Overview

Climate change impacts and adaptation in South Africa

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In this paper we review current approaches and recent advances in research on climate impacts and adaptation in South Africa. South Africa has a well-developed earth system science research program that underpins the climate change scenarios developed for the southern African region. Established research on the biophysical impacts of climate change on key sectors (water, agriculture, and biodiversity) integrates the climate change scenarios but further research is needed in a number of areas, such as the climate impacts on cities and the built environment. National government has developed a National Climate Change Response White Paper, but this has yet to translate into policy that mainstreams adaptation in everyday practice and longer-term planning in all spheres and levels of government. A national process to scope long-term adaptation scenarios is underway, focusing on cross-sectoral linkages in adaptation responses at a national level. Adaptation responses are emerging in certain sectors. Some notable city-scale and project-based adaptation responses have been implemented, but institutional challenges persist. In addition, a number of knowledge gaps remain in relation to the biophysical and socio-economic impacts of climate change. A particular need is to develop South Africa's capacity to undertake integrated assessments of climate change that can support climate-resilient development planning. © 2014 The Authors. *WIREs Climate Change* published by John Wiley & Sons, Ltd.

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INTRODUCTION

Climate change is a key concern within South Africa. Mean annual temperatures have increased by at least 1.5 times the observed global average of 0.65°C over the past five decades and extreme rainfall events have increased in frequency. These changes are likely to continue: the 2013 South African Long Term Adaptation Scenarios and the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

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(IPCC AR5) for Representative Concentration Pathway (RCP) 8.5 suggest warming relative to 1986–2005 of 3–6°C by 2081–2100 in the interior, yet less certain precipitation changes in terms of both direction and magnitude.[a] Climate change poses a significant threat to South Africa's water resources, food security, health, infrastructure, as well as its ecosystem services and biodiversity. Considering South Africa's high levels of poverty and inequality, these impacts pose critical challenges for national development.[2]

Like many other parts of the world, early climate change research in South Africa was initially framed as an environmental problem, rather than a developmental one. Nonetheless, after 2001, public communication of the results of the country's Initial National Communication to the UNFCCC drove a strong adaptation and mitigation action agenda both in national policy development and in UNFCCC negotiations. Encouragingly, South Africa's policymakers and academics have worked together quite closely on climate change. In 2005 this was evidenced by interlinked science and policy plenary sessions at the National Climate Change Summit, 'Climate Action Now'. Key policies that resulted include the National Climate Change Response White Paper[3] and South Africa's Second National Communication under the United Nations Framework Convention on Climate Change[2] (SNC).

South Africa's per capita emissions are high as compared with other countries on the African continent and even globally, and as a result climate change mitigation has been a focus for a number of years.[2,3] For example, the government commissioned research, first proposed at the 2005 National Climate Change Summit, that culminated in the Long Term Mitigation Scenarios.[4] Responding to these scenarios, policies have been developed, including the Renewable Energy Independent Power Producer Procurement Programme and more recently National Treasury consideration and planned implementation of carbon taxes.[5,6]

Increasingly, however, the issue of climate adaptation is coming to the fore. In the context of South Africa's urgent socio-economic developmental needs and threatened ecosystem services, adaptive responses that reduce vulnerability to current as well as future climate variability and change are critical. Reducing the so-called 'adaptation deficit', that is exposure and sensitivity to the present-day climate variability and observed change, is an important dimension of long-term adaptation planning.[7] Responses at the national level have started to focus on integrated development trajectories more broadly. South Africa's new National Development Plan 2030[8] goes some way toward reframing climate change as a development challenge. Several government departments across all three spheres of government—national, provincial, and local—are now developing climate change strategies and/or plans.

To develop a coherent national adaptation response, there is a need to integrate climate science, impacts and vulnerability studies, as well as results from assessing various adaptation options, into both sectoral and cross-sectoral decision-making processes. Our aim is to review various approaches to impacts and adaptation research, and present a brief overview of some of the key findings, as well as point to significant knowledge gaps that warrant further research.

Many of the key findings are drawn from the Long Term Adaptation Scenarios (LTAS) process that released first phase reports for comment in mid 2013, and the second phase of which will be finalized during 2014[1] (see Box 1). The LTAS process pulls together much of South Africa's existing climate science and impacts work and offers new analysis that highlights ways in which the country should be approaching climate adaptation in the context of its development priorities.

