Appendices to

To live within Earth's limits

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

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The international agenda of Earth system science

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The full report is available online at
www.science.org.au/natcoms/nc-ess.html

Appendix A

Summary of some existing research plans relevant to an Australian Earth system science plan

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▸A.1 Australian Climate Change Science: A National Framework

Department of Climate Change, 2009

This document was prepared by the Department of Climate Change after a national workshop (March 12–13, 2008) had been convened to address "Future directions for Australian climate change science". The plan was structured to address the fundamental climate change science needed to support three pillars of Australian Government climate change policy: reduction of greenhouse gas emissions, adaptation to unavoidable climate change, and helping to shape a global solution to climate change.

The plan set out the reasons for needing a nationally integrated renewal of the Australian Climate Change Science Program. The national government-funded program should build on past impressive Australian climate-science achievements by investing in fundamental climate change science (especially Southern Hemisphere aspects) which will keep the knowledge-base of our researchers at the forefront. In this way, the applied climate-related questions that the private sector will ask (and invest in) can be addressed.

In order to better predict future climate (on all time scales up to centuries, but especially on the decadal timescale) there is an urgent need to improve Australian long-term climate observation systems, climate process studies, integration of observations and modelling. As a platform for applying climate prediction to policy and adaptation, there is a growing need for "Integrated Assessment Models"; these can couple socio-economic processes and climate, thereby identifying key dynamic feedbacks between human responses and climate change. To achieve these objectives there is an urgent need to invest, securely and in the long term, in climate change science education and training, observational and supercomputing infrastructure, recruitment of top next-generation scientists, and appropriately trained support staff.

Five major elements of the Framework are:

First, there is the move from physical climate simulation to full climate system simulation. This will capture all the feedbacks between the physical, chemical and biological systems not captured in previous IPCC assessments, but which are essential to make climate simulations more accurate.

Second, there is the move to support global policy analysis through developing an Australian Integrated Assessment Model – a new capability for Australia – that will couple climate simulations dynamically to economic and social models.

Third, the Framework will provide for the national coordination of all of Australia's climate change science intellect, through a new, high level nationally representative climate change Science coordination group chaired by the Chief Scientist that will provide advice on national priorities, oversee the development of an implementation plan and report to government on progress. The Framework will bring the university sector's capabilities into the national Framework as co-contributors with government agencies to deliver the nation's long-term, strategic climate science needs.

Fourth, the coordination of the university sector and government science agencies will ensure that the necessary human capital renewal and its expansion as needed to deliver the Framework goals is a key element.

Fifth, the Framework also provides a coherent rationale and maximises opportunities for co-investment in landmark infrastructure (e.g. research vessel, and high performance scientific computing) needed to deliver a fully functional and effective national climate science capability.

▸A.2 Strategic Science Plan (2008)

The Centre for Australian Weather and Climate Research (CAWCR)

CAWCR is a joint virtual centre between CSIRO and the Bureau of Meteorology for Earth system science centered on weather and climate prediction on time scales from hours to centuries. Centre-wide objectives are grouped under three foci:

- Earth system simulation to lead the Australian science community in the development of a world-competitive coupled climate and Earth system simulator and modelling system.
- An Australian Earth system observation goal to transform the Centre's current observational science into a comprehensive, integrated information system that informs decisions.
- A water cycle goal to advance scientific knowledge of Australia's water cycle, particularly its predictability, reduce uncertainty based on this knowledge, and develop strategies for managing uncertainty.

To those ends the Centre has groups whose specific objectives are:

- To develop the techniques and knowledge to monitor, observe, and understand atmospheric and land processes, their interactions, and the role they play in Australia's environment.
- To create the infrastructure and knowledge to monitor, observe, and understand the key processes that drive variability and change in Australia's marine and deep ocean waters.
- The development of a world-competitive coupled climate and Earth system simulator and modelling system.
- To advance an understanding and ability to predict short-term weather events that affect Australia on both weather and climate time scales.
- To monitor, model, and predict the variability of the oceans and the surface marine environment of the Australian region and, in concert with the ocean observation and assessment group, develop an understanding of the processes and mechanisms that determine the ocean's role in climate and climate change.
- To deliver new knowledge and applications for decision-making in climate-sensitive industries and also that informs policy for managing Australia's environmental resources.

- To understand and project future climate change and its impacts so as to improve adaptive responses and to inform policy and decision-making.

▶A.3 Future Climate Change Research and Observations

GCOS/WCRP/IGBP, 2007

This international research planning activity derived from a workshop held in Sydney (in October 2007) in which 66 IPCC authors and experts (associated with the three international programmes, GCOS, WCRP, and IGBP) discussed gaps and shortcomings of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. It made recommendations in terms of "guiding principles" for setting priorities in climate change and set out urgent needs for climate change science, including observations additional to those described in the GCOS Implementation Plan.

The guiding principles for setting and updating future climate change research and observations were to:

- Address the key science areas needed to further understand the climate system and improve predictive capability.
- Include consideration of vulnerability in framing climate change research and observations.
- Ensure effective links between global and regional modellers and the communities concerned with impacts adaptation and vulnerability assessment.
- Ensure the development of 10–30 year climate predictions to complement longer term projections.
- Address the need for effective communication of the uncertainty of information provided to users.
- Ensure continuity of the climate record while incorporating new observation requirements deriving from research.

Within the context of those guiding principles, the workshop identified the following urgent research needs:

- Identification of regions where society is most vulnerable to climate change ("climate hot spots").
- Identification of thresholds beyond which "dangerous" changes (to society) will occur ("climate tipping points").
- An authoritative set of information at the scales relevant to adaptation policy.
- Better understanding of ice-sheet dynamics.
- Identifying and addressing the research and observations needs of the communities concerned with impacts adaptation and vulnerability.
- Better regional information on past and future climate change.
- Methodologies to define, determine, and communicate uncertainties and limitations in regional observations and module products in a context-sensitive manner.

- Quantification of radiative forcing due to aerosols and clouds by comprehensive model–model and model–observation comparisons.
- Better understanding of the hydrologic cycle, especially convection and precipitation processes.
- Ensuring sustained observations of the ocean and land surface.
- Continuity of key satellite missions for climate.
- Ensuring analysis, reanalysis, and processing of all climate data, with attention to observing system changes.

▸A.4 National Climate Change Adaptation Framework

COAG, 2006

The development of this Framework was requested by the Council of Australian Governments (COAG) in February 2006. It outlines the agenda for collaboration between Australian state and national governments to address the key demands from business, policy makers, and the community for targeted information on climate change impacts and fill gaps that inhibit adaptation. The Framework was intended to guide action over the next 5–7 years in order to:

- Support decision-makers with practical guides and tools to assist in managing climate change impacts.
- Establish a new centre for climate change adaptation to provide decision-makers with robust and relevant information on climate change impacts, vulnerability, and adaptation options.
- Provide, for the first time, climate change projections and regional scenarios at scales relevant to decision makers.
- Generate the knowledge to understand and manage climate change risks to water resources, biodiversity, coasts, agriculture, fisheries, forestry, human health, tourism, settlements, and infrastructure.
- Work with stakeholders in key sectors to commence developing practical strategies to manage the risks of climate change impacts.
- Assess the implications of climate change and possible adaptations for important regions such as the Murray–Darling Basin, south-west Western Australia, the tropical north, and the drying regions of eastern Australia.

▸A.5 A Marine Nation: National Framework for Marine Research and Innovation

Oceans Policy Science Advisory Group, 2008

This Framework, developed by the Oceans Policy Science Advisory Group (OPSAG), provides for a renewed Australian national effort in marine science through better planning, coordination, collaboration, and communication. Key findings were:

1. The five major opportunities and challenges for Australia's marine domain are:

- Opportunities for increased economic and energy security from marine and subsea resources;
- Conservation of marine biodiversity and ecosystem services;
- Management and protection of the marine coastal environments;
- Understanding and adapting to the marine impacts of climate change;
- National security and safety at sea.

