understood. © NASA/Goddard Space Flight Center Scientific Visualization Studio

page 33 Terrestrial ecosystem structure can be profoundly changed by agriculture. Dryland cropping in the Liverpool Plains, New South Wales (top); Australian native vegetation at Port Hacking, NSW (middle); sheep at a watering hole (bottom). Top photo by Anne Greenwood, © iStockphoto; middle photo by Max Brown, © Stock.xchng; bottom photo by Robert van Beets, © iStockphoto

page 39 High-production cropping involves major inputs of mineral nutrients and fossil fuel, thereby contributing to the changing biogeochemical cycling and atmospheric composition. Photo by Michael Hieber, © iStockphoto

page 45 "Free" Earth system services: what value rain and pollinating insects? Left photo by Pawel Gaul, © iStockphoto; right photo by T. Anutka, © iStockphoto

page 46 Melting permafrost on the Alaskan tundra – a risk from global warming. Photo by Steven Nourse, © AccentAlaska.com (www.accentalaska.com)

page 47 River valley destruction of native forests in Tasmania. Deforestation has its limits – what are they? Photo by Terrasprite, © iStockphoto

page 53 Smoggy sunrise at Christchurch, New Zealand. The atmosphere's capacity to carry pollutants is not infinite. Photo by Colin Monteath, © Hedgehog House

page 56 Satellites and marine buoys – important tools for the Earth observation. Top photo © iStockphoto; bottom photo by Kara Lavender, © Argo Project Office (www-argo.ucsd.edu)

page 60 Mangroves on Cape York Peninsula, Queensland. Photo by Jean-Paul Ferrero, © Hedgehog House

page 62 Effective Earth system science requires long-term programs in the face of changing policies. At right a scientist works on an observation tower at the Cape Grim Baseline Air Pollution Station, Tasmania. Left photo © iStockphoto; right photo © CSIRO

page 67 The extent of sea ice around the North Pole in September 2010 confirms a shrinking trend. © NASA

page 68 Discard or recycle? Photo by Colin Monteath, © Hedgehog House

page 70 Bushfire smoke over Sydney. Photo by Jean-Paul Ferrero, © Hedgehog House

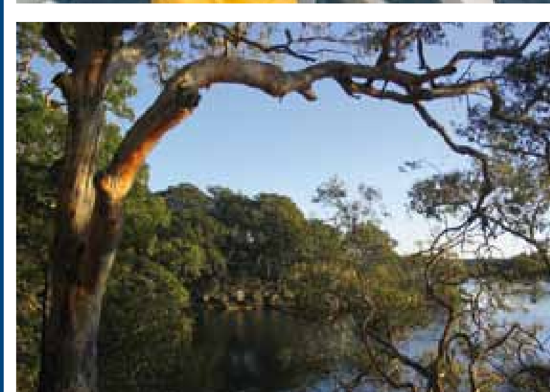
page 71 The Earth at night shows how humans are consuming energy to produce light. © NASA

page 74 Eucalypt forest after fire, Dargo High Plains, northeast Victoria. Photo by Jean-Marc La Roque, © Hedgehog House

page 80 Coral reef at Kimbe Bay, Papua New Guinea. Can coral reefs survive global warming and other global environmental changes? Photo by Andy Belcher, © Hedgehog House

back cover Images selected from pages inside. © iStockphoto, CSIRO, Stock.xchng

This precious and beautiful blue planet on which we live is complex beyond measure, so complex, we argue here, that a whole new science – an integrative science of the Earth system (Earth System Science or ESS) – is needed to understand it. There is an imperative to predict its potential future states, particularly those influenced by human impacts on the atmosphere, oceans, land, and biosphere. The Earth is now entering an epoch that has been called the "Anthropocene", a time in which humans are profoundly changing the environment, even the stratigraphy, of the planet. Rising carbon dioxide levels and associated global warming is the iconic example of human-induced global change, but climate change is only the most prominent of a series of changes to the Earth that are ultimately driven by exponential growth in the world's population. These changes involve so many interconnecting factors that how they will unfold in the future is far from clear. We believe that ESS, as a body of fundamentally interdisciplinary knowledge, offers the understanding necessary to move us towards a sustainable occupation of the planet. Here we set out a systematic and coherent plan to create an Australian scientific enterprise – combining inputs from the natural and social sciences, economics, and the humanities – which is devoted to understanding the planet's life support systems. Its primary aim will be to discover the Earth's biophysical limits and how to live within them.



Australian Academy of Science

Australian Government

Department of Climate Change and Energy Efficiency