THE STATUS OF CLIMATE SCIENCE IN SOUTH AFRICA

South Africa arguably has the most advanced research, observation, and climate modeling program on the African continent. This expertise is situated across a number of universities and science councils and covers most aspects of earth system science (ESS), including atmosphere, oceans, land surface, biogeochemistry, and hydrology. The number of South African researchers leading and participating in international global-change research programs and scientific bodies, such as the Intergovernmental Panel on Climate Change (IPCC), is relatively high, as is the count of journal articles published by South African authors.[b] South Africa has co-led major regional earth system science initiatives such as Safari 94 and Safari 2000, and the Benguela Current Large Marine Ecosystem program. Under the SA Global Change programme, significant support for ESS has been provided through national programs such as South African Environmental Observation Network (SAEON) and Applied Centre for Climate and Earth Systems Science (ACCESS).[c]

Within the broader SA ESS research, climate process studies have mostly focused on mechanisms that control inter-annual and decadal variability and, in recent years, on understanding how these mechanisms might be affected by climate change. Another

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BOX 1

LONG TERM ADAPTATION SCENARIOS (LTAS) PROJECT

South Africa's 2011 national policy position on climate change emphasizes that socio-economic risks resulting from a range of emission scenarios need to be better understood and quantified in order to inform planning and practice.[3] In an effort to address the problem, in 2013, the National Department of Environmental Affairs commissioned the Long Term Adaptation Scenarios (LTAS) project.[1]

The objectives of LTAS are to develop national and sub-national adaptation scenarios under a range of plausible future climate conditions and development pathways, so as to enable the incorporation of 'climate resilience' in future development planning. Underpinning the LTAS process is new research in which the CSAG and CSIR downscaling approaches were intended to provide an internally consistent suite of high-resolution climate projections.[2] These projections were downscaled from the two most recent generations of GCMs (CMIP3 and CMIP5) and emissions scenarios (SRES and RCP) that were used in the Fourth and Fifth IPCC assessments, respectively. LTAS represents the first common, dynamical as well as statistical suite of high resolution projections for South Africa, as well as a comparison between two generations of global climate models, resulting in an ensemble of 78 individual projections.[e]

The LTAS climate scenarios result in a wide range of projected changes, both in extent of warming, but also in the direction and magnitude of ensemble-mean precipitation change across different approaches (Table 1). Even greater ranges in precipitation change emerge when individual projections in the ensemble are investigated (not shown).

An additional set of climate scenarios, developed by Massachusetts Institute of Technology (MIT), has also been included in LTAS because it had been applied in a parallel project sponsored by National Treasury to quantify economic impacts of climate change at the national scale. The MIT process generates a very wide range of potential outcomes by design, in order to address uncertainty, but the methodology is limited in mechanistic realism order to allow for the many thousands of scenarios it generates.[31]

The inherent uncertainty in the LTAS climate projection data is an aspect that has yet to be robustly examined, but is common to all multi method and/or multi-model ensemble-based scenarios worldwide. This issue is emerging as a key challenge for the global climate services community as evidenced by the science agenda of World Climate Research Programme (WCRP) and similar organizations, and the call for a more rigorous framework to generate and assess downscaled information as outlined in Hewitson et al.[32]

Although these new scenarios do not provide any strong and consistent message regarding precipitation, they do represent a significant advance in the representation of the uncertainty. The implication is that scientists engaged in vulnerability and impacts assessments will need to consider a wider range of potential climate scenarios in order to assess risk fully.

In an attempt to capture this spread of results, the LTAS scenarios report suggests the use of four contrasting scenarios for South Africa: Hot-Dry, Hot-Wet, Warm-Dry and Warm-Wet futures. The 'Hot' and 'Warm' scenarios correspond to high and mid-level emissions respectively, while the 'Dry' and 'Wet' permutations capture the spread of uncertainty in precipitation projections. Impact modelers are currently researching ways to robustly use the four scenarios, although this is not without challenges, especially because at a sub-national level rainfall scenarios may diverge from the national average change.

key focus has been the links between local and remote ocean drivers of rainfall variability.[9,10]

South Africa has some of the best terrestrial vegetation, geology, and soils data in the region, and is developing greater capacity in the area. The South African research community's understanding of the functioning of the natural ecosystems and hydrology are well developed, and its modeling capacity is strong (see for example Refs[11–14]). The South African Weather Service and other agencies have coordinated relatively good quality and numerous meteorological observations compared to other African countries. These data have enabled a number of climate change detection studies[15–19] and a good understanding of natural variability. They have also supported model evaluation and model forecast development.[20–22]

The two key centers for climate modeling in South Africa are: (1) the University of Cape Town, where global and regional atmospheric, ocean and coupled modeling is undertaken by the Climate System Analysis Group (CSAG) and the Department of Oceanography, with a focus on ocean-atmosphere

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process studies, seasonal forecasting and climate change projections and (2) the Council for Scientific and Industrial Research (CSIR), which focuses on global and regional modeling for seasonal forecasts and decadal to centennial projections, as well as coupling to land surface dynamics. The two centers have slightly different foci.[23] CSAG has a long history of statistical downscaling using neural net approaches,[24] but has also produced a limited set of scenarios with regional climate models (RCMs), most notably MM5 and Weather Research and Forecasting model[25] (WRF). The CSIR has focused on the use of the variable-resolution CCAM model, which runs globally but at much higher resolution (down to km scale in some experimental simulations) over the southern African region.[20,26] The advantage of this in-country modeling expertise and experience is that substantial evaluation, tuning and development of the statistical and dynamical modeling tools that produce climate change projections has occurred (e.g., Refs[27,28]). This contrasts with many African countries where climate projection data products tend to be sourced from international centers.