2. Australia requires a renewed, strengthened and cohesive national approach to marine research and innovation, to be achieved through more effective coordination and increased investment in Australian marine science guided by an agreed National Framework for Marine Science and Innovation.

3. The key elements of a National Framework for Marine Research and Innovation are:

- Marine exploration and discovery;
- Marine observations and understanding;
- Marine industries development; with a strong focus on consultation and delivery through information and technology transfer.

4. Supporting the growth and development of Australian marine industries requires strong and expanded engagement with marine research and innovation providers, based on the development of innovative technologies and solutions, and the creation of formal partnerships.

5. Australian marine science suffers from acute shortages of skilled marine scientists and technologists, including trained engineers, mathematicians, statisticians, modellers, physicists, chemists, microbiologists, economists, geographers, and taxonomists. Shortages are compounded by the lack of career pathways for young researchers.

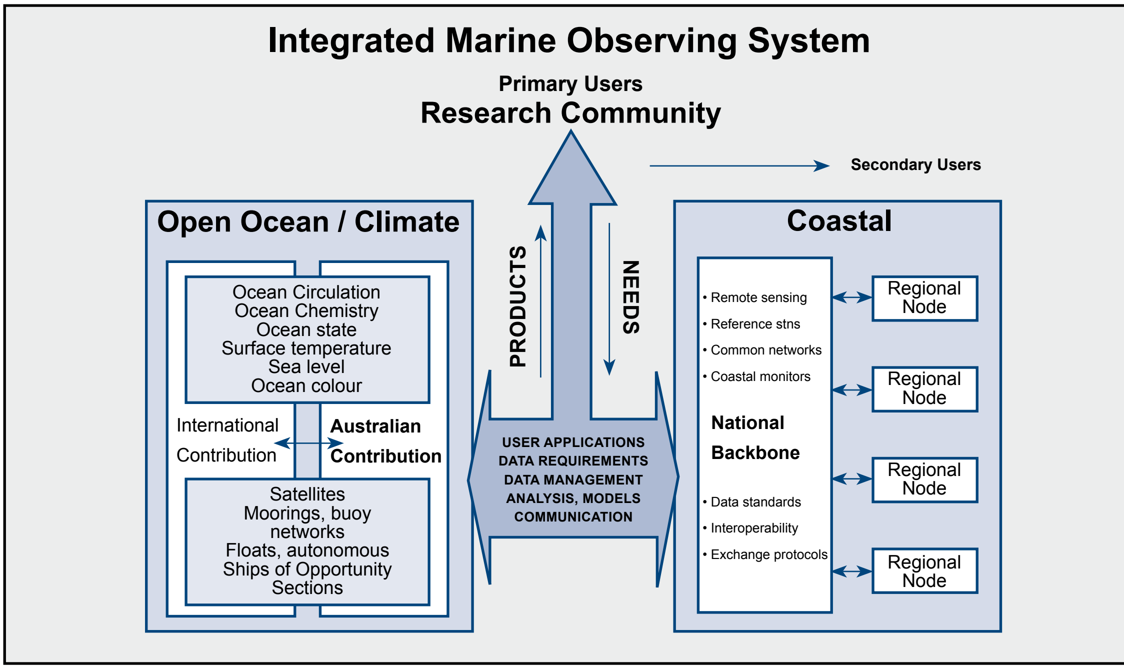
6. Australian education and training in marine science, technology, and innovation needs to provide for new human capability through better coordination, linkages, and investment to meet current and future demand for qualified marine scientists and technologists.

7. Australia requires new investment in marine research and innovation infrastructure, particularly in the areas of:

- National research vessel capability;
- Novel technologies and remote sensing;
- Ocean and coastal monitoring;
- Integrated ocean observations;
- Improved data management, synthesis and integration.

8. A national steering committee for marine research and innovation should be appointed with responsibility for further development and implementation of the National Framework for Marine Science and Innovation, and for providing a critical high level interface with industry and policy makers.

9. It is suggested that the Australian government, jointly with States and Territories, consider mechanisms for providing a national, comprehensive, and inclusive policy "umbrella", or principles to provide high-level focus and direction for its coasts and ocean domain.



▸A.6 Integrated Marine Observing System, IMOS

National Collaborative Research Infrastructure Strategy (NCRIS), 2007

The Integrated Marine Observing System was launched in 2006/07. It brings together all the major marine observing systems around Australia as an observational resource for marine science with the following organisational structure.

IMOS underwent a mid-term review in 2008. The review consisted of two parts, a re-focus on priorities for the final two years of IMOS and approaches to developing IMOS-2 after July 2011.

▸A.7 Blueprint for Australian Terrestrial Carbon Cycle Research 2005–2010

Australian Greenhouse Office, 2005

This document was prepared by Will Steffen for the Australian Greenhouse Office following a carbon cycle workshop in February 2005. It adopted a thematic approach with the research themes being:

a) Patterns of sources and sinks of carbon across Australia.

> This priority was designed to complement the national green house gas emissions reporting system (the

National Carbon Accounting System, NCAS). It utilises inverse modelling of fluxes across the nation using time and space variation in atmospheric CO_2 concentration over the continent, the NCAS model operating in research mode (NCAS-R), diverse measurements of carbon cycle related processes using eddy covariance measurements at fixed towers, soil carbon measurements, forest biomass inventories and such like, and modelled estimates of sources and sinks across the nation.

b) Vulnerability of terrestrial carbon sinks into the future

This priority is concerned with natural feedbacks within the atmosphere/climate/vegetation system that may accentuate or diminish terrestrial sinks such as the CO_2 fertilising effect, temperature sensitivity of heterotrophic respiration, temperature and rainfall response of biological productivity, influence of climate change on natural disturbances like wildfire, pests, and diseases, and land management responses.

c) Interactive coupling of the carbon cycle to the physical climate system.

This priority was concerned with taking early steps to incorporate some features of the terrestrial land surface into a global climate model, thereby taking a step towards an "Earth system" model, where "Earth system" is considered in a narrower sense than it is in the present document.

d) Cross-cutting issues

The interaction of the terrestrial carbon cycle with the hydrologic cycle and other biogeochemical cycles was supported. A plea was also made for an expanded program of systematic observations of the terrestrial carbon cycle in Australia.

▶A.8 Vegetation dynamics and global climate change 2010–2020

Australian Academy of Science, 2010

This is a decadal strategic plan to follow on from and expand the scope of the Blueprint for Terrestrial Carbon Cycle Research. It was developed from an open planning workshop in August 2007. It made two over-arching recommendations to focus the decade's research on Australian terrestrial vegetation in the Earth system. The two over-arching recommendations follow. The full report is available at www.science.org.au/natcoms/nc-ess/documents/nc-ess-14-15august07.pdf

Recommendation 1

A coordinated program of ecosystem research be instigated to develop a capacity in Australia to construct high resolution vegetation models for purposes of policy relevant climate change impacts analysis, and for coupling the vegetated land to physical climate change models.

Recommendation 2

A coordinated hierarchical network of several hundred long-term (permanent) eco-hydrological observation sites be established as an Integrated Terrestrial Observing System to cover the spectrum of Australian climates and ecosystems including the range of management intensities.

Another 22 recommendations added content for Recommendation 1, using in part the infrastructure provided under Recommendation 2, by addressing gaps of knowledge and understanding that must be filled, especially for Australian ecosystems. A comprehensive representative network of time series data and observation sites will provide foci for many component projects, thereby creating synergism between them. In approximate sequence from shorter term processes to longer term processes, these recommendations embrace the following subject areas.

