Global Change Grand Challenge

National Science Plan, South Africa

Chapter 7: Global Change Research Agenda: Infrastructure and Capacity Needs

contents

tables

boxes

CHAPTER 7.
GLOBAL CHANGE RESEARCH AGENDA, INFRASTRUCTURE AND CAPACITY NEEDS

Lead authors: Emma Archer, Belinda Reyers and Bob Scholes

Contributing authors: Babatunde Abiodun, Nicky Allsop, Stewart Bernard, William Bond, Joel Botai, Ernst Brunke, Mike Burns, Steven Chown, Marius Claasen, Lee-Ann Clark, Christine Colvin, Sheldon Dudley, Francois Engelbrecht, Barend Erasmus, Nicolas Fauchereau, John Field, William Froneman, Johan Groeneveld, Patience Gwaze, Bruce Hewitson, Timm Hoffman, Richard Knight, Monika Korte, Pieter Kotze, C. Labuschagne, Willem Landman, Christopher McQuaid, Guy Midgley , Pedro Monteiro, Pat Morant, Patrick O'Farrell, Ben Opperman, Kim Prochazka, Chris Reason, Coleen Vogel, Hannes Rautenbach, Michael Schleyer, Roland Schulze, Colleen Seymour, Clifford Shearing, Frank Shillington, Neville Sweijd, Mark Swilling, Mark Tadross, John van Breda, Rudy van der Elst, Stephanie Wand , Alan Whitfield and Russell Wise

7.1 INTRODUCTION

'Global Change' is truly a global phenomenon, both in the sense that it is happening everywhere, and affecting everyone, but also in the sense that many of the key processes operate at global scale. As a result, South African research and action on the topic cannot be effective in isolation. This is recognised in the research agenda presented here, which acknowledges the importance of context provided, for example, by the Earth System Science Partnership (ESSP, see www.essp.org), which has as partners the International Geosphere- Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), DIVERSITAS (the research programme on biodiversity) and UNEP's International Panel for Sustainable Resource Management (which has the South African Government as a founder member). Regional context is also important, illustrated by the need for synergy, for example, with initiatives such as the International Council for Science (ICSU) Regional Office for Africa science plan for Global Change (Scholes *et al.* 2008) and the AfricanNESS plan (Odada *et al.* 2008). Here, related information sources include the Global Earth Observation System of Systems implementation plan (GEOSS 2006).

In relation to global processes, such as the accumulation of CO_2 in the atmosphere, the South African research and monitoring activity is small when viewed in isolation. Nonetheless due to the location of observations, which give a unique perspective on the Southern Ocean, it makes a significant contribution. On its own this is of little direct relevance to local and immediate needs; however, it is an important element of the global science and observation effort, from which South Africa benefits greatly, directly and immediately.

There are a variety of research fields in which the South African contribution is disproportionate to its physical size, research budgets or scientific human resources. Global Change as a whole is one such field, which is why (along with national interest) it has been selected as a pillar of the Department of Science and Technology's 10-year strategy. The Global Change research effort in South Africa, to be maximally effective, must emphasise particular areas of advantage, although not to the exclusion of other fields and opportunities. Some areas where South Africa enjoys a comparative advantage include its particular location and social and political context.

7.1.1 The arguments for South African comparative advantage

South Africa is the leading scientific resource on the African continent, and one of a handful of leading scientific nations in the southern hemisphere. The country's socio-economic and political context (see further details below and in Chapter 6) provide unique challenges in terms of understanding Global Change impacts and adaptation – and also unique opportunities for understanding such aspects more broadly in the context of SADC and the African continent. As a result of its colonial-era and recent history, South Africa occupies an intermediate position as an economy in transition between the developed and the developing countries. This allows it to see both points of view and to conduct research in both realms. As a nation, we have developed skills in negotiation, finding workable compromises, and designing innovative institutions.

All countries have research points of strength, largely as an accident of history. In this sense, South Africa has some remarkable strengths, developed over a long period, in palaeo-climatic and palaeo-ecological studies, Earth System studies, biodiversity research, marine and terrestrial ecology, development economics, sustainability in developing economies, rural dynamics and urban phenomena.

South Africa has examples of globally-important but under-studied African ecosystems within its territory. Two examples are: the mixed C3-woody plant and C4-grass dominated ecosystems, notably savannas, but also including karroid shrublands and tropical grasslands; and the Benguela upwelling system on the west coast. It also has some ecosystems which are only or largely represented in South Africa: e.g. fynbos and succulent karoo. They possess unique "megadiversity" – i.e. outstanding species richness and endemism across many taxa.

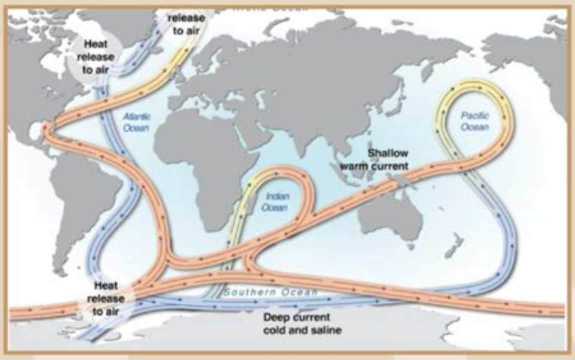
Africa is predicted to be especially vulnerable to climate change and it is therefore fortuitous that South Africa's location in the ocean-dominated southern hemisphere opens up many critical research opportunities for understanding the global climate system. In this regard, the effect of the southern tip of Africa in terms of functioning as a choke point in the global oceanic circulation is important. The warm surface waters of the 'ocean conveyor belt' that transports heat and matter between the Indo-Pacific basin and the Atlantic basin must pass around the Cape (Box 7.1). It is intermittently blocked by the upwelling of the cold, deep Benguela current, forming the Agulhas retroflection and budding off gyres of warm water into the South Atlantic. Cape Town, along with outposts in the Prince Edward islands and Antarctica are important staging point for investigations in the Southern Ocean.

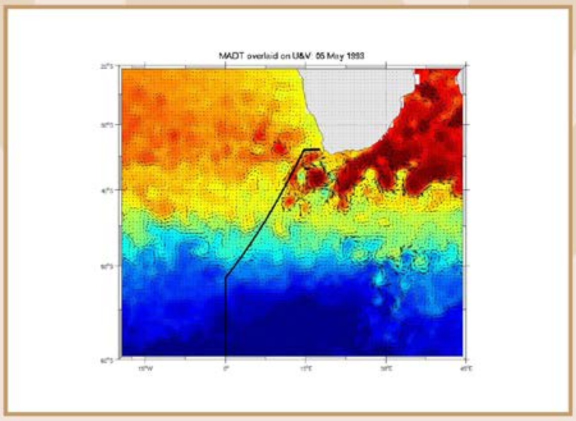
The semi closed atmospheric circulation over southern Africa lends itself to regional-scale studies of chemistry and physical dynamics and it is this unusual feature which, for example, was the basis of the SAFARI 2000 campaign.

South Africa has adopted a position of shared research responsibility for phenomena with SADC- and Africa-scale impacts, with our sense of responsibility for the leadership and support of such studies diminishing as the pool of available resources elsewhere on the continent and the distance from South Africa increases. Examples of topics in this category include: consequences of global treaties on human development in Africa; fires in C4-grass dominated ecosystems and winter rainfall shrublands; the carbon and greenhouse gas budgets of African ecosystems; the challenges of megacities in Africa; consequences of climate change for major African diseases such as malaria, cholera and infant diarrhoea; desertification; water resources in shared river systems; sustainable resource management with special reference to minerals and biomass; and, transboundary air pollution.

Box 7.1. South Africa at the crossroads of the Global Ocean Conveyor Belt

South Africa is situated in a unique position geographically, lying close to the intersection of three pathways of the "Global Ocean Conveyor Belt", which plays such a vital role in the heat and CO_2 balance of the Earth, and hence its climate.





This thermohaline circulation transports warm surface water from the tropical Pacific and Indian Ocean around southern Africa - via the Agulhas Current and its ring-shedding – to the Atlantic Ocean, and on to the polar northern hemisphere. Any changes to this flow not only influences summer rains falling on the subcontinent, but also affects Europe's climate. During its long journey across the ocean surface, evaporation increases the salinity of this water, which also cools as it approaches the poles. Cold, salty water has a greater density, so it sinks in the Arctic and flows southward as a return current. In the Southern Ocean, this North Atlantic Deep Water mixes with the Antarctic Circumpolar Current, which then redistributes it to the Pacific, Indian and Atlantic Oceans. It also drives Earth's largest upwelling system, south of the Polar Front.

South Africa's location at this marine crossroad presents an unsurpassed opportunity to increase understanding of climate-scale variability of heat and productivity in the world's oceans.

(Graphics: UNEP and Sebastiaan Swart, Oceanography, UCT)

7.2 THE EARTH AS A CONNECTED SYSTEM

This section focuses on the fundamental processes that have kept the planet, the Earth System, within a range of variation that is tolerable for its current biota and, in particular, for the needs of an advanced human society. Where these processes have their centre of gravity within the terrestrial, marine, atmospheric or human subsystems, the substantive discussion and elaboration of a research agenda is deferred to sections 7.3 – 7.6 after noting the important role of forcings and feedbacks at the Earth System scale. This section deals only in detail with topics which: 1) involve the Earth System as a whole; or, 2) are important sources of the changes propagating through the system (i.e. 'drivers' or 'shapers' of Global Change). Furthermore, it is highly selective in those Earth System topics it focuses on – only those that have a particular relevance to South Africa, or in which South Africa has some form of comparative advantage are included.

7.2.1 The resilience of southern African socioecological systems

What determines the resilience of coupled socioecological systems in southern Africa to changes in climate, resource use, species composition and nutrient loading?

Our working hypothesis is that the relative resilience of systems is enhanced by: (1) diversity (in particular, redundancy and complementarity) at all levels; and (2) past exposure to similar stresses. For example, the diversity of the South African economy, and the presence of inter-dependent formal and informal sectors, may have decoupled it to a degree from global economic shocks. Similarly, a high level of topographic and geomorphological diversity underpins the ecosystem diversity of South Africa, which may confer resilience to climate change of the services that those ecosystems provide.

Subsidiary questions include:

- How can resilience be maintained and enhanced, through, for instance, the design of institutions, the encouragement of a degree of redundancy, and the promotion of connectivity in landscapes?
- What characteristics of ecosystems promote systems-level stability in the face of climate change?
- What elements of biodiversity are functionally resilient to Global Change impacts?
- Are there absolute limits to the natural resources and eco-system services that our socio-economic systems can extract and how far are we from breaching these limits?

Approach and activities

The approach to this broad set of questions will be through actively supporting research in the related fields of complex systems and sustainability science, and in particular by using the emerging notion of resilience as an organising concept. Participation in international networks focussed on these issues, such as the Resilience Alliance, the Stockholm Resilience Centre, and the work of international panels such as the IPCC and the International Panel for Sustainable Resource Management, will help to keep South African research abreast of recent developments. The methods used will be a combination of empirical comparative analysis and theoretical studies.

7.2.2 Globally-important questions best addressed in South Africa

What aspects of the planetary ecology are especially sensitive to processes that manifest in southern Africa and its adjacent oceans?

