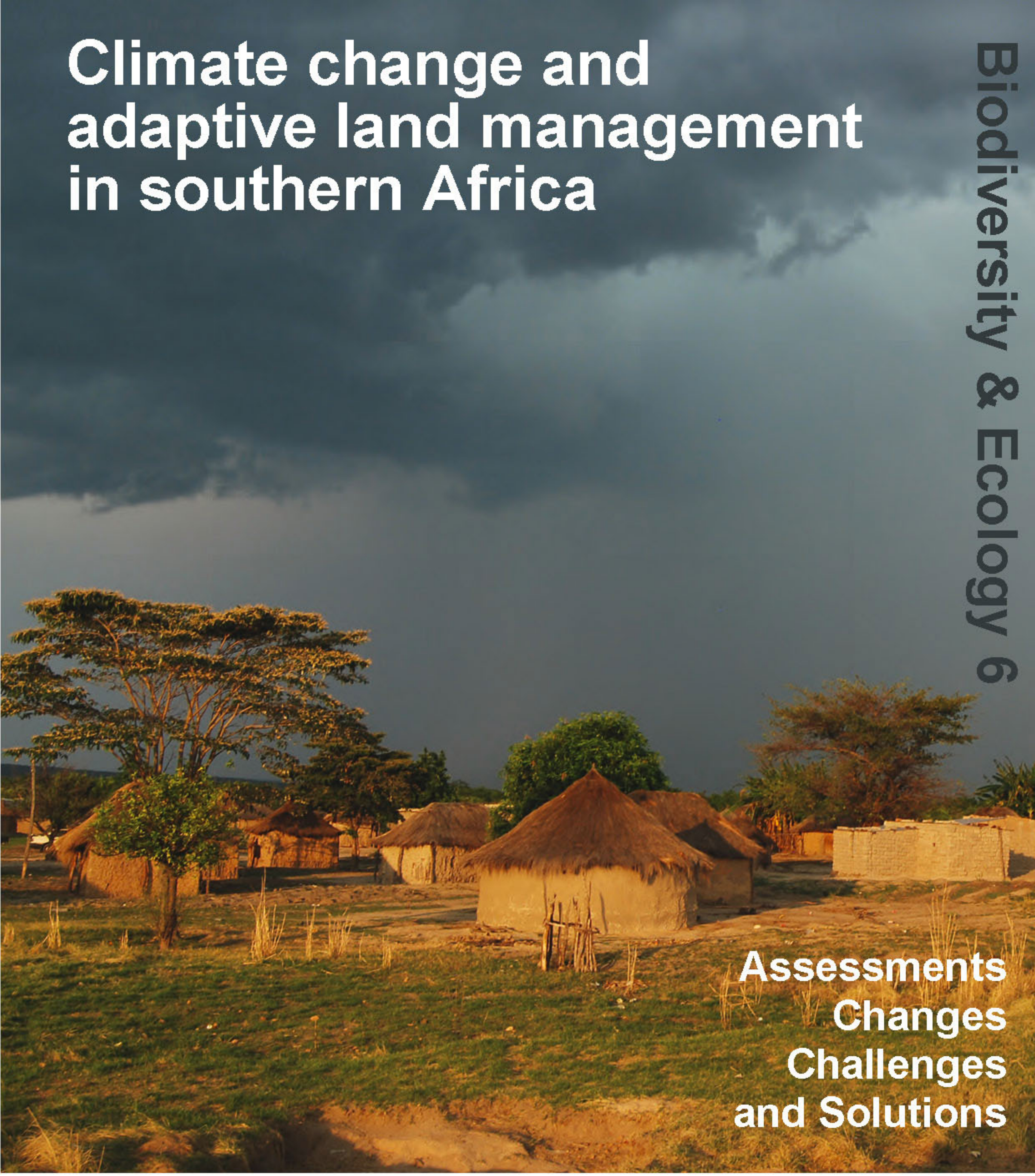
# Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



Assessments
Changes
Challenges
and Solutions

Product of the first research portfolio of

**SASSCAL 2012–2018**

Southern African
Science Service Centre for
Climate Change and
Adaptive Land Management

SPONSORED BY THE

Federal Ministry
of Education
and Research

Klaus Hess Publishers
Göttingen & Windhoek
www.k-hess-verlag.de

ISBN: 978-3-933117-95-3 (Germany), 978-99916-57-43-1 (Namibia)

Language editing: Will Simonson (Cambridge), and Proofreading Pal
Translation of abstracts to Portuguese: Ana Filipa Guerra Silva Gomes da Piedade
Page desing & layout: Marit Arnold, Klaus A. Hess, Ria Henning-Lohmann
Cover photographs:
front: Thunderstorm approaching a village on the Angolan Central Plateau (Rasmus Revermann)
back: Fire in the miombo woodlands, Zambia (David Parduhn)
Cover Design: Ria Henning-Lohmann

ISSN 1613-9801

Printed in Germany

Suggestion for citations:
Volume:
Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N. (eds.) (2018) Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions. *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek.

Articles (example):
Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M. & Helmschrot, J. (2018) Seasonal prediction and regional climate projections for southern Africa. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N.), pp. 14–21, *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek.

Corrections brought to our attention will be published at the following location:
http://www.biodiversity-plants.de/biodivers_ecol/biodivers_ecol.php

# Biodiversity & Ecology

Journal of the Division Biodiversity, Evolution and Ecology of Plants,
Institute for Plant Science and Microbiology, University of Hamburg

Volume 6:


# Climate change and adaptive land management in southern Africa

## Assessments, changes, challenges, and solutions


Edited by

Rasmus Revermann[1], Kristin M. Krewenka[1], Ute Schmiedel[1],
Jane M. Olwoch[2], Jörg Helmschrot[2,3], Norbert Jürgens[1]

1 Institute for Plant Science and Microbiology, University of Hamburg
2 Southern African Science Service Centre for Climate Change and Adaptive Land Management
3 Department of Soil Science, Faculty of AgriSciences, Stellenbosch University



Hamburg 2018

Please cite the article as follows:

Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M. & Helmschrot, J. (2018) Seasonal prediction and regional climate projections for southern Africa. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N.), pp. 14-21, *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek. doi:10.7809/b-e.00296

Climate

# Seasonal prediction and regional climate projections for southern Africa

Emma Archer[1,5]*, Francois Engelbrecht[3,7], Andreas Hänsler[2], Willem Landman[4], Mark Tadross[6], Jörg Helmschrot[8,9]

1 CSIR Natural Resources and the Environment, Building 1, cnr Carlow and Rustenburg Roads, Emmarentia 2193, Johannesburg, South Africa

2 Climate Service Center Germany (GERICS), Chilehaus – Eingang B, Fischertwiete 1, 20095 Hamburg, Germany

3 CSIR Natural Resources and the Environment, Building 33, Meiring Naude Road, Pretoria 0001, South Africa

4 Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

5 Global Change Institute, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein 2000, Johannesburg, South Africa

6 UNDP/Climate Systems Analysis Group, University of Cape Town, Pvt Bag, Rondebosch 7700, South Africa

7 School of Geography, Archaeology and Environmental Sciences, University of the Witwatersrand, Private Bag 2, WITS 2050, South Africa

8 SASSCAL Regional Secretariat, 28 Robert Mugabe Avenue, Windhoek, Namibia

9 Stellenbosch University, Faculty of AgriSciences, PO Box X1, Stellenbosch 7602, South Africa

* Corresponding author: earcher@csir.co.za

**Abstract:** Temperatures over southern Africa have been increasing rapidly over the last five decades, at a rate of about twice the global rate of temperature increase. Further drastic increases, in the order of 6°C by the end of the century relative to the present-day climate, may occur over the central and western interior regions under low-mitigation futures. Moreover, southern Africa is projected to become generally drier under low-mitigation climate change futures. Such changes will leave little room for adaptation in a region that is already characterised as dry and hot. Impacts on crop and livestock farming may well be devastating, and significant changes may occur in terms of vegetation cover in the savannas, particularly in the presence of human-induced land degradation. Under modest to high mitigation, southern Africa will still experience further climate change, but amplitudes of change will be reduced, potentially leaving more room for adaptation. Skilful seasonal forecasts may become an increasingly important adaptation tool in southern Africa, especially when combined with a robust weather station monitoring network.