- The acclimatisation of photosynthesis, stomatal conductance, and plant respiration to increased atmospheric CO_2 concentration and temperature.
- The regulation of allocation of plant dry matter to different parts of the ecosystem above and below ground, and the influence of atmospheric CO_2 concentration and temperature on such allocation.
- The regulation of organic matter decomposition (heterotrophic respiration) and associated mineral transformations and fluxes, especially in relation to temperature over different time scales.
- Standardised methodology for determination of net primary production (NPP) at long-term ecological sites.
- The regulation of greenhouse gas emission to, and removal from, the atmosphere by ecosystems including the soil.
- Long-term impact of elevated CO_2 concentration, warming, and changed rainfall on native vegetation in the field.
- The decadal-to-century timescale interactions between the carbon cycle and mineral cycles, especially the nitrogen cycle, for predicting the impact on atmospheric and climatic change on carbon storage by ecosystems.
- Interaction of mammalian and insect herbivory with atmospheric and climatic changes in dynamics of vegetation.
- Understanding and modelling of the implications for vegetation dynamics of changed wild fire regimes in relation to atmospheric CO_2 increase and climate change.
- Understanding of the role of black carbon in soil carbon and nutrient cycles and vegetation dynamics.
- Further development of the plant functional type concept and determination of parameter values for plant functional types for application as a simplifying strategy in digital vegetation models.

- Implications of anticipated continuous climate change on strategies for conservation of Australian biodiversity.

By evaluating the significance of these recommendations to the following 11 areas of application of the research:

1. Incorporating land surface behaviour into global climate models.
2. Understanding and predicting impacts of climate change on natural ecosystems, agriculture, and forestry.
3. Conservation of biodiversity loss under a changing climate.
4. Managing national water resources under climate change.
5. Quantifying and tracking purposeful sources and sinks for GHGs now and in the future to assist with the national carbon accounting and other GHG emission inventories.
6. Understanding the potential future of the natural terrestrial CO_2 and other GHG sinks.
7. Documenting and predicting changes in vegetation distribution.
8. Understanding climatic risks to ecosystem services that lie outside the monetary system.
9. Designing climate change adaptation strategies for agriculture and forestry production and for biological conservation.
10. Development of biosequestration strategies.
11. Development of alternative sustainable agro-forestry and bioenergy production systems.

It was evaluated that the top-priority supporting recommendations for immediate action were:

Recommendation 22

Research effort into understanding the roles of various factors determining the distribution and functioning of vegetation types in Australia should be enhanced preparatory to attempting to incorporate more realistic vegetation distribution as a function of climate into DGVMs and other ecosystem models.

Recommendation 10

A methodology, applicable everywhere, for measuring annual NPP and associated ecosystem C-transformations should be agreed and deployed routinely at the proposed continental representative network of long term ecological sites. The sites should be instrumented with automatic weather stations to determine key climatic variables continuously (rainfall, air temperature, humidity, solar radiation, wind, soil temperature and soil moisture at specified depths). The sites selected should include those where flux towers, remote sensing and in situ sampling are already located in order to provide complementary data-benefits to each type of measurement.

Recommendation 9

The existing literature on decomposition of litter and heterotrophic respiration should be analysed in relation to temperature as a function of time of exposure to warming, and the results used to design long term field experiments for establishing the relationship on timescales pertinent to global warming.

▶A.9 Terrestrial Ecosystem Research Network TERN

National Collaborative Research Infrastructure Strategy (NCRIS)

The following investment plan proposal is under consideration by NCRIS (November 2008).

The *Terrestrial Ecosystem Research Network* Investment Plan (October 1, 2008) has four broad objectives:

- The institutional framework to promote the scientific interactions and planning necessary to establish an appropriately stratified and representative national terrestrial ecosystem site and observational network to meet terrestrial ecosystem and natural resource management research needs in the longer term.
- Commence implementation of some coordinated national observational networks to facilitate cooperation and operational experience; learning by doing.
- Facilitate improved access, by electronic means, to quality-assured observational data to the terrestrial ecosystem and natural resource management community.
- Involve the terrestrial ecosystem research community in defining future needs and to strengthen the technical and operational capability of the terrestrial ecosystem community and hence sustain the terrestrial observing paradigm into the longer term.

The institutional framework proposed is based on a science reference framework shown in the diagram below (Fig 1 from the Investment Plan) together with the associated six science questions below that diagram. The investment in the 4 years of the TERN funding is intended to be the starting point for subsequent expanded national commitment to a long-term, integrated Australian terrestrial ecosystem monitoring system.

The following initial priorities for TERN investment to 2011 are proposed in the plan:

1 A TERN Office incorporating an Australian Centre of Ecological Analysis and Synthesis.

2 A data management facility.

3 A federated national terrestrial remote sensing data, calibration, and information service.

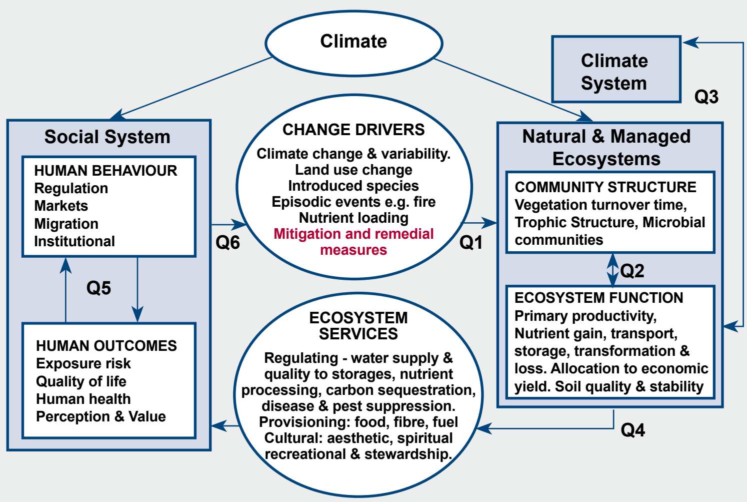
There will be an investment in the *commencement* of two national scale observation activities (Level 1) and two Queensland super-sites (Level 2). These investments meet immediate science objectives, promote the cooperative behaviours, and road test the practical issues necessary to implement nationally coordinated observing networks. The super-site development is made possible by Queensland Government co-investment.

4 A set of permanent science reference sites in the Australian Rangelands.

5 A national network of flux sites to provide nationally consistent observations to serve the land-surface and ecosystem modelling communities.

6 Two super-sties in Queensland, namely the SE Queensland Peri-Urban Site and the Far North Queensland Rainforest Biodiversity Site.

TERN – Science Reference Framework



Q1 How does natural and human induced change, both short and long-terms interact to alter ecosystem structure and function including remedial and mitigation measures?

Q2 How does biotic structure vary and be both a cause and consequence of ecological fluxes and energy?

Q3 What is the outcome for the net terrestrial CO_2 sink of the competing effects of CO_2 fertilisation, declining water availability, global warming, changing nutrient dynamics anddisturbance by impacts?

Q4 How do altered community structure and ecosystem dynamics affect ecosystem services?

Q5 How can decision support systems modelling complex processes lead to mitigation and/or remedial measure-based on human behaviour?

Q6 Which human actions influence the frequency, magnitude or form disturbance regimes across ecosystems and conversely which human actions are required to mitigate or remediate degradation?

(Adapted from The Decadal Plan for LTER: Integrative Science for Society and the Environment; A Plan for Research, Education and Cyberinfrastructure in the US Long Term Ecological Research Network. www.lternet.edu/decadalplan)

▸A.10 National Biodiversity and Climate Change Action Plan 2004–2007

Natural Resources Management Ministerial Council, 2004

The main intent of this 3-year biodiversity action plan was to:

- identify priority areas for research and monitoring, and improve understanding of potential climate change impacts on biodiversity to a point where specific strategies can be developed.
- use existing knowledge about the impacts of climate change and draw from ecological principles to review and amend current biodiversity conservation policies and strategies.
- improve communication about the impacts of climate change on biodiversity between researchers, resources managers, and decision makers.
- raise community awareness of the potentially significant and specific impacts of climate change on biodiversity.