This component of the plan is aimed at making a South African contribution to planetary ecology, and in doing so making maximum use of our comparative advantage. In particular, South Africa has both a locational and intellectual advantage in two specific ecosystems that are important in Earth System terms: the savannas and the Southern Ocean. The basis of this importance and advantage is elaborated in Boxes 7.1-7.3. South Africa also has a comparative advantage in winter rainfall ecosystems (Box 7.4), for reasons largely related to their unique biodiversity.

Approaches that look into the history of the Earth System over the past several million years are invaluable for understanding present and future dynamics. The current changes in the Earth System are essentially a global-scale, unreplicated experiment – the current and future state has no exact analogue in the past. But it is possible to gauge the adequacy of our understanding of the coupled Earth System by examining past behaviour, and seeing how well we can reconstruct it in models.

A final comparative advantage lies in the opportunities that exist to understand the phenomenon of change in the Earth's magnetic field over the southern African region and to anticipate the implications of this change. The Southern Atlantic Anomaly (SAA) is a region where the geomagnetic field is significantly weaker than over the rest of the Earth at equivalent latitudes and altitudes. As a consequence, the shielding effect of the magnetic field is reduced, allowing high energy particles of the hard radiation belt to penetrate deep into Earth's upper atmosphere. Box 7.5 provides more information on this topic and advantage.

Key research questions include:

- What Earth System proxies exist in southern Africa and what do they reveal about the climate, atmosphere, hydrology, sea levels and biota during the Pleistocene (past million years), and particularly since the last interpluvial period (i.e. over the past 50 000 years)? Possible proxies include spelaeothems, sediment cores, shoreline geomorphology, tree rings, aquifers, pollen records, archaeological sequences and fossil assemblages, among others.
- What evidence is there for alternate states of land and ocean ecosystems, and regional ocean circulation and climate? Can the thresholds at which the states change from one to another be predicted? For instance, what drove the sudden expansion of the C4 (tropical grass) life-form, the emergence of savannas and hominins, and the oscillation of atmospheric CO_2 from about 4 million years ago?
- What can be learned from the rich palaeo-anthropological, archaeological and historical record of southern Africa about past climates and human and biotic adaptation? For instance, was the rise and fall of the Mapungubwe civilisation in any way linked to climate change?
- How does fire in neo-tropical ecosystems (i.e. grasslands, savannas and fynbos) contribute to net global radiative forcing, the transfer of nutrients between land and sea, and the global carbon and greenhouse gas budget?
- How do plants and animals disperse across landscapes in response to changing climates and at what rates? How do soil discontinuities, altitudinal gradients and land use impacts influence the process of dispersion?
- How does the Agulhas retroflection regulate the flow of heat from the Indian into the Atlantic basins?
- To what degree is export production (i.e. phytoplankton growth that is heavy enough to sink to the ocean floor) in the Southern Ocean dependent on fluxes of micronutrients such as iron, phosphorus and silica from the continents, and in particular from southern Africa?
- How much longer will the Southern Atlantic Anomaly continue to grow, how deep will it become, and what are the implications for Earth System adaptation?
- Is the Earth's magnetic field entering a reversal? Does the dipole decay continue to decrease (more than 10 % during the last 150 years) due to changes in the field beneath the South Atlantic region - which are connected to the growth of the South Atlantic Anomaly?

Box 7.2. Why mixed C4-grass and C3-woody plant co-dominated ecosystems are an important area of focus

Ecosystems co-dominated by grasses (typically with a C4 photosynthetic system) and woody plants (C3 system) are globally extensive, very sensitive to both climate and CO_2 increases, and have globally-important feedbacks to the climate system. These are notably savannas, but for the purpose of this plan, a broad definition is adopted which includes the summer-rainfall shrublands and thickets, and the tropical grasslands (which are projected to be invaded by trees this century). Savannas by themselves are the largest single terrestrial biome, covering about an eighth of the global land surface; C4-grass dominated systems as a whole may cover up to a quarter, including most of South Africa. Two thirds of sub-Saharan Africa is covered by this type of vegetation. As a result of their huge extent, mixed tree-grass ecosystems are important to the global carbon budget, particularly because they are highly variable at the annual timescale (a big part of the interannual variability in the growth of CO_2 in the atmosphere is thought to be due to the sensitivity of savannas to EÑSO-induced rainfall variations), and prone to structural change over a period of a few decades, through the phenomenon of 'bush encroachment'. Most of the area burned worldwide is in savannas, and the largest fraction of those fires is in Africa. There is an intriguing, but as yet unresolved set of links between the declining atmospheric CO_2 (and global temperature) during the Pliocene, the evolution of C4 grasses, the radiation of mammalian herbivores, the increasing importance of fire, the expansion of savanna trees and ultimately, the evolution of hominins.

South Africa has an acknowledged leadership position in savanna, thicket and shrubland ecology, woody plant-shrub interactions, C4 grass ecology and systematics, fire ecology and the palaeoecology of Africa.

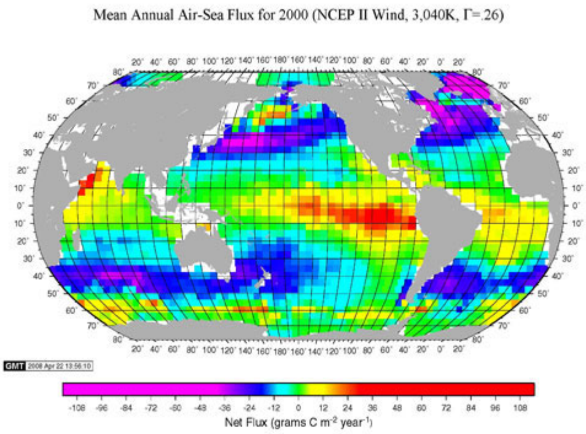
Box 7.3. Why the Southern Ocean as a research focus

The oceans south of southern Africa play an important role in shaping the greenhouse gas feedbacks that influence global warming. The region is a key CO_2 uptake zone, accounting for about half of the total ocean uptake of the CO_2 generated by human activities every year. The total ocean uptake of approximately 2.2 billion tons per year has been valued at $US 20-60 per ton, so even small changes in uptake would have a major impact on mitigation measures for carbon emissions.

Less well understood is the role played by the Southern Ocean in modulating albedo – the Earth's reflectivity of solar radiation. Trace gases emitted by ocean productivity help seed low clouds, which increase reflectivity, but they also reduce stratospheric ozone, allowing more radiation to reach the Earth's surface.

Improved knowledge of Southern Ocean biogeochemistry is therefore vital in elucidating the atmospheric concentration of CO_2, both now and over the interglacial cycles of the past 2.5 million years.

South Africa's location as a key logistics base for Southern Ocean and Antarctic studies, its satellite receiving capability for the region, the record of marine research and the long-established research bases at Marion Island and in Antarctica all give us a comparative advantage in Southern Ocean studies



(Graphic from Takahashi et al. 2008: LDEO)

Box 7.4: Why the winter rainfall ecosystems matter

Although the winter rainfall region of southern Africa (including the fynbos and the succulent karoo) occupies less than 10 % of South Africa, it has one of the richest concentrations of biodiversity of any area in the world. The recent creation of a World Heritage Site in the region bears testimony to its international significance. Most climate change predictions suggest that the winter rainfall region will be affected by increases in temperature and reductions in rainfall as a result of the southward shift of the circumpolar westerlies. In response to these predictions southern African researchers have assembled several large and unique data sets (e.g. the Protea Atlas), allowing them to be at the forefront of research into the impact of climate change on biodiversity, population range shifts and biome level responses. The movement of plants and animals along altitudinal gradients and their responses to soil nutrient discontinuities, as this is influenced by changes in temperature, drought and land use, is a key topic on which work has already begun. Significant experimental work on the impact of climate change (e.g. increases in temperature and nitrogen) on the endemic succulent and geophyte flora is underway. Extensive archaeological and historical evidence of past land use impacts provides novel insights into how people have influenced the landscape over time. It is also the region where several ambitious transdisciplinary conservation initiatives have taken place, that serve as a model for other areas in the world facing pervasive environmental change.

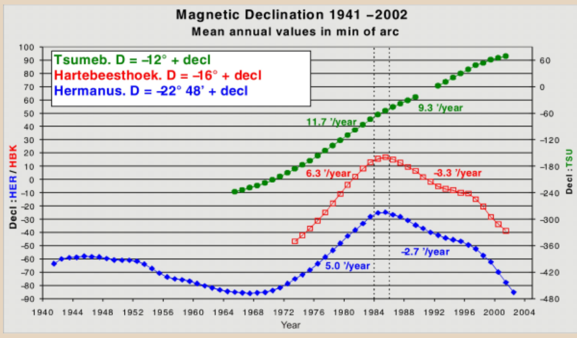
Box 7.5: Understanding the phenomenon of change in the Earth's geomagnetic field

The Earth's core magnetic field is currently declining, with the expectation that the dipole field will vanish within about a millennium. The rapidly decreasing field has evoked the suggestion that a reversal of the geomagnetic field may have already commenced. The most intense reverse patch, already observed, is beneath the southern tip of Africa.

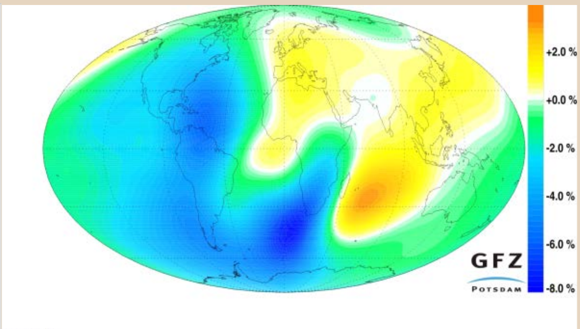
The figure on the right, below, clearly shows that within the last 25 years the magnetic field decreased by more than 10% in the area which coincides partly with the South Atlantic Anomaly - a vaguely-defined, oval-shaped geographic region, centred to the east of Brazil, where the geomagnetic field is significantly weaker than over the rest of the Earth at equivalent latitudes and altitudes. It is in this region that the shielding effect of the magnetic field is severely reduced, thus allowing high energy particles of the hard radiation belt to penetrate deep into the upper atmosphere to altitudes below 100 km. The hazards of this region appear to be under-appreciated.

The figure on the left, below, shows the changes in field strength recorded at three observatories. Although all the curves show a declining trend, neither the rate of change nor its temporal variation is identical at the three sites. There are obviously significant gradients in the field decline across the region

A detailed study of the geomagnetic field in this key region, supported by the global monitoring of the magnetic field from satellites like CHAMP, will help to better explain the phenomenon of geomagnetic field change on a larger scale. It will also advance our understanding of magnetic field behaviour, its consequences for space weather, and the implications for society in the context of Global Change.



Evolution of the geomagnetic declination at Hermanus, Hartebeesthoek and Tsumeb magnetic observatories.



Percentage change of the geomagnetic field intensity from 1980 to 2006, as determined by the magnetic satellites MAGSAT and CHAMP

Approaches and activities:

The approach in this area will be to make South Africa a preferred destination to host interdisciplinary studies into selected planetary processes. The analysis of Earth System behaviour over the past several million years will be a key emphasis, as will the establishment of several reference research platforms and open-source databases.