**Resumo:** A temperatura no Sul de África tem vindo a aumentar rapidamente ao longo das últimas cinco décadas, a uma taxa de cerca do dobro da global. Aumentos adicionais drásticos, na ordem dos 6°C até ao final do século em relação ao clima actual, poderão ocorrer nas regiões interiores centrais e ocidentais sob cenários futuros de baixa mitigação. Além disso, prevê-se que o Sul de África irá tornar-se geralmente mais seco sob cenários futuros de baixa mitigação das alterações climáticas. Tais alterações deixarão pouco espaço para a adaptação numa região que já é caracterizada como seca e quente. Os impactos na agricultura e na pecuária poderão ser devastadores, e alterações significativas poderão ocorrer em termos de cobertura vegetativa nas savanas, particularmente na presença de degradação da terra induzida pelo Homem. Com uma mitigação média-alta, o Sul de África continua influenciado pelas alterações climáticas, mas as amplitudes são reduzidas, deixando potencialmente mais espaço para a adaptação. Previsões sazonais competentes poderão tornar-se numa ferramenta de adaptação cada vez mais importante no Sul de África, especialmente quando combinadas com redes robustas de monitorização por estações meteorológicas.

## Introduction

The past few years in southern Africa (in both the summer and winter rainfall regions) have demonstrated yet again the vulnerability of the subcontinent to climate variability. Multi-year below-normal summer rainfall has had a severe impact on key sectors, including agriculture and water, as have multiple more recent winters with below-normal rainfall (see, for example, Archer et al., 2017).

Such conditions have highlighted the need for climate science in the region that truly enables us to both predict conditions of climatic risk in the shorter to the longer term and to use such information to improve short- and long-term readiness (Winsemius et al., 2014). In this overview article, we describe work in climate prediction undertaken on both longer-term climate change projections and seasonal early warning. We conclude by a brief discussion of the essentials beyond climate science, where we may potentially effectively translate information into real utility.

## Projections of future climate change over southern Africa

Later in this chapter, we consider climate observations and data availability; and it should be noted at the start of discussing the latest findings in terms of climate change projections for the continent that observation and data gaps remain a significant concern. Observed data also constrain our work in the area of seasonal forecasting and early warning (see section to follow). Figure 4, for example, shows the uneven coverage of observed climate data for the continent, particularly outside of South Africa. That limitation notwithstanding (and we provide more detail later in the chapter), substantive work has been undertaken in terms of climate change projections on the continent. Climate change is projected to have widespread impacts in southern African during the 21st century, particulalrly under low-mitigation futures (Niang et al., 2014). Temperatures are projected to rise rapidly, at 1.5 to 2 times the global rate of temperature increase (James & Washington, 2013; Engelbrecht et al., 2015). Indeed, the observed rate of temperature increase is particularly high over the interior regions of southern Africa. Here temperature trends as high as a 2 to 3.6°C increase per century have been recorded over the period 1961–2010 (Engelbrecht et al., 2015; Kruger & Sekele, 2013). In addition to the projected increases in surface temperature, the southern African region is also projected to become generally drier under enhanced anthropogenic forcing (Christensen et al., 2007; Engelbrecht et al., 2009; Haensler et al., 2010, 2011; James & Washington, 2013; Niang et al., 2014). These regional changes will plausibly have a range of impacts in southern Africa, including impacts on energy demand (in terms of achieving human comfort in buildings and factories), agriculture (e.g., reductions of yield in the maize crop under higher temperatures and reduced soil moisture; Landman et al., 2017), livestock production (e.g., higher cattle mortality as a result of oppressive temperatures), water security (through reduced rainfall and enhanced evapotranspiration; Engelbrecht et al., 2015) and human health (through oppressive temperatures; Garland et al., 2015).

Moreover, climate change is to take place not only through changes in average temperature and rainfall patterns, but also through changes in the attributes of extreme weather events. For the southern African region, generally drier conditions and the more frequent occurrence of dry spells are plausible over most of the interior (Christensen et al., 2007; Engelbrecht et al., 2009; Haensler et al., 2011). Tropical cyclone tracks are projected to shift northward, bringing more flood events to northern Mozambique and fewer to the Limpopo province in South Africa (Malherbe et al., 2013). Cut-off low related flood events are also projected to occur less frequently in South Africa (e.g., Engelbrecht et al., 2013) in response to a poleward displacement of the westerly wind regime. Intense thunderstorms plausibly may occur more frequently over South Africa in a generally warmer climate (e.g., Engelbrecht et al., 2013). Perhaps most important is that the regional changes in circulation that are plausible over southern Africa, in particular an increase in the frequency and intensity of mid-level high-pressure systems, may plausibly induce the more frequent occurrence of heat-wave events over the region (e.g., Engelbrecht et al., 2015; Garland et al., 2015).

It is against this background that a focused effort was made to further explore the climate change futures of southern Africa through a coordinated SASSCAL research programme, in addition to other research active in the subcontinent and on the continent more broadly. At the CSIR in South Africa and at the Climate Service Center Germany (GERICS), the most recent global circulation model (GCM) projections of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC) were downscaled to 50 km resolution over Africa. These simulations are for the period 1961 to 2100, follow the experimental design recommended by the Coordinated Downscaling Experiment (CORDEX), and have been derived for low- (Representative Concentration Pathway 8.5 [RCP8.5]), modest-high- (RCP4.5) and high-mitigation (RCP2.6) scenarios. The data of these simulations are also made available to the international science community via the CORDEX databases. The regional climate model used at the CSIR is the conformal-cubic atmospheric model (CCAM), a variable-resolution global climate model (GCM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor, 2005). At GERICS the simulations have been conducted with the REMO regional climate model. For each of the RCPs, six different GCMs were downscaled, so that the results presented below are based on an ensemble of possible future developments. The CCAM simulations were performed on supercomputers at the Centre for High-Performance Computing (CHPC) of the Meraka Institute of the CSIR in South Africa; the REMO simulations were conducted at the German Climate Computing Center in Hamburg, Germany.