Key strategies proposed included:

- promoting ecological connectivity to aid migration and dispersal of species,
- protecting refuges, and
- creating specific management zones around important habitats.

Research into proposed actions was evaluated under 7 objectives:

Objective 1. To improve our understanding of the impacts of climate change on biodiversity.

Objective 2. To increase awareness of climate change impacts and our capacity to respond.

Objective 3. To minimise the impacts of climate change on inland aquatic and semi-aquatic ecosystems.

Objective 4. To minimise the impacts of climate change on marine, estuarine, and coastal ecosystems.

Objective 5. To minimise the impacts of climate change on native terrestrial species, communities, and ecosystems.

Objective 6. To minimise the impact of invasive organisms on biodiversity in future climates.

Objective 7. To factor the impacts of climate change on biodiversity into natural resource management and land-use planning.

▸A.11 An Australian Strategic Plan for Earth Observations from Space

Australian Academy of Science, 2009

This is a comprehensive plan for Australia's role in Earth observation from space for all applications of which an important one is for environmental science applications. The following essential messages are from the Executive summary of the document.

www.science.org.au/reports/documents/EOS-executive-summary.pdf

The essential messages

- Earth observations from space (EOS) are the single most important and richest source of environmental information for Australia. They enable a wide range of essential services to be given to the community, with multi-billion dollar annual benefits to the nation as a whole.
- Australia's needs for EOS data are increasing rapidly. Extensive EOS information is essential for addressing urgent national challenges in climate change, water, natural disaster mitigation, transport, energy, agriculture, forestry, ecosystems, coasts, oceans, and national security.
- The satellite-provider nations have many new missions planned for the next 10 to 15 years, providing powerful new EOS capabilities for addressing Australia's needs. We have, however, become fully dependent on foreign-owned satellites and we can no longer significantly influence their capabilities in support of our unique requirements. Time is running out for our historical free-rider status on the international EOS system.
- Australia must immediately embark on a national strategy to secure long-term access to the international EOS system and to better focus its capabilities on Australian-specific needs for EOS information. We must also greatly strengthen our national EOS operational, data acquisition, data processing, research, education, and industry infrastructure to take full and timely advantage of existing EOS satellites and the many new opportunities that will become available over the next decade.
- The opportunity costs of living with the national EOS status quo are mounting rapidly. The strategy set down in this plan will ensure that Australia realises the additional multi-billion dollar economic, social, and environmental benefits that are potentially available from full participation in the global EOS enterprise, and which are likely to be widespread across the Australian community.

Appendix B

The international agenda of Earth system science

Contents

There are many international projects that contribute to the concerns of Earth system science. The objectives of UNESCO's Man and the Biosphere project (MAB), and of ICSU's International Geosphere Biosphere Program (IGBP) and World Climate Research Program (WCRP), have all been developed to embrace a notion of Earth system science. We here describe two composite programs that are particularly relevant. One is a program of largely applied research – the Earth System Science Partnership (ESSP). The second is a program of global data meta-synthesis – the Global Earth Observation System of Systems (GEOSS).

▶B.1 The Earth Systems Science Partnership (ESSP)

In 2001 an Earth System Science Partnership was formed as a joint project of the International Geosphere Biosphere Program (IGBP), the World Climate Research Program (WCRP), the international biodiversity program called DIVERSITAS, and the International Program for Human Dimensions of Global Change (IHDP). Preparatory to the formation of the Earth Systems Science Partnership, the following Amsterdam declaration was published:

The Amsterdam Declaration on Global Change

"The scientific communities of four international global change research programmes – the International Geosphere–Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP) and the international biodiversity programme DIVERSITAS – recognise that, in addition to the threat of significant climate change, there is growing concern over the ever-increasing human modification of other aspects of the global environment and the consequent implications for human well-being. Basic goods and services supplied by the planetary life support system, such as food, water, clean air and an environment conducive to human health, are being affected increasingly by global change.

"Research carried out over the past decade under the auspices of the four programmes to address these concerns has shown that:

- The Earth System behaves as a single, self-regulating system comprised of physical, chemical, biological and human components. The interactions and feedbacks between the component parts are complex and exhibit multi-scale temporal and spatial variability. The understanding of the natural dynamics of the Earth System has advanced greatly in recent years and provides a sound basis for evaluating the effects and consequences of human-driven change.
- Human activities are significantly influencing Earth's environment in many ways in addition to greenhouse gas emissions and climate change. Anthropogenic changes to Earth's land surface, oceans, coasts and atmosphere and to biological diversity, the water cycle and biogeochemical cycles are clearly identifiable beyond natural variability. They are equal to some of the great forces of nature in their extent and impact. Many are accelerating. Global change is real and is happening *now*.
- Global change cannot be understood in terms of a simple cause–effect paradigm. Human-driven changes cause multiple effects that cascade through the Earth System in complex ways. These effects interact with each other and with local- and regional-scale changes in multidimensional patterns that are difficult to understand and even more difficult to predict. Surprises abound.

- Earth System dynamics are characterised by critical thresholds and abrupt changes. Human activities could inadvertently trigger such changes with severe consequences for Earth's environment and inhabitants. The Earth System has operated in different states over the last half million years, with abrupt transitions (a decade or less) sometimes occurring between them. Human activities have the potential to switch the Earth System to alternative modes of operation that may prove irreversible and less hospitable to humans and other life. The probability of a human-driven abrupt change in Earth's environment has yet to be quantified but is not negligible.
- In terms of some key environmental parameters, the Earth System has moved well outside the range of the natural variability exhibited over the last half million years at least. The nature of changes now occurring simultaneously in the Earth System, their magnitudes and rates of change are unprecedented. The Earth is currently operating in a no-analogue state.

"On this basis the international global change programmes urge governments, public and private institutions and people of the world to agree that:

- An ethical framework for global stewardship and strategies for Earth System management are urgently needed. The accelerating human transformation of the Earth's environment is not sustainable. Therefore, the business-as-usual way of dealing with the Earth System is not an option. It has to be replaced – as soon as possible – by deliberate strategies of good management that sustain the Earth's environment while meeting social and economic development objectives.
- A new system of global environmental science is required. This is beginning to evolve from complementary approaches of the international global change research programmes and needs strengthening and further development. It will draw strongly on the existing and expanding disciplinary base of global change science; integrate across disciplines, environment and development issues and the natural and social sciences; collaborate across national boundaries on the basis of shared and secure infrastructure; intensify efforts to enable the full involvement of developing country scientists; and employ the complementary strengths of nations and regions to build an efficient international system of global environmental science.

"The global change programmes are committed to working closely with other sectors of society and across all nations and cultures to meet the challenge of a changing Earth. New partnerships are forming among university, industrial and governmental research institutions. Dialogues are increasing between the scientific community and policymakers at a number of levels. Action is required to formalise, consolidate and strengthen the initiatives being developed. The common goal must be to develop the essential knowledge base needed to respond effectively and quickly to the great challenge of global change."

Berrien Moore III (Chair, IGBP); Arild Underdal (Chair, IHDP); Peter Lemke (Chair, WCRP); Michel Loreau (Chair, DIVERSITAS). "Challenges of a Changing Earth", Global Change Open Science Conference, Amsterdam, The Netherlands, 13 July 2001.

The ESSP was initiated with four independent projects. These are the Global Carbon Project, the Global Water System Project, the Global Environmental Change and Food Systems Project, and the Global Environmental Change and Human Health Project. Two of these four major projects (GCP and GEC&HH) involve top leadership by Australians working in Australia.

These projects are described below.

The Global Carbon Project (GCP)

The GCP was established in 2001 as a Joint Project of the Earth System Science Partnership.

The science framework of GCP is organised around three themes:

- Patterns and Variability: What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?
- Processes and Interactions: What are the control and feedback mechanisms – both anthropogenic and non-anthropogenic – that determine the dynamics of the carbon cycle?
- Carbon Management: What are the dynamics of the carbon–climate–human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?

