South African Reserve Bank Working Paper Series WP/22/09

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Authorised for distribution by Chris Loewald

5 August 2022

South African Reserve Bank

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Head: Economic Research Department
South African Reserve Bank
P O Box 427
Pretoria 0001

Tel. +27 12 313 3911

A climate change modelling framework for financial stress testing in Southern Africa

Vafa Anvari,[*] Channing Arndt,[†] Faaiqa Hartley,[‡] Konstantin Makrelov,[§] Kenneth Strzepek,[**] Tim Thomas,[††] Sherwin Gabriel[‡‡] and Bruno Merven[§§]

5 August 2022

Abstract

Central banks play a critical role in the economy, with policy levers that influence and are influenced by climate change. An important part of central bank interventions is conducting climate-related stress tests and scenario analysis to increase awareness in the financial sector of the effects of climate change, improve the integration of climate-related risks into financial companies' decisions, identify important data gaps, and start building capacity to develop more advanced and accurate climate scenarios. These exercises, however, are a challenge to central banks and financial companies because of their complexity and the new data and tools required for scenario development and analysis. The development of scenarios for climate-related stress testing requires the integration of different model frameworks to assess the impacts of climate change, translate these impacts into macroeconomic scenarios, and evaluate the subsequent financial sector outcomes. This integration requires multidisciplinary skills such as the joint work of energy system modellers, climate scientists and macroprudential experts. This paper provides an overview of the modelling frameworks available for assessing climate change impacts in South Africa, covering both local and global models. This should assist financial institutions and regulators with developing partnerships to build scenarios and assess the impact of climate-related risks. Gaps in current models and modelling for financial stress testing are also identified as considerations for future research.

JEL classification: E52, O230, Q540

Keywords: climate change models, transition risk, physical risk, central banks, South Africa

[*] Head: Stress Testing Division, South African Reserve Bank (SARB).

[†] Director: Environment and Production Technology Division, International Food Policy Research Institute (IFPRI).

[‡] Scientist: Environment and Production Technology Division, IFPRI.

[§] Lead Economist, SARB.

[**] Research scientist at MIT's Joint Program on the Science and Policy of Global Change, faculty fellow at the MIT Office of Sustainability, professor emeritus of civil, environmental, and architectural engineering, University of Colorado, and consultant with Industrial Economics.

[††] Senior Research Fellow: Environment and Production Technology Division, IFPRI.

[‡‡] Scientist: Environment and Production Technology Division, IFPRI.

[§§] Senior Research Officer: Department of Chemical Engineering, University of Cape Town.

1. Introduction

Both mitigation of climate change and adaptation to deal with its effects require changes throughout society, including new policies, new institutions and new roles for many existing institutions. As Mark Carney, then Governor of the Bank of England, observed in 2015, central banks are institutions with a critical role at the centre of the economy, with policy levers that influence and are influenced by climate change. Carney observed that mitigation of and adaptation to climate change are likely to be sources of major structural change, with significant financial and macroeconomic impacts (see also Fankhauser and Tol 2005; Stern 2013; Deryugina and Hsiang 2014; Bolton et al. 2020).

The Network of Central Banks and Supervisors for Greening the Financial System (NGFS) reflects central banks' growing interest in the implications of climate change. The NGFS contributes to monitoring their readiness and helping to inform central bank policies on climate change.

An important part of central bank interventions is conducting climate-related stress tests and scenario analysis. Their primary objective is to increase awareness in the financial sector of climate change, improve the integration of climate-related risks into financial companies' decisions, identify important data gaps, and start building capacity to develop more advanced and accurate climate scenarios. These exercises, however, are a challenge to central banks and financial companies because of their complexity and the new data and tools required for scenario development and analysis (Arndt, Loewald and Makrelov 2020). Climate change is a very different shock to those usually modelled in stress tests. The impacts are often more permanent and there are large relative price changes, driven by policy actions but also changes in consumer sentiments and rapid technology developments. Climate-related financial risks are also unprecedented, with impacts often being non-linear and exacerbated by internal financial sector trends.

Recently, the South African Reserve Bank (SARB) added a climate change risk add-on to its common scenario stress test (CSST) of the six systemically important banks in the country. The biennial CSST covers both solvency and liquidity risk. CSST scenarios are designed to be severe yet plausible. Risks covered in the scenarios are formally identified using the risk assessment matrix, which is part of the SARB's financial stability monitoring framework. Generating the scenario highlighted the challenges faced by central banks in assessing the impact of climate change on the financial system.

One of these challenges, a tripartite one, is integrating different model frameworks. First, it is necessary to develop or acquire models capable of building climate scenarios (to cover both transition risk and physical risk). Second, models need to translate the climate scenarios (impacts of extreme events, global warming and mitigation actions) into macroeconomic scenarios (measuring economic vulnerability to risks related to climate change). Finally, models are needed to translate macroeconomic scenarios into outcomes for the financial sector (measuring the sector's vulnerability and exposure). This integration requires multidisciplinary skills such as the joint work of energy system modellers, climate scientists and macroprudential experts. Many of these skills are not available in central banks and many financial institutions. Successfully developing these new tools and scenarios will require strong partnerships and collaborations with universities and specialised institutes (Arndt, Loewald and Makrelov 2020).

This paper identifies modelling frameworks available in South Africa for assessing climate change impacts. This should assist financial institutions and regulators with developing partnerships to build scenarios and assess the impact of climate-related risks. The paper seeks to be reasonably complete but not comprehensive. Other models not presented here certainly exist, both for the impact channels presented and for others not discussed here (e.g. implications of heat for labour productivity). However, the models presented here represent a good sample of the models that South African financial institutions and regulators could use to assess climate change risks. The modelling frameworks are divided into two types – those assessing transition risks (section 2) and those assessing physical risks (section 3) – in line with the conceptual framework of the NGFS. In addition to discussing local modelling frameworks, the paper briefly presents key global integrated assessment modelling frameworks and their limitations for application at the national decision-making level (section 4). The paper also highlights gaps in current models and modelling for financial stress testing (section 5).

2. Modelling transition risk in South Africa

Several models have been used to assess climate change transition risk in South Africa. As 80% of emissions (excluding forestry and other land uses) in the country are from the energy use, these models have focused on mitigation in the energy system and the associated impacts (DFFE 2021). Studies have, however, been conducted to assess the risks related mitigation in other sectors, such as agriculture, forestry and land use (AFOLU) and waste, albeit to a lesser extent (see DEA 2014a, b; DEA 2018). Within energy, a key focus has been on power systems models, given the sector's dependence on coal and hence the role of power generation in emissions.

Models available in South Africa to assess the transitional impacts of mitigation include technical energy systems, economic, embedded energy/economic, and linked energy-economic models. Pure technical energy/power systems and economic models differ primarily in the emphasis placed on technological details of the energy system relative to the comprehensiveness of endogenous market adjustments. These models also provide a limited set of indicators needed for assessing transitional risks. Alternatives for addressing the shortcomings of stand-alone energy and economic models, such as embedded energy/economic and linked models, are also available for South Africa but are fewer. Linked models are superior to embedded models as they allow for the combination of model strengths, enabling a broader assessment of policy changes on energy prices, demand and welfare as well as the identification of possible abatement opportunities. (Abatement here refers to efforts to reduce the output of greenhouse gases.) To date, SATIMGE, the linked energy-economic model of the Energy Systems Research Group (ESRG), is the only hard-linked full sector energy-economic model in the country. Table 1 provides a summary of energy and energy-applied economic models available in South Africa. These are discussed in more detail in the following sections.

Table 1: Summary of mitigation risk assessment models used in South Africa, by institution

Institution	Model	Description	Notes
Energy models			
Department of Mineral Resources and Energy (DMRE)	Open-Source Energy Modelling System (OSeMOSYS)[1]	Full sector energy	Energy demands are exogenous.
Energy Systems Research Group (ESRG)	SATIM (TIMES)[2]	Full sector energy	Economic indicators are exogenous; energy demand is endogenous. Lower time resolution than PLEXOS.
Council for Scientific and Industrial Research (CSIR)	PLEXOS PypSA[3]	Power and gas	Energy demands are exogenous. High energy profile time resolution (down to hourly/sub-hourly).
Eskom	PLEXOS[4]	Power only	Energy demands are exogenous. High energy profile time resolution.
DMRE			
National Business Initiative (NBI) and Boston Consulting Group (BCG)			
Economic models used for soft linking			
National Treasury	SAGE[5]	CGE	Includes an energy-extended social accounting matrix (SAM).
University of Pretoria	Partnership for Economic Policy[6]	CGE	Not yet applied to energy/mitigation.
NBI	SAM multiplier model		SAM is updated to reflect structural changes in the economy.
Department of Forestry, Fisheries and the Environment (DFFE)	Macro-Economic Impact Assessment Model / INFORUM[7]	SAM multiplier / econometric model	SAM multiplier model linked to econometric model. Exogenous changes to intermediate production structure of the INFORUM model to account for changes resulting from mitigation options.
CSIR	Customised National Renewable Energy Laboratory's International Jobs	Multiplier	Model uses input-output multipliers to estimate direct and indirect employment impacts for different power technologies.