The CCAM projected changes in annual rainfall over southern Africa are shown in Figure 1 for the far-future period 2080–2099 compared to the present-day (1971–2000). A general pattern of rainfall decreases is projected for subtropical southern Africa. An exception is Mozambique, where rainfall increases are projected for the central and northern parts in particular. There is some uncertainty in the projections over the interior of the central subcontinent, where a minority of projections indicate rainfall increases over specific regions, or decreases that are small in amplitude. The largest rainfall decreases are projected for Angola and over the southern parts of South Africa. The projected decreases in Angola may be occurring in conjunction with changes in the Angola low-pressure system and the general strengthening of the subtropical high-pressure belt over southern Africa (e.g., Engelbrecht et al., 2009). Over South Africa, the rainfall decreases projected for the southwestern Cape are occurring in association with a poleward displacement of the westerlies and frontal systems under low mitigation (e.g., Christensen et al., 2007; Engelbrecht et al., 2009).

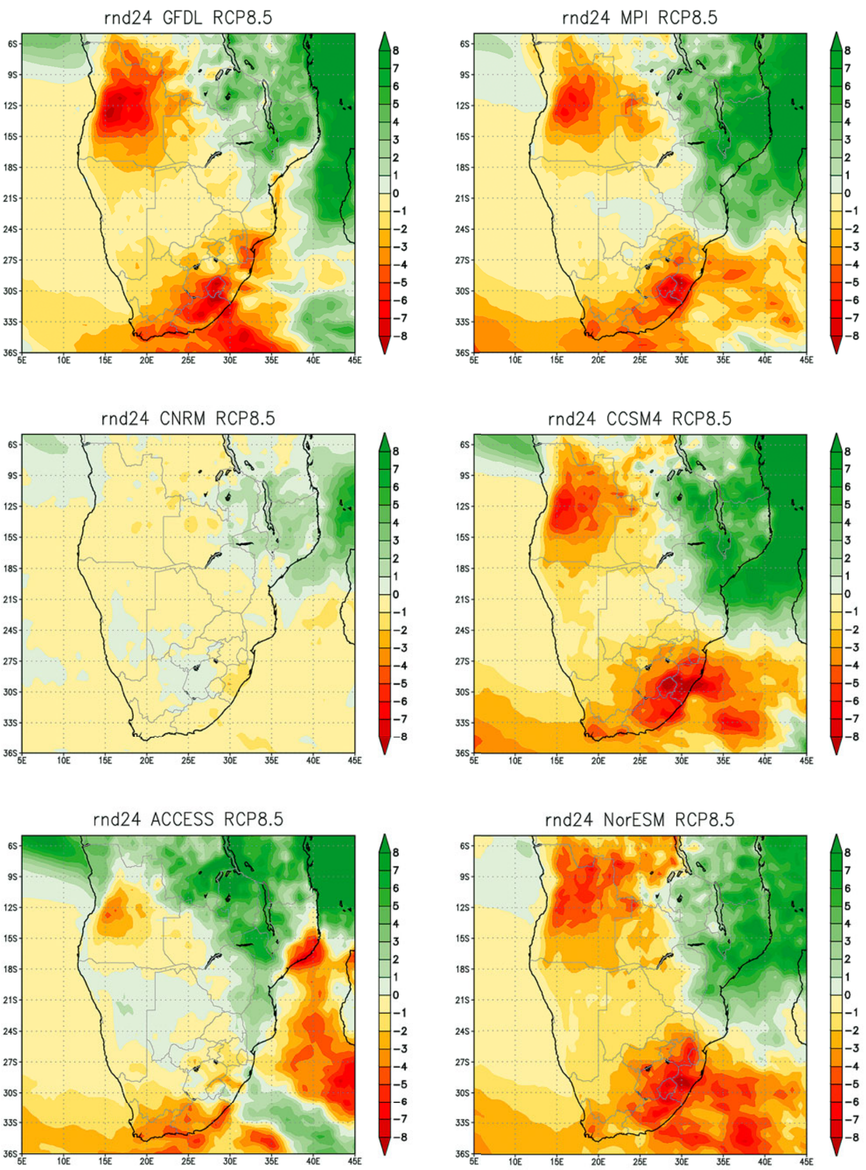



Figure 1: CCAM projected change in the annual average rainfall totals (units 10*mm/day) over southern Africa at 50 km resolution, for the time period 2080–2099 relative to 1971–2000. The downscalings were obtained from six different CMIP5 GCM projections under low mitigation (RCP8.5).

Drastic temperature increases of 4–7°C are projected to occur over the western interior regions of southern Africa under low mitigation (Fig. 2). Relatively smaller increases are projected for Mozambique (where general increases in rainfall and cloud cover are projected) and along the coastal areas (due to the moderating effects of the ocean).

Incorporating 16 regional climate change projections conducted by GERICS (using the REMO model) and other institutions in the frame of the CORDEX initiative for the southern African region, analyses of projected changes for a set of climate indices along various transects over the SASSCAL region have been conducted based on larger regional climate model ensembles for RCP4.5 and RCP8.5. The median projection of change in annual maximum temperature is about 3°C (RCP4.5) to 5°C (RCP8.5) in the interior and about 1.5 to 2°C less at the coastal areas in the west, east, and south. The spread between the different simulations is about 2°C (RCP4.5) to 3°C (RCP8.5), leading to a maximum projected increase in maximum annual temperature of about 7°C (RCP8.5) over the semi-arid to arid western parts of the SASSCAL region (Fig. 3). The CCAM projections (Fig. 2) are consistent with the range of changes projected by the CORDEX ensemble (Fig. 3).

The SASSCAL projections and analyses convey a clear message that a low-mitigation climate future may have devastating impacts on the southern African region. Drastically rising average temperatures and related extreme events (e.g., very hot days, heat-wave days, and high fire danger) are plausible to have a negative impact on crop yield, livestock production, and human health. The general reductions in rainfall may induce further stress for rainfed agriculture in the region. For example, the Kalahari Desert receives annual precipitation rates of about 250 mm in the arid south-western parts and rising to more than 600 mm towards the centre and north-east of Botswana. For the end of the century, not only rising temperatures are projected but also a reduction in the annual rainfall rate. With a later onset of the rainy season and an earlier cessation, the number of dry days outside the rainy season increases and the rainy season itself shortens. As a result, semi-arid and arid domains are estimated to expand by 5–8%, influencing the ecosystem and its vegetation, hydrology,