Despite this relative abundance of locally developed scenario expertise, only a limited number of impacts studies have made use of both statistically and dynamically downscaled data. For example, an analysis of the impacts studies cited in South Africa's SNC, shows that only 5 of 35 studies (in which the sources for climate change projection were described) used both statistical and RCM scenarios driven by more than a single global circulation model (GCM). While most impact studies in South Africa have depended on CSAG and CSIR scenarios, other studies have made use of GCM outputs from the international Coupled Model Intercomparison Project (CMIP) archives, using simple change factor approaches to obtain higher spatial resolution. A few studies have made use of RCM downscaled products from international centers.[d] A consequence of this 'pick and mix' approach to the use of climate scenarios is that it has been difficult to compare and to synthesize the results of different impacts studies.

BIOPHYSICAL AND SOCIAL IMPACTS AND VULNERABILITY

In this section we summarize the main approaches that have been used to assess climate impacts and vulnerabilities in five sectors, namely biodiversity, agriculture, water, cities and health. We then discuss some of the key results from the LTAS process for each sector.

TABLE 1 | Summary of the Ensemble Mean Projected Changes in Precipitation in the 2080s for Differing Emissions Scenarios and Differing Downscaling Methods

			Summer Rainfall Region			Winter Rainfall Region		
			SON	DJF	MAM	MAM	JJA	SON
CSAG	CMIP 5	RCP8.5	**↑**	**↑**	**↓**	**↓**	**↑**	**↑↓**
		RCP4.5	**↑**	**↑**	**↓**	**↓**	**↑**	↑
	CMIP3	A2	**↑**	**↓**	**↑**	**↑**	**↑**↓	**↑↓**
		B1	**↑↓**	**↑**	↓	↑	↑	**↑**↓
CSIR	CMIP 5	RCP8.5	**↓**↑	**↑**↓	**↓**	**↓**	**↓**	**↓**
		RCP4.5	**↑↓**	**↑↓**	**↑↓**	↓	↓	↓
	CMIP3	A2	↑↓	↑↓	↑↓	↑↓	↓	↓

SON, September, October, November; DJF, December, January, February; MAM, March, April, May; JJA, June, July, August.
Single arrow implies consistent direction of change across the summer or winter rainfall region respectively, with upward and downward arrows indicating increases and decreases respectively; large and small arrows indicate strong and weak responses, and upwards and downwards arrows together indicate areas of both increase and decrease in the rainfall region.
Source: extracted via analysis of the projection maps within SA LTAS.

Biodiversity

Within the biodiversity sector, species and ecosystem modeling has been prioritized to reveal potential changes in key biodiversity indicators.[33] South African researchers have made significant contributions to models of climate and CO_2 impacts on vegetation structure and function, such as net primary productivity,[34] ecosystem-based adaptation approaches[35] as well as conservation adaptation plans. Many of the data sets required to apply these models are available in South Africa, but the very high levels of species richness and rarity, and the challenges of unique ecosystem types, make the application of these approaches particularly testing. Despite this, a wide range of impacts assessments have been undertaken.[34,36–43] In order to develop insights beyond those of conservation interest, integrated assessment approaches are needed to enhance relevance for policy formulation and implementation related to land-use and infrastructure planning, and investment decision-making.

The latest findings from South Africa's LTAS show that for the wettest and coolest climate scenarios for ~2050, minor impacts on most biomes are indicated. The biome most under threat of significant structural change, independent of which climate scenario is used, the grassland biome, which could face significant encroachment by woody vegetation due to increased temperatures and rising atmospheric CO_2. A further four biomes assessed to be significantly threatened by climate change include the Nama

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Karoo biome, the Indian Ocean coastal belt, the Fynbos biome, and the Forest biome.

Agriculture

Impact assessments in the agricultural sector have focused on staple crops and key commodities, such as maize and plantation forestry, using a range of crop modeling approaches. One common approach incorporates process based mechanistic modeling such as Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems Simulator[44–46] (APSIM). Another common approach uses climate envelope distribution modeling to estimate any changes in crop or plantation forestry suitability.[47–49] The latter approach uses observed empirical relationships between abiotic variables such as climate, and current distribution or crop presence points to estimate suitable areas under future climate. Further studies have investigated the economics of climate change impacts on crops,[50–53] yield and soil nitrogen level interactions,[54] changes in pest and disease distribution[48] and the impact of climate change on the livestock sector.[55–60]

The Agricultural Technical Report of LTAS details a series of both risks and opportunities. Results of concern include a possible projected increase in irrigation demand (see also the water sector findings) since most parts of the country may experience an increase in average annual irrigation demand in the order of 4–6%. LTAS indicates largely negative projected impacts for key cereal crops, including maize for the summer rainfall region, and wheat for the winter rainfall region. The sugarcane industry seems to show no substantive losses in area suitability. Viticulture is projected to shrink, although 'niche' producers may benefit through innovation, for example, through adoption of organic or fair trade certification. Impacts on key agricultural pest species are a critical concern, with a number of key pests and pathogens projected to increase net range suitability in South Africa and on the continent more broadly.[61–63]