1 See Howells et al. 2011.
2 See Hughes et al. 2020.
3 See Hörsch and Calitz 2017.
4 See www.energyexemplar.com.
5 See Alton et al. 2013.
6 See www.pep-net.orgs.
7 See DEA 2014b.

	and Economic Development Impacts model (I-JEDI)[8]		
Embedded and linked energy-economic models			
ESRG	SATIMGE[9]	Hard-linked SATIM-SAGE model	Includes external modules for AFOLU and waste.
United Nations Environment Programme	South African Green Economy Modelling (SAGEM)[10]	System dynamics model	
University of Pretoria	UPGEM[11]	Computable general equilibrium (CGE)	Includes a nested structure of power by technology as a factor of production.
International Conference on Electricity Distribution (CIRED)	IMACLIM-SA[12]	CGE model with detailed power sector	Leontief power sector, with coefficients informed by SATIM. Application to carbon tax, with a focus on employment.
Nong (2020)	GTAP-E-PowerS – an adaptation of the GTAP-E-Power model	CGE model with detailed power sector module. Includes transmission and distribution	Electric power substitution is represented with a nested additive constant elasticity of substitution.

2.1 Energy systems models

There are three key energy systems frameworks or tools used in South Africa, namely PLEXOS, TIMES and OSeMOSYS. The PLEXOS tool is applied to the power sector only (the CSIR includes gas as well) but includes power demand modelled at a granular time scale capturing electricity demand patterns in a very detailed way. It includes detailed techno-economic characteristics of power supply, information on constraints facing the power system and reliability requirements. Energy demand is externally included in the model and is not influenced by changes in the power sector pathway. Demand-side

8 See www.i-jedi.org/south_africa.

9 See Appendix A.

10 See UNEP 2013.

11 See Dixon et al. 2013.

12 See Schers 2018.

flexibility can be modelled explicitly, as can abatement technologies. PLEXOS as a modelling framework can primarily be run in two main modes: (i) in long-term capacity expansion mode, where an optimised long-term least-cost energy mix is established; and (ii) in short-term production-cost mode, where detailed unit commitment and economical dispatch are undertaken.

The South African TIMES[13] (SATIM) model (see Hughes et al. 2020) is a full sector model of the South African energy system. In such a model, both demand (e.g. boiler or vehicle) and supply (power plant, refinery) technologies are represented in detail. The demand for energy services such as process heat, lighting and mobility are exogenously specified,[14] whereas the demand for energy commodities such as electricity and diesel are endogenous.[15] This allows for more harmonious accounting of structural changes in demand (e.g. different sectors with different energy needs growing at different rates), fuel switching (e.g. from conventional vehicles with combustion engines to electric vehicles) and energy efficiency. The advantage of a full energy systems model compared to a power sector only model such as PLEXOS is that it enables the analysis of technologies and energy commodities other than electricity, in a comprehensive way.

The national power system interacts with the rest of the energy system at several levels upstream (fuel supply) and downstream (demand). Modelling the power sector in isolation would require the user to specify those interaction points exogenously, whereas if it is modelled as part of a full sector model, many of these interactions are taken care of endogenously as core scenario assumptions, such as economic growth and changes in international fuel prices. An example of upstream interaction would be how much liquefied natural gas capacity is required given that natural gas could be used not only in the power sector but in other sectors for thermal applications. The uptake of gas in industry

[13] TIMES: The Integrated MARKAL-EFOM System is an open-source energy modelling platform that was developed and is maintained by an implementing agreement of the International Energy Agency (IEA) called ETSAP. See https://iea-etsap.org/

[14] Exogenous: specified by the user.

[15] Endogenous: calculated by the model.

potentially affects the price of gas “seen” by the power sector. An example of downstream interactions would be on the demand side.

The SATIM model has a very detailed transport sector, which considers technology options for different modes and uses of transport by considering the evolution of the transport fleet. The timing and extent of a switch to electro-mobility and its impact on electricity demand thus becomes a function of the core assumption. In a power sector only model, the demand for electricity from the transport sector would have to be estimated “outside” the model and revisited each time core assumptions change. The other advantage of using a full energy sector model is that emissions can be accounted for across the full energy chain. A mitigation target such as the Nationally Determined Contribution specifies the carbon space available to the whole energy sector. The model is then able to allocate carbon space to different sectors based on an approach that considers the full supply chain, the technology options available to different sectors and their relative merits in terms of cost and other factors, such as other pollutants. This is important for mitigation policy goals such as net-zero emissions, as mitigation would need to occur across sectors in the economy. Merven et al. (2018) illustrate how a particular instance of SATIM was able to replicate the outcomes from PLEXOS.

OSeMOSYS is an open-source modelling platform similar to TIMES. It was developed as an alternative to TIMES for users who do not use the General Algebraic Modelling System (GAMS).[16] Although OSeMOSYS provides modellers with an alternative for starting off in the realm of energy systems modelling, it does not yet incorporate all advanced features that have been incorporated into the TIMES platform over its more than 20 years of development. OSeMOSYS is thus more cumbersome for developing large, complex models. The South African OSeMOSYS model was used by the national Department of Mineral Resources and Energy to develop various drafts of the national Integrated Energy Plan (see DMRE 2012 for more information).

[16] For information about GAMS, see https://www.gams.com/.

Each of the models described above can incorporate the impact of carbon pricing on the relative costs of electricity generation technologies. This is of particular relevance for stress testing near-term transition risks for South Africa given the country's dependence on coal for power generation. However, the model outcomes still need to be translated into economic and financial outcomes to be useful for stress testing. Energy demand projections used in these models do not endogenously respond to the impact of energy prices or changes in the financial system resulting from transition risks.

2.2 Economic models

Economy-wide models are generally used to assess the transitional risks of mitigation, as they enable the analysis of a broader range of impacts than other economic methodologies. There are three key types of economy-wide modelling technique that have been applied to changes in the energy system in South Africa. These include computable general equilibrium (CGE), SAM and multiplier models such as the International Jobs and Economic Development Impacts (I-JEDI) model. While SAM and multiplier analysis account for the direct, indirect and induced impacts of changes to the economy, they do not account for changes in relative prices, investment and macroeconomic constraints and the implications of these on the overall outcome. The I-JEDI model, for example, estimates the gross economic impacts from wind, solar, biopower and geothermal energy projects by increasing the demand for goods and services these projects need. This increase in demand has a multiplier effect on the economy, creating added value. In reality, the increase in demand for these types of goods and services is likely to lead to higher prices, which would negatively affect other producers demanding the same goods and services. Such effects could dampen the overall positive impact from increased investment in cleaner energy technologies. Similarly, labour and capital supply constraints affect the cost of these factors in production.

CGE models provide a more robust analysis than SAM and multiplier models, as they account for these price and behavioural changes endogenously while respecting macroeconomic constraints such as the supply of labour. In the case of dynamic CGE models, sector capital stocks are endogenously updated based on previous-year levels of investment. CGE models are structural models that capture the functioning of a real market economy in which the interactions of producers, households, government and the rest of the world are mediated via prices and markets. They are based on microeconomic fundamentals in which agents optimise behaviour subject to constraints (i.e. households maximise utilities subject to a budget constraint and producers maximise profits subject to a production technology constraint), while respecting the macroeconomic and resource constraints of the country. They contain detailed information on sectors and households, therefore providing a useful simulation laboratory for quantitatively examining how policies and shocks to an economy influence production, trade and employment patterns, as well as income distributions.

Several CGE models have been used to study the impacts of mitigation and adaptation scenarios. The SAGE model is a dynamic recursive version of the standard International Food Policy Research Institute (IFPRI) CGE model by Löfgren et al. (2002), built on the framework of Diao and Thurlow (2012). The model can include up to 104 sectors and commodities, and currently includes four labour groups (differentiated by level of education) and 12 representative households. The representation of sector production enables the analysis of climate risks that generally affect the supply side, while the detailed sector representation and expression of linkages between sectors enable the assessment of direct as well as indirect climate impacts that may not be accounted for in other types of assessments. The outputs from SAGE include changes in economic structure, growth, employment, relative prices, household welfare, exchange rates and trade (Arndt et al. 2020). Versions of the model have been used for carbon tax and energy transition analysis as well as the impact of climate change scenarios on the South African economy (see, for example, Alton et al. 2014; Arndt et al. 2016; Merven, Hartley and Schers 2020). A similar CGE model is used by Devarajan et al. (2011) to study the economic impacts of introducing carbon taxation.

Other CGE models, outlined below, have primarily been used to investigate the introduction of carbon taxes in South Africa.

- Van Heerden et al. (2016) use a modified version of the UPGEM model, which includes a nested electricity production sector with eight competing generation technologies. The model is linked to databases accounting for CO2 emissions and energy consumption, which enables the tracking of industry and final user sources of emissions. The UPGEM model is based on the MONASH model (Dixon and Rimmer 2002) and uses linearised equations to describe market behaviour. The structure of the South African economy is accounted for using a database of 53 activities and commodities.
- Nong (2020) uses the GTAP-E-PowerS model, which is an energy- and power-extended GTAP CGE model, to investigate carbon taxes in South Africa. The model distinguishes electricity generation not only by generating technology but also by baseload or peak demand. The GTAP-E-PowerS model builds on the GTAP-E-Power model (see Peters 2016) by extending emissions accounts to include non-CO_2 emissions, ignored in most other studies, thus allowing for an increase in total estimated emissions. Furthermore, in this model the carbon price is levied on industrial sectors rather than imposed on the prices of fossil fuel commodities.
- Schers (2018) uses the IMACLIM-South Africa model to assess how a carbon tax affects South African gross domestic product (GDP), employment, CO_2 emissions and socio-economic inequality. IMACLIM-SA is a two-period open-economy "accounting-style" CGE model for South Africa. The model differs from other CGE models as it does not include perfect factor markets, optimisation or diminishing returns. Profit mark-ups are included for prices, while the labour market includes wage rigidities using wage curves. The model structure comprises five energy and five non-energy sectors, with physical volumes included for the energy sectors. The electricity sector is soft linked to outputs from the SATIM energy system model (ERC 2015) to account for future technology changes.