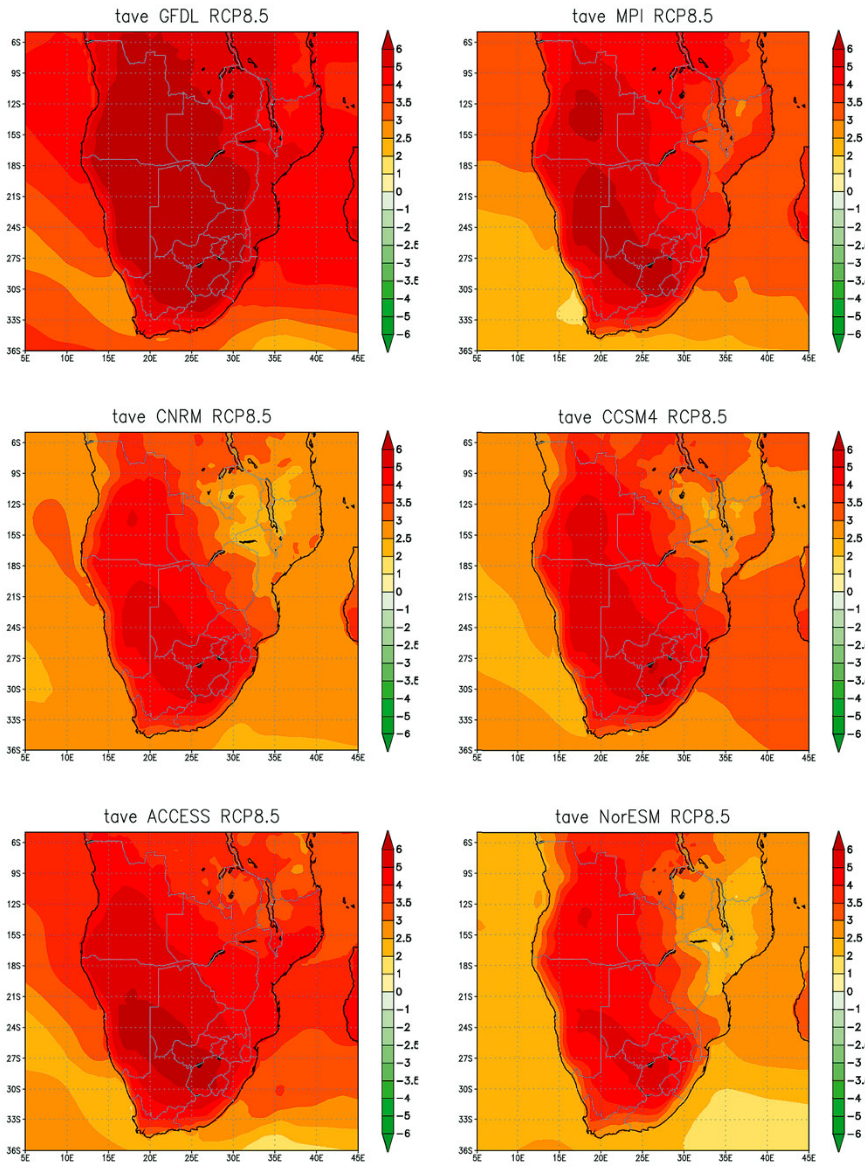



Figure 2: CCAM projected change in the annual average temperature (°C) over southern Africa at 50 km resolution, for the time period 2080–2099 relative to 1971–2000. The downscalings were obtained from six different CMIP5 GCM projections under low mitigation (RCP8.5).

and human proceedings (Stringer et al., 2009). Climate change has already been noticeably present during the past decades (Kusangaya et al., 2014), and the associated intensification and expansion of agriculture and livestock farming has reinforced land use pressure. Due to the absence of sufficient surface water resources, groundwater resources are used to address the rising demand for water and, consequently, the number of wells and boreholes in the Kalahari Desert has increased remarkably during the last century (Christelis & Struckmeier, 2011). Projected climate extremes, in combination with population growth, may cause an overutilization of limited resources in central Botswana, which in turn may cause migration to other areas.

Also, coastlines may be affected. While the west coast of southern Africa is comparably dry (< 500 mm), the east coast receives more rainfall (700–1200 mm), with a decreasing trend from north to south. As shown by Oltmanns (2015), projections indicate a decline in precipitation for most coastlines, except for northern Mozambique, for which an increase by approximately 10% is projected. A similar tendency can be seen for rainfall intensity. The west coast will barely experience extreme events (more than 20 mm/day), but an increase in extreme events is projected for the northern Mozambican coastline (declining slightly towards the south). Although aspects of agriculture in Mozambique may benefit from an increase in rainfall, the country simultaneously needs to prepare for the likelihood of an increasing number of flood events associated with landfalling tropical lows and cyclones under climate change. The plausibility of a significant reduction of rainfall over the mega-dam region of South Africa is a further cause for concern. Even under modest-high mitigation, southern Africa will experience potentially significant changes in the regional climate. Over the interior regions, temperature increases may well still reach values of 3–4°C, and it remains plausible that the region will become generally drier. Nevertheless, temperature increases under modest-high mitigation, though significant, are on the order of half the amplitude of changes under low mitigation. This implies the availability of more options for adaptation and more time to adapt before critical temperature thresholds are exceeded for the first time.

It is important to consider what the implications of the projected changes in climate may be for vegetation in southern Africa, particularly in the savannas, where complex interactions occur between grasses, trees, fire, and $CO_2$ (Bond & Midgley, 2012). In fact, rising levels of $CO_2$ strongly favour trees over grasses in the savannas, potentially causing bush encroachment and spawning the hypothesis of the "forestation of Africa" under climate change (West et al., 2012). However, the substantial reductions in rainfall projected for southern Angola and Zambia in particular, in combination with more frequent fires occurring under drastic temperature increases (Engelbrecht et al., 2015) and human-induced land degradation, may in fact result in decreasing tree cover in the savannas (Engelbrecht & Engelbrecht, 2016). Dynamic vegetation-fire models that can also incorporate scenarios of human-induced changes in land use are required to objectively project the vegetation future of southern Africa, yet few such models have to date been developed and applied over the region.