Water

Hydrological models using downscaled climate projections have been the primary means of assessing sectoral impacts.[29,64–66] The hydrological system is dynamic, and changes in climate may result in unanticipated hydrological responses, possibly beyond the ranges for which the models' ability to represent processes has been tested.[67] Preliminary projections under the wide range of scenarios generated by the MIT hybrid approach (see LTAS side bar) for runoff range from a 20% decrease to a 60% increase by as early as 2050 under an unmitigated emissions pathway, while under a constrained emissions scenario projections of runoff range from a 5% decrease to a 20% increase. It is worth noting that a 60% increase in rainfall is a low probability outcome from the modeling framework, and is also physically very implausible. Spatially, the eastern seaboard and central interior of the country are likely to experience increases while much of the Northern and Western Cape are likely to experience decreases in runoff.

Impact studies for the water resources sector have begun to look beyond changes in streamflow to changes in the timing of flows and the partitioning of streamflow into baseflows and stormflows, reservoir yields, and extreme hydrological events.[68] Under all future climate scenarios considered by the LTAS, higher frequencies of flooding and drought events are projected. Complexities of the hydrological cycle, influences of land use and management and the linkages to society, health, and the economy indicate far higher levels of complexity in the water resources sector than in other sectors. What has emerged is that land uses that currently have significant impacts on catchment water resources will place proportionally greater demands on the catchment's water resources if the climate were to become drier.[69] The influence of climate change on water quality is an emerging research field in South Africa, with assessments limited to water temperature[48] and non-point source nitrogen and phosphorus movement.[70] A critical interaction that has not been explored is between changes in water quality and quantity and the combined impacts, such changes might have impact on various types of water use, e.g., irrigation, domestic consumption, or aquatic ecosystems support.

Cities and the Built Environment

The built environment has not been assessed in LTAS, which represents a significant gap, given the growing importance of cities as locations of particular exposure to climate change. In the big metropolitan centers, broad reviews of projected climate change impacts on the city have been undertaken in order to inform adaptation planning.[71–75] However, limited quantitative impacts modeling of climate change exists. The exceptions are eThekwini[f] municipality and the City of Cape Town.[76–79] Integrated approaches that assess observed or projected impacts of climate change in South African cities as a whole are lacking. Most existing work takes a spatial or sectoral subset of the city as the unit of analysis.

Sector specific research in cities has predominantly focused on sea level rise and the water sector. Impacts of sea-level rise in both eThewkini

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and Cape Town have been evaluated using a risk exposure approach based on a combination of statistical analysis, geographical information system modeling and expert consultation.[76,78–81] Possible impacts on water supply and demand in cities under climate change has been assessed in a few studies, ranging from semi-quantitative to quantitative.[82,83] In most cases, the spread of precipitation projections, coupled with high natural variability of precipitation, lead to considerable uncertainties in the potential climate impacts on water in cities. In one study, for the city of Polokwane,[82] the most useful adaptation was identified as demand management, with a delayed and phased approach to supply augmentation, should a drying trend emerge over time. These quantitative studies have been complemented in some instances by more qualitative approaches to suggest the kinds of strain that climate change is likely to place on water management and flood governance in the future[84–86] as well as the economic impacts on securing water under climate change.[87]

Health

The health impacts of climate variability and change are increasing. Studies in South Africa have focused on climate sensitive health outcomes including diarrheal, respiratory, cardiovascular health, and vector-borne infectious diseases such as malaria.[88,89] The potential impacts of climate change are relevant to a range of key health risks, including heat stress, along with high precipitation and drought have been shown to influence morbidity as measured by hospital admissions[90] and mortality.[91] Scovronick and Armstrong[92] provide evidence for the effects of informal versus formal or traditional housing type in modifying temperature mortality relationships. Mathee et al.,[93] using focus groups, found decreased productivity among outdoor workers exposed to high temperatures.

LTAS indicates climate change's potential impact on vector borne disease,[1] although the incidence of vector-borne infectious diseases, principally malaria, in the South African context, has declined over recent years. Modeling predicts no overall increase in malaria incidence for sub-Saharan Africa but a shift from west to south and east as driven by climate change impacts.[94,95] Further key health risks seen as potentially impacted by climate change include: food insecurity; hunger and malnutrition; natural disasters; air pollution; communicable diseases, specifically HIV/AIDS; non-communicable disease; high injury burden; mental health; and occupational health[1] (see, for example, LTAS's detail on heat stress risks for agricultural workers). Significant limitations in this field include the unavailability of data[96] especially at small scale for both climate determinants and health outcomes as well as the lack of a clear conceptual model for causal pathways from climate exposures to health outcomes. Although there are key skills in specific areas of health research in South Africa, a lack of interdisciplinary or complex assessment methods is resulting in poorly developed inter-sectoral perspectives.[89,95] To date, very little work has been undertaken on the links between climate change, food security, nutrition, and health.