Chitiga et al. (2019) is one of the few examples in South Africa where the CGE model has been used for physical climate impact assessment. The authors use a modified version of the dynamic CGE model developed by the Partnership for Economic Policy (PEP) to assess the impact of climate change on labour groups disaggregated by gender and ethnicity. The PEP and IFPRI models have the same theoretical foundations and are coded in the same programming language. The main differences are the flexibility of macroeconomic closures, the forms of the production function and the treatment of investment and government spending (Traore 2012). Climate change scenarios are illustrated as productivity shocks to agriculture and water, alongside higher world prices for agriculture, increased depreciation of water capital, and increases in labour supply due to climate-induced migration.

The nature of many mitigation options, which generate transitional risks, is that they create relative price changes in the economy. These, in turn, produce medium- to long-run structural changes. CGE models are structural models, based on microeconomic fundamentals, and suitable for this type of analysis. They have been widely used to assess the impacts of climate change mitigation and adaptation. Stress testing is, however, often focused not on the structural economic or financial changes but on large cyclical shocks. The macroeconomic models used in stress testing produce short-term indicators that are particularly important for price and financial stability analysis. Many of these indicators are not generated by CGE models as this is not their focus. Climate stress testing will require soft or hard linking of CGE and current central bank models to understand the structural impacts of climate change that have the potential to become major economic and financial shocks in the short to medium term (Arndt, Loewald and Makrelov 2020).

At present, the emphasis is on soft linking. The NGFS uses the National Institute Global Econometric Model (NiGEM) to complement CGE frameworks.[17] NiGEM provides insights into the short-term price and output effects, considering global economic linkages.[18] In South Africa, there are similar models that can be used for soft linking. The Reserve Bank Core model[19] is already used in stress-testing analysis. The Bureau for

17 See Hantzsche, Lopresto and Young 2018.

18 See Holland and Young 2020.

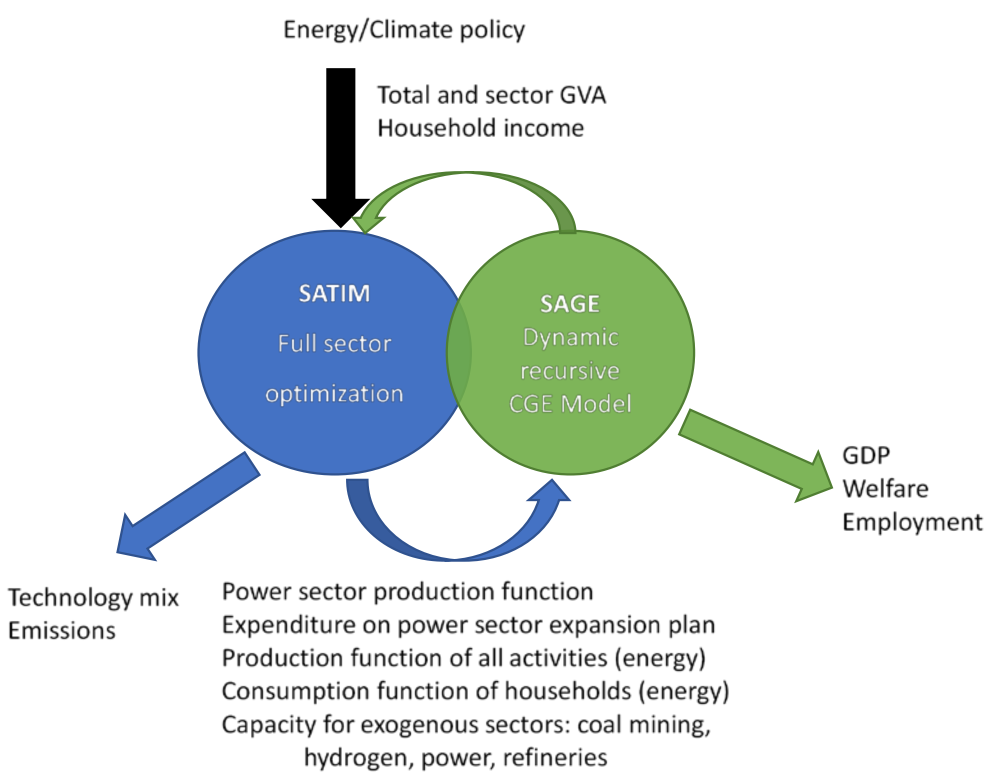
19 See Smal, Pretorius and Ehlers 2007.

Economic Research model[20] and the National Treasury econometric models have a similar structure. A limitation of these models is that they are reduced-form models and not structural. They are based on historical relationships which may become invalid in the presence of large structural climate-related shocks.

2.3 Fully linked energy-system and economy-wide model

The energy-extended version of the SAGE model is the only CGE model that has been hard linked to a full sector energy systems model for South Africa. The model is hard linked to the ESRG's TIMES model. A schematic of the approach is shown in Figure 1. The linked modelling system is called SATIMGE. In terms of linked model approaches, SATIMGE is the most advanced tool available in South Africa and has been applied to many mitigation assessments (see Altieri et al. 2015; DEA 2018; Merven et al. 2021).

Figure 1: Schematic of SATIMGE



[20] See Grobler and Smit 2015.

Example outputs from SATIMGE include information on the pace of decommissioning coal-fired power generation plants and affected coal mines; changes in energy sector technologies and the levels of investment needed; changes in energy prices; and information on energy assets stranded as a result of changes in technology choices. This information can be used to better understand the pace of impacts of changes in asset and company valuations, and the investment requirements for new energy builds. Changes in energy prices are also useful for understanding impacts on inflation.[21]

3. Physical risk and impact modelling

Physical climate vulnerability is often assessed using three key methodologies: indicator-based methods (e.g. a vulnerability index), model- and GIS-based approaches (quantitative approaches), and participatory approaches (e.g. cognitive mapping, interviews and surveys). Each methodology has its own strengths and weaknesses (Davis-Reddy and Vincent 2017), and a combination of approaches is often considered ideal. For the purpose of risk assessments within central banks, methodologies that provide quantitative outputs are, however, necessary as these feed into central bank stress-testing modelling frameworks.

South Africa is well capacitated in climate research and modelling capabilities, with a well-developed research community with expertise in natural ecosystems and hydrology. Research groups and science councils focusing on climate change include the Climate Systems Analysis Group, the Department of Oceanography, the African Climate and Development Initiative and the Energy Systems Research Group (all at the University of Cape Town); the Council for Scientific and Industrial Research; the African Climate Foundation; the Centre for Sustainability Transitions and the School for Climate Studies (at Stellenbosch University); the Global Change Institute (University of the Witwatersrand); the South African National Biodiversity Institute; the Agricultural

21 An example of the capabilities of SATIMGE can be found in the policy brief 'Analysing the trade-offs between mitigation and development objectives for South Africa using a linked modelling framework', for the Climate Compatible Growth series for COP26 (see also Appendix A for a list of selected publications).

Research Council; the South African Weather Service; the Water Research Commission; and the Human Sciences Research Council.

The skills of this research community have resulted in several studies assessing the biophysical impacts of climate change in the areas of agriculture, water, built environment, biodiversity and health (Ziervogel et al. 2014; Abraha and Savage 2006; Ding et al. 2021; Cammarano et al. 2020; Shayegh et al. 2021; Chersich et al. 2018; Ogundeji et al. 2018; Strydom and Savage 2017; Tibesigwa et al. 2017; Walsh et al. 2013). This expertise has also led to important advances in statistically downscaled climate models for South Africa (see, for example, Hewitson and Crane 2006). Global climate models, also known as general circulation models (GCMs), have a rather coarse spatial resolution. The typical horizontal resolution for current GCMs is roughly 1 to 2 degrees. This translates to a range of about 25 to 100 grids over the country. There are, however, over 1 800 quaternary and 148 secondary catchments in South Africa used by water and agricultural analysts for policy and management decision-making. Spatially downscaling the GCM projection to a higher resolution closer to the national scale is therefore important for decision-making.

There are two primary approaches to downscaling, namely dynamical and statistical. In dynamical downscaling, regional high-resolution models are essentially nested in global climate models. Outputs (large-scale changes) from global climate models are fed into regional meteorological models to simulate local weather conditions. Regional models can produce detailed regional climate changes (in temperature and precipitation) because the local topography is better resolved by the model. Statistical downscaling, machine learning and classical spatial statistics techniques convert selected windows of global-scale model output to regional-scale conditions. It is based on the concept that large-scale climate signals modelled well in the coarse global models have a fixed relationship with local climate signals via physiographical features such as topography and vegetation. Statistical downscaling requires identifying empirical links between large-scale patterns of climate elements and local climate (Cooney 2012). Table 2 shows the advantages and disadvantages of both techniques.

Table 2: Strengths and weaknesses of statistical and dynamical downscaling

	Statistical	Dynamical
Advantages	• Comparatively cheap and computationally efficient. • Can provide point-scale climatic variables from GCM-scale output. • Able to directly incorporate observations into method.	• Produces responses based on physically consistent processes. • Can resolve atmospheric processes on a smaller scale (e.g. orographic and rain-shadow effects in mountainous areas).
Disadvantages	• Dependent on choice of predictors. • Does not account for non-stationarity in the predictor-predict and relationship. • Regional climate system feedbacks not included. • Affected by biases in underlying GCM.	• Computationally intensive. • Limited number of scenario ensembles available. • Dependent on GCM boundary forcing; affected by biases in underlying GCM. • Dependent on regional climate model (RCM) parameterisations. • Different RCMs will give different results.

Source: Cooney 2012

Table 3 provides a summary of key models used in these assessments. This summary is primarily derived from Ziervogel et al. (2014).