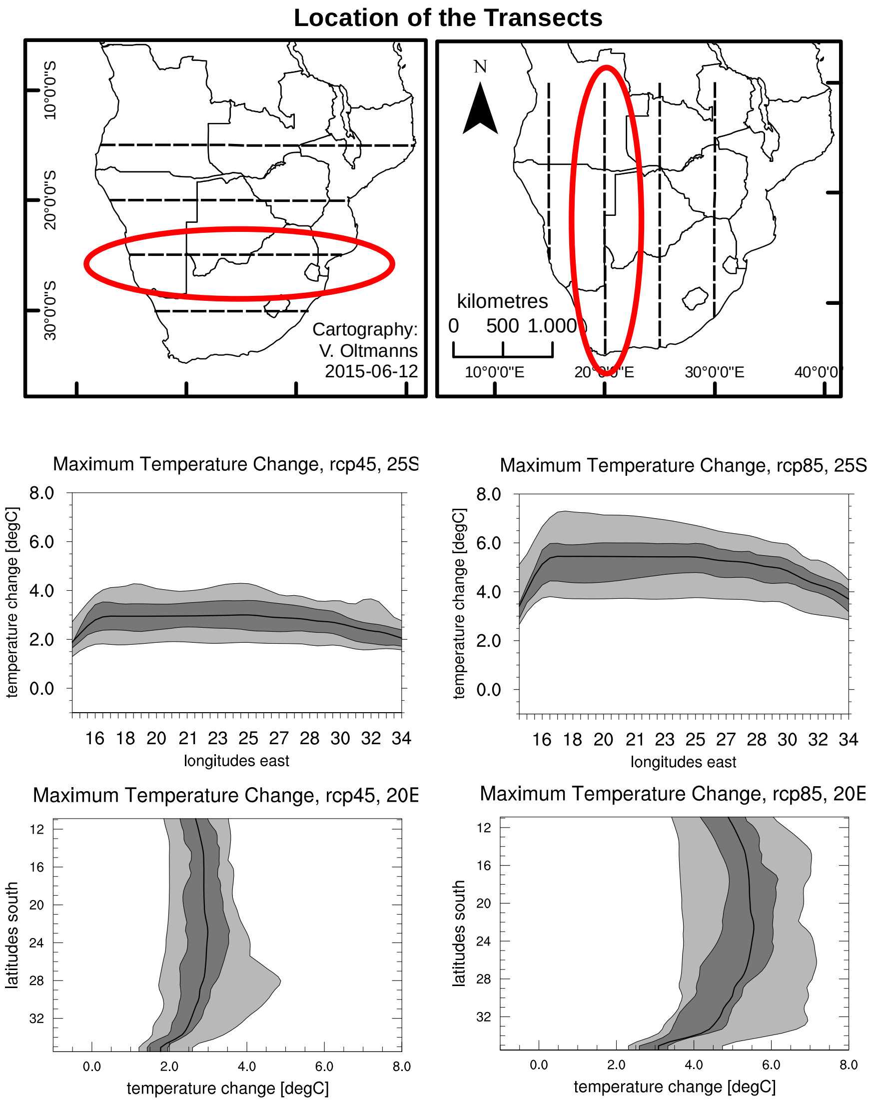



Figure 3: Range of projected changes in annual maximum temperature along an east-west (25S) and a north-south (20E) transect for the time period 2071–2100 relative to 1971–2000 for the RCP4.5 and RCP8.5 scenarios. For each of the scenarios, the projections are based on an ensemble of 16 transient regional climate change simulations from the CORDEX Africa database. The black line represents the median change. The dark-grey area reflects the range defined by the 25th to 75th percentiles of all simulations centred on the median. The light grey area spans the range between the ensemble minimum and maximum. Figures are taken from Oltmanns (2015).

## Seasonal variability and early warning

Southern African seasonal climate anomalies are (generally) predictable (Barnston et al., 1996), although work in this area remains challenged by the lack of observational data in certain areas (see section to follow). The notion of a predictable climate, further supported by the discovery in the 1980s of the El Niño-Southern Oscillation (ENSO) phenomenon as a primary driver of seasonal-to-interannual variability over the region (Ropelewski & Halpert, 1987, 1989), led to the development of operational seasonal prediction systems for rainfall (Mason, 1998; Jury et al., 1999) and for temperature (Klopper et al., 1998). The initial modelling in southern Africa was undertaken mainly from the early 1990s by a number of institutions that developed statistical seasonal forecast models (Mason, 1998; Jury et al., 1999; Landman & Mason, 1999). A few years later, in the early 2000s, atmospheric general circulation models (AGCMs) for operational seasonal forecasting and research began to be used (e.g. Landman et al., 2001). Major advances in seasonal forecast system and infrastructure development have occurred since then, including the World Meteorological Organisation's recognition of the South African Weather Service (SAWS) as a Global Producing Centre for Long-Range Forecasting, the development of objective multi-model forecasting systems for southern Africa (Landman & Beraki, 2012), and, significantly, the development of a fully coupled ocean-atmosphere model at SAWS for operational seasonal forecast production (Beraki et al., 2014). Nested regional climate models as seasonal forecasting tools were also investigated (Landman et al., 2005, 2009; Kgatuke et al., 2008; Ratnam et al., 2011). A review on aspects of seasonal forecast development in South Africa can be found in Landman (2014).

After forecasts were demonstrated to obtain the highest levels of skill when statistical methods and global model forecasts are blended into a multi-tiered forecast system (Landman et al., 2001), a move away from compiling operational forecasts subjectively through consensus discussions was introduced by making use of objective multi-model forecast systems (Landman & Beraki, 2012). Over the past 10 years or so, modelling advances obtained locally were largely focused on the development, testing, and use of fully coupled ocean-atmosphere models in seasonal forecast production (Beraki et al., 2012; Landman et al., 2012), the demonstrated potential of forecasts through the development of objective applications models (Malherbe et al., 2014), and the modelling of intra-seasonal characteristics (Engelbrecht et al., 2017).

Notwithstanding these developments, a number of caveats regarding seasonal forecasting in South Africa may be identified that require the attention of modellers, forecast producers, and users of forecasts. These include (but are not limited to) the need to demonstrate the benefits derived from using seasonal forecasts, including financial benefits; expanding on the knowledge of current skill levels and identifying factors limiting forecast skill; the development and testing of forecast systems for areas of southern Africa largely neglected up to now (i.e., the south-western and southern Cape); the development of schemes