There are several steps to make this a reality:

- Continue, and increase, the South African engagement in international networks, such as PAGES, dedicated to creating, sharing and analysing global palaeo-ecological and palaeo-climatic databases, including supporting the collection of new proxy records in southern Africa.
- Design, initiate and run at least one major international campaign focussed on an important Earth System process, based in South Africa.
- Maintain research and observation platforms in selected key ecosystems within the summer and winter rainfall regions and the Southern Ocean.
- Create and maintain a few unique environmental databases that can be used by researchers from around the world to advance Earth System studies.
- Develop a number of collaborative studies utilizing the CHAMP satellite and ground based data. Some of the potential research topics are:
    - geomagnetic field modelling, particularly the comparison of satellite-derived and ground-based tested secular variation models;
    - studies of the rapid dipole field decrease and rapidly changing geomagnetic declination;
    - modelling of magnetic fields at the core-mantle interface; and
    - studies of the deepening South Atlantic Anomaly.

7.2.3 Limits and tipping points

Are there critical thresholds of change which if exceeded, would have a disproportionately negative effect on the wellbeing of South Africans?

The premise underlying this question is that a substantial degree of Global Change is now unavoidable. South Africa's commitment to global efforts to mitigate further change must be informed by an understanding of the limits beyond which change becomes excessively costly, or impossible, to adapt to in South Africa. Of particular concern is the likely existence of thresholds (‘tipping points’) beyond which change is effectively irreversible within realistic human timescales. Crossing of such thresholds is often abrupt and may occur with little or no warning if the dynamics of the system are not well-understood. Thresholds are often associated with the increase in dominance of positive feedback loops in the local, regional or global system. For example, there is evidence suggesting that the nutrient-rich upwelling system that supported a major fishery off the coast of Luderitz in Namibia has been undermined by inflows of warm water from the north, quite likely as a result of climate-induced changes in ocean circulation. Could the upwelling centres further south, which support the South African fishing industry, be similarly threatened, and at what level of warming? In another example, is it possible that rainfall in parts of South Africa is sensitive to regional-scale feedbacks from land cover, setting up a positive feedback loop where drying out leads to ecosystem degradation, which in turn promotes further drying out. As a further example, are there tipping points in household socioeconomic and/or health status beyond which the household is unable to recover after a severe drought?

Specific questions nested within this broad focus include:

- What is the shape of the relationship between risk-of-damage and sea level rise for locations on the South African coast? Does the risk suddenly increase above a certain sea level?
- Is there a rate and final degree of climate change that permits the majority of plants, animals and agricultural systems in southern Africa to adapt of their own accord, through migration, evolution or physiological acclimation?
- Are there warning signals (indicators) of the imminent approach of thresholds, or alternatively, can the presence and location of thresholds be deduced from system properties?
- Where thresholds are likely to be breached, what institutional structures and/or interventions best support the transition to a more sustainable socioecological regime?
- Given that our economies and urban systems depend on extensive use of natural resources and ecosystem services, what aspects of these systems will need to change to avoid certain tipping points?

Approach and activities

The approach to this area will involve developing advanced system analysis and modelling capability, including: (1) theoretical approaches (such as those based on qualitative models, relatively reduced-form differential equations, or emerging approaches such as network theory);

(2) numerical modelling using high-performance computing; (3) case studies of systems that are known or suspected to have exhibited threshold transgressions; and, (4) material and energy flow analyses of local urban and national economic systems. Undertaking these studies in an explicit socioecological system context will require improved capabilities in socioeconomic data modelling and institutional analysis.

7.2.4 The regional improvement of global models

What key processes need to be taken into account in General Circulation Models if they are to capture the dynamics of African ecosystems and southern hemisphere oceans and climate systems reliably?

Fully-coupled land-atmosphere-ocean models (General Circulation Models or GCMs) have become a key tool in both Earth Science and in the development of climate policy. But GCMs have been developed almost entirely by institutions located in the northern hemisphere temperate regions, and thus include better process detail for those areas than for the tropical southern hemisphere. This limits their reliability over southern Africa.

For instance, the following issues are acknowledged to be problems in current global models:

- What new plant functional types need to be included in Dynamic Global Vegetation Models (DGVMs), the link between the atmosphere and the land surface in General Circulation Models, in order to represent important southern African land cover types, for instance the fynbos, the succulent karoo and the miombo woodlands and mopane shrublands?
- How can neo-tropical wildfire be realistically represented in General Circulation Models?
- How can subtropical convective rainfall processes, which dominate the precipitation in southern Africa but occur at sub-grid scale, be more realistically parameterised in General Circulation Models?
- Is the production ecology and biological carbon pump, as it occurs in the Southern Ocean, well characterised in the ocean part of General Circulation Models, and is it appropriately linked to nutrient transport from the African continent?

Approach and activities

The essence of the approach is not to try to develop a new and stand-alone ‘South African General Circulation Model’, which would represent a huge investment of effort, and is unlikely to be particularly novel. Rather, it is to ensure that:

- South African researchers are trusted partners of several leading global climate and ocean modelling teams, through arranging collaborations and regular exchange of researchers.
- South Africa has skilled climate modellers able to understand the workings of General Circulation Models, and those skills are sustained by running versions and subsets (such as nested regional models and the land-atmosphere or land ocean exchange code) of the models on high-performance computers in South Africa, and by working on regional outputs of the models and their downscaling.
- South Africa maintain a few key sites, networks and datasets for the main purpose of developing, calibrating and validating climate models and Earth observation systems. Such sites should be part of a global resource.

7.2.5 Scenarios and options

What are the global and regional implications of the various development pathways that could be chosen by South Africa?

The Long Term Mitigation Studies project has confirmed at a national scale what is also globally apparent: business-as-usual leads to an unsustainable future in the 21st century. Viable alternatives need to be developed and explored that are consistent with national commitments to human development, increased wellbeing, reduced inequality, and a safe environment. Chapter 6 clearly indicates the need for South Africa's transition to be one that leads eventually to a sustainable socioecological regime. This relates to both energy-related carbon emissions at the points of generation and use, as well as material flows and their respective impacts as they pass through urban and national economies.

Questions that need to be addressed in order to answer the broad question include:

- What are the present and past greenhouse gas emissions and uptakes from South Africa? Provision of these estimates is a recurrent obligation on the South African government under the UNFCCC. Making them accurately and defensibly has important economic and political consequences for the country. This includes development of emission factors for quantitatively significant emission sources that are to some degree specific to South Africa: for example, methane emissions from South African livestock breeds (possibly including indigenous ruminants) and under local management conditions; emissions from South African coal grades; transport emissions from a vehicle fleet that differs in age and operating conditions from the norm in developed countries; and particularly high emissions levels caused by the spatial and architectural design of South Africa's urban systems. Developing methods for the cost-effective estimation of emissions and sinks, especially for non-point sources such as land use management and the governance of urban economies (as they address the apartheid spatial legacy), is also of great policy relevance.

- How are the net greenhouse gas emissions likely to evolve under various future development scenarios for South Africa? This requires development of activity models for key South African sectors, including transport, domestic (household) emissions, construction, industry (especially petrochemicals and coal, metallurgy and mining), and agriculture. Models for particular cities will be particularly important given that City Governments actually control some the key levers for emission reduction (energy use, waste disposal, construction design, layout and transport).This also requires data collection on activity levels in these sectors and cities, and development of statistical and 'integrated' (i.e. demographics and economics-based) models of their future evolution. It needs a predictive and integrative understanding of the tradeoffs and other interactions between sectors, technologies, drivers of emissions and national development plans.
- What technological, behavioural and policy interventions can reduce the net emissions from South Africa, at what cost, and what barriers prevent their adoption? For instance, what are the technology acquisition and transfer needs of the nation? And what institutional development processes and configurations are needed to ensure that appropriate technologies are translated into production and consumption systems in ways that stimulate both formal and informal economies?
- What are the co-benefits, in terms of reduced air, land and water pollution of various options, and what are the associated impacts on biodiversity, water supplies, sustainable livelihoods, etc., and how can we best build on these?
- How will development-related changes in habitat, climate, pollution and resource use alter the population viability of indigenous species and increase the susceptibility of southern African ecosystems to invasion by alien species?
- What will need to change with respect to extraction and use of primary natural materials, such as minerals, water, forest products and soil nutrients (embodied in agricultural products)? Are the maximum economic benefits for all South Africans being derived in the most efficient and productive ways? Are the processes of extraction, beneficiation and (where applicable) export designed in ways to minimize energy consumption and unproductive/toxic wastes?

Approach and activities

To the extent that some aspects of the future are unpredictable, a scenario-generating approach based on shared, plausible narratives is one necessary element. South Africa has already demonstrated strong capabilities in this domain. In addition, the rigour imposed by quantitative modelling prevents the creative exercise of imagining alternative futures from becoming pure fantasies. A key approach will be the development of an 'integrated assessment model' for South Africa. Integrated models handle the dynamic interactions between population, economic activity, resources and climate in a way that allows the tradeoffs between them to be made explicit. Such a model would need to have 'boundary conditions' (i.e. inputs and outputs beyond the region) imposed by being nested within global climate and economic models. Such activities further build on the requirement for a more substantive long term monitoring system for socioeconomic and political characteristics in key sites. Improved methods of institutional analysis are essential – enabling South Africa to focus specifically on developing what Chapter 6 refers to as a 'new institutional imagination', defining structures and/or interventions that best support the transition to a sustainable socioecological regime.

7.3 RESEARCH AGENDA: TERRESTRIAL SYSTEMS

Here we explore these key research challenges associated with South Africa's terrestrial ecosystems (both natural and managed) in more detail.

7.3.1 Securing living landscapes

The long-term well-being of South Africans depends on the management of healthy, living landscapes that are able to support life of all forms, now and into the future. Global Change represents a significant threat to these living landscapes. We need to understand landscapes in order to manage them so that they continue to support people and economies.

Examples of research questions

- How are the risks and impacts of Global Change to biodiversity distributed in space and time?
- How do the predicted impacts on biodiversity translate into changes in biodiversity based economies?
- Are there critical elements of biodiversity (i.e. those critical to these economies) which are more at risk?
- Are current biodiversity-based economic activities sustainable under Global Change conditions?
- How do ecosystem-level responses feed back into predicted species-level Global Change impacts?
- How will South Africa meet international conservation obligations in the face of change?
- What biodiversity management skills are needed to deal with responses to Global Change?

- What institutions and/or incentives best support the building of a functional landscape for resilience of socioecological systems?

7.3.2 Accelerating land cover change – facing an unfamiliar world

The southern African land surface supports a remarkable variety of ecosystems, biomes, vegetation types and animal communities that provide a wide variety of land use options for human society. Steep climatic gradients place contrasting ecosystems in close proximity, with boundaries that have shifted along with changes in climate and atmospheric CO_2 concentration in the past. Socio-economic and political forces have also caused significant changes in land-cover, and will do so into the future as society considers options such as expanded food, fibre and biofuel production, and conservation. How will the interacting impacts of climate and atmospheric change, disturbances such as fire and grazing, and critical societal drivers change land cover over the next fifty years?