Table 3: Quantitative climate risk assessment methodologies applied to South Africa

Biophysical analysis	Scale of analysis	Examples of methodologies used
Agriculture	Single key crops	• Crop simulation models and modelling frameworks (e.g. Decision Support System for Agrotechnology Transfer; Agricultural Production Systems Simulator) • Climate envelope models • Ricardian approach (cross-sectional analysis)
Water	Range of climate scenarios	• Hydrological and hydraulic models using downscaled climate projections
Built environment	• Limited number of studies • Small unit of analysis (e.g. city level)	• Risk exposure approach based on a combination of statistical analysis, geographical information system modelling and expert consultation • In the case of Durban (Walsh et al. 2013), a city-scale integrated assessment modelling tool was developed specifically for the region to assess the

	• In most cases assess impacts on sea level rise and the water sector	impact of climate changes on human health, agriculture, emissions, plant species and vegetation type distribution, extreme events and sea level rise
Health	• Limited number of studies • Focus on specific diseases • Assess productivity impacts	• No interdisciplinary or complex assessment methods currently exist • Econometric frameworks
Biodiversity	Range of climate scenarios	Includes impact analysis of vegetation structure and function, ecosystem-based adaptation approaches as well as conservation adaptation plans

There are few studies that link the impact of climate change to the South African economy or parts thereof using an integrated assessment modelling framework. These studies cover specific sectors rather than providing economy-wide impacts. More recent studies include the following:

- Cammarano et al. (2020) use the Agricultural Model Intercomparison and Improvement Project Regional Impact Assessment (AgMIP-RIA) tool to assess the impact of climate change on maize in the north-eastern region of the Free State province. AgMIP-RIA assesses the impact of computed potential climate outcomes on maize using the Decision Support System for Agrotechnology Transfer (DSSAT) and the Agricultural Production Systems sIMulator (APSIM). Outputs from crop models are then assessed in the Trade-Off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) to estimate the impact of changes on farm income and poverty rates. The TOA-MD model provides for detailed farm income analysis and includes farm heterogeneity.

- Ding et al. (2021) use a coupled or linked model consisting of an agent-based model of water demand and management and a local hydrologic model of the "Big Six" reservoir system to study the food-energy-water nexus,[22] connecting the

[22] The water, energy and food security nexus, according to the Food and Agriculture Organization of the United Nations, means that water security, energy security and food security are linked to one

agricultural, urban, and hydroelectric generation sectors in the City of Cape Town. Their study reports on the impacts for household water use and pricing.

- Ogundeji et al. (2018) use the Ceres Dynamic Integrated Model (CDIM) to evaluate the impact of different adaptation strategies to climate change on the agricultural sectors of Ceres, in the Western Cape. CDIM is an optimisation model that maximises the economic value of the net returns to water from agricultural water users. The modelling framework includes modules for climate, hydrology and agricultural production.
- Shayegh et al. (2021) use an analytical model of overlapping generations to study the long-term impacts of future climate changes (temperature only) and socio-economic changes on labour supply, output and welfare in South Africa.

Based on the literature assessed, the Systematic Analysis for Climate Resilient Development (SACReD) framework, used in the economic impact assessment of the South African Long Term Adaptation Scenarios (LTAS) project, is the only integrated assessment model (IAM) that combines several climate-induced biophysical impacts consistently into one economic impact assessment model and provides economy-wide impacts (see Cullis et al. 2015; DEA 2016). While the SACReD framework only captures three biophysical channels (i.e. crop yields, water availability and infrastructure), it allows for additional channels to be added. The framework is described in detail below.

3.1 SACReD framework

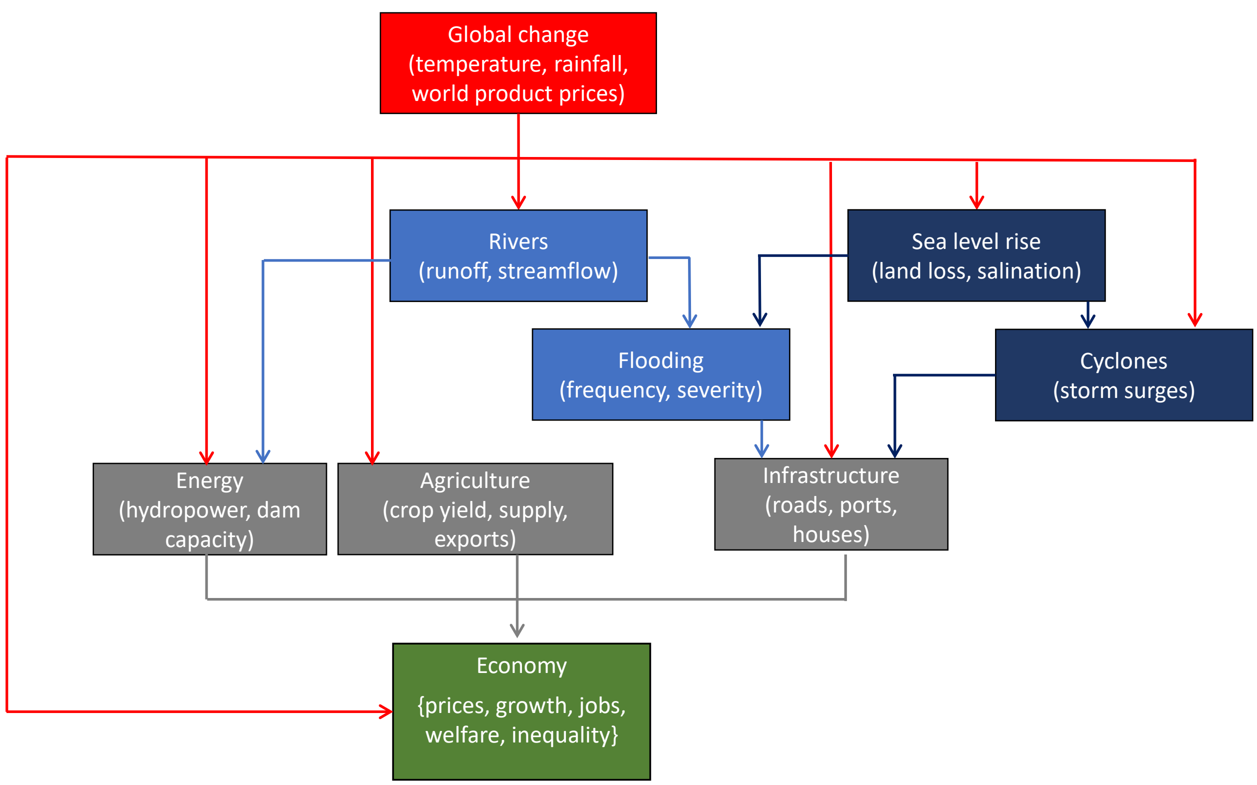
With respect to physical risks and impacts, IFPRI in collaboration with UNU-WIDER and MIT developed a modelling framework to extend climate changes to impacts on physical infrastructure and natural systems and link these to the economy through pathways called channels (see Figure 2). Wherever possible, existing local models are used; if these are not available, models based on frameworks in similar hydro-climatic regions are developed. SACReD has been applied throughout Africa and Asia (see Appendix A) and has supported government projects such as the LTAS project (Cullis et al. 2015).

another, meaning that the actions in any one area often has effects on one or both of the others.

The key elements of SACReD are:

- Country- or regional-level focus rather than global.
- Structural approach. Component models are typically bottom-up and drawn from first principles and local expertise where possible.
- Completeness. All relevant climate impact channels are treated in a coherent framework.
- Flexibility. While it is important that the elements of the framework interact appropriately, the exact modelling frameworks are flexible.
- Risk and uncertainty. SACReD has a distinctive probabilistic modelling approach that reflects the uncertainty in climate change projections. This "hybrid-frequency" method allows for a risk-based analysis of climate impacts, facilitating analysis of extreme events.

Figure 2: Schematic of the SACReD framework



Compared with many IAM frameworks, SACReD provides granular representations of key features such as water systems, agriculture and infrastructure. The economic model within SACReD has strong detail in water and in regional agriculture, aligning it well with the biophysical modelling approaches that are key to appropriately representing climate change within the economic model. Key components of SACReD are discussed below.

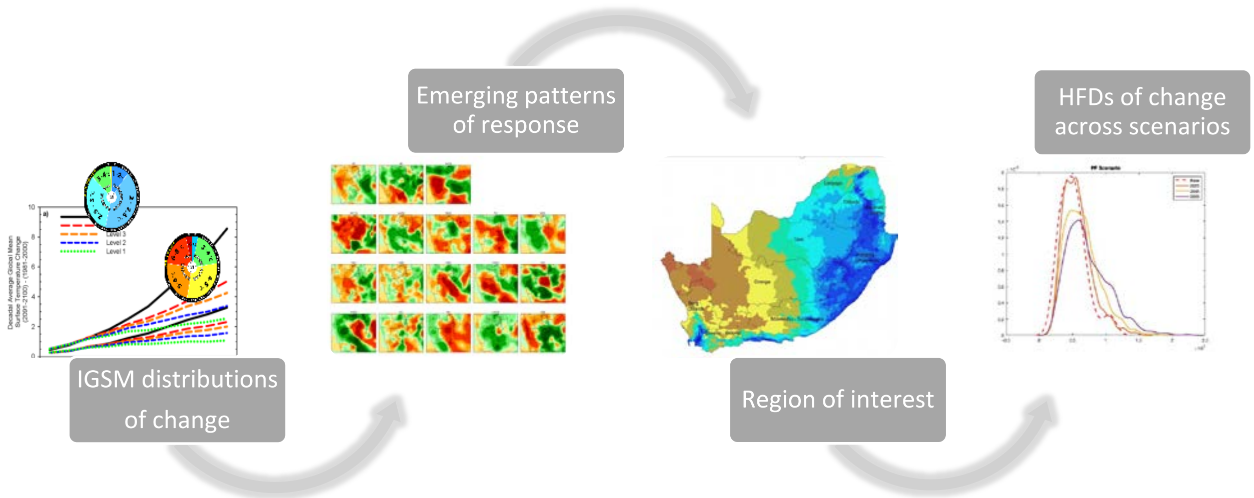
3.1.1 Global change

Due to the importance of risk and uncertainty, the SACReD framework frequently links to global change outputs from the Integrated Global Systems Model (IGSM)[23] (Sokolov et al. 2009). IGSM captures the combined uncertainties related to the volumes and timings of greenhouse gas emissions from human systems and the reaction of earth systems to changes in the atmospheric composition, and solves for zonal temperature and precipitation (e.g. by latitude band). Using a procedure developed by Schlosser et al. (2015), these outcomes are distributed regionally using patterns of response from Climate Model Intercomparison Project (CMIP) models.[24] The result is monthly Hybrid Frequency Distributions (HFDs) of precipitation and temperature anomalies for each socio-economic scenario (see Figure 3).