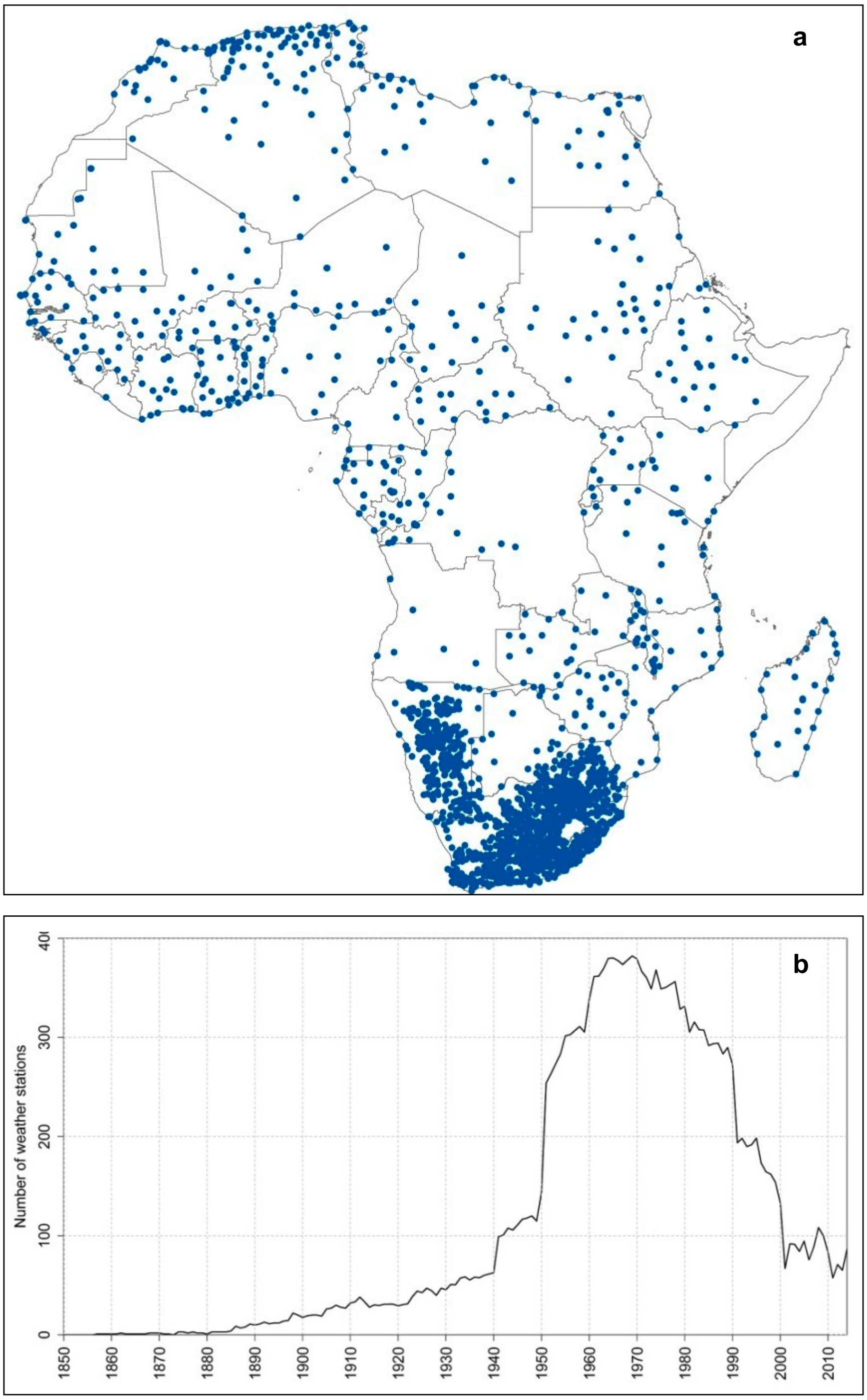



Figure 4: The locations of NOAA's Global Historical Climate Network (GHCN) weather stations, as used by CRU, across Africa (a) and the number of weather stations collecting daily temperature records across southern Africa from 1850 to 2014 used in the gridded CRUTEM4 product (b). Station density increased consistently from the start of the 20th century and peaked in the 1970s, after which it began to decline. Source: Davis & Vincent, 2017 (reproduced with the permission of the authors).

for process-based verification; the building of so-called earth system models for improved forecasts through, for example, data assimilation systems and tropical-extra-tropical ocean-land-atmosphere coupling; the operational production of forecasts to address seasonal characteristics such as onset, cessation, and sub-seasonal variations; the production and testing of high spatial and temporal resolution forecasts; operational applications model development; and, through co-production, the development of methodologies to better communicate seasonal forecast information to a variety of users in terms of complexity and application.

## Data gaps and needs

Lötter et al. (2018) describe a key challenge in the SADC region as being the lack of long-term reliable climate records, particularly outside of South Africa. Such records are essential both for measurement and interpretation of current trends (e.g., Kruger & Sekele, 2013; Engelbrecht et al., 2015) and for providing the critical ability to interpret the occurrence of extreme events against the historical record. In addition, a robust observation network supports a range of tasks from shorter-term forecasting to seasonal predictions to multi-decadal climate change projections (Engelbrecht et al., 2011) through the process of model evaluation and validation and by providing options for statistical downscaling (e.g., Landman et al., 2017). It also supports adaptation efforts, such as climate index–driven insurance schemes (e.g., Malherbe et al., 2018).

Figure 4 (from Lötter et al., 2018) shows the sparseness of climate records, making it evident that certain areas are particularly poorly served. It may be noted that in this regard SASSCAL has in recent years made a considerable effort to rescue historic climate data and to expand the weather station observational network in Namibia, Botswana, Zambia, and Angola (Kaspar et al., 2015; Muche et al., 2018; Posada et al., 2018).

### Moving forward

At a time of recent and current drought in both southern Africa's summer and winter rainfall periods, it is an opportune moment to consider the role of climate prediction in supporting both shorter-term coping and longer-term adaptation to climate variability and change. While improved prediction can by no means stand alone in support of improved response, improvements are essential at both a national and regional level. It is hoped that such improvements in prediction as those detailed here (including attention to gaps in data and the observational network) might be matched with improved support for response and adaptation to support the evolution of a more resilient subcontinent.

Climate

## Acknowledgements

The research was carried out in the framework of SASSCAL and was sponsored by the German Federal Ministry of Education and Research (BMBF) under promotion number 01LG1201M. The CCAM simulations contributed by the CSIR as a contribution to the SASSCAL climate tasks were performed on the supercomputers of the Centre for High Performance Computing (CHPC) of the Meraka Institute of the CSIR. Co-funding for this work was provided by a CSIR Parliamentary Grant project on the development of the first African-based Earth System Model. Further co-funding was provided by the NERC project UMFULA, grant number NE/M02007X/1.

## References

Archer, E.R.M., Landman, W., Tadross, M., Malherbe, J., Weepener, H., Maluleke, P. and Marumbwa, F. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. *Climate Risk Management*, **16**, 22–28.

Barnston, A.G., Thiao, W. & Kumar, V. (1996) Long-lead forecasts of seasonal precipitation in Africa using CCA. *Weather Forecast,* **11,** 506–520.

Beraki, A.F., DeWitt, D., Landman, W.A. & Oliver, C. (2014) Dynamical seasonal climate prediction using an ocean-atmosphere coupled climate model developed in partnership between South Africa and the IRI. *J Climate*, **27,** 1719–1741.

Bond, W.J. & Midgley, G.F. (2012) Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B*, **367**, 601–612.

Christelis, G. & Struckmeier, W. (2011) *Groundwater in Namibia. An explanation to the hydrogeological map*. Namibian Ministry of Agriculture, Water and Rural Development, **2**, 1–132.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W-T., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Raisanen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. *Climate change 2007: the physical science basis* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, A.B. Averyt, M. Tignor and H.L. Miller). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Davis-Reddy, C. & Vincent, K. (2017) *Climate risk and vulnerability: a handbook for southern Africa*, 2nd ed. Council for Scientific and Industrial Research, Pretoria, South Africa.

Engelbrecht, C.J. & Engelbrecht, F.A. (2016) Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and applied climatology*, **123**, 247–261. DOI 10.1007/s00704-014-1354-1

Engelbrecht, C.J., Engelbrecht, F.A. & Dyson, L.L. (2013) High-resolution model projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *International Journal of Climatology*, **33**, 173–187. doi:10.1002/joc.3420

Engelbrecht, C.J., Landman, W.A., Graham, R.J. & McLean, P. (2017). Seasonal predictive skill of intraseasonal synoptic type variability over the Cape south coast of South Africa by making use of the Met Office Global Seasonal Forecast system 5. *International Journal of Climatology,* **37,** 1998-2012.

Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Roux, B., Bopape, M.M., McGregor, J.L. & Thatcher, M. (2011) Multiscale climate modelling over southern Africa using a variable-resolution global model. *Water SA*, **37**, 647–658.

Engelbrecht, F.A., McGregor, J.L. & Engelbrecht, C.J. (2009) Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *International Journal of Climatology*, **29**, 1013–1033.

Engelbrecht, F., Adegoke, J., Bopape, M.M., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. & Gatebe, C. (2015) Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**. doi: 10.1088/1748-9326/10/8/085004

Garland, R., Matooane, M., Engelbrecht, F.A., Bopape, M., Landman, W., Naidoo, M., Van der Merwe, J. & Wright, C. (2015) Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health. *International Journal of Environmental Research and Public Health*, **12**, 12577–12604.

Haensler, A., Hagemann, S. & Jacob, D. (2010) How the future climate of the southern African region might look like: results of a high-resolution regional climate change projection. *Nova Acta Leopoldina*, **112**, 183–193.

Haensler, A., Hagemann, S., & Jacob, D. (2011) The role of the simulation setup in a long-term high-resolution climate change projection for the southern African region. *Theoretical and Applied Climatology*, **106,** 153-169.

James, R. & Washington, R. (2013) Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, **117**, 859–872. doi:10.1007/s10584-012-0581-7

Jury, M.R., Mulenga, H.M. & Mason, S.J. (1999) Exploratory longrange models to estimate summer climate variability over southern Africa. *Journal of Climate,* **12,** 1892–1899.

Kaspar, F., Helmschrot, J., Mhanda, A. et al. (2015) The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12**, 171–177.