Examples of research questions

- How have human land use practices, policies and socio-economic activities in the more recent past altered land-cover and associated energy and biogeochemical cycles? How will land-cover trends and their biogeochemical implications create feedbacks to atmospheric and climate change into the future?
- How has land use and climate change interacted in the past to shift biome boundaries and associated animal and plant communities?
- Will C4-grass dominated and drought- and fire-driven ecosystems continue to shape the structure of much of southern Africa, or will increasing CO_2 and changing water balance shift land cover towards native or alien-invasive woody plant-dominated ecosystems? What will the impacts of large-scale ecosystem changes be on human land use options and livelihoods? Is atmospheric CO_2 a 'wild-card' driver that will have significant impacts on land cover and biodiversity in the short to medium term?
- Are invasive alien species a significant potential threat to the resilience and biodiversity of southern African ecosystems, and will this threat be exacerbated by interacting Global Change drivers?
- Changing the fire rules with implications for ecosystems, societal assets and human safety – how will shifts in land cover and land management interact with changing climatic conditions to alter the potential for fire ignition and spread in southern Africa?
- Regional to national policy and development pathways will have significant impacts on land-cover in the short to medium term – how will political dynamics and changing regional co-operation (such as SADC and NEPAD free trade zoning) affect land-use decisions and practices at landscape, regional and national scales, especially as

influenced by global trends in resource demand, trade and climate policy? What are the optimal land-use mixes that balance human extractive value with long term sustainability and biodiversity values?

7.3.3 Ensuring water security into the future

South Africa is already a largely water-stressed country as a result of its geographical location, and it exhibits spatially and socio-economically skewed water supply and demand. How do we ensure water security in an uncertain future of Global Change, taking into account surface and ground water resources, water quantity and quality, the amplification of any changes in the hydrological responses to changes in climate, international water obligations, and the important links which water has to other systems such as agriculture, health, energy, as well as marine, terrestrial and freshwater aquatic ecosystems?

Examples of research questions

- How do drivers of Global Change impact on the hydrological system with respect to both overall quantity and quality of water, and temporal flow distributions in its different hydro-climatic zones? These drivers include:
    - Climate: i.e. changes in CO_2, temperature, and rainfall, individually and in combination with one another, taking into account attributes such as changing rainfall intensity, timing, persistence and spatio-temporal variability, and including appropriate downscaling of climate information for hydrological purposes and uncertainty analysis;
    - Land use and land cover: in their historical, current and future contexts, including effects of fire, invasions, conversion to and from agricultural usage (both intensive and extensive), soil loss and degradation through land management choices, nutrient/pesticide/herbicide inputs, urbanisation (both formal and informal), industrial development (e.g. mining);
    - Engineered water systems: i.e. effects of dams, inter-basin transfers, irrigation and other abstractions, return flows, and effects on system design, system life or curtailment rules; and
    - Interactions between the above in a complex supply-demand system, with a particular focus on the dynamics between the climate-water-agricultural systems.
- Which areas in South Africa are hydrologically most vulnerable to the pressures arising from Global Change, in response to the drivers mentioned above?
- Transboundary (shared) water resources are a key feature of the regional water sector. What will the impacts of Global Change be on cross-boundary water security, water

exports *from* South Africa and imports *into* South Africa, and possible amendments to international water agreements?

- How will water reconciliation (balancing supply and demand) be achieved in different water management regions of South Africa in light of Global Change? In particular, how can demand side management be improved? What are the absolute limits to this resource?
- The South African water law imposes an obligation to maintain an ecological water reserve. How will changes in the hydrological cycle impact on terrestrial, freshwater aquatic, estuarine and marine ecosystems and their interlinkages, particularly in regard to changes in water temperature, partitioning of flows into base flows and storm flows, and water quality?
- Groundwater is likely to play an ever-increasing role in South Africa's future water security. How will Global Change impact groundwater recharge, abstraction patterns, and the quality of groundwater, and where will these impacts be most severe?
- Through the Millennium Development Goals, we have an obligation to eradicate water poverty. How will Global Change affect programmes aimed at ensuring water security for the poor? Will water scarcities eventually become constraints on economic growth and job creation if water management systems remain unchanged?
- Appropriate, updateable physically-based hydrological models (with user support) to simulate outputs at fine spatial and temporal resolutions, which would reflect local response differences to Global Change phenomena should be developed. Together with such models go the development of up-to-date, quality controlled and readily accessible hydro-climatic databases. How are these best achieved?
- How do we best undertake a major review of water management in the agricultural sector in order to promote much great water efficiency and productivity?
- There is a need to develop and implement autonomous and planned adaptive management strategies, identified via cost-benefit analysis, at national, provincial and local levels, including water-related disaster management plans, and avoiding counteractive maladaptation. How is this best achieved?
- How is adaptive management mainstreamed into policy frameworks for Global Change to include legislative, governance, socio-economic, research and monitoring issues?
- How is the notion of water as a 'binding constraint' best communicated to government, and is government's further investment in an appropriate sustainable resource use approach supported?

7.3.4 Vulnerable people and vulnerable places

Global Change will alter our terrestrial ecosystems, the way they function and the services they provide. Some of the people and places affected by these changes are highly vulnerable to these effects and are particularly likely to experience much of the damage to well-being and loss of life that such changes will entail.

Examples of research questions

- Which areas of South Africa are valuable in terms of the ecosystem services they supply and the communities who depend on them? How have these changed in the past and how are they likely to change in the future?
- Which ecosystems and ecosystem services are most vulnerable to the impacts of Global Change? The answers to this question require an understanding of the interactions between:
    - the uncertainties and risks of the impacts of change;
    - the sensitivities of ecosystem services and beneficiary communities to change; and
    - the adaptability of these services and communities to change
- How can vulnerable areas and services be managed, especially considering the risks, uncertainties and multi-sectoral nature of service management?
- Can incentives to reduce vulnerabilities and enhance the sustainability of these services and the communities using them be created and used?
- How do we integrate ecosystem services and biodiversity into policy-making, development planning and natural resource management in these vulnerable places? In particular, what reforms are required to clarify Local Government responsibilities and obligations for biodiversity and ecosystem management?
- How do we best build and support innovative partnerships beyond public responsibility for the protection of ecosystem services?

7.3.5 Feedbacks from the southern African land surface to the climate system

Southern African ecosystems, along with most semi-natural ecosystems around the world, seem to be acting as moderate carbon sinks at present. This sink behaviour helps offset, to a degree, the emissions from land use change and fossil fuel burning. Sink behaviour is not guaranteed or constant, however, and could saturate due to internal capacity limitations, or altered by changing climate or atmosphere.

Examples of research questions

- What are the processes responsible for climate regulation in South African ecosystems?

- How do these processes interact with one another?
- How can we best manage and enhance these interacting process?
- What policy and economic instruments will be required to facilitate this management?
- How will the extent and structure (cover and height of trees) of savannas change in a warmer, wetter or drier, higher CO_2 world, and what will be the consequences for the regional carbon balance?
- How will regimes (frequency, extent, intensity and season) of wild fires change in future, and how amenable is the fire regime to management? How will changing fire regimes change the net climate forcing, biodiversity and risk exposure of people?
- How will high temperatures (above the optimum for plant growth) alter the productivity, composition, soil and plant respiration rate and carbon storage potential of southern African ecosystems?
- How will changes in the surface reflectivity (albedo) resulting from land use changes, management or vegetation shifts alter the net radiant forcing of the region? What are the tradeoffs between land management for carbon storage (e.g. tree planting) and albedo changes?
- What agricultural practices could enhance the carbon content levels of cultivated soils?

7.3.6 Better landscapes for better lives

A key set of research challenges is one that addresses the need for science-based responses and solutions to the effects of Global Change on multi-functional terrestrial landscapes. The major challenge comprises the creation of ‘functional’ landscapes that simultaneously support production, conservation, diversity and resilience to external and internal stresses, with clear and quantifiable benefits. Such a challenge reiterates the emphasis placed in previous sections on multiple benefits strategies, as we seek to prioritize strategies that fulfil more than one objective.

Examples of research questions

- How can we better understand the spatial and temporal scales of resources and the distribution and planning horizons of ecosystem service-providers and -users so we can better engage with them to promote desired service levels and outcomes? This is particularly relevant in situations where those responsible for an ecosystem service are in a different administrative unit to those benefiting from that service. The classic example here is in river catchments where upstream water providers and downstream users are not linked.
- What interventions across all levels of government and between government and civil society are required to promote sustainability? This is essential in South Africa’s water

sector, for example, where catchment management agencies comprise a diversity of state and private stakeholders that are responsible for ensuring effective and efficient management of water resources and delivery of water services.

- What are the key characteristics of successful market-based mechanisms and can these be created within the South African context? How will the Land Redistribution and Restitution programmes affect the design and adoption of such mechanisms? What other incentive-based mechanisms, which are sensitive to South Africa's unique cultural and historical contexts, can the Global Change science and policy communities innovate to promote effective and efficient landscape development and management? How can incentive-based mechanisms be implemented to maximize their beneficial outcomes and minimize the potentially negative consequences that often result - such as landholders becoming victims of market adopting land use practices in response to economic prices instead of fulfilling social or cultural needs?
- What are the benefits of reducing morbidity and mortality risks associated with environmental degradation and how can these best be measured, valued and communicated? What is the relationship between a change in the provisioning of environmental goods and services and the resultant change in morbidity or mortality?
- How do different communities within South Africa tend to respond to government interventions (e.g. environmental standards, regulations, subsidies)? Why do they respond in this way, what are the effects of this, and how can these behavioural responses be influenced to improve the successful implementation of interventions? What will be the benefits of disseminating environmental information and how should this information best be disclosed?

7.4 RESEARCH AGENDA: MARINE SYSTEMS

Here we explore the key research challenges associated with South Africa's marine systems in more detail.

7.4.1 Understanding the ocean as part of a coupled regional system

The importance of regional ocean basin-scale processes to southern Africa is that they regulate its climate variability and change. Furthermore, they also act as an important link determining the variability and long-term change in global climate through biogeochemically mediated feedbacks of greenhouse gases and gases that influence atmospheric chemistry. The regional ocean is thus central to understanding both regional and global climate variability and long-term change. These two scales form the basis of three key research sub-foci which have been identified as the main gaps in our understanding of how the region will respond to global warming.

7.4.1.1. Research sub-focus: Importance of the ocean in reducing the uncertainty of seasonal, interannual and decadal climate projections in southern Africa

The most immediate societal benefit of research conducted under this sub-focus will be the access that is provided to operationally reliable climate projections.

The projected regional responses to anthropogenic global warming constitute what is widely termed the regional impacts of climate change.

Examples of research questions

- How will heat and moisture flux characteristics of the tropical Atlantic and Indian Oceans respond to global warming?
- Will the Hadley and Walker cell circulations weaken or strengthen?
- How will characteristics of the Southern Annular Mode change in response to global warming?
- How are seasonal, interannual and decadal ocean climate characteristics changing?
- How will regional modes of the Benguela Niño and the South Indian Ocean Dipole respond to global warming?

7.4.1.2. Research sub-focus: Understanding the feedbacks between the regional and global systems

The most immediate societal benefit of research conducted under this sub-focus will be access to operational regional and global indicators that provide an insight into how the regional ocean is adjusting in response to global warming.