The Global Water System Project (GWSP)

The Joint Project GWSP of the Earth System Science Partnership has cast its work around several fast-track activities that address the central research question:

How are humans changing the global water cycle, the associated biogeochemical cycles, and the biological components of the global water system and what are the social feedbacks arising from these changes?

The GWSP seeks to expand its portfolio of activities and to develop partnerships with colleagues around the world by endorsing pioneering projects concerned with critical questions about the global water system.

The Global Environmental Change and Food Systems Project (GECAFS)

The Joint Project GECAFS is a comprehensive programme of interdisciplinary research focused on understanding the links between food security and global environmental change. GECAFS will improve understanding of the relationship between food systems and the Earth System to deliver science-based tools for analysing the socioeconomic and environmental consequences of adaptation strategies. These will be designed to help policy-makers and managers evaluate the best options for reducing vulnerability of food systems to global environmental change while minimising further environmental degradation.

The GECAFS goal is:

To determine strategies to cope with the impacts of global environmental change on food systems and to assess the environmental and socioeconomic consequences of adaptive responses aimed at improving food security.

This goal will be achieved by improved understanding of the interactions between food systems and the Earth System's key socioeconomic and biogeophysical components. The research agenda will be specifically targeted towards delivering the new science necessary to underpin policy formulation for improving food security in the face of global environmetal change.

The Global Environmental Change and Human Health Project (GEC&HH)

The Project's main research goals are to:

- Identify and quantify health risks posed by GEC, now and in the reasonably foreseeable (scenario) future.
- Develop methods of modelling/ understanding tradeoffs between economic development, environmental change, and human health.
- Take account of the roles of culture, social institutions, and technology choices in modulating health risks, affecting vulnerability, and influencing policy response.
- Describe spatial (geographic, inter-population) and temporal differences in health risks, to better understand vulnerabilities and priorities for interventions.
- Develop adaptation strategies for reducing health risks, assess their cost-effectiveness, and communicate results (especially to decision-makers).

These objectives will be achieved by articulating the implementation strategy for this Joint Project around the following integrated themes that examine the relationships between Global Environmental Change and Human Health:

1 Atmospheric composition changes and their health impacts
   - i) Climate change and health
   - ii) Stratospheric ozone depletion and health

2 Land use/land cover changes and human health issues

3 Infectious disease and Global Environmental Changes
   - i) Land use/land cover change and vector/rodent-borne infectious diseases
   - ii) Changes in human–animal relationships and emergence/spread of zoonoses
   - iii) Food-borne, water-borne, and other infectious diseases

4 Food-producing systems and health

5 Urbanisation and health

6 Vulnerability and adaptability: formal assessment of the situational and constitutional susceptibility of the at-risk community or population, and of the social and institutional resources available for reducing that susceptibility and coping with adverse health impacts.

▶B.2 Global Earth Observation System of Systems (GEOSS) themes

The Group on Earth Observations (GEO), a voluntary partnership of over 70 governments and over 50 international organisations, established GEOSS in 2005. GEOSS has a 10-year implementation plan (2005–2015). The purpose of GEOSS is to achieve comprehensive, coordinated and sustained observations of the Earth system. The objective is to improve monitoring of the state of the Earth, increase understanding of Earth processes, and enhance prediction of the behavior of the Earth system. GEOSS will meet the need for timely, high-quality, long-term global information as a basis for sound decision making, and will enhance delivery of benefits to society in the following initial areas:

- Reducing loss of life and property from natural and human-induced disasters;
- Understanding environmental factors affecting human health and well-being;
- Improving management of energy resources;
- Understanding, assessing, predicting, mitigating, and adapting to climate variability and change;
- Improving water resource management through better understanding of the water cycle;
- Improving weather information, forecasting, and warning;
- Improving the management and protection of terrestrial, coastal, and marine ecosystems;
- Supporting sustainable agriculture and combating desertification;
- Understanding, monitoring, and conserving biodiversity.

GEOSS is a step toward addressing the challenges articulated by the United Nations Millennium Declaration and the 2002 World Summit on Sustainable Development, including the achievement of the Millennium Development Goals. GEOSS will also further the implementation of international environmental treaty obligations.

▶B.3 History of the human–environment relationship (IHOPE)

Understanding the history of how humans have interacted with the rest of nature can help clarify the options for managing our increasingly interconnected global system. Simple, deterministic relationships between environmental stress and social change are inadequate. Extreme drought, for instance, has triggered both social collapse and ingenious management of water through irrigation. Human responses to change in turn feed into climate and ecological systems, producing a complex web of multidirectional connections in time and space. Integrated records of the co-evolving human–environment system over multiple temporal and spatial scales (from millennia to decades and from local to global) are needed to provide a basis for deeper understanding of the present and a better basis for forecasting the future. IHOPE's key overarching question can be stated as: What are the complex and interacting mechanisms and processes resulting in the emergence, sustainability, decline or collapse of social-ecological systems?

The IHOPE project has three long-term goals:

1. Map the integrated record of biophysical and human system change on the Earth over the last several thousand millennia, with higher temporal and spatial resolution in the last 1000 and the last 100 years.
2. Understand the socio-ecological dynamics of human history by testing human–environment system models against the integrated history.
3. Based on these historical insights, develop credible options for the future of humanity.

To achieve the ambitious goals of IHOPE, multiple scientific challenges must be met. This includes linking disparate disciplinary approaches, cultures, and models across the sciences and humanities, development of an appropriate information infrastructure to link such disparate information, and developing a common understanding and approach.

B.4 IHDP Earth System Governance Project

This major project of the International Human Dimensions Program developed a science plan. The Executive summary is as follows.

Executive Summary

Humans now influence all biological and physical systems of the planet. Almost no species, no land area, no part of the oceans has remained unaffected by the expansion of the human species. The four main global change research programmes, affiliated in the Earth System Science Partnership, see evidence today that the entire earth system now operates "well outside the normal state exhibited over the past 500,000 years", and that "human activity is generating change that extends well beyond natural variability – in some cases, alarmingly so – and at rates that continue to accelerate". Given this situation, the Earth System Science Partnership has declared an "urgent need" to develop "strategies for Earth System management". Yet what such strategies might be, how they could be developed, and how effective, efficient and equitable such strategies would be, remain unspecified. It is apparent that the institutions, organizations, and mechanisms by which humans currently govern their relationship with the natural environment and global biochemical systems are not only insufficient – they are also poorly understood.

This is the rationale for the Earth System Governance Project, a new long-term research programme developed under the auspices of the International Human Dimensions Programme on Global Environmental Change. This Science Plan elaborates upon the concept of Earth system governance and on the central questions, methods, and processes of a global research effort in this field.

Earth system governance is defined in this project as the interrelated and increasingly integrated system of formal and informal rules, rule-making systems, and actor networks at all levels of human society (from local to global) that are set up to steer societies towards preventing, mitigating, and adapting to global and local environmental change and, in particular, Earth system transformation, within the normative context of sustainable development. The notion of governance refers here to forms of steering that are less hierarchical than traditional governmental policy-making (even though most modern governance arrangements will also include some degree of hierarchy), but rather decentralised, open to self-organisation, and inclusive of non-state actors that range from industry and non-governmental organisations to scientists, indigenous communities, city governments, and international organisations.

Conceptual Framework. Based on this general notion, the Earth System Governance Project advances a science plan that is organised, first, around five analytical problems:

1. The first analytical problem – the *architecture* of Earth system governance – includes questions relating to the emergence, design, and effectiveness of governance systems as well as the overall integration of global, regional, national, and local governance. Core questions include: How is performance of environmental institutions affected by their embedding in larger architectures? What are the environmental consequences of non-environmental governance systems? What is the relative performance of different types of multilevel governance architectures? How can we explain instances of "non-governance"? What are overarching and crosscutting norms of Earth system governance?