Kgatuke, M.M., Landman, W.A., Beraki, A. & Mbedzi, M. (2008) The internal variability of the RegCM3 over South Africa. *International Journal of Climatology,* **28,** 505–520.

Klopper, E., Landman, W.A. and Van Heerden, J. (1998) The predictability of seasonal maximum temperature in South Africa. *International Journal of Climatology,* **18,** 741–758.

Kruger, A.C. & Sekele, S.S. (2013) Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, **33**, 661–676.

Kusangaya, S., Warburton, M., Archer van Garderen, E. & Jewitt, G. (2014) Impacts of climate change on water resources in southern Africa: a review. *Physics and Chemistry of the Earth*, **67**, 47–54.

Landman, W.A. (2014) How the International Research Institute for Climate and Society has contributed towards seasonal climate forecast modelling and operations in South Africa. *Earth Perspectives,* **1,** 22.

Landman, W.A. & Beraki, A. (2012) Multi-model forecast skill for mid-summer rainfall over southern Africa. *International Journal of Climatology,* **32,** 303–314.

Landman, W.A., DeWitt, D. Lee, D.-E., Beraki, A. & Lötter, D. (2012). Seasonal rainfall prediction skill over South Africa: 1- vs. 2-tiered forecasting systems. *Weather and Forecasting,* **27,** 489-501.

Landman, W.A., Engelbrecht, F.A., Hewitson, B., Malherbe, J., & Van der Merwe, J. (2017) Towards bridging the gap between climate change projections and maize producers in South Africa. *Theoretical and Applied Climatology*, 11-17.

Landman, W.A., Kgatuke, M.M., Mbedzi, M., Beraki, A., Bartman, A. & du Piesanie, A. (2009) Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *International Journal of Climatology* **29**, 1535-1549.

Landman, W.A. & Mason, S.J. (1999) Operational long-lead prediction of South African rainfall using canonical correlation analysis. *International Journal of Climatology,* **19,** 1073–1090.

Landman, W.A., Mason, S.J., Tyson, P.D. & Tennant, W.J. (2001) Retro-active skill of multitiered forecasts of summer rainfall over southern Africa. *International Journal of Climatology,* **21,** 1–19.

Landman, W.A., Seth, A., Camargo, S.J. (2005) The effect of regional climate model domain choice on the simulation of tropical cyclone-like vortices in the southwestern Indian Ocean. *Journal of Climate*, **18,** 1263–1274.

Lötter, D., Davis, C., Archer, E., Vincent, L., Pardoe, J., Tadross, M., Landman. W., Stuart-Hill, S. & Tadross, M. (2018) *Climate information needs in southern Africa*. CCCEP Working Paper (under review).

Malherbe, J., Engelbrecht, F.A. & Landman, W.A. (2013) Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing. *Climate Dynamics*, **40**, 2867–2886.

Malherbe, J., Iyahen, E., Engelbrecht, F., Chamunorwa, M. & Helmschrot, J. (2018) The Extreme Climate Index (ECI), a tool for monitoring regional extreme events. This volume.

Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H. & Luo, J.-J. (2014). Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. *Meteorological Applications,* **21,** 733-742.

Mason, S.J. (1998) Seasonal forecasting of South African rainfall using a non-linear discriminant analysis model. *International Journal of Climatology,* **18,** 147–164.

McGregor, J.L. (2005) C-CAM geometric aspects and dynamical formulation. CSIRO Atmospheric Research Technical Paper, 70.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects* (ed. by V.R. Barros, C.B. Field, D.J. Dokken et al.), pp. 1199–1265. Cambridge University Press, Cambridge, UK.

Oltmanns, V. (2015). *Analysing regional rainfall and temperature dynamics in Southern Africa using CORDEX climate projections*. MSc thesis, Friedrich Schiller University Jena (unpublished).

Posada R., Riede, J., Kaspar, F., Mhanda, A., Radithupa, M., Stegling, J., Nascimento, D., Tima, L., Kanyanga, J., Nkonde, E., Swaswa, M. & Waitolo, D. (2018) Cooperation of meteorological services within SASSCAL on improving the management of observed climate data. This volume.

Ratnam, J.V., Behera, S.K., Masumoto, Y., Takahashi, K. & Yamagata, T. (2011) A simple regional coupled model experiment for summertime climate simulation over southern Africa. *Climate Dynamics*, **39,** 2207–2217.

Ropelewski, C.F. & Halpert, M.S. (1987) Global and regional scale precipitation patterns associated with the El Niño–Southern Oscillation. *Monthly weather review,* **115,** 1606–1626.

Ropelewski, C.F. & Halpert, M.S. (1989) Precipitation patterns associated with the high
index of the Southern Oscillation. *Journal of Climate,* **2**, 268–284.

Stringer, L., Dyer, J., Reed, M., Dougill, A., Twyman, C. & Mkwambisi, D. (2009) Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12**, 748–765.

West, A.G., Midgley, G.F. & Bond, W.J. (2012) The reforestation of Africa? *South African Journal of Science*, **108**, 2–4.

Winsemius, H.C., Dutra, E., Engelbrecht, F.A., Archer Van Garderen, E., Wetterhall, F., Pappenberger, F. & Werner, M.G.F. (2014) The potential value of seasonal forecasts in a changing climate in southern Africa. *Hydrology and Earth System Sciences*, **18**, 1525–1538.

## References [CrossRef]


Archer, E.R.M., Landman, W., Tadross, M., Malherbe, J., Weepener, H., Maluleke, P. and Marumbwa, F. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. *Climate Risk Management*, **16**, 22–28. CrossRef

Barnston, A.G., Thiao, W. & Kumar, V. (1996) Long-lead forecasts of seasonal precipitation in Africa using CCA. *Weather Forecast*, **11,** 506–520. CrossRef

Beraki, A.F., DeWitt, D., Landman, W.A. & Oliver, C. (2014) Dynamical seasonal climate prediction using an ocean-atmosphere coupled climate model developed in partnership between South Africa and the IRI. *J Climate*, **27,** 1719–1741. CrossRef

Bond, W.J. & Midgley, G.F. (2012) Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B*, **367**, 601–612. CrossRef

Christelis, G. & Struckmeier, W. (2011) *Groundwater in Namibia. An explanation to the hydrogeological map*. Namibian Ministry of Agriculture, Water and Rural Development, **2**, 1–132.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W-T., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Raisanen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. *Climate change 2007: the physical science basis* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, A.B. Averyt, M. Tignor and H.L. Miller). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Davis-Reddy, C. & Vincent, K. (2017) *Climate risk and vulnerability: a handbook for southern Africa*, 2nd ed. Council for Scientific and Industrial Research, Pretoria, South Africa.