DEVELOPING ADAPTATION RESPONSES

In South Africa and internationally there is a growing body of research that focuses on understanding adaptation to medium- or long-term changes in the climate. Despite this, most adaptation responses still focus on reducing vulnerability to present-day climate exposure, such as through disaster risk reduction, early warning systems, and water demand management. There is little practical experience of implementing adaptation programs related to longer-term climate change except at a rather small (sectoral or local) scale, such as responding to sea level rise.[23] There is also limited experience with climate adaptation monitoring and evaluation internationally and in South Africa, despite it being prioritized by South African government in many other sectors. South African government has now prioritized this at the national level[97] and is engaging in research to explore the design of a system to evaluate adaptation.

A vulnerability-based approach to developing adaptation responses is a useful complement to impacts-based approaches. Although some impacts models incorporate assessments of future vulnerability, there is a far greater certainty about current vulnerability. In the South African context, the concept of vulnerability has been applied in a limited fashion and generally only mentioned in physical modeling studies.[46] It has been included in a number of national level reviews[2,98] and sector-specific vulnerability assessments are starting to emerge. While some studies have looked at vulnerability to climate in the context of multiple stressors, e.g., water, health, climate, economics, etc.,[50,99–101] so far, no studies have assessed vulnerability to different climate impacts across sectors.

As a first step to assessing adaptation options that best serve the country's development objectives, it will be important for vulnerability assessments to move from site- or community-specific to sector wide, with a particular focus on assessing how sectoral and cross-sectoral impacts affect the rural and urban poor.

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South Africa's 2011 National Climate Change Response White Paper[3] is the first coherent outline of national government's responsibilities relating to mitigation and adaptation. The strategy adopts a strongly sectoral approach, but also identifies the need for coordination of responses between sectors. Although many adaptation options are suggested across sectors, fewer examples exist of a move beyond coping with current variability to adapt to climate change in practice. Below we illustrate a few of the adaptation responses that have been implemented.

In the biodiversity sector, adaptation planning has incorporated climate change impacts scenarios into national plans for expansion of protected areas out to the middle of this century.[102] The planning process took account of a wide range of considerations other than climate change scenarios, and also used a multi-model, multi-downscaling set of climate scenarios that provided a range of climate changes that could be expected, given current climate and biodiversity modeling skills. Ecosystem service decision tools have also been applied in this sector to assess trade-offs resulting from management interventions. Integrated assessments and economic cost benefit analyzes have also been undertaken,[103] with substantial progress in the area of invasive alien species.[104] One study showed the benefit of interventions in ecosystem restoration for increasing resilience to climate change and broader community benefits,[105] such as wetland restoration. More recently, the implementation of ecosystem based adaptation (EBA) concepts has been explored.[106] In the Namakwa District Municipality, for example, Conservation South Africa, an affiliate of Conservation International, took the lead in developing pilot projects which show how EBA may work in practice.[107] The Namakwa District Municipality initiative is of particular interest, because it occurs in an area of significant rural poverty located in a biome of critical biodiversity importance.

In the agricultural sector, Benhin[51] used a cross sectional (Ricardian) method to measure possible economic impact of climate change on crop farming in South Africa and suggest adaptation measures. As in the biodiversity sector, agricultural researchers have since undertaken studies assessing adaptation options in terms of avoided damages.[50,53,108] Participatory modeling approaches and adaptation designs directly involving stakeholders have been used to develop locally relevant adaptation plans for agriculture and water management.[107,30] Implementing these plans have highlighted the challenges with actively mainstreaming climate change into catchment-management work, given the significant levels of vulnerability in South Africa.[68,109] A key finding was that uncertainties around organizational and institutional issues were more important for stakeholders to consider in adaptation planning than uncertainties around the modeling results.

A handful of examples of adaptation practice go beyond addressing the current adaptation deficit, to explicitly consider changing climate and take a longer-term planning approach.

In the agricultural sector, individual farmers and farmers' associations are extremely interested in climate change findings and many have started adapting to their experience of historical changes.[110] For example, in the Western Cape, apple orchards have been replaced by vineyards which are more tolerant of higher temperatures; and in the southern Cape commercial farmers have changed from crops to pasture and have increased their water-storage capacities.[110] In the Suid Bokkeveld, in South Africa's arid western region, work on understanding impacts of climate variability and change on rooibos tea farming has been undertaken in partnership with the emerging agricultural sector in this area. Using participatory research methodologies, as well as community-based adaptation planning, adaptation has become an iterative co-learning process, rooted in farmers' existing knowledge of what works in practice.[111–114] Such 'rooted' adaptation strategies have included (but are not limited to) soil and water conservation measures, *in situ* biodiversity conservation measures as well as measures to protect livestock from heat and water stress.

