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A Delphi assessment of climate change risks in southern Africa in the 21st century

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ABSTRACT

Climate change is acknowledged as one of the greatest environmental and development challenges society faces. Many organisations are now encouraged to conduct assessments of the climate risks they will be exposed to over the next decades. The Global Change Institute (University of Witwatersrand, South Africa) conducted such an assessment for the southern Africa region, to identify some of the main clusters of climate-change related risks. A list of over fifty risks was scored and ranked using a modified-Delphi process; an iterative process of expert-driven risk identification and ranking that was informed from our collective experience and the literature. We focused on the likelihood and consequence in the mid-term (2041–2060) and scored each risk according to this time frame (risk score = [likelihood of event occurring] × [the impact of the event], moderated by the multiple lines of evidence available (*Evidence confidence*), and the expert rankings of the assessors (*Scorer confidence*)), using the assumption of the IPCC RCP8.5 climate scenario. The top quartile was organized into five clusters of risk: food insecurity; water shortages; failed energy transition; human heat stress; and risks to nature and the bioeconomy. This paper describes these risk clusters, explored through the lens of available literature, and analysed within the broader framework of the sustainable development goals (SDGs), and the individual and collective actions that can be taken to reduce or adapt to these risks. There are many technical solutions to these risks, but these typically are costly and only function up to a point where the risks become unmanageable. For solutions to be successful, a 'systems view' and the complex interlinkages between climate change and socio-economic development must be addressed. The interconnected and cross-sectoral nature of the climate risk domains certainly presents a challenge for governance; the success of some of the measures discussed in this paper

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depends on the existence of strong, well-resourced, well-coordinated and influential governance mechanisms and state institutions and focusing on investigating the many synergies that exist among solutions.

1. Introduction

Southern Africa is a climate change 'hotspot' (Betts et al., 2018; Engelbrecht et al., 2015; Engelbrecht and Monteiro, 2021; Hoegh-Guldberg et al., 2018). This is due to the strong climate signal in the region that is expected to exacerbate vulnerabilities inherent to the region's naturally dry and warm climate, and a receiving environment that is both sensitive to changes in climatic conditions and low in adaptive capacity. The region has a greater-than-average biophysical and socio-economic risk profile in relation to several important aspects of climate change (Jury, 2013), and increasingly, also at risk of reaching regional tipping points in its climate system, which if crossed will result in a new climate regimes and unprecedented high-impact climate events (Engelbrecht and Monteiro, 2021). In this paper, we examine this risk landscape outlining those areas that may be urgently needing more concerted actions to reduce risks and develop robust responses moving forward. We begin by first setting the climate change context and then examine some concatenating risks including food insecurity; water shortages; failed energy transition; human heat stress; and risks to nature and the bioeconomy.

1.1. Southern Africa – A climate change hotspot

Climate change is already apparent and having generally negative effects in the region (Engelbrecht et al., 2015; Ray et al., 2019; Trisos et al., 2022). The near-surface air temperature in the interior of southern Africa has risen at about double the global mean rate over the last six decades (Engelbrecht et al., 2015). All climate models indicate that southern Africa will continue to warm drastically in the 21st century. In the increasingly unlikely event that the world succeeds in keeping global mean warming below 2 °C above pre-industrial levels, the interior regions of southern Africa are likely to still experience warming in the order of 3–4 °C. Currently, the (inadequate) emission-reduction commitments of countries commit the world to global warming of 3 °C or more in the 21st century (Almazroui et al., 2021), translating to temperature increases as high as 6 °C in large parts of the southern African interior.

Although there is relatively greater model uncertainty regarding the spatial details of future rainfall, the southern African region is likely become generally drier under low mitigation futures; a drying trend that can already be observed in the Western Cape of South Africa and over the Limpopo basin (Christensen et al., 2007; Engelbrecht et al., 2009, 2015; Hoegh-Guldberg et al., 2018; Niang et al., 2014; Maúre et al., 2018; Pohl et al., 2017; Serdeczny et al., 2017; Sperna Weiland et al., 2012).

Climate change affects not only rainfall totals, but also seasonality. In Zambia, late onset, and early cessation of the rains, and increased frequency of dry spells during the rainy season have become more prominent since the 1980s (Makondo and Thomas, 2020). In South Africa, recent observations indicate decreases in the strength of seasonality and reductions in winter rainfall over the last 30 years. This is likely a result of declining rainfall associated with cold fronts (Burls et al., 2019; Engelbrecht et al., 2009), as well as trends towards later starts to the wet season, and lower summer rainfall totals (Roffe and Fitchett, 2020).

Notwithstanding the inconsistencies across studies, most projections suggest that although the number of storm days will decrease (Hoegh-Guldberg et al., 2018; Roffe and Fitchett, 2020), daily rainfall will intensify (Engelbrecht et al., 2013; Pohl et al., 2017). This has repercussions for groundwater recharge and soil loss, with increased deep drainage, runoff and soil erosion and is a critical factor in determining flooding risk. High intensity convective storms are also associated with hail and wind damage.

Sea level is rising inexorably and at an accelerating pace on the southern African east, south and west coasts (Department of Environmental Affairs, 2018). Globally, the projected rise by the end of the 21st century is 0.5–1 m (Makondo and Thomas, 2020). Resultant flooding and damage compounded by increasing storm surges and wind-driven waves, when they coincide with abnormally high tides, can produce significant damages placing coastal infrastructure throughout the region at risk. Mozambique in