[23] IGSM was developed and is maintained at the Joint Program on the Science and Policy of Global Change at MIT.

[24] The CMIP is a standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models. This facilitates assessment of the strengths and weaknesses of climate models, which can enhance and focus the development of future models.

Figure 3: Basic method for estimating regional outcomes from zonal results



A total of 7 200 climate projections were recently estimated for Southern Africa under four global socio-economic scenarios (Schlosser et al. 2021), namely:

- Reference: continuing early twenty-first century emissions patterns
- Paris Forever (PF): Paris Agreement commitments are met with no further mitigation
- 2-degree (2C): mitigation efforts stabilise global average temperature gains at 2 degrees above pre-industrial levels
- 1.5-degree (1.5C): mitigation efforts stabilise global average temperature gains at 1.5 degrees above pre-industrial levels.

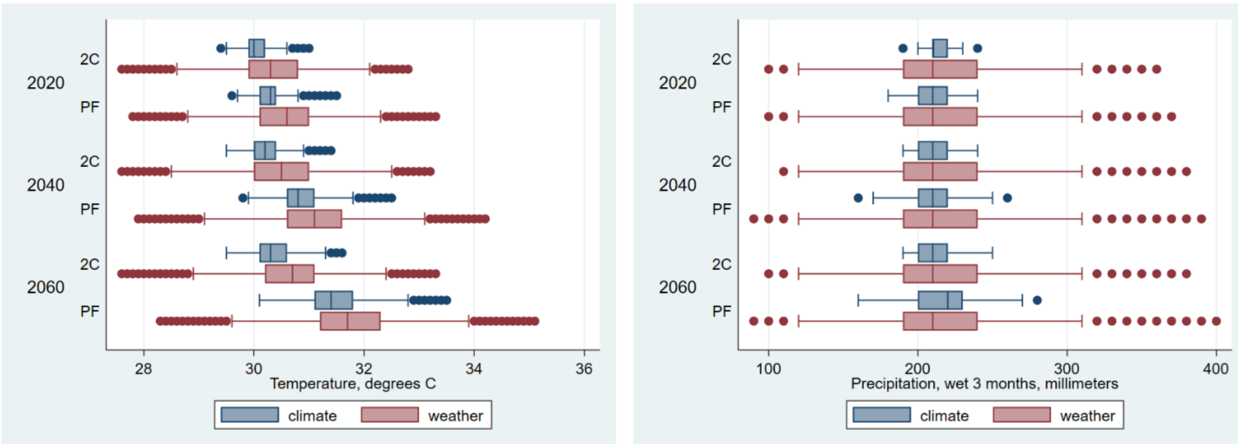
3.1.2 Incorporating weather into climate change risk and uncertainty analysis

The models discussed in section 3.1.1 help to quantify the impact of uncertainty about future emissions and climate impacts on temperature and precipitation. They do not, however, cover inter-annual variation, which is important to extreme climate events. The importance of this is shown in Figure 4: blue plots depict the HFDs for temperature and precipitation, while red plots incorporate inter-annual variability.[25] It is notable that the

[25] Methods for overlaying the historical variability of weather and smoothed climate projections are discussed in Appendix C.

combination of climate change and variability broadens the distribution significantly and increases the probability of extreme events.

Figure 4: Temperature and precipitation projections for South Africa with and without inter-annual variability, 2C and PF



Notes: Precipitation values are for the wettest three months of the year for each pixel, for the given decade. Temperature values are for mean daily maximum temperature for the warmest month during the wettest three months of the year for each pixel, for the given decade.

3.1.3 Informed selection of future climates

Climate projections generated from processes described in sections 3.1.1 and 3.1.2 are too large (about 720 000) to be computationally feasible in SACRED. A technique called Gaussian Quadrature is therefore used to reduce the number of projections (to 455) while maintaining, for two time periods, the first, second and third moments for two key climate variables for three agriculturally important Southern African regions (see Arndt et al. 2015). It is also possible to model a smaller number of climate projections (e.g. the four NGFS scenarios).

3.1.4 Modelling crops under climate uncertainty and variability

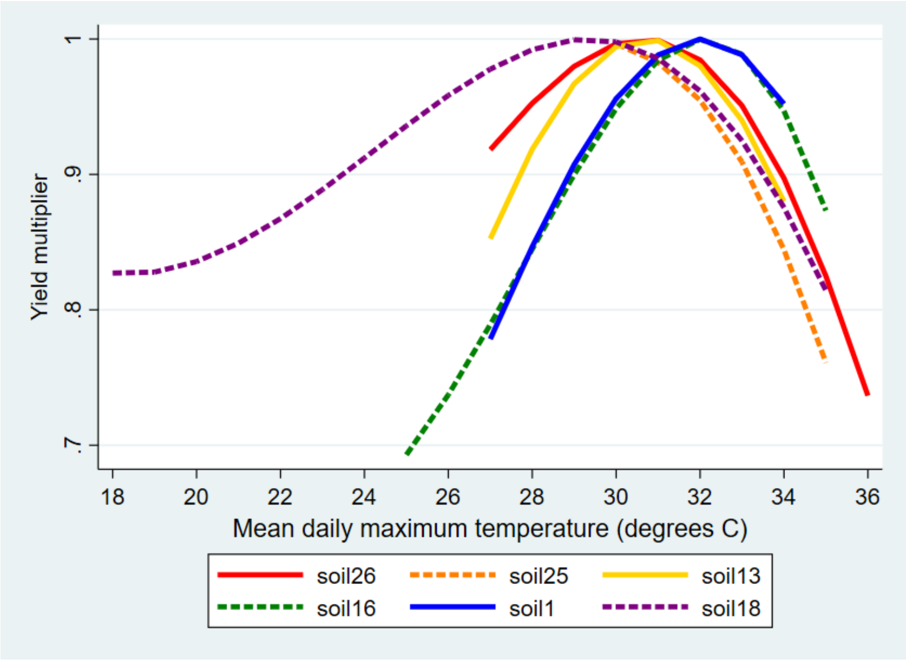
Decision Support System for Agrotechnology Transfer (DSSAT) is a crop simulation software suite that consists of multiple crop-specific models (Jones et al. 2003).[26] It is

[26] DSSAT includes more than 42 crops. IFPRI has experience in applying DSSAT to at least 21 crops, although analysis of all 42 crops is possible if the relevant information is available.

used together with daily weather and information on soils and farming methods to determine yields of key crops. A regression is run using these yields and monthly climate aggregates to create crop yield emulators (Franke et al. 2020; Blanc and Sultan 2015; Ostberg et al. 2018) – a much faster and more flexible means of generating annual values at fine spatial resolution. Emulators also assist in explaining crop temperature and precipitation responses.

Figure 5 shows the yield response of rainfed maize in Southern Africa to the mean daily maximum temperature of the second month following planting. The results show a strong decline in yield for suboptimal temperatures, with optimal crop temperatures differing by soil type. Similar curves can be generated for monthly precipitation.[27]

Figure 5: Relative yield benefits for high-yield rainfed maize on the six most common soil types in South Africa in response to the mean daily maximum temperature of the second month, ^{0}C



[27] The SACReD framework can be expanded into other agricultural activities. For example, IFPRI, with the International Livestock Research Institute, has developed simple livestock and herd dynamics models that can be incorporated into SACReD.

Notes: Cubic specification for rainfall and mean daily maximum temperature with log yield as the dependent variable. Each soil is mapped over the range from the 5th to 95th percentile for temperatures used in the emulator.

3.1.5 Modelling droughts

Given the information that can be generated by the models discussed in sections 3.1.1 to 3.1.4, we can investigate the impact of droughts. Thomas et al. (2022) show that for South Africa, a one in 20-year low-yield maize event is likely to increase to one in 10.2 years by the 2040s and one in 6.7 years by the 2060s (see Table 4).