2. Second, understanding effective Earth system governance requires understanding the *agents* that drive Earth system governance and that need to be involved. The research gap here refers especially to the influence, roles, and responsibilities of actors (apart from national governments) such as business and non-profit organisations, the ways in which authority is granted to these agents, and how it is exercised. Core questions advanced in this Science Plan are: What is agency? Who are the agents of Earth system governance (especially beyond the nation state)? How do different agents exercise agency in Earth system governance, and how can we evaluate their relevance?

3. Third, Earth system governance must respond to the inherent uncertainties in human and natural systems. It must combine stability to ensure long-term governance solutions with flexibility to react quickly to new findings and developments. In other words, we must understand and further develop the *adaptiveness* of Earth system governance. But what are the politics of adaptiveness? Which governance processes foster it? What attributes of governance systems enhance capacities to adapt? How, when, and why does adaptiveness influence Earth system governance?

4. Fourth, the more regulatory competence and authority is conferred upon larger institutions and systems of

governance – especially at the global level – the more we will be confronted with questions of how to ensure the *accountability* and *legitimacy* of governance. Simply put, we are faced with the need to understand the democratic quality of Earth system governance. What are the sources of accountability and legitimacy in Earth system governance? What are the effects of different forms and degrees of accountability and legitimacy for the performance of governance systems? How can mechanisms of transparency ensure accountable and legitimate Earth system governance? What institutional designs can produce the accountability and legitimacy of Earth system governance in a way that guarantees balances of interests and perspectives?

5 Fifth, Earth system governance is, as is any political activity, about the distribution of material and immaterial values. It is, in essence, a conflict about the access to goods and about their *allocation* – it is about justice, fairness, and equity. The novel character of Earth system transformation and of the new governance solutions that are being developed, puts questions of allocation and access, debated for millennia, in a new light. It might require new answers to old questions. But how can we reach interdisciplinary conceptualisations and definitions of allocation and access? What (overarching) principles underlie allocation and access? How can allocation be reconciled with governance effectiveness?

Crosscutting Themes. In addition, the Earth System Governance Project emphasises four crosscutting research themes that are not only crucial for the study of each analytical problem but also for the integrated understanding of Earth system governance: these four themes are the role of *power*; the role of *knowledge*; the role of *norms*; and the role of *scale*.

Flagship Activities as Case Studies. Finally, the Earth System Governance Project advances the integrated, focused analysis of case study domains in which researchers combine analysis of the overall governance architecture, the role of different agents in this governance architecture, the overall adaptiveness of the governance system, mechanisms of accountability, and modes of allocation. Four flagship activities of the Earth System Governance Project have been identified: research on the *water system*, on *food systems*, on the climate *system*, and on the *global economic system*.

Policy Relevance. The Earth System Governance Project, while being essentially a scientific effort, is also designed to assist policy responses to the pressing problems of Earth system transformation. All analytical problems studied in the project have profound policy implications. For example, the problem of the architecture of Earth system governance is a key concern of current negotiations and political processes that are often faced with "treaty congestion" and complex interlinkages between different institutions, for instance between multilateral environmental agreements and the World Trade Organization. "Fragmented" governance architectures are also an increasing problem for decision-makers, particularly in climate policy. A related concern is the reform of the United Nations – for example, whether there should be a United Nations Environment Organization. At national and local levels, architecture is a key concern for decision-makers dealing with policy integration, the comparative effectiveness of policy instruments, and the integration of decision-making from international, national, and local levels. Research on agency within the project will generate novel ideas on the integration of civil society actors in Earth system governance, and on the advantages and disadvantages of private and public–private governance arrangements. Research on governance of adaptation and the adaptiveness of governance arrangements will inform policy-makers who have to deal with adapting politics and policies to a changing world. The accountability and legitimacy of decision-making, from local to global levels, is equally a key problem for public policy. Finally, the research on allocation and access will help to improve governance outcomes and advance philosophical and ethical discourses on an equitable approach to Earth system governance.

Process. The drafting of this Science Plan of the Earth System Governance Project has been mandated in March 2007 by the Scientific Committee of the International Human Dimensions Programme on Global Environmental Change (IHDP), the overarching social science programme in the field. The project builds on the results of an earlier long-term research programme, the IHDP core project Institutional Dimensions of Global Environmental Change (IDGEC). The Science Plan was written by an international, interdisciplinary scientific planning committee, which from 2004 drew on a consultative process. Several working drafts of this Science Plan have been presented and discussed at a series of international events and conferences, and numerous colleagues in the field, as well as practitioners, have offered useful suggestions, advice, and critique.

[Frank Biermann, Michele M. Betsill, Joyeeta Gupta, Norichika Kanie, Louis Lebel, Diana Liverman, Heike Schroeder, and Bernd Siebenhüner (2009). *Earth System Governance: People, Places, and the Planet.* Science and Implementation Plan of the Earth System Governance Project. Earth System Governance project, Bonn, 144 pp.]

▸B.5 ICSU/ISSC Earth System Science for Global Sustainability – The Grand Challenges

www.icsu-visioning.org

The International Council for Science (ICSU) working with the International Social Science Council (ISSC) has gone through a process to identify a way to conduct an integrated program of global change research. It started the process by seeking via the internet on-line opinion on the big Earth System issues. From that a set of grand challenges for sustainability research was developed as follows.

The Grand Challenges

Consistent with the use of the concept of grand challenges in other areas of science, we consider the grand challenges in Earth system science for global sustainability to be a call for scientific innovation or understanding that would remove critical barriers to deciding how to achieve sustainable development. We list five grand challenges and within each, we list several top-level research priorities that must be addressed during the next decade to make significant progress in resolving the problem posed by the grand challenge. The list of research priorities is neither exhaustive nor necessarily sufficient. Nonetheless, it is our judgment that these questions must be addressed to achieve the most rapid progress. In virtually all cases, a deep base of research and knowledge already exists in the areas identified by these research priorities and, building on that base, it is thus plausible that the research area can be substantially advanced in less than a decade. However, it is by no means inevitable that all the questions can be answered. These are, by definition, big and difficult problems, and will require a focused, multidisciplinary, and integrated research commitment to have a reasonable prospect of success.

The resulting challenges cover a diversity of topics but are united as elements of a systems approach that examines how the coupled social-environmental system is changing (including the dynamic responses of people and the environment) and what actions and interventions may alter the environmental and social outcomes (see Figure 1). The grand challenges adopt a systems approach from the perspective of what is being studied: the full social-environmental global system rather than independent components of that system. They also adopt a systems approach from the perspective of how research can inform actions to achieve global sustainability: none of the challenges can be fully addressed without progress in addressing the other challenges.

Consequently, the five grand challenges are an indivisible package, and the topics are not prioritized either across or within the challenges. *Progress on every one of the challenges and research questions is urgently needed.* The research community has unique capacities to contribute to the solution of these challenges, but all of them will require working with partners outside of this research community as it currently exists.

Challenge 1: Forecasting

Improve the usefulness of forecasts of future environmental conditions and their consequences for people.

Priority Research Questions

1.1 What significant environmental changes are likely to result from human actions? How would those changes affect human well-being, and how are people likely to respond?

1.2 What threats do global environmental changes pose for vulnerable communities and groups and what responses could be most effective in reducing harm to those communities?

We consider a 'useful' forecast to be one that is responsive to the needs of societies and decision-makers for information at relevant spatial and temporal scales and is timely, accurate, and reliable. Our limited ability to anticipate the outcomes resulting from the interaction of complex and diverse human societies with equally complex natural processes is a significant barrier to timely and effective decision-making and action. Although we may never be able to accurately forecast the future of coupled social-environmental systems beyond a time horizon of several decades, there is tremendous potential to improve our ability to use scenarios and simulations to anticipate the impacts of a given set of human actions or conditions (e.g. population size, levels of consumption, greenhouse gas emissions, deforestation, increased agricultural productivity) on global and regional climate and on biological, geochemical, and hydrological systems on seasonal to decadal time scales. Building on this work, significant advances are now also needed in our ability to assess the potential impact of those environmental changes on human well-being (e.g. impacts on economies, health, food security, energy security, etc.) and the potential human response to such changes. Such forecasts and assessments should be tailored to respond to the questions and needs of the people potentially affected, and the uncertainty should be quantified and clearly communicated.