The regional ocean systems play an important part in driving the variability of the global climate system through both biogeochemical and physical feedbacks. Feedbacks are possibly the most important characteristic of system behaviour as they not only shape the resilience to change (negative feedbacks), but also set thresholds or tipping points (positive feedbacks).

Examples of research questions

- What drives the seasonal, interannual and long-term change of CO_2 fluxes in the Southern Ocean?
- Is the Southern Ocean CO_2 sink weakening?
- How will Southern Ocean albedo change with global warming?

- How will the transport of heat south of Africa adjust to global warming?
- Will the equatorial Oxygen Minimum Zone in the eastern Atlantic strengthen or weaken with global warming?

7.4.1.3. Research sub-focus: Reconstruction of past ocean climate

The most immediate societal benefit of research conducted under this sub-focus will be a more reliable assessment of the most important thresholds that may shape our transition to a warmer southern Africa, with consequences for adaptation plans by the end of the century (2100).

An important weakness in our present capabilities to project regional climate change to global warming is the lack of observational data against which to test coupled climate models. Modern directly-observed data sets are mostly limited to the past 50 years, which is too short to measure large-scale re-organization of the ocean system and its impacts on climate. A strong research emphasis on high quality palaeo-ocean data, linked to terrestrial data sets of comparable time scales, will provide the most rigorous assessments of the models on which we base climate projections.

Examples of research questions

- How has the seasonal cycle changed since the Pliocene and between the Glacial and Inter-Glacial periods?
- How does the ocean drive the transition between Glacial and Inter-Glacial periods?
- How was the regional ocean organized during the Pliocene?

7.4.2 Sustainable coastal development: Vulnerability, risks and responsibility

Human impacts on the marine and coastal environment are an integral part of development benefits. The challenge lies in maximising those development benefits without impairing the ability of the system to provide them sustainably. This applies to the exploitation limits of fisheries as much as it applies, for example, to urban and port impacts on coastal erosion.

7.4.2.1. Research sub-focus: Physical coastal processes (including extreme events)

The most immediate societal benefit of research conducted under this sub-focus will be a prioritization system of coastal areas at risk to storm surge flooding and possible management and mitigation approaches.

Physical drivers in the coastal zone include naturally varying waves, winds, currents and tides that impact on the provision of ecosystem goods and services.

Examples of research questions

- What principles of physical processes should be applied in coastal planning?
- Can extreme events and their potential impacts be forecast, and can this information be disseminated with adequate lead-times for contingency implementation?
- What scientifically-based management tools are appropriate for use in an integrated approach to mitigate and limit the impact of physical dynamics in the coastal zone?

7.4.2.2. Research sub-focus: Coupled urban coasts and estuarine systems

The most immediate societal benefit of research conducted under this sub-focus will be indicators of ecosystem state, and optimization of the value of ecosystem services in the context of urban and rural resource needs.

Estuarine-based research that addresses Global Change issues can be categorised into three primary areas, namely:

- Changes in freshwater inflow that are driven by Global Change
- Degradation/destruction of estuarine habitats and living resources
- Estuarine mouth dynamics.

Examples of research questions:

- How will altered river flows, sea levels and storm events arising from Global Change affect the structure and functioning of South African estuaries?
- What is the likely response of aquatic biota to climate change in our estuaries and how will this affect these ecosystems in the future?
- Estuarine ecosystem integrity is being threatened by Global Change – do we understand the consequences for the productivity and connectivity of these systems?
- What are the carrying capacity limitations to the development of urban bays, and how can these be measured?
- How can certainty be improved in predicting the impacts of Global Change on coastal zones including, for example, urban bays?

- What are the urgent priorities in respect of coastal zone and urban bay management in order to mitigate the risks associated with Global Change?

7.4.2.3. Research sub-focus: Environmental security and coping capacity

The most immediate societal benefit of research conducted under this sub-focus will be operational models and contingency plans to assess and mitigate threats to coastal environmental security.

The impacts of coastal development on the environment have a range of implications for environmental security. Given that coastal economies depend to a large extent on goods and services of coastal ecosystems, any Global Change impacts on the coastal zone will impact on coastal economies.

Examples of research questions

- What is the distribution of the range of threats to coastal environmental security in southern Africa?
- What are the appropriate contingency and mitigation plans for these threats?
- What scientifically-based management tools are appropriate for application in an integrated approach to mitigate and limit threats to environmental security?
- How can coastal zone planning be improved to minimise risk, given the diverse elements of potential impact?

7.4.3 The response of marine ecosystems and ecosystem services to Global Change

7.4.3.1. Research sub-focus: Continental shelf and fisheries

The most immediate societal benefit of research conducted under this sub-focus will be indicators of ecosystem state and fish stock status.

Understanding the response and resilience of coastal and marine ecosystems to change requires an integrated approach, partly achieved by an Ecosystem Approach to Fisheries (see Chapter 4). In this regard, socio-economic aspects play a particularly prominent role. For government to develop defensible strategies to manage the diverse impacts of change on ecosystem services will require good scientific information.

Examples of research questions:

- How do we separate climate variability from fishing as factors affecting sustainable fish catches?
- How can we improve fisheries management and get better fisher cooperation?
- How do we optimise the siting and size of marine protected areas?
- How best can we measure and evaluate the condition of ecosystems that sustain our fisheries?

7.4.3.2. Sub-focus area: Inshore ecosystem services

The most immediate societal benefit of research conducted under this sub-focus will be the identification and location of threatened coastal ecosystem services.

The coastal zone is one where climate change will have especially profound effects on human populations, both directly and indirectly through ecological effects. Marine ecosystems are especially strongly shaped by physical conditions, so that changes to the latter will have marked effects. Apart from direct, practical problems associated with the predicted consequences of Global Change, the geographic situation of South Africa raises the possibility of strengthening our science by making valuable theoretical contributions through addressing research questions of global relevance.

Examples of research questions

- How are coastal ecosystems shaped by the interactive effects of temperature and nutrient regimes?
- How are coastal ecosystems altered by land-sea interactions in the coastal transition zone?
- What are the relationships among ecosystem productivity, ecosystem stability and biodiversity?
- What properties of ecosystems make them resilient or vulnerable to biological invasions?

7.4.4 Operational capabilities: Marine Science for society

The research foci below are structured to yield operational deliverables - mechanisms that generate research outputs, with well-documented methods and demonstrable value, to be translated into socially beneficial applications and products on a routine basis. The operational component, in addition to completing the research value chain, will ensure the technical development and ongoing operation of the necessary marine observational, modelling, analysis and dissemination systems.

7.4.4.1. Observational systems and networks: GEOSS

Real-time observations of the oceans are very important to understand oceanographic processes, to enhance operational weather forecast capabilities as they are affected by global climate change, and to evaluate the regional consequences of climate change. The development of a regional ocean observing network will allow measurements to be made at the wide variety of scales necessary to resolve the variability of complex marine systems. Such a network - the regional implementation of GEOSS - will demonstrate how multi-scale and multi-sensor observations can be linked to remote sensing and modelling initiatives to provide integrated system assessment. As well as providing observations for a better understanding of the regional consequences of climate change, these regional ocean observation networks, operating in real time, can provide early warning of potential disasters such as cyclones and other extreme weather events, as well as, for example, the impact of pollution on human health and ecosystems that provide important ecosystem services.

7.4.4.2. Operational models

Global and regional ocean models are needed to assimilate data from the observing systems and produce real-time input to coupled ocean-atmosphere models to understand our regional climate system, enabling seasonal forecasts. These models will do for the oceans what the South African Weather Service does for weather forecasting: provide a predictive capability over a wide range of time scales. As well as providing projections of the regional consequences of climate change, these regional modelling systems, operating in real time and coupled to observation systems, can provide predictions of extreme events, ocean state and dispersion, for example, for oil spill and harmful algal bloom movement, or search and rescue operations. Over longer time scales, the South African Weather Service produces operational global sea-surface temperature (SST) anomaly forecasts and probabilistic ENSO forecasts every month. These forecasts are produced using multi-model approaches and should be integrated into the proposed operational oceanographic capability.

7.4.4.3. System indicators

Key outputs of the research foci are system indicators: relatively simple metrics, obtained from analyses of observations and model output, allowing a rapid assessment of system state and change. Examples of these are risk indicators to resources in the Benguela upwelling system based on wind regime shifts, or longer-term carbon sequestration indicators in the Southern Ocean. Similar indicators need to be developed for the east coast. Indicators of ecosystem state also need to be developed. The distillation of complex research and operational data into these system indicators will create effective convergence points between science and society.

7.4.4.4. Delivery to society

Transforming ocean observations and forecasts into beneficial operational products for end-users requires dissemination systems capable of managing and synthesizing large volumes of multi-source marine geo-spatial data through powerful, flexible visualisation and analysis systems. Outreach, education and communication programmes that empower a broad spectrum of users to fully exploit available information are also critical components of these dissemination systems. Investment in these systems, using international programmes and partners such as ChloroGIN and SensorWeb as springboards for effective technology exchange, will ensure value addition and broad take up of research and operational outputs. Linkages with accelerated science education and training initiatives are especially relevant here.

7.5 RESEARCH AGENDA: ATMOSPHERIC SYSTEMS

Here we explore the key research challenges associated with South Africa's atmospheric systems in more detail.

7.5.1 Dynamics and variability of the atmosphere

While there has been focused research in South Africa in the area of developing robust understandings of atmospheric dynamics and variability, notable and critical gaps remain. For example, the understanding of the physical linkages between the region and global modes of variability, feedback mechanisms, or historical trends in the context of natural variability. These issues determine the climate envelope that conditions all physical, biological and social systems of the region. Consequently, the improved understanding of atmospheric variability, and the dynamics and drivers of such variability requires attention.

Key research questions include:

- What are the main natural (i.e. non-anthropogenic) drivers of weather, climate variability and climate change over southern Africa?
- What are the key temporal and spatial scales of weather and climate variability, and how do the processes interact on these time scales?

Challenges in order to address these include:

- Identify and quantify time scales of natural variability on synoptic and regional scales.
- Determine the degree of spatial coherence between processes operating on different time scales.
- Understand the atmospheric dynamics and physics that modulate the above attributes.
- Identify and understand local and remote teleconnections amongst atmospheric variables and with larger scale boundary forcing (EÑSO, global sea surface temperatures, land use change, solar and cosmic influences).
- Identify and improve understanding of the dynamics of physical processes relevant to model development.
- Explore the nature of non-linearity in the climate system coupling.
- Expand the observational network and enhance the general database of observations for the southern Africa region.
- Develop improved forecasting/projection methodologies through drawing on the best attributes of dynamical and stochastic modelling.
- Improve understanding of extreme events.
- Learn more about paleao-climates to understand climate history, and to aid model development and validation model simulations.
- Improve coordination between institutions to collaborate and share data for analysis of climate processes.

7.5.2 Regional climate change

As climate change is increasingly recognized by decision makers as a key aspect across all sectors, there is a rapidly growing need for more robust information on the regional nature of climate change. Substantive attention has been paid to developing methods for providing indications of climate change at the regional scale, but these techniques urgently need improvement and greater application if the base knowledge for stakeholder response is to be generated. Historical change needs to be retroactively understood with regard to the relative roles of anthropogenic forcing and natural processes. Alongside this is the necessity to develop regional scale projections of the envelope of future climate change, on scales appropriate to stakeholders and tailored to the probabilistic and risk assessment needs of decision makers.