Table 4: Frequency of 20-year low-yield events for rainfed maize, reference scenario

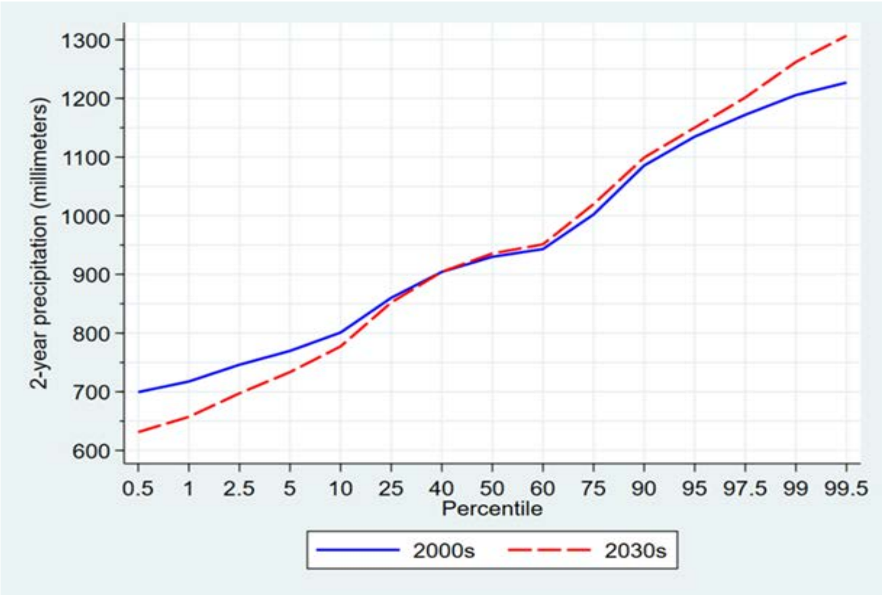
Area	1.5C 2040s	1.5C 2060s	2C 2040s	2C 2060s	PF 2040s	PF 2060s	REF 2040s	REF 2060s
Region	15.3	16.3	13.3	13.1	11.7	6.5	9.6	3.5
Angola	20.7	33.7	20.1	21.0	13.9	12.3	12.7	7.1
Botswana	18.1	14.9	14.3	10.8	10.8	6.3	10.8	5.0
Eswatini	17.8	17.1	15.5	12.1	11.6	7.1	13.8	6.3
Lesotho	20.9	14.3	16.0	14.8	23.1	12.7	12.8	10.2
Malawi	16.8	21.8	10.6	17.1	15.3	8.0	11.2	4.7
Mozambique	16.5	18.7	16.5	16.1	12.9	7.1	9.9	4.2
Namibia	14.1	14.1	14.5	12.9	10.9	5.5	14.6	5.6
South Africa	16.7	16.6	11.9	12.3	10.3	8.2	10.2	6.7
Zambia	19.5	19.8	12.3	9.1	10.6	5.1	7.1	3.3
Zimbabwe	19.4	21.4	15.2	14.0	12.3	8.1	8.8	5.2

Source: Thomas et al. 2022

A separate study (Thomas et al. 2022) shows that the severity of drought events also increases. Under the PF scenario, the level of rainfall over a two-year period in a 1-in-100-year drought in South Africa would decrease by 8.4% by the 2030s, relative to the 2000s.[28] This is a 30% reduction in rainfall relative to the 2000s median (see Figure 6).

28 This is similar to the 1991–1992 drought, which reduced normal crop yield by 40%.

Figure 6: Cumulative distribution function plot: rainfall



3.1.6 Water resources modelling

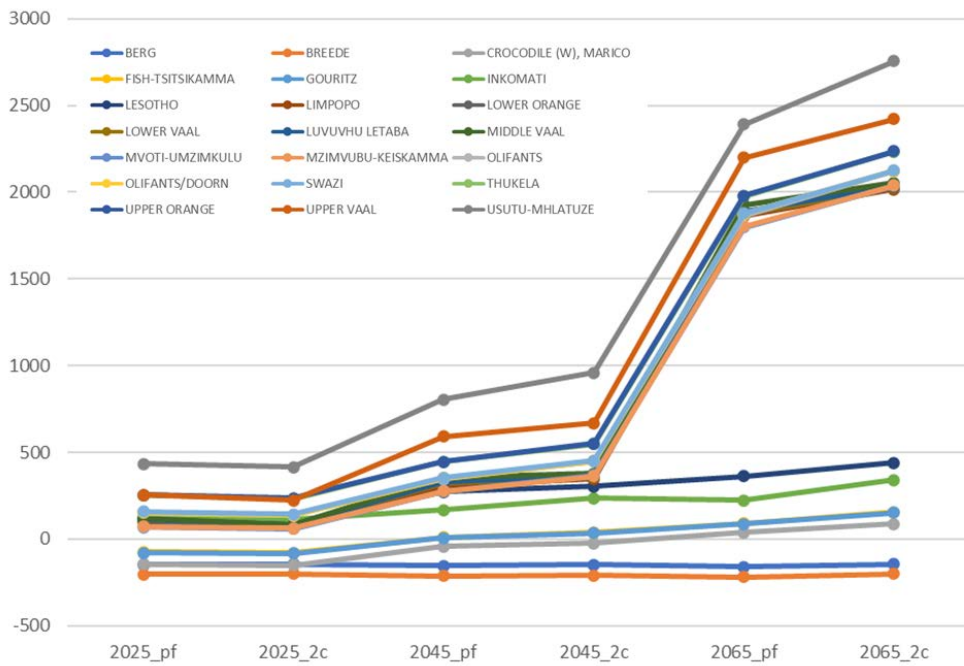
A national Water Resources Yield Model was developed for use in SACRED for South Africa under the LTAS project to evaluate potential climate change impacts on water supply and availability across all river basins, including the transboundary rivers of the Orange and Limpopo (Cullis et al. 2015). In the model, South Africa is divided into 19 water management areas (WMAs) to account for regional differences in supply and demand.[29]

Figure 7 shows the mean impact on the average annual total water supply surplus by WMA (and Lesotho and Swaziland) for the PF and 2C scenarios relative to the baseline scenario. The results show a reduction in current water supply shortfall for the Berg and Breede catchments, but a significant increase for the Usutu to Mhlatuze, Upper Orange and Upper Vaal WMAs, particularly by the 2065 scenario. This outcome is partly driven by increased future demand for bulk water. The upper lines mainly represent primary

29 From a governance perspective, a number of these WMAs are now grouped together under the management of a single catchment management agency (CMA). The current proposal is to establish six CMAs across South Africa, down from an original nine, but only two of these CMAs have so far been established.

catchments with minimal water infrastructure, while the lower lines have significant storage and inter-basin transfers. These results highlight the significant benefits of South Africa's highly integrated bulk water supply system in mitigating future climate change impacts.

Figure 7: Mean impact of climate change on average annual total water shortfall by WMA (Mm^3/a) (relative to baseline) in PF and 2C scenarios



3.1.7 Flooding

Flooding occurs over a shorter period and is regionally more localised than information included in a water supply system. To properly model the impacts of floods caused by climate change, modelling efforts need to be at a maximum of a daily time step and at the quaternary catchment level (Hughes 2004). For detailed urban flooding, hourly- and kilometre-scale modelling is needed. Recent advances in global databases[30] have proven sufficient for limited modelling of urban flooding in Africa. More detailed local light detection and ranging systems and GIS data on urban drainage surface and sub-surface systems will improve the accuracy and comprehensiveness of this modelling and make

30 That is, digital elevation model and land use data.

design-level climate change analysis possible. However, current data can provide meaningful material for analysis of climate change at the planning level.

For impact assessment at national and regional scales of flooding caused by climate change, the most widely used model is the Soil and Water Assessment Tool Plus (SWAT+).[31] SWAT+ is a small watershed- to river basin-scale model that simulates the quality and quantity of surface and groundwater and predicts the environmental impact of land use, land management practices and climate change. In addition to assessing flooding, SWAT+ is widely used to assess soil erosion prevention and control, non-point source pollution control and regional management in watersheds. South Africa has extensive expertise in using SWAT+ (see Mengistu et al. 2019; Gyamfi et al. 2016; Querner and Zanen 2013).

3.1.8 Infrastructure

The Infrastructure Planning Support System (IPSS) was developed to estimate specific transportation infrastructure costs related to climate change, under adaptation and non-adaptation scenarios (Chinowsky and Arndt 2012).[32] The model considers engineering design standards in relation to climate in a stressor-response methodology (Chinowsky and Arndt 2012). The climate stressors considered are temperature and precipitation, and include their associated extreme event stressors (i.e. flooding and extreme heat). The IPSS allocates budgets in accordance with rules to obtain a projection of the density of the network under alternative climate, investment and adaptation scenarios. The framework has been applied in many countries, including the United States (Schweikert et al. 2014; Chinowsky et al. 2013).

Figure 8 illustrates the cost of maintaining a fixed-size road network in 2050 for two climate scenarios, namely Unconstrained Emissions (UCE) and Level 1 Stabilisation

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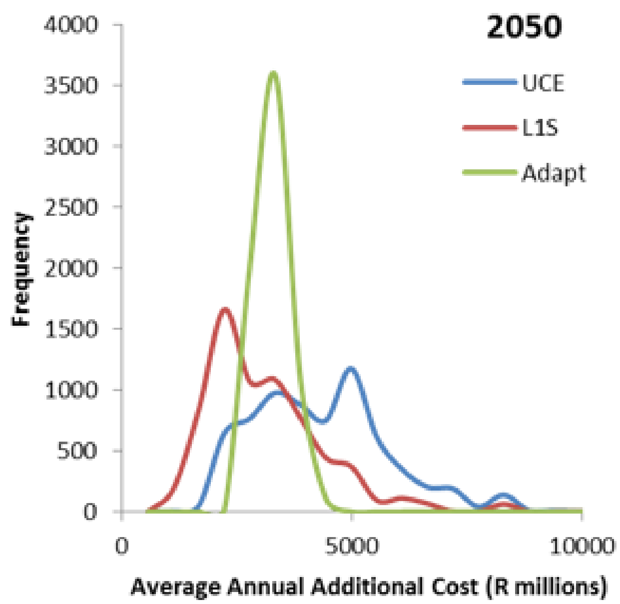
[31] See https://swat.tamu.edu/.