Answering the research questions posed here will require a major new scientific endeavour to build the capacity to predict changes to the Earth system. It includes a pressing need to develop a new suite of Earth system models with the ability of predicting changes to the Earth system from anthropogenic influence at global, regional and, where possible, local scales. This will necessitate major scientific advancements in integrated analyses of the dynamics of interlinked biophysical systems on Earth and coupling these with the human dimensions of global environmental change, both in terms of drivers and impacts. This in turn will have to build on continued progress in disciplinary Earth system research, and major improvements in and intensification of Earth observation systems.

Science cannot, as yet, provide adequate predictions of the Earth system response to pressures from the coupled socio-environmental complex. This is a major dilemma for humanity as a whole. We know that humanity is pushing systems on Earth towards risks that may cause abrupt, and potentially irreversible and disastrous changes. Despite major advancements in Earth system science over the past decade, the uncertainties and risks of anthropogenic change remain too high for comfort.2 Human development continues along a dimly lit path of uncertainties and risks; in the absence of clarifying headlights policy makers and society at large inappropriately assume that the stability of the planet will prevail. Scientific evidence to date strongly suggests that it is too risky to continue along this development pathway. We urgently need improved capabilities for analyzing and understanding the global environmental change risks facing humanity. We assess that major improvements to an integrated model to predict the Earth

Improve the usefulness of forecasts of future environmental conditions and their consequences for people system response to anthropogenic pressures is within reach, but will require a major international undertaking over the coming decade, as part of the grand challenge endeavour.

Significant improvement is needed in our ability to provide forecasts that address the full range of plausible outcomes within a probabilistic framework, that incorporate the dynamic response of both the natural and social system, and that provide results at appropriate spatial and temporal scales to assess impacts on economies, ecosystem services and human well-being. Progress in this area of research will require advances in understanding and modelling the fundamentals of physical phenomena, advances in modelling capability (including development of the ultra-high performance computing infrastructure), the incorporation of information from paleo-climate change as well as historical information on social and behavioural responses and a more interdisciplinary framework of analysis. By meeting this challenge, models and analyses of global and regional environmental change will be able to provide direct support to governance and management at national and regional scales, and over the typical time frames of political and management decisions.

The human consequences of global environmental change will vary across regions and within societies because of geographic differences in impacts and because of differences in the vulnerability of groups of people. An important focus of efforts to improve forecasting capability must be to better understand which groups of people are most vulnerable to global change, what threats global change poses for those communities, and the potential consequences of different adaptation and mitigation actions. These communities will experience the greatest impacts associated with global change; consequently, there is an urgent need for the scientific community to provide decision-makers and society with information that can guide action to lessen those impacts.

Examples of key questions that need to be answered include: How will regional climate change over decadal time scales? What will be the environmental and health impact of changes to other biogeochemical cycles (e.g. nitrogen, phosphorus) or to increased loadings of toxic pollutants? How will the social, economic and health impacts of global environmental change vary across regions and within societies? What adaptation strategies are needed to reduce vulnerability to global environmental change? When do individual human actions aggregate to cause consequences for larger regions or the Earth system? How are changes in ecosystems and biodiversity going to affect ecosystem services and human well-being? What trade-offs occur among services and human well-being and are there strategies to minimize the adverse consequences of such trade-offs? What kinds and levels of biodiversity are needed to buffer the impacts of environmental change on ecosystem services?

Challenge 2: Observing

Develop, enhance and integrate the observation systems needed to manage global and regional environmental change.

Priority Research Questions

2.1 What do we need to observe in coupled social-environmental systems, and at what scales, in order to respond to, adapt to, and influence global change?

2.2 What are the characteristics of an adequate system for observing and communicating this information?

Major investments are being made to build more effective global and regional monitoring systems and to ensure their international coordination (e.g. through arrangements like the Global Earth Observation System of Systems, GEOSS). But these systems, which provide a firm foundation, still fall well short of what is needed. The current supply of information needed to manage the socio-environmental system, especially at a global scale, as well as the system for delivering that information to decision-makers, is inadequate for the task. Further advances in theories, models, scenarios, projections, simulations, or compelling narratives used to understand the coupled social-environmental system and to forecast changes are constrained by limited availability of data needed to set parameters and validate predictions. Moreover, the paucity of empirical data on changes in social-environmental systems undermines the ability of decision-makers and the public to establish appropriate responses to emerging threats and to address the needs of vulnerable groups of people.

To meet any of the grand challenges, a robust data and information system is needed that can combine data and knowledge gathered over centuries with new observations and modelling results to provide a range of integrated, interdisciplinary datasets, indicators, visualizations, scenarios, and other information products. Ensuring wide access to both past and future data, especially with regard to societal dimensions, is a key challenge that cannot be taken for granted.

The observation, data preservation and information systems required need to: encompass both natural and social features; be of high enough resolution to detect systematic change; assess vulnerability and resilience; include multiple sources of information (quantitative, qualitative and narrative data and historical records); provide information about both direct drivers of change and indirect drivers; involve multiple stakeholders in the research process; support effective decisions at global to local scales; be formally part of adaptive decision making processes; provide full and open access to data; and be cost effective. They would include critical data needs such as comprehensive time-series information on changes in: (1) land cover and land use, biotic systems, air quality, climate and the oceans; (2) spatial patterns and changes in freshwater quantity and quality, for both ground- and surface-water; (3) stocks, flows and economic values of ecosystem services; (4) trends in perceived and real components of human well-being (particularly those not traditionally measured, such as access to natural products that are not marketed); (5) socio-economic indicators, including population distribution, economic activities and mobility; (6) patterns of human responses to these developments including changes in policies, technologies, behaviours and practices; and (7) empirical measures of the efficiency of responses. The design of such a system would need to address the question of how local and regional changes can be scaled accurately and effectively to enhance the assessment of global changes, and vice versa. The entire design should include a process and institutional arrangements for observation systems to be aligned with assessment and policy processes.

This grand challenge is both a research challenge and a challenge for science policy. Fundamental scientific questions need to be addressed in the design of cost-effective systems that can meet the needs of managers and decision-makers. The implementation of such systems, on the other hand, is not a research challenge but will nevertheless require an ongoing and concerted effort by the scientific community if it is to be achieved, even beyond the timescale of the work envisaged here.

Challenge 3: Confining

Determine how to anticipate, recognize, avoid and manage disruptive global environmental change.

Priority Research Questions

3.1 Which aspects of the coupled social-environmental system pose significant risks of positive feedback with harmful consequences?

3.2 How can we identify, analyze and track our proximity to thresholds and discontinuities in coupled social-environmental systems? When can thresholds not be determined?

3.3 What strategies for avoidance, adaptation and transformation are effective for coping with abrupt changes, including massive cascading environmental shocks?

3.4 How can improved scientific knowledge of the risks of global change and options for response most effectively catalyze and support appropriate actions by citizens and decision-makers?

It is increasingly likely that human interference will trigger highly nonlinear changes in the global environment. Such changes may be abrupt or slow, but in all cases they tend to alter the very character of the life-support system in question and to be largely irreversible on human time-scales. Examples are major shifts in regional climate, rapid collapse of ice sheets, methane release associated with thawing permafrost and warming oceans, and discontinuous transitions in the structure and functioning of biological systems. In turn, disruptive changes in social systems can result from such events, as well as from more gradual environmental changes such when reduced precipitation or degrading soil fertility eventually leads to the creation of environmental refugees. Moreover, an increasingly interconnected world generates linked trends and shocks in seemingly disparate sectors such as energy, finance, food, health, water and security. Public policies and social and economic institutions are rarely designed with such human-induced disproportional changes and regime shifts in mind.