Although the impact of climate change on the private sector has not been an explicit focus in national assessments, many of the studies mentioned above have important implications for the private sector and have prompted adaptive responses. Within business, a more innovative response to climate change can be seen through the case study of a short-term insurance company, Santam. The company noticed increasing insurance claims particularly in the Eden District Municipality in the Western Cape Province, associated with extreme weather events—specifically fires (enhanced by periods of drought and fanned by strong winds), flooding, and storm surges. Rather than increase insurance premiums the company embarked on a pilot project in collaboration with CSIR and WWF (Worldwide Fund for Nature) to assess landscape-wide measures to reduce such risks.[115] They identified 'proximate drivers' of climate risks, which are amenable to direct or indirect intervention by Santam and its partners (e.g., reducing fire risk through support for the 'Working for Water' programme).

Local adaptation strategies have recently been developed for some cities and municipalities. These strategies often highlight the need for clear

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identification of institutional responsibility for effective implementation of adaptation responses[116] (e.g., Western Cape Climate Change Response Strategy). The cities of Cape Town and eThekwini both have municipal adaptation plans of action that link current priorities with expected future considerations. Key emerging research questions relate to the extent to which such response strategies are translated into action, and understanding the barriers and enablers to effective local government.[116] Recent analyzes have raised some interesting contrasts between capacity and barriers for adaptation in large cities and smaller municipalities. Cities generally have the resources to develop adaptation responses, but are hampered with regarding implementation due to their large size and organizational complexity. Smaller municipalities on the other hand, do not have the human capacity to undertake systemic adaptation planning, but are more successful implementers because of their smaller, less complex organizational nature, and because key individuals across functions are well-networked and have a history of working together.[117]

THE WAY FORWARD

At the research and applied level, South Africa is making significant progress in understanding the impacts of climate change, and in starting to implement and evaluate adaptation responses. Despite this, substantial work is still needed in two areas: (1) the knowledge gaps related to inadequate impacts assessment and the quantification of the socioeconomic costs of climate change and (2) the institutional challenges that make it difficult for organizations in both the public and private sectors to work and collaborate effectively to meet the country's adaptation needs.

Addressing Key Knowledge Gaps

Despite nearly two decades of climate and impacts modeling in South Africa, many knowledge gaps remain. This affects the predictive chain from climate scenarios and associated biophysical impacts, through assessing socioeconomic vulnerability and adaptation responses.[118] Gaps are in part due to a lack of climate scenario products; under-synthesized and potentially contradictory climate information; incomplete impacts modeling approaches and inadequate process understanding; poor traceability between impacts assessments and the climate scenarios on which they are based; inadequate socioeconomic and vulnerability assessments; and lack of cross-sectoral integration in impacts and adaptation assessments.

The potential impacts of climate change will remain incompletely characterized due to some of these knowledge gaps being irresolvable within practical timeframes. On top of this, the lack of a consistent approach that can be adopted as 'best practice' makes it difficult to disentangle uncertainties that are due to fundamental scientific and modeling uncertainties from those due to the assessment methodology itself. For example, the sectoral impacts studies in the LTAS represent a synthesis of pre-existing studies, making use of a range of approaches and climate scenarios. The LTAS climate change scenarios offer an additional opportunity for a systematic, consistent approach to new impacts assessments that has yet to be realized.

South Africa lacks a robust national system that provides spatially extensive climate data. The most recent quality controlled and nationally gridded climate data date back to 2000. Up-to-date national data for hydrology are increasingly difficult and costly to obtain or generate through modeling. This represents a key constraint for impacts modeling in South Africa, as many sectors, including biodiversity, agriculture, urban settlements, and even human health, use climate and water as a key resource underpinning their impacts modeling.

Over the medium and long term, adaptation assessments are constrained by inadequate impacts modeling approaches. In the biodiversity sector for example, it is not clear how insects, animals, wildfire, and dispersal rates of species might respond to changing temperature and rainfall patterns or how CO_2 levels might interact with climate-yield interactions and with soil nitrogen and ozone. A growing understanding of how current climate impacts on livelihoods and sectors have not been matched with sufficient understanding of what a change in climate might mean for future well-being. For example, urbanization is resulting in increased urban densification (in both formal and informal settlements); the associated costs of higher concentrations of people and infrastructure, coupled with extreme weather events have not been sufficiently explored. Little work has been done on effectively costing adaptation measures and identifying suitable financing options. This is a major stumbling block for implementation.

Integrated assessments have been undertaken in only a limited way in South Africa. These assessments are potentially important because they integrate information from multiple sources on climate change impacts, vulnerabilities, and priorities for adaptation. Such cross-sectoral approaches help to explore some of the linkages between sectors and regional vulnerabilities. For example, it is important that the agricultural and water sectors are considered in tandem for many adaptation responses. One example of research

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that integrates these two sectors is a study of the water-stressed Sandveld in the Western Cape region. The study looked explicitly at implications of climate change for groundwater recharge, on which the agricultural sector is so heavily dependent.[107]

Integrated assessments could address ways of incorporating climate change research into broader development concerns.[84,119] An international example of such an approach is the UK's Climate Change Risk Assessment[120] (CCRA). The CCRA synthesized existing knowledge on climate impacts, related to over 100 risks (prioritized from an initial list of over 700). Drawing from disparate sectors, the risks were chosen based on the magnitude of the impact and confidence in the evidence base. The research highlighted the most severe risks, interactions between risks, and how risks varied regionally. This now forms the evidence base for the UK government's policy on adaptation.