[32] Data on road lengths, types (primary, secondary, tertiary), surface (paved or gravel), age, maintenance schedules and so forth are readily available in South Africa, as is information on budgets for road construction/maintenance/rehabilitation.

(L1S) without adaptation, and for the UCE scenario with adaptation.[33,34] The graph illustrates the uncertainty approach, with some future climates substantially augmenting the cost required to maintain the network while others are much less damaging.

Figure 8: Climate change impact on the decadal average annual additional costs for roads infrastructure in South Africa by 2050, UCE and L1S



3.1.9 Economic models

A version of the SAGE model (see section 2.2) is used in SACRED for South Africa. This version includes additional detail on subnational production, crop activities and farming methods, and water and land production factors (see Cullis et al. 2015). Figure 9 illustrates the impact of climate change on agricultural value added in South Africa by 2050 under the UCE scenario (relative to a fictitious no-climate-change baseline) by WMA.[35] At the national level, the results show a general decline in real GDP, ranging

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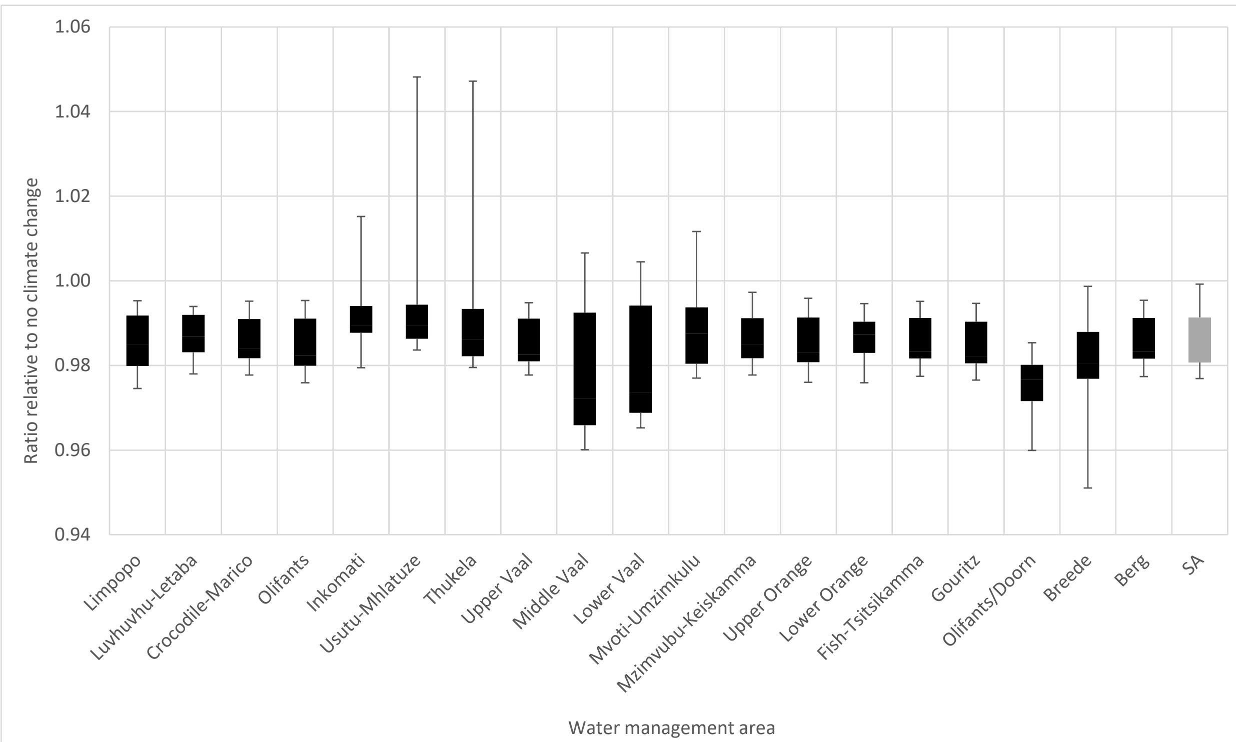
33 UCE is the same as the Reference scenario. L1S refers to an emissions scenario where total atmospheric concentrations of CO_2 are limited to 450 ppm (successful mitigation), a scenario similar to 2C.

34 In the Adapt scenario, pavement mixes and other measures are taken to render roads more resilient to the expected impacts of climate change under the UCE climate scenario.

35 The uncertainty depicted in Figure 9 is due purely to climate. Weather variation can relatively easily be incorporated to allow for analysis of shorter-term dislocations. It is important to highlight that the numbers shown in the figure are sums of value added for all agricultural and non-agricultural activities

between -0.1% and -2.3% (median: -1.5%). For most regions, the GDP impact is consistently negative, although there are climate scenarios under which regional GDP increases (i.e. Mpumalanga (WMA 5), KwaZulu-Natal (WMAs 6, 7, 11), Free State (WMA 9) and North West (WMA 10)). These instances are, however, exceptions, occurring in fewer than 25% of climate models (Hartley et al. 2021).

Figure 9: Regional real GDP estimates (2045–2050), deviation from no-climate-change scenario



4. Global IAMs

Integrated assessment models (IAMs) aim to provide policy-relevant insights into global environmental change and sustainable development issues by providing a quantitative description of key processes in the human and earth systems and their interactions. The

in the WMA. Focusing on agricultural activities, climate/weather impacts for principal agricultural activities are obtained from detailed crop models. If the activities are irrigated, water availability is determined by best-in-class water resources models. If insufficient water exists, irrigated ground is shifted to dryland. If shutting down all irrigation in the WMA fails to conserve sufficient water, municipal and industrial use of water becomes constrained. This level of detail enables the pinpointing of potential problem spots. The comprehensive nature of the model allows one to assess the degree of importance of a given shock at regional or national level.

modelling is integrated, that is, it uses information from many scientific disciplines and describes both human and earth systems. The term 'assessment' refers to a focus on generating useful information for decision-making, even in the case of large uncertainties. IAMs, for instance, have been successfully applied in support of climate policy (insights on future greenhouse gas emissions and options for mitigation) and in several environmental assessments (e.g. the Millennium Ecosystem Assessment). IAMs have also generated many scientific papers.[36]

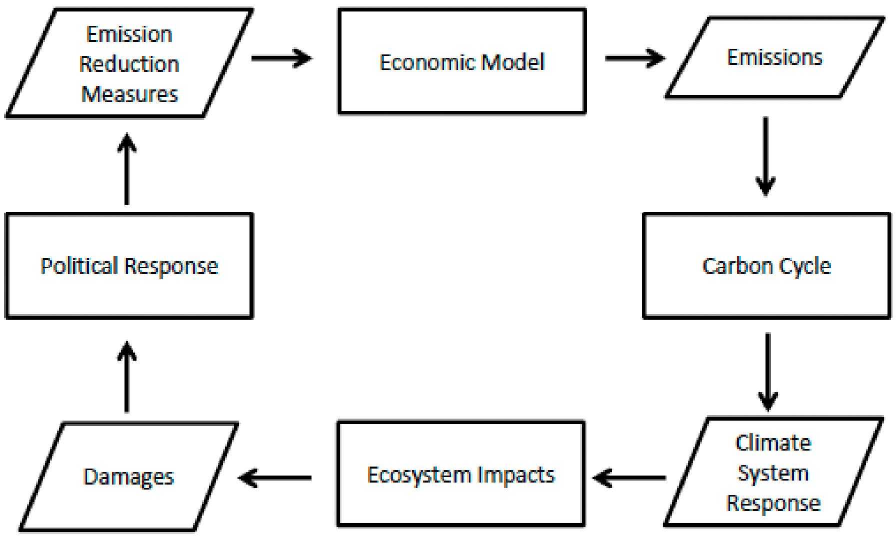
This definition is broad and includes a variety of models that, by themselves, may address global change but not climate change costs or emission policy impacts specifically. According to Metcalf and Stock (2015), models that can do this must combine an economic model with a model of the atmosphere and ocean (and possibly land) such that impacts on geophysical and economic variables of interest can be tracked.

> An IAM constructed to address climate change must be able to track emissions, the concentration of greenhouse gases in the atmosphere as well as other carbon sinks, temperature and other climate impacts arising from increased concentrations of greenhouse gases in the atmosphere, and damages resulting from those climate impacts. Emissions follows from economic behavior, and policies scenarios can be posited to affect emissions along a number of dimensions. (Metcalf and Stock 2015: 5)

Figure 10 illustrates the modules (rectangles) and model inputs/outputs (parallelogram) of a generic IAM as defined by Metcalf and Stock and adapted from Nordhaus (2013). As noted by the authors, not all IAMs would include all the elements illustrated. An example provided by Metcalf and Stock is the lack of IAMs which include an explicit political response module that captures changes in emission mitigation policies in response to climate change damages.

36 See https://www.iamconsortium.org/.

Figure 10: Integrated assessment model schematic



Source: Metcalf and Stock 2015

Table 5 lists the six major global IAMs used by the Intergovernmental Panel on Climate Change (IPCC) in developing the shared socio-economic pathways for current assessment. Three important additional global IAMs that are used internationally and heavily by the US government are GCAM (Joint Global Change Research Institute), MERGE (Electric Power Research Institute) and IGSM (Massachusetts Institute of Technology).