An urgent research challenge is to understand the underlying non-linear dynamics. This will require, in particular, the future integration of environmental and complexity science, two fields that until now have developed largely separately. In order to confine global change to tolerable domains we will have to identify and track our proximity to planetary boundaries (like critical levels of ocean acidification) and in order to confine the impacts of unavoidable excursions into dangerous systems territory we will have to find optimal ways for enhancing resilience to disruptive change. A major focus of research must also be to better determine strategies for avoidance, adaptation or transformation of social-environmental systems to accommodate changes that are dangerous because of their speed, scale, non-linear nature, cumulative impact, self-amplifying nature or irreversibility.3 Such research can also inform steps that societies should take to increase their resilience to natural and human induced disasters. Research into appropriate response and adaptation strategies must extend beyond considerations of 'optimal' approaches to advance understanding of the political and social dynamics of responses. For example, despite the best efforts of analysts to identify optimal policies that might prevent a crisis, it is not uncommon for policies to be changed only when that crisis comes to pass; what does this imply for the design and promotion of response options? And a most exciting task will be to find out whether there are positive social tipping points, i.e. pioneering action that can tip economic machineries or social dynamics into sustainable regimes.

Challenge 4: Responding

Determine what institutional, economic and behavioural changes can enable effective steps toward global sustainability.

Priority Research Questions

4.1 What institutions and organizational structures are effective in balancing the trade-offs inherent in social-environmental systems at and across local, regional and global scales and how can they be achieved?

4.2 What changes in economic systems would contribute most to improving global sustainability, in the context of global environmental change, and how could they be achieved?

4.3 What changes in behaviour or lifestyle, if adopted by multiple societies, would contribute most to improving global sustainability, in the context of global environmental change, and how could they be achieved?

4.4 How can institutional arrangements prioritize and mobilize resources to alleviate poverty, address social injustice and meet development needs under rapidly changing and diverse local environmental conditions and growing pressures on the global environment?

4.5 How can the need to curb global environmental change be integrated with the demands of other inter-connected global policy challenges, particularly those related to poverty, conflict, justice and human security?

4.6 How can effective, legitimate, accountable and just, collective environmental solutions be mobilized at multiple scales? What is needed to catalyze the adoption of appropriate institutional, economic or behavioural changes?

Global change exposes gaps in social institutions, including governance and economic systems, for managing emerging global (and local) problems. The time and spatial scales of global change differ fundamentally from the types of problems that humanity has addressed in the past. Currently, decision-makers have incentives that favour short-term and private benefits, rather than long-term and collective benefits. Addressing the problems of global change, including unsustainable resource use, pollution of the global commons, growing resource demand resulting from increased population growth and per capita consumption, increased distrust by citizens of each other and their officials, and growing poverty, will require a step change in research addressing fundamental questions of governance, economic systems and behaviour.

An effective response to global change will also require much greater understanding of the inter-relations between global environmental change, global poverty and development needs, and global justice and security. For example, how will global environmental change influence progress toward the goals of preventing and eradicating poverty and hunger and improving human health? How does global environmental change shift the agenda for sustainable development in the world?

Determining how to achieve changes in social organizations, institutional arrangements and human behaviour is just as important as establishing what changes are desirable. In many cases, successful changes in institutions will stem from steps taken to achieve collective social action in response to the challenge. How can timely actions be undertaken at unprecedented and multiple geographical and geopolitical scales, where the nature and scale of the issues involved means that the actors have widely differing—and disconnected—values, ethics, emotions, spiritual beliefs, levels of trust, interests and power? How can we better understand the role of individual decisions within diverse settings as the building block of societal decisions? How can we better understand the factors shaping individual behaviour, values and perceptions of threats and risks and how those values and perceptions influence both individual action in relation to global change and the potential for collective action? Recognizing individuals, not just policy makers, as a fundamental unit forces attention to a new level of detail on how information about the environment and feedback on thresholds being reached and breached can impact social changes and actions. Such information can influence individuals, who then incorporate this information along with other factors such as institutions or policies, to make decisions that then aggregate to impact society and the environment.

Challenge 5: Innovating

Encourage innovation (coupled with sound mechanisms for evaluation) in developing technological, policy, and social responses to achieve global sustainability.

Priority Research Questions

5.1 What incentives are needed to strengthen systems for technology, policy and institutional innovation to respond to global environmental change and what good models exist?

5.2 How can pressing needs for innovation and evaluation be met in the following key sectors?

a) How can global energy security be provided entirely by sources that are renewable and that have neutral impacts on other aspects of global sustainability, and in what time frame?

b) How can competing demands for scarce land and water be met over the next half century while dramatically reducing land-use greenhouse gas emissions, protecting biodiversity, and maintaining or enhancing other ecosystem services?

c) How can ecosystem services meet the needs for improving the lives of the world's poorest peoples and those of developing regions (such as safe drinking water and waste disposal, food security and increased energy use) within a framework of global sustainability?

d) What changes in communication patterns are needed to increase feedback and learning processes to increase the capacity of citizens and officials, as well as to provide rapid and effective feedback to scientists regarding the applicability and reliability of broad findings and theoretical insights to what is observed in the field?

e) What are the potentials and risks of geo-engineering strategies to address climate change, and what local to global institutional arrangements would be needed to oversee them, if implemented?

Unprecedented challenges require novel and rapid innovative responses. While many of these grand challenges address the need for solutions-oriented research, it is increasingly clear that the scale and potential impact of global environmental change may necessitate the consideration of entirely novel technologies, institutions and policies at multiple levels.

A number of issues demand particular research attention in this regard. First, it is clear that fundamental changes are needed in our systems of energy production and use in order to avoid dangerous climate change. Research is needed to help identify and develop new systems for energy production, metering and use, and to assess the impacts of these systems on the environment and society.

Second, at current rates of growth in agricultural yield and improvements in water use efficiency, it will be extremely difficult to simultaneously meet the needs over the next half century for: (a) increased food demand from growing (and wealthier) populations; (b) increased human demand for freshwater for agricultural and urban uses; (c) reduced greenhouse gas emissions associated with land use change and agricultural production; (d) potential increased production of biofuels; (e) reduced rates of biodiversity and forest loss; and (f) enhanced ecosystem services. What are plausible scenarios for addressing this problem? What are the costs, benefits and risks of different policy, technological or ecosystem-based management strategies that might be applied?

Third, solving the problem of poverty is integral to solving the problems of global environmental change: one is as important as the other since the two issues are tightly coupled. The poor will experience the greatest harm from global environmental change. It is imperative that solutions to the problem of global change simultaneously contribute to the needs for preventing and eradicating poverty and vice versa.

Fourth, in order to rapidly address the challenges of global environmental change, we must greatly enhance our capacity for learning and this in turn requires much more effective feedback loops at multiple scales. One factor that exacerbates the challenge of dealing with global environmental change is that the time scale of human impacts on the global environment (years to centuries) does not provide the immediate feedback that could inform the public and decision-makers. Mechanisms for providing feedback between the slow variables of global change and the fast variables of human response must be developed. Better communication and feedback is also needed that can enable more rapid uptake of solutions and learning across communities and societies. And the scientific community itself needs to develop better means of learning about the applicability of research findings to real-world situations.

Finally, considerable work is underway to explore innovative approaches such as geo-engineering and green energy technologies. How can such innovation be responsibly intensified? How can risks associated with global environmental management be adequately assessed? Although research is needed to explore the entire set of policy, institutional and behavioural changes that could mitigate climate change and enhance adaptation to climate change, increased attention should now be given to research to understand the costs, benefits, and risks of various geo-engineering strategies and the institutional arrangements that would be needed to oversee and assess such strategies if they were implemented.