Adaptation will inevitably have to deal with uncertainty around both climate and its impacts, and also the social, political, and economic conditions within which the impacts and responses will take place.[121] As yet this is not reflected in adaptation research and practice in South Africa. A critical area for collaborative research is to develop approaches that support 'robust', 'resilient,' or 'adaptive' decision frameworks that take account of uncertainty, and avoid lock-in to particular scenarios.[122]

The ability to take adaptation findings from case study sites generalize them to the national level, and to make recommendations that cut across sectors remains constrained. This requires critical attention, particularly in the light of the primacy of 'climate-resilient development' as outlined in South Africa's National Climate Change Response White Paper. Very little is known about institutional design that fosters adaptation and the capacity to deal with uncertainty, complex system feedbacks and non-stable states. The following section explores some of the institutional challenges that could be addressed to strengthen adaptation.

Building on Institutional Strengths and Addressing Barriers

Institutional barriers for addressing climate change have been identified across a range of South African studies that include: a lack of capacity (both in terms of numbers of people and expertise), high turnover of staff within government departments; limited understanding of and expertise in tackling climate-related issues; the positioning of climate change as an environmental issue rather than as a development issue; conservative financial management practices; and poor communication and coordination between departments and between different levels of government[74,84,116,119,123–125] (especially national to local and provincial to local).

Internationally, a number of Organisation for Economic Co-operation and Development (OECD) countries have established dedicated support bodies to assist with impacts and adaptation assessments. For example the UK Climate Impacts Programme (UKCIP), established in 1997, provides access to successive generations of climate scenarios. More importantly it has also provided advice to stakeholders on how to approach impacts and adaptation assessments, to pilot innovative approaches to adaptation, and to review and reflect on best practice.[126] This approach is sorely lacking in South Africa, where expertise and advice is sought on an ad-hoc basis from a stretched research community. Climate scenario and impacts data provision is generally provided when and if experts have the free time to respond, or through specific consulting contracts. If adaptation is to become embedded in South Africa's development, a mechanism similar to UKCIP is required.

Weak relationships exist between many different stakeholder groups in South Africa (government, civil society, researchers, practitioners, private sector), yet these relationships are critical in driving adaptation. Authentic deliberation is particularly important between disparate stakeholders yet this is difficult to achieve especially in a highly unequal society.[106] Climate change adaptation, as a complex problem, would benefit from 'collaborative intermediary organizations'. A comparative study of such intermediaries in the Cape Town metropolitan area identified particular leadership capabilities that are likely to contribute to success, with a focus on creative approaches to ambiguity and conflict.[106] Another role for intermediary organizations is to translate science into messages relevant to policy and different user groups. Many organizations that could act as intermediaries, such as NGOs and extension officers, will need to improve methods for communicating climate science and impacts findings in order to reach a wide audience effectively and credibly.

Although local governments do not get much financial or technical support from the national level to undertake climate change adaptation, evidence suggests that a number of municipalities and metros are integrating adaptation into their plans and practice.[116,123,127,128] The innovative work in some of the large cities in South Africa showcases how adaptation as a process has been prioritized.[116] Although there is recognition of climate change by many smaller municipalities the evidence for action is limited.[129] eThekwini Municipality has

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highlighted the importance of versatility, experimentation and 'learning-by-doing'.[123,124,127] This has been in response to high levels of uncertainty associated with climate change projections at the local level, the complexity of local economic, political and social contexts, and the variety of possible climate impacts. They have also recognized the need for new research partnerships between municipalities and academic institutions and systems for monitoring and evaluating the effectiveness of adaptation investments. eThekwini has also promoted ecosystem-based approaches to climate change adaptation, as a way to address human development needs (e.g., the provision of clean water, the creation of employment opportunities, etc.) as well as those of other species.[127]

One of the challenges that local government face in mainstreaming adaptation is the lack of authority held by environmental departments to address climate change.[116] Although national and provincial governments are mandated to address climate change, at municipal level it is contested and regularly referred to as an 'unfunded mandate'. Although new policy suggests that it is a mandate, municipal financing allocations do not reflect this yet. Small municipalities have almost no capacity to act on climate change and the larger metros have sought international funding to initiate activities.[116] eThekwini, for example, has creatively used government funding for biodiversity and from bilateral donors to support its climate change work.

Lastly, the silo approach of government departments does not support an integrated approach to addressing climate change adaptation. So although rhetoric and policy is changing it is important that political and bureaucratic infrastructure changes to support more integrated cross-sectoral responses.