Engelbrecht, C.J. & Engelbrecht, F.A. (2016) Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and applied climatology*, **123**, 247–261. CrossRef

Engelbrecht, C.J., Engelbrecht, F.A. & Dyson, L.L. (2013) High-resolution model projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *International Journal of Climatology*, **33**, 173–187. CrossRef

Engelbrecht, C.J., Landman, W.A., Graham, R.J. & McLean, P. (2017). Seasonal predictive skill of intraseasonal synoptic type variability over the Cape south coast of South Africa by making use of the Met Office Global Seasonal Forecast system 5. *International Journal of Climatology*, **37,** 1998-2012. CrossRef

Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Roux, B., Bopape, M.M., McGregor, J.L. & Thatcher, M. (2011) Multi-scale climate modelling over southern Africa using a variable-resolution global model. *Water SA*, **37**, 647–658. CrossRef

Engelbrecht, F.A., McGregor, J.L. & Engelbrecht, C.J. (2009) Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *International Journal of Climatology*, **29**, 1013–1033. CrossRef

Engelbrecht, F., Adegoke, J., Bopape, M.M., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. & Gatebe, C. (2015) Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**. CrossRef

Garland, R., Matooane, M., Engelbrecht, F.A., Bopape, M., Landman, W., Naidoo, M., Van der Merwe, J. & Wright, C. (2015) Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health. *International Journal of Environmental Research and Public Health*, **12**, 12577–12604. CrossRef

Haensler, A., Hagemann, S. & Jacob, D. (2010) How the future climate of the southern African region might look like: results of a high-resolution regional climate change projection. *Nova Acta Leopoldina*, **112**, 183–193.

Haensler, A., Hagemann, S., & Jacob, D. (2011) The role of the simulation setup in a long-term high-resolution climate change projection for the southern African region. *Theoretical and Applied Climatology*, **106,** 153-169. CrossRef

James, R. & Washington, R. (2013) Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, **117**, 859–872. CrossRef

Jury, M.R., Mulenga, H.M. & Mason, S.J. (1999) Exploratory longrange models to estimate summer climate variability over southern Africa. *Journal of Climate*, **12,** 1892–1899. CrossRef

Kaspar, F., Helmschrot, J., Mhanda, A. et al. (2015) The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12**, 171–177. CrossRef

Kgatuke, M.M., Landman, W.A., Beraki, A. & Mbedzi, M. (2008) The internal variability of the RegCM3 over South Africa. *International Journal of Climatology*, **28,** 505–520. CrossRef

Klopper, E., Landman, W.A. and Van Heerden, J. (1998) The predictability of seasonal maximum temperature in South Africa. *International Journal of Climatology*, **18,** 741–758. CrossRef

Kruger, A.C. & Sekele, S.S. (2013) Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, **33**, 661–676. CrossRef

Kusangaya, S., Warburton, M., Archer van Garderen, E. & Jewitt, G. (2014) Impacts of climate change on water resources in southern Africa: a review. *Physics and Chemistry of the Earth*, **67**, 47–54. CrossRef

Landman, W.A. (2014) How the International Research Institute for Climate and Society has contributed towards seasonal climate forecast modelling and operations in South Africa. *Earth Perspectives*, **1,** 22. CrossRef

Landman, W.A. & Beraki, A. (2012) Multi-model forecast skill for mid-summer rainfall over southern Africa. *International Journal of Climatology*, **32,** 303–314. CrossRef

Landman, W.A., DeWitt, D. Lee, D.-E., Beraki, A. & Lötter, D. (2012). Seasonal rainfall prediction skill over South Africa: 1- vs. 2-tiered forecasting systems. *Weather and Forecasting*, **27,** 489-501. CrossRef

Landman, W.A., Engelbrecht, F.A., Hewitson, B., Malherbe, J., & Van der Merwe, J. (2017) Towards bridging the gap between climate change projections and maize producers in South Africa. *Theoretical and Applied Climatology*, 11-17. CrossRef

Landman, W.A., Kgatuke, M.M., Mbedzi, M., Beraki, A., Bartman, A. & du Piesanie, A. (2009) Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *International Journal of Climatology* **29**, 1535-1549. CrossRef

Landman, W.A. & Mason, S.J. (1999) Operational long-lead prediction of South African rainfall using canonical correlation analysis. *International Journal of Climatology*, **19,** 1073–1090. CrossRef

Landman, W.A., Mason, S.J., Tyson, P.D. & Tennant, W.J. (2001) Retro-active skill of multitiered forecasts of summer rainfall over southern Africa. *International Journal of Climatology*, **21,** 1–19. CrossRef

Landman, W.A., Seth, A., Camargo, S.J. (2005) The effect of regional climate model domain choice on the simulation of tropical cyclone-like vortices in the southwestern Indian Ocean. *Journal of Climate*, **18,** 1263–1274. CrossRef

Lötter, D., Davis, C., Archer, E., Vincent, L., Pardoe, J., Tadross, M., Landman. W., Stuart-Hill, S. & Tadross, M. (2018) *Climate information needs in southern Africa*. CCCEP Working Paper (under review).

Malherbe, J., Engelbrecht, F.A. & Landman, W.A. (2013) Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing. *Climate Dynamics*, **40**, 2867–2886. CrossRef

Malherbe, J., Iyahen, E., Engelbrecht, F., Chamunorwa, M. & Helmschrot, J. (2018) The Extreme Climate Index (ECI), a tool for monitoring regional extreme events. This volume. CrossRef

Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H. & Luo, J.-J. (2014). Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. *Meteorological Applications*, **21,** 733-742. CrossRef

Mason, S.J. (1998) Seasonal forecasting of South African rainfall using a non-linear discriminant analysis model. *International Journal of Climatology*, **18,** 147–164. CrossRef

McGregor, J.L. (2005) C-CAM geometric aspects and dynamical formulation. CSIRO Atmospheric Research Technical Paper, 70.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges and achievements of the regional climatic observation network and database. This volume. CrossRef

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects* (ed. by V.R. Barros, C.B. Field, D.J. Dokken et al.), pp. 1199–1265. Cambridge University Press, Cambridge, UK.

Oltmanns, V. (2015). *Analysing regional rainfall and temperature dynamics in Southern Africa using CORDEX climate projections*. MSc thesis, Friedrich Schiller University Jena (unpublished).

Posada R., Riede, J., Kaspar, F., Mhanda, A., Radithupa, M., Stegling, J., Nascimento, D., Tima, L., Kanyanga, J., Nkonde, E., Swaswa, M. & Waitolo, D. (2018) Cooperation of meteorological services within SASSCAL on improving the management of observed climate data. This volume. CrossRef

Ratnam, J.V., Behera, S.K., Masumoto, Y., Takahashi, K. & Yamagata, T. (2011) A simple regional coupled model experiment for summer-time climate simulation over southern Africa. *Climate Dynamics*, **39,** 2207–2217. CrossRef

Ropelewski, C.F. & Halpert, M.S. (1987) Global and regional scale precipitation patterns associated with the El Niño–Southern Oscillation. *Monthly weather review,* **115,** 1606–1626. CrossRef

Ropelewski, C.F. & Halpert, M.S. (1989) Precipitation patterns associated with the high index of the Southern Oscillation. *Journal of Climate,* **2**, 268–284. CrossRef

Stringer, L., Dyer, J., Reed, M., Dougill, A., Twyman, C. & Mkwambisi, D. (2009) Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12**, 748–765. CrossRef

West, A.G., Midgley, G.F. & Bond, W.J. (2012) The reforestation of Africa? *South African Journal of Science*, **108**, 2–4. CrossRef

Winsemius, H.C., Dutra, E., Engelbrecht, F.A., Archer Van Garderen, E., Wetterhall, F., Pappenberger, F. & Werner, M.G.F. (2014) The potential value of seasonal forecasts in a changing climate in southern Africa. *Hydrology and Earth System Sciences*, **18**, 1525–1538. CrossRef