Table 5: Global IAMs used in the IPCC shared socio-economic pathways process

Model name (hosting institution)	Model category	Solution algorithm
AIM/CGE (NIES)	General equilibrium	Recursive dynamic
GCAM (PNNL)	Partial equilibrium	Recursive dynamic
IMAGE/TIMER (PBL)	Partial equilibrium	Recursive dynamic
MESSAGE-GLOBIOM (NASA)	General equilibrium	Intertemporal optimisation
REMIND-MAgPIE (PIK)	General equilibrium	Intertemporal optimisation
WITCH-GLOBIOM (FEEM)	General equilibrium	Intertemporal optimisation

Almost all IAMs focus on the energy and mitigation question, and the spatial resolution for impacts is very coarse. The impact modelling is focused on including high-level impacts as feedbacks to the economy, either negative or positive. In some cases, the impact modelling via biophysical models of the natural, water resource, agricultural and energy systems is done at a very high-resolution global grid to capture the increasing resolution of climate models. While this detailed gridded modelling is able to provide a welcome richer estimate of impacts, global top-down model outputs are in most cases of limited value for detailed analysis of national and subnational impact and adaptation. The global boundary conditions such as world market energy and agricultural prices are crucially important foundations for such national analyses.

5. Modelling gaps

All models have limitations. The complexity of climate change analysis and the need to use multiple models amplify these limitations and create new ones. An example of this is the uncertainty inherently related to models, which are based on a set of assumptions. Passing information from one model to the next increases the uncertainty of outputs and findings. This issue requires careful scenario design and sensitivity analysis and also recognition that, at least in the initial stages of climate stress testing, the results should be used as a communication tool rather than an input to inform capital or other prudential requirements. This section outlines some of the gaps in the model frameworks.

Many of the limitations of the current economic and financial models are due to data gaps, including issues related to quality and access. For example, it is not possible to develop frameworks that distinguish between green and brown financial assets in the absence of disclosure and taxonomy requirements. Another example is the lack of South African credit risk data by economic activity classification or municipal level, which has hindered the development of granular models with credit and economic linkages. Unlike other G20 countries, South Africa does not have a central credit register. The G20 has set up a new data gap initiative to address data gaps related to climate change, and the SARB is taking part in it. Financial institutions can support these efforts by providing their own data. There are also data gaps beyond economic and financial models. An example is the lack of comprehensive weather data for all geographic locations in South Africa.

A large body of literature criticises IAMs.[37] Similarly, central bank models have been subject to criticism.[38] It is difficult to find a widely used model framework that has not been criticised. Models are simplified versions of reality and by definition imperfect. They provide useful insights, but the results should be interpreted in the context of their limitations.

The major limitation of current global climate models (GCMs) is the model spatial resolution (grid spacing) that ranges for typical CMIP6[39] resolutions at about 250 km in the atmosphere and 100 km in the ocean. Even for the high-resolution CMIP6 models, the spatial resolution is between 30 km and 100 km. An additional limitation is the modelling of rainfall. The coarse spatial grid can lead to misting as opposed to actual very localised rain patterns due to mathematical averaging over grids of 10 000 km^2 for standard GCMs (even the highest-resolution GCMs have grids of 525 km^2 or more). Additionally, the physics of rainfall is modelled differently in each GCM and thus the sign of precipitation changes over grids and large regions can be opposite and/or vary greatly in magnitude. Regional climate models on the scale of 1 to 4 km grids can overcome some of these limitations but are so computationally expensive they are usually run for only one or two GCM boundary conditions. With the cost of computing decreasing and the advent of cloud computing, the computational burden of dynamical downscaling has decreased. Furthermore, a global effort known as the Coordinated Regional Climate Downscaling Experiment (CORDEX), has produced a number of downscales data sets for Africa with a hub at the University of Cape Town.[40]

One of the big limitations of economic models was discussed earlier. CGE models have no cyclical and financial sector dynamics, while current central bank models lack the detail and structural dynamics required for climate risk analysis. Financial dynamics need to be

37 See, for example, Gambhir et al. 2019.

38 For example, Duca and Muellbauer (2014) criticise dynamic stochastic general equilibrium models. Macro-econometric models are not structural and subject to the Luca critique (see Lucas 1976).

39 CMIP6 – Coupled Model Intercomparison Project Phase 6. See https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6.

40 See https://www.csag.uct.ac.za/cordex-africa/.

improved across all models and sufficiently included in financial stress testing. This can be done by hard linking the models, as in Makrelov et al. (2020), which will require some reduction in model complexity to trace and understand model shocks. Alternatively, they can be soft linked, as discussed earlier. Soft linking allows for more detail, but it also requires that feedback loops between the different models be run. Stress tests are often criticised for not considering feedback loops, which change the economic assumptions and outcomes. Climate change analysis requires, more than any other economic or financial shock, that these mechanisms be present.

Another important limitation is that these models are linear, whereas climate change risks are likely to generate non-linear, often exponential responses characterised by tipping points.[41] Incorporating tipping points is possible, as illustrated by Makrelov, Davies and Harris (2021), but the impossible task at this point is identifying when these tipping points are reached. Scenario analysis needs to consider different tipping points.

Many of the model limitations are driven by the limited analysis in particular areas to inform model behaviour and assumptions. These include, for example, technology evolution and its impact on energy planning, crop yields and crop water demand, irrigation efficiencies or water demand in particular industries – especially thermal electric cooling and waste-water treatment. A major limitation is the modelling of extreme events such as droughts and floods, which occur infrequently and require probabilistic methods to produce statistically significant results. These are very computationally expensive in terms of resources required (such as time), with varying levels of data inputs available.

Finally, the effective use of model-generated stress scenarios requires micro analysis. Micro analysis can aid in identifying potentially destabilising risk concentrations that macro analysis may not include. Stress-testing approaches by central banks often involve the use of existing macroeconomic models developed for monetary policy analysis. The models fail to sufficiently account for financial system interactions (Foglia 2009).

41 See NGFS (2020) and NGFS (2021) for a list of current limitations associated with climate stress testing.

Furthermore, micro analysis can help to provide more detailed guidance to those conducting stress tests, which would help to ensure that information from financial institutions is comparable.

6. Conclusions

South Africa has significant capabilities in climate analysis and economic modelling. Many of the local frameworks also cover the region. This can be used to assist regulators and the financial sector with developing climate stress-test scenarios that reflect physical and transition risks specific to South Africa and the region. The frameworks available for South Africa and the region are more detailed than global approaches. They capture, for example, important differentiation in regional implications. For instance, in transitioning away from coal, existing models can track which power plants (and hence coal mines) are likely to shut down first. On the impact side, integrated assessment modelling has already highlighted the importance of South Africa's system of inter-basin transfers for the resilience of water supply. There is a need for further model development to address current limitations. In tandem with this, new data sources need to be developed and more analysis conducted to inform climate actions and specific model properties.

Scenarios need to be carefully designed because of the large number of assumptions both within and across models, the limitations of models, major structural changes, multiple policy changes, lack of data and high levels of climate uncertainty. It also needs to be recognised that stress tests (at least initially) are likely to be a communication tool that highlights possible climate risks, rather than an active policy tool justifying capital changes. This role as a communication tool is very important. If stress tests are shared with the public, this can create momentum around transformation and partnerships, and support the development and sharing of new data. Greater public and academic involvement and scrutiny will create greater accountability.

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Appendix A: Selected publications related to SATIMGE

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Appendix B: Selected publications related to SACReDSACReD

Special issue of *Climatic Change*: 'Climate change and the Zambezi River Valley', consisting of the following six articles:

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5) Chinowsky, P S, Schweikert, A E, Strzepek, N L and Strzepek, K. 2015. 'Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia'. *Climatic Change* 130(1): 49–62.
6) Arndt, C and Thurlow, J. 2015. 'Climate uncertainty and economic development: evaluating the case of Mozambique to 2050'. *Climatic Change* 130(1): 63–75.

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Appendix C: Approach for overlaying weather on climate change

To generate the plots for Figure 4, we merged historical weather deviations from the trend with the monthly climate change information in the 7 200 climate models per emissions scenario. The weather data are from the Princeton Global Forcings (PGF) dataset, version 3 (based on Sheffield, Goteti and Wood (2006)). PGF provides daily data for a number of weather variables, including the ones relevant to this analysis: precipitation and daily minimum and maximum temperatures. The data span the period from the beginning of 1948 to the end of 2016, and are at a quarter-degree resolution, which in most places reflects rectangles with 25–30 km on each edge. For most of our work we are interested in monthly data, so we aggregated the data, summing the precipitation and computing monthly values for mean daily maximum and mean daily minimum temperatures.

We detrended each monthly weather variable linearly, allowing for a shift in the trend in 1975, to allow for different rates of climate change through the trajectory. Because the data have some inter-annual serial correlation that complicates decoupling consecutive years of data to simulate future weather, we removed some of this inter-annual correlation by creating "meteorological years" that began in the middle month of the driest three months, thus keeping together the wettest months.[42] We took 5 000 random draws with replacement to form 100 50-year sequences of weather.

Each of the 100 weather sequences of weather deltas (inter-annual variability) was added to each of the smoothed climate models, allowing us to have 720 000 possible future climates per emissions scenario at each quarter-degree pixel, for each month between 2020 and 2069. Such a large collection of weathers climates allows us to better understand change in risk over time as well as over space. The impact of climate will differ by location, depending in part on the current climate at each location, but also on how climate change will alter that climate. This pixel-based approach allows us to not only

42 In areas where December and January are among the wettest months, separating them through a calendar year approach contributes significantly to the inter-annual correlation of precipitation.

generate a carefully computed impact at national level, but also anticipate both opportunities and challenges on a fine geographic scale, allowing different policy prescriptions and different interventions, if desired, for each subnational region.