CONCLUSION

In this review of current approaches and recent advances in South African research on climate impacts and adaptation, we have shown that South Africa benefits from having a small group of scientists who are strongly integrated into climate change research internationally. Climate scenarios generated in South Africa are as good as those produced in many OECD countries and, in some areas, environmental data sets are of high quality. South African researchers have studied the biophysical impacts of climate change, assessing, for example, the combined impacts of climate change and other drivers on biodiversity, and applying these insights to spatial-planning processes and the optimizing of conservation responses[39,102,104,130] and water management.[66–68,131,132] Initiatives under the SA Global Change Programme have injected new momentum into research, training and monitoring for earth system science that should enhance South Africa's existing capacity. The LTAS sectoral assessments are helping to identifying key knowledge gaps and priorities for new research.

At the level of national policy, the National Climate Change Response White Paper[3] makes substantial new demands related to national adaptation planning in key sectors that are directly linked to economic development, including agriculture, forestry, marine fisheries, and water. South Africa is moving ahead with sectoral planning at the national level, drawing increasingly on detailed impacts modeling, and benefiting from national adaptation research processes such as LTAS. However, this planning still needs to be mainstreamed into sectoral policy in many instances and importantly, followed through in practice, i.e., implementing and evaluating actual management interventions. In this regard, while LTAS is designed partly to improve national capacity around climate change, a more comprehensive capacity-building program requires the establishment of a dedicated national facility for impacts and adaptation support that can also function as an intermediary for connecting scientists, policymakers and stakeholder groups.

Focusing specifically on the issue of adaptation, we outlined a wide range of adaptation activities that are occurring in South Africa, from local community-based initiatives, often stimulated by NGOs, through to local, regional and national government, and also in the business and parastatal (e.g., National Parks) sectors. However, few of these activities are well documented by the research community, reflecting the need for more transdisciplinary, action-research oriented approaches, and for the non-academic community to become more engaged in documenting and analyzing their activities. Where adaptation research has occurred, it tends to be sector-based as opposed to cross-sectoral. Few studies integrate an understanding of impacts through to vulnerabilities, adaptation and implementation. Three critical research areas that would strengthen adaptation research and practice include: (1) the development and testing of approaches that enable integrated and flexible adaptation strategies; (2) an improved understanding of the social, political, governance and financial barriers or enablers of adaptation in the South African context; and (3) how adaptation can address the reduction of poverty and inequality, which is one of the key priorities of the National Climate Change Response White Paper.[3]

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Adaptation cannot be disentangled from South Africa's national development objectives. Considerable opportunities exist for linking adaptation to development and employment activities that are already underway, producing multiple benefits. We have suggested that, where possible, adaptation responses should focus on multiple synergies—prioritizing activities that fulfill a range of objectives, of which climate adaptation is one. This is specifically important in South Africa where guidelines of good governance are not well implemented and organizational challenges persist. Such an approach also calls for additional interdisciplinary research that extends into a joint framing of questions and exploring of responses. Close cooperation between academics and practitioners in small local projects needs to be expanded into multi-disciplinary and multi-scalar work that will require new kinds of partnerships and funding. The process of envisaging, together with stakeholders, and at least partially quantifying adaptation scenarios using various modeling approaches appears to hold promise as one of many potential solutions.

Climate change adaptation requires forward-looking decision making that marries scientific diagnoses and technical innovation with social organization and political debate around competing value systems. Experimentation, learning and the capacity to shift practices in the light of new findings need to be seen as part of the adaptation process. Excellent examples of such practices are emerging in particular instances across government departments, businesses, and civil society, driven by innovative and forward-thinking individuals. The challenge remains how to enable these innovative approaches to occur at scales that will make a significant difference to South Africa's resilience in the face of climate change.

NOTES

[a] Under RCP 4.5, near surface mean temperature is indicated at 1–1.5°C on the coast and around 3°C inland for South Africa (reference period 1986–2005 and future period 2081–2100). Under RCP 8.5 (using the same reference and future periods), we see around 4–6°C inland and 2–3°C at the coast.[1]

[b] For example, between 2006 and 2012, in the fields of atmospheric science, meteorology and oceanography, authors with South African affiliations produced an average of 270 ISI publications per year, whereas the next most prolific African country was Nigeria, with an average of 50 per year.

[c] ACCESS is a government-funded consortium of over 20 universities and research centers that supports a range of coordinated research projects, with a strong focus on capacity development (www.access.ac.za).

[d] For example, in an assessment of water-related impacts studies, Warburton et al.[29] and Andersson et al.[30] used projections from the Swedish Meteorological and Hydrological Institute (SMHI) downscaled with the RCA3 regional model from three coupled atmosphere-ocean global climate models, covering three SRES emissions scenarios, and adjusted using the distribution-based scaling (DBS) approach for bias correction.

[e] Between 6 (CSIR; A2 emissions scenario) and 10 (CSAG; A2 & B1) CMIP3 models, were downscaled, and by end of 2014, between 10 (CSIR; RCP4.5 & RCP 8.5) and 16 (CSAG; RCP4.5 & RCP 8.5) CMIP5 models will have been downscaled.

[f] eThekwini is the name of the City of Durban municipal government.

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