These issues are foundational to nearly all climate change responses. Without clear, credible, defensible, and actionable regional climate change information, decision makers can, at best, only take the costly route of building buffer capacity into societal activities so as to enhance resilience.

Key research questions include:

- Is historical change detectable and attributable to anthropogenic forcing?
- What are the probabilistic future regional climates?

Challenges in order to address these include

- Access to quality controlled observational data for understanding past changes in order to develop and validate models for projections of the future.
- Detection of past change in regional climates and processes.
- Attribution of detected changes to causal mechanisms, including anthropogenic forcing.
- Quantify the magnitude of regional natural variability relative to the anthropogenic forced change.
- Estimate the relative roles of regional scale synoptic and hemispheric scale processes in driving regional climate response.
- Understand how anthropogenic change influences the modes of natural variability.
- Assess the stability of linkages in the climate system, especially teleconnections such as El Niño.
- Integrate dynamical model and empirical downscaling products to maximize the information content of forecasts and projections of regional change.
- Enhance downscaling methodologies and generate multi-model downscaled forecasts and change projections on time and space scales relevant to stakeholders.
- Identify and understand sources of regional climate change and variability uncertainty.
- Develop techniques to quantify and address uncertainties in a robust manner.

- Create large-ensemble and multi-model projections of the distribution of possible future climate and weather events to understand the envelope of possible future climates.
- Develop methods to derive probabilities of projected regional change.
- Understand the derivative attributes of climate change that are of key relevance to society (e.g. dry spell duration, heat waves, extreme events and seasonality).
- Analyze extreme event dynamics and assess future changes in extreme events, particularly in the context of societal relevant thresholds.
- Develop data archive and access centers to share model and downscaled data within the research community in standardized formats.
- Create science output appropriately translated for stakeholder interests.
- Develop communication frameworks for interfacing between science and society.

7.5.3 Atmospheric aerosols and pollution

South Africa's relative strength in understanding dynamics and characteristics of aerosols and pollution forms a solid base for further work in this regard. Transport and distribution dynamics in regard to aerosols and trace gases require substantive attention, as do their role as drivers of possible dynamics in extreme events, ocean states and land cover.

Key research questions include:

- How are aerosols and trace gases transported and distributed over southern Africa?
- What are the linkages and feedbacks between atmospheric composition and extreme climate modes, weather events, ocean state and land cover?

Challenges include:

- Understanding regional mechanisms for pollution dispersion, transport, and chemistry (including trans-boundary pollution).
- Understanding regional forcing (including fluxes and emissions) to the composition of the regional atmosphere.
- How will future climate change modify atmospheric composition and chemistry?
- What role is played by regional atmospheric pollutions and chemistry in modulating regional climate?
- Improving parameterization of aerosol-cloud interactions (microphysics) in atmospheric models.

- Understanding how atmospheric processes modulate regional air quality forecasting.
- Evolving and/or incorporating more sophisticated land surface, aerosol and chemistry sub-models in existing atmospheric models.
- Improve on local air pollution modelling (winds and dispersion of chemicals).

7.5.4 Atmospheric modelling

Significant research challenges remain in atmospheric modeling, critical for applications such as forecasting and climate change projection. Improved simulation and model design will move the science (and application thereof) to a point of greater model skill and utility.

Key research questions include:

- How to improve model simulation of the regional and global atmospheric physics and dynamics on time scales of turbulence, weather, and climate?
- How can model experiment design be evolved and simulation output better analyzed to improve forecasts and projections of the weather and climate (including data assimilation and stochastic pre- and post-processing)?

Challenges include:

- Identify priority parameterization and sub-model issues and develop model enhancements (particularly turbulence, convection, cloud formation, precipitation, land surface schemes, and chemistry and aerosols).
- Improve numerical weather prediction skills through assimilation of observations and new pre- and post-processing techniques.
- Development and improvement of land-surface and ocean coupled models for simulations and forecasts and projections on different time scales.
- Improve on modelling facilities for anthropogenic climate change simulations.
- Develop the application and implementation of multiple coupled ocean-atmosphere models.
- Develop capabilities of variable resolution and nested modelling.
- Engage in transferability experiments to assess the robustness.
- Undertake multi-model and perturbed physics experiments.
- Verification of model outputs as aids for model improvement.
- Consolidate data repositories in standardized formats for sharing within the community.

- Training of skilled scientists in mathematical and stochastic modelling as well as computer programming.
- Ensure supercomputer facilities for model simulations and development.

7.6 INFLUENCING AND ADAPTING TO CHANGE AFFECTING SOCIOECOLOGICAL SYSTEMS

What information and knowledge is needed to enable a transition to a more sustainable socioecological system? How are the new possibilities to become an established basis for human existence? Answering these questions requires research and analysis with an explicit *human interest* to bring about a sustainable future for humanity as well as the millions of other species with whom humans share the planet. This research and thinking will have to provide a basis for answering profoundly important ethical questions that recognize the impossibility, as humans shape their future, of separating the two questions: what *can* we do and what *should* we do?

Given the social transformation of nature, these questions have become completely inseparable. The multi-dimensional problems emerging from the polycrisis mentioned in Chapter 2 can only be effectively studied through inter- and transdisciplinary approaches. As such, the structuring and framing of the research questions must, from the onset, lead our methodological endeavours in this direction of collaborating across, between and beyond our disciplinary, institutional and sectoral boundaries. A research agenda that permits South Africans to tackle the polycrisis facing all humans in ways that respond to our particular political imperatives will have to focus on finding ways of integrating these with the ecological imperatives this plan has set out.

Social-economic and ecological sciences can make clear to us what the challenges are. They can also inform us of the binding constraints within which we will be required to work in responding to these challenges. These sciences can help us scan horizons across space and time to see what has happened and to identify responses that hold promise; however, they cannot alone provide answers. Science can help us understand what *is* but it cannot alone chart a course into the future. It can generate the knowledge base that will inform new policy frameworks, new institutional arrangements, and technology options. What these sciences can also do is enable us to reflect on the process of innovation that we will require so that we can move as rapidly forward as possible.

7.6.1 Sustainable agriculture and food security

The need to feed a growing population with changing dietary expectations, to make South Africa food secure in the future, as well as to make a positive contribution towards foreign exchange earnings all place huge responsibilities on the formal and informal South African agriculture sectors to increase food and fibre production. They also place similar responsibilities on government to facilitate enhanced agricultural productivity. These needs take place in an already highly variable climate from place to place and from year to year, on arable land further constrained by physiography and land that is in various states of degradation often as a footprint of recent past and present political engineering. Uncertainties in the future through changes in a combination of demographic, socio-political and climate drivers present a huge challenge to the research communities in these fields, in particular in regard to responding to climate changes. The findings of the International Assessment of Agricultural Science Technology and Development (IAASTD) are relevant to the crisis of degrading soils, declining average growth in yields (gross and per hectare), and the longer-term implications for food security of global warming impacts, This final report of this Assessment strongly recommends the incorporation of ecosystem science and indigenous knowledge systems into mainstream conventional agri-science.

The key challenge here is to produce research that will support policy and interventions to enable sustainable agriculture that is resilient under external stresses (associated with Global Change), yet further addresses food and commodity insecurity. Research on sustainable agriculture - with special reference to soil quality - has typically tended to focus on challenges rather than opportunities. The approach taken in Chapter 6 is thus a valuable one in conceptualizing a workplan in this regard – focussing on taking advantage of opportunities for agriculture.

Examples of research questions

- How can state-of-the-art appropriately downscaled projections/scenarios for climate change be best utilized for practical application in agriculture in South Africa?
- What are the magnitudes, rates and directions of 1st order changes in atmospheric CO_2 concentrations, in temperature patterns/attributes and in rainfall patterns and attributes in the different agricultural regions of South Africa?
- What are the 2nd order changes in agriculture-related climate derivatives, for example, changes in heat units, chill units, frost distribution and characteristics, soil moisture and the beginning and duration of growing seasons and how would these impact on commercial, subsistence or emerging agriculture?

- What are the 3rd order impacts on commercial and emerging farming of future climate perturbations on, for example, shifts in optimum production areas and yields of food and agronomic and horticultural export crops, veld and pasture grazing, plantation and agriforestry and pest and disease occurrences, and how can these be simulated with complex, intermediate and rule-based models?
- To what extent, and where geographically within South Africa, can adaptation be effected in rainfed agriculture, both commercial and emerging, through changes in tillage practice and management, in crop type, cultivar choice and planting dates, in fertilizer and pesticide application, etc?
- How can sustainable agriculture that still meets food and commodity security challenges best be supported by institutions and interventions?
- What role will irrigation play in future climates, in regard to changes in total and seasonal irrigation water demands and to scale efficiencies of small- versus large-scale projects. To what extent and where in South Africa can adaptation be effected through improved application, and other measures, of water use efficiencies, including deficit irrigation or fractional water allocation, and links to agriculture-targeted climate forecasts with lead times of days to weeks?
- What effects could projected future climates have on carbon:nitrogen ratios of the soil and grazing quality, declining soil nitrogen levels (with effects on yields) and other agriculture related cycles (C,P,N)?
- With the strong links to water sector, how will the dynamics of interrelationships between water's influence on agriculture and agriculture's influences on water change in future climates?
- What are the wider ranging impacts of climate change on household and national food security, international trade, balance of payments, new land being freed for agriculture and agricultural policy in general?
- What agricultural database (spatial and temporal) and model development (with links to water and economics) need to be enhanced in South Africa to implement effective adaptation strategies for the future?
- Is the American eight class land capability evaluation system and its clones appropriate for South African conditions? Or should a South Africanized version of the FAO's land suitability evaluation framework and guidelines be developed to guide land use decisions? Given that approximately 30% of the 14 million hectares of arable land in South Africa is degraded, what farming practices and techniques contribute to soil health restoration on both degraded and non-degraded land?
- Given that the costs of off-farm chemical inputs are steadily escalating as the oil price rises over the long-term, what kinds of 'low external input' farming systems are most appropriate for South African conditions?

7.6.2 Sustainable cities

Urbanisation is a global phenomenon that is most recently apparent in developing countries. In South Africa it is compounded by the legacy of nearly a century of efforts by the state to control the rights of movement of people. Once those restrictions were released, the population of South Africa changed from being predominantly rural, to predominantly urban - although the reality in South Africa is much more complex than this simple characterisation. Accompanying this population shift is a large increase in resource use. For example, the per capita use of water increases by nearly ten-fold when water is supplied from a nearby tap, and the use of fossil fuels by urban populations is many times higher than that by rural people. The demands that cities impose on mineral, water, forest, marine and agricultural resources, as well as the load they impose on the absorptive capacity of the biosphere for sewage, solid waste and air pollution are severe. On the benefit side, the process of urbanisation is key to achieving a 'demographic transition' whereby population growth stabilises and wellbeing improves. Although the physical footprint of urban settlements is locally concentrated, it has global dimensions in a world where goods are traded widely. The size of the ecological footprint of a city depends greatly on where the city is located and how it is designed, constructed and operated.

As cities in sub-Saharan Africa become the primary nodal points of economic and population growth, they also become the focus of substantial investments in urban infrastructures that could either be designed in traditional high carbon, resource- and waste-intensive ways, or with a long-term future in mind - equipping cities to become zero waste, low carbon, self-sufficient and high quality environments to live in. Energy, transport, food supplies, solid waste, water and sanitation are the big issues that need to be rethought in light of ecological thresholds, poverty eradication and dematerialised economic growth. Chapter 6 notes that inequality in such urban areas is likely to become worse, given macro-economic and Global Change trends. The exposure and vulnerability of urban populations to Global Change differs from that of rural populations, not only in the obvious ways. For example, urban conglomerations are prone to developing 'heat islands', but on the other hand the population is better served by health facilities in which to treat vulnerable populations. Around the world, an increasing fraction of urban development is along the coast, where there is high vulnerability to sea level rise and flooding resulting from extreme weather events. The research challenge in cities thus involves research to support the development of more equitable urban settlements, while decoupling their material growth from increased resource use and environmental degradation.

Examples of research questions

- How will the increasing concentration of the population in large cities alter the footprint of South Africa on the regional and global environment, and the vulnerability of those populations to Global Change*?*
- How can new transport infrastructure be optimised to reduce dependency on fossil fuels and reduce climate change impacts?
- How can building design and construction techniques minimise the energy demands over the life-cycle of the building, and provide a comfortable living environment despite a changing climate?
- How can the resource demands by urban areas be reduced by closing their ecological cycles internally, through for instance domestic energy generation, rainwater harvesting, local waste treatment and recycling, and urban agriculture and forestry?
- How can urbanisation occur sustainably and lead to a reduction in poverty through the development of new green economies that cut across the formal and informal sectors?
- What decision-support and monitoring tools will Local Governments require in order to measure energy and material flows and progress towards sustainable resource use?

Approach and activities

Many of South Africa's major cities, plus many smaller towns, are attempting to introduce sustainability principles into their Integrated Development Plans and sector strategies (e.g. waste management, energy, transport). There is, however, a need for a standardised approach that deploys systems dynamics modelling to build up decision-support tools for Local Governments interested in linking current decisions to long-term outcomes. The City of Cape Town has led the way in this regard with a model that addresses energy, waste, water and sanitation. These sectors alone comprise 50% of Local Government expenditure and 10% of the Gross Geographic Product of a metropolitan economy. If one adds to this the transport and food supply sectors, then one has an agenda for sustainable resource use in our cities that links together technological, institutional and relational innovations. The key activities would include the following:

- Development of modelling tools
- Comparative analysis of the resource efficiency of the major sectors – energy, waste, water, sanitation, transport and food

- Analysis of technological innovations that will significantly improve efficiency (better use of resources using existing technologies) and resource productivity (more output per unit of input of resources using new technologies)
- Analysis of institutional innovations required to foster more sustainable resource use
- Support for urban entrepreneurs who contribute to wealth creation within poor constituencies

7.6.3 New modes of governance

Appropriate modes of governance for building developmental states will be required. In particular, modes of governance are needed that understand the intersection between ecological resource thresholds and development interventions, and are not simply about investing in infrastructure as a growth stimulant but are also about investing in social learning, innovation and the emergence of new value chains. Such an approach has been reiterated in several research questions and activities described earlier. Essentially, the approach considered focuses on what Chapter 6 refers to as a 'new institutional imaginary'; or, more specifically, what institutional structures (including interventions) best support the transition of the developmental state to a sustainable socioecological regime. It is important to observe here that research in this area needs to focus on what is *currently* working (i.e. best practice in governance broadly understood), as well as what new models or frameworks might be effective.

7.6.4 Social learning, innovation and building new value chains

Instead of finding specialist niches within the global economy and focussing investment on these, South Africa must find ways of building more resilient economic regions that are dependent on sustainably managed ecosystems and local economies which are diverse and knitted together via locally connected value chains. The challenge is to create regional 'bio-economic diversity'.

Chapter 6 calls for substantial public investments in social learning for sustainable living – both at the techno-infrastructural level (incorporating, for example, new technologies for sustainable cities), and in relation to institutional arrangements and social behaviour (for example, new incentive and regulation structures for water use in agriculture). A key research question, thus, concerns what types of investments in social learning may trigger innovations that are informed by ecological criteria and help support South Africa's transition to a sustainable socioecological regime?

7.6.5 Ethics, values, spirituality, behaviours, capabilities, sensibilities and mentalities

Human institutions and practices arise out of deeply embedded traditions of thought that have for centuries, within Western philosophies, separated humans from their sustaining environment. This has been associated with values and ethics that have set ‘man’ against ‘nature’ in ways that have led humans to systematically destroy the very grounds for sustainable human existence. There have been many critiques of this from across a wide spectrum of disciplines. However, this has yet to bring about a commensurate widespread shift in practice, institutional arrangements and social technologies. What is required is a dramatic shift in the deeply embedded sensibilities (institutions and technologies) that underlie human understandings of the planet and their relationship to it.

A key research question that could trigger practical responses might involve new understandings of how faith-based groups and networks may be engaged in social learning around sustainable living, for example, in urban settlements. Another research question might be the kind of environmental ethics that may be required, in particular an ethics of pragmatism that proceeds from what is required by particular contexts as perceived by stakeholders rather than an ethics that derives from a set of abstract first principles and applied uniformly across contexts.

7.6.6 Social capital, solidarity, identity and cohesion

Much thought has been given to the consequences of the breakdown of ‘dense’ social ties – often understood as “social capital” (Putman 2000) or “collective efficacy” (Sampson 1999) – for human activity. Social capital, it is argued, contributes to cohesion and well being. Similar arguments can be applied to a failure to recognize the close ties and solidarity that must exist between humans and crucial ecosystems. Key research questions here may contribute to the existing work on the role of social networks in, for example, preventing a vulnerable household from exceeding the threshold of potential concern in coping during a severe drought; or the role of social networks and capital in promoting institutional learning in support of sustainable agriculture.

7.6.7 Risk, security, disaster management and resource wars

There is a body of research that argues that science itself has created, and is creating, hazards of enormous proportions. This has led to what Beck (1992; see also Giddens 1990) terms a “risk society”. Human knowledge systems, often as a result of their attempts to improve human well being, sometimes become a fundamental source of environmental insecurity and this can lead to societal collapse (Diamond 2005). One consequence of this has been increased conflict arising from competition for resources (Klare 2008). A critical research question here would involve new forms of conflict resolution (possibly involving substantively different institutional structures), for example, in community disputes around groundwater.

7.6.8 Greening the macro and micro economies

The challenges outlined require new economies that will create human well-being in ways that do not compromise ecosystem services. Identifying the opportunities and conditions for these new 'bright green' economies and their relationship to developmental (and *new* developmental) agendas is crucial to emerging developmental states such as South Africa. Our broad challenge remains to develop transdisciplinary research responses and administrative and institutional arrangements that support the developmental state's transition to a sustainable socioecological regime. Materials and energy flow analysis should lie at the centre of this approach. Materials and energy flow analysis helps to determine the current average level of carbon in tons and extracted materials used per capita in tons in order to develop a framework for setting long-term targets including zero carbon, zero waste and high resource productivity economies.

7.7 SKILLS AND INFRASTRUCTURE NEEDED

While South African research in the field of Global Change is internationally well established and respected it needs to be strengthened to increase critical mass and to enhance interdisciplinary work. Furthermore, it needs to provide ongoing capacity-building to ensure it remains viable and continues to provide benefit to a society having to cope with a future environment of increasing uncertainty and greater complexity. This changing environment has implications for providing ecosystems services, economic development, shaping urbanization, poverty alleviation and food and health security. Against a positive opportunity to develop strong research expertise that addresses national needs and informs strategic planning, there is the recognition that this scientific excellence currently has insufficient critical mass to ensure its sustainability. This is manifested in the near crisis situation of providing leadership and supervision for post-graduate training and skills acquisition within various government agencies. Other constraining factors include:

- A lack of a career path for graduating students due to limited post-doctoral or research funded opportunities of any significant duration, and limited growth of research posts.
- A shortage of Information Technology (IT) literacy and training for computationally focused research.

- Limited under- and postgraduate bursaries and research funding available to support students and research.
- Limited post-doctoral funding at appropriate competitive levels in order to attract post-doctoral candidates of excellence.
- A shortage of peripheral computational infrastructure to support the core supercomputer performance; notably in the areas of data storage, management and dissemination in an open framework to support all researchers.
- A declining observational network compounded by difficult access from archives with data held in a variety of formats that constrain usage.

The high dependence on various single individuals scattered across spatially separated institutions represents a risk that skills and facilities could easily be lost without some form of intervention. There is also a lack of high-level courseware to fulfil the needs of an emerging Global Change community. Inter- and transdisciplinarity is required for effective research in this arena, but must rest on a base of strong specialization, combined with the incentives and arrangements to facilitate interaction across disciplines.

7.7.1 Skills

7.7.1.1. Disciplinary skills

The core disciplinary skills needed to address fundamental Earth System questions, including the analysis of the human subsystems coupled to the biosphere, are (in alphabetic order):

- Biogeography and evolution
- Climatology and climate modelling
- Development studies
- Disturbance, population and dispersal ecology
- Ecophysiology, both terrestrial and marine, and of both plants and animals
- Environmental history, particularly over the past 300 years
- Human demography
- Geomorphology
- Hydrology
- Palaeoecology and palaeoclimatology, including palynology
- Physical and biological oceanography
- Resource and environmental economics

- Social anthropology and sociology
- Systems ecology and biogeochemistry

7.7.1.2. Interdisciplinary and transdisciplinary skills

In addition to the above core disciplines, interdisciplinary and transdisciplinary competencies are essential. These include:

- Modelling skills, including both quantitative and qualitative models.
- Scenario development and communication skills (including techniques for communicating uncertainty and probability).
- Advanced statistical techniques for dealing with spatial patterns, socioeconomic data analysis, time series (including longitudinal modelling of socioeconomic, health and demographic data) and complexity.
- Sustainability science, focussing on understanding the coupled human-environment systemic relationships, complexity theory, and on issues such as resilience, institutional design (governance), sustainability indicators and development economics. There is a specific need here for training in institutional analysis, and the field of social learning (see research questions related to new institutional designs for a sustainable socioecological regime).
- Interdisciplinary communication specialists, who are able to facilitate the interaction between social and natural science researchers, as well as foster better science-policy links, better integration of climate change with development studies, and links between the research, academic, non-governmental, business sector and government communities.

Critical mass is needed in all the above domains. In practice, this means at least ten experienced researchers in each field, and often more. At least one tertiary education department needs to have a specialisation in each field.

7.7.2 Infrastructure needs

This agenda requires certain research infrastructure in order to make progress. Some of this infrastructure already exists, but needs to be maintained or expanded. Other items are new.

7.7.2.1. Centres for integrative modelling, data collection and databasing

Modelling is a core skill in order to be able to test our understanding of complex systems. Models occupy a range of computational intensity, from those that can run comfortably on desktop computers (but may need specialist software, and good bandwidth to access datasets), to those that need high-performance computing capacity. As important as the hardware and software, is the data needed to drive and parameterise the models – and typically this is the area where the globally-developed models are weakest with respect to Africa and its surrounding oceans. The necessary datasets include both biophysical and socioeconomic data. For example, spatially-disaggregated data on population distribution, economic activity and the location of key infrastructure is as essential as maps of land cover or bathymetry. While collecting new data is critical, there is a lot of past (historical) data (including museum and herbarium records) that could be used in Global Change research. A starting point would be the preparation of databases of expertise, together with descriptions of various existing datasets on atmospheric conditions, soil and land use status, freshwater, and marine ecosystems, socioeconomic, health and demographic conditions, resource utilization and restoration interventions. The South African Environmental Observation network (SAEON) and the Council for Scientific and Industrial Research (CSIR) are presently developing an interoperable portal for archiving and sharing spatially and temporally explicit observational data.

It is also important that mandates for distribution of data continue. Further, public-domain data should be put online with good metadata descriptions. Where data are not in the public domain its metadata should be made freely available. Given that many departments and agencies have data, but have insufficient capacity to distribute it, de-centralised data distribution could be considered where the data use is registered through an online service (with terms and conditions of use). Once these agreements are cleared they can be shared between research partners.

Further improvements include:

- Substantial development of the observational archive including rigorous quality control, collation of relevant data from disparate sources, standardization of formats to user-friendly forms compatible with general research tools, and facilitation of simple access for free by all researchers.
- Extending and strengthening the observational data network with appropriately supported personnel to reliably ingest data into standardized archives.
- Support the creation of a data centre for collation and sharing of data emanating from individual research projects and so catalyse a far broader base of analysis and study[1].

[1] A notable example in this regard, which has been exceptionally successful, is the archive of model data for the IPCC AR4. This initiative massively enhanced the value of the data and spawned a broad array of studies which significantly amplified the value of the data.

7.7.2.2. Sites on land and oceans that are instrumented for micrometeorology and biogeochemistry

On land these sites typically include flux towers equipped with eddy covariance sensors, radiometric instruments, meteorological sensors and soil moisture sensors. In the oceans they take the form of on-ship instruments, moored buoys, and systems of drifting buoys. These instrument arrays are expensive to establish and technically demanding to maintain, so strategic thought needs to be applied to their distribution. Guiding principles include the importance of the ecosystems to southern Africa, the degree to which the ecosystems are represented in global systems, and the practicality of servicing the equipment. A minimum set should include a replicated package (i.e. at least two of each, to allow for redundancy) of shipboard sensors, moored buoys and land-based flux towers.

7.7.2.3. Ecophysiological and laboratory instrument packages

The equipment needed to conduct key research and train the next generation of ecophysiologists includes portable infrared gas analysis photosynthetic systems, *in situ* respiration arrays, porometers, psychrometers and pressure chambers, leaf area meters, fluorescence instruments and spectral radiometers. Many analytical laboratories which have certifications need to be maintained and expanded (e.g. Isotope, Atomic Absorption and Mass Spectrometry Laboratories). These should be linked more explicitly with key flagship experiments.

7.7.2.4. Meteorological observation network

Continuous data is collected through automated systems such as weather stations and hydrological monitoring stations. Adequate sampling needs to be maintained at the surfaces of land and ocean, in the upper atmosphere and below the ocean surface (temperature, current and salinity profiles), to match the scale at which key studies are being conducted. A commitment is needed to maintain both the hardware required and the data basing facilities for storage of the data obtained.

7.7.2.5. Access to Earth Observation remotely sensed data

Researchers need affordable and practical access to remotely-sensed data, largely from satellites, at a variety of spatial and temporal resolutions, and with coverage of the southern African subcontinent and adjacent oceans. Key data for Earth System analysis include (Table 7.1):

Table 7.1: Key data for Earth System analysis

Sensor	Resolution	Products	Frequency
Meteosat second generation	2 to 5 km	Clouds, radiation, profile water content, winds, fire radiative energy	15 minutes
MODIS, Envisat	250 m to 1 km	Multi-band visible (VIS) and near infra-red (NIR) Land greenness indices: e.g. NDVI, EVI, FAPAR etc. Ocean colour, temperature and salinity Aerosols Albedo	Daily, composited weekly
SPOT, landsat IRS	5 to 30 m	Multiband VIS and NIR	1 per year
Radarsat, ERS	30 m	Synthetic Aperture Radar, Digital Elevation Models, scatterometry winds, Tree height and biomass	Variable; some once only or every 5 years, others up to daily
Ikonos, Quickbird, Sumbandilasat, MSMI	1-5 m	Multispectral images, hyperspectral data	1 per year

To use these data effectively also requires bandwidth, memory (including large-capacity archives), computational power and specialised software.

A major component of marine observation systems is marine remote sensing: a powerful and cost-effective means of observing the marine and coastal environment, allowing routine measurements of a wide variety of near-surface ocean characteristics over decadal time scales. The Marine Remote Sensing Unit (MRSU) is a multi-institutional collective that has been mandated to serve southern Africa's marine earth observation needs, and will implement the marine component of the Global Earth Observation System of Systems (GEOSS) and the South African Earth Observation Strategy (SAEOS). The Marine Remote Sensing Unit is one of the few African centres of excellence in marine remote sensing, and has demonstrated that it has the expertise to develop, acquire, process and disseminate user-focussed satellite-derived marine geo-spatial products on a pre-operational basis. Investment in infrastructure and technical support, in addition to skills development through research, will create an operational capability allowing the climate-focused use of multi-disciplinary earth observation data over decadal time scales.

7.7.2.6. Advanced measurement and analytical capability

There needs to be national capacity, with some built-in redundancy, to undertake high-precision measurements and laboratory analyses. The Global Atmosphere Watch facility operated by the South African Weather Service at Cape Point is a key example, as is the radiocarbon dating facility at the CSIR. Important techniques include gas chromatography, stable isotope mass spectroscopy, and precision trace gas analysis, including standards preparation. The high-level technical skills to operate the instruments and to analyse the data are obviously prerequisites.

7.7.2.7. Big field experiments

South Africa should consider a set of key flagship experiments that could serve as nuclei for foreign scientists and skills development of young South African scientists.

Terrestrial examples could include flux towers equipped with eddy covariance sensors, radiometric instruments, sensors and soil moisture sensors. Oceanographic examples could include on-ship instruments, moored buoys, and systems of floating buoys. Location needs to be guided by the representivity and national significance of the ecosystems as well as degree to which they are represented in global systems together with the practicality of servicing the equipment. A minimum set should include a replicated package of shipboard, moored buoy and land flux towers.

Socioeconomic and demographic flagship experiments are critical, building on the aforementioned call for long term observational datasets in socioeconomic and demographic surveillance (as well as building of skills). At least one flagship experiment should explicitly incorporate institutional analysis, building skills in this regard. Useful existing models in this regard include the Africa Centre for Health and Population Studies at the University of Kwazulu-Natal (Demographic Information System) and the Agincourt Demographic and Health Surveillance System of the University of Witwatersrand's School of Public Health (Agincourt Health and Population Unit).

7.7.2.8. Marine observational technology

Ship- and satellite-based observations cannot provide ocean observations at the wide variety of spatial and temporal scales necessary to resolve complex marine processes. A modular, scalable and low-cost observational architecture is required, and this can be achieved through autonomous technology: moorings, profiling floats and autonomous vehicles equipped with a wide variety of sensors. Investment should aim at the creation of a sustainable multi-institutional *in situ* marine observation capability, focussing primarily on autonomous systems, implemented as part of a national marine-Earth observation strategy. Development of infrastructure, technical expertise and a technological base will serve the needs of many marine and coastal stakeholders, from estuarine to open ocean. The use of regional technological test-sites over a variety of marine and coastal environments will pave the way for better observational capabilities, and a South African marine technology capability driving knowledge and human capital development.

7.7.2.9. Research fleet

At present all research vessels in South Africa are operated under the auspices of the Department of Environmental Affairs and Tourism: Marine and Coastal Management for their primary line function - that of fisheries monitoring and management. Nearly all sea-going research is done as an add-on to routine monitoring cruises or Antarctic supply trips. The Marine and Coastal Management budget does not allow the full capacity of the vessels to be utilized. South Africa badly needs these vessels (and their replacements) to be placed in a pool as a national research facility, with a realistic operating budget and technical support. Research ships are too expensive to be run on any basis other than that of a national facility. Clearly, Marine and Coastal Management would need to have first call on the fleet for their line-function needs, but the rest of ships' time could be allocated to research projects on a competitive basis, as is done in UK, France and many other countries.

7.7.2.10. Magnetic Observatories

Southern Africa is the continental area where geomagnetic field changes can be best studied (Mandea *et al*. 2007). Since the establishment of the Hermanus Magnetic Observatory in South Africa in 1941, the total field intensity has decreased by more than 20%, which is greater than the decrease at any other magnetic observatory (Kotzé *et al*. 2007). This is mainly due to the presence of the South Atlantic Anomaly (SAA), a region where the geomagnetic field is about 30% less than expected and also decaying at an anomalous rate. The SAA is the result of geodynamo processes taking place at the core-mantle-boundary, some 3000 km below the surface of the Earth.

Presently, the Hermanus Magnetic Observatory operates four geomagnetic observatories in southern Africa. Three of the four observatories, namely Hermanus and Hartebeesthoek, and in Namibia, Tsumeb, are INTERMAGNET quality stations. The fourth station, Keetmanshoop, also in

Namibia, does not yet qualify as such a station; however, it is anticipated that it will soon achieve this status. It is also anticipated that a new observatory will be installed in Botswana and discussions about a suitable site with the necessary infrastructure, finding reliable personnel for the absolute observations and how to share the tasks of data processing and distribution have started with Botswana's Department of Geological Survey. These discussions must be pursued towards successful implementation.

7.7.2.11. Geomagnetic field measurements in the Southern African Repeat Station Network

Critical information needed for understanding the Earth's core geomagnetic variations are obtained from high-quality measurements in a network of stations well distributed over the area of interest. Recently, the Hermanus Magnetic Observatory and GeoForschungsZentrum (GFZ) teams have measured some 40 secular variation field stations distributed over southern Africa (in South Africa, Namibia and Botswana). Recent experience has shown that this number of stations is near-sufficient to accurately model the secular variation, even with the important temporal and spatial gradients over the southern African region. However, it is proposed that the secular variation field stations include Zimbabwe. All stations must be visited annually, with revision of this strategy every 5 years. The repeat station services must continue to be adapted to international quality standards.

7.7.2.12. Bandwidth and High Performance Computing

An immediate priority is provision of reliable, low-cost and fast bandwidth into researchers' labs, including high speed international connectivity. High Performance Computing capacity also needs to be accessible in researchers' labs to facilitate training and experiment design for larger activities that might take place on computers at South Africa's Centre for High Performance Computing.

7.7.3 Additional interventions

In addition to the skills and infrastructure needs outlined above, there is an important final set that must be provided for. The following are included in this:

- Incorporating Information Technology skills training in the core curriculum of Global Change related tertiary education.
- Significantly enhancing bursaries, research and post-doctoral funding at competitive levels and committed for multi-year periods to maximise the value of training, research and post-doctoral fellows.

- Creating new research career opportunities to retain the growth in research capacity of new graduates.
- Leveraging existing research capacity that has momentum in key areas by providing low administrative overhead support for ancillary functions to allow growth beyond the scale of small project teams, and so tackle grand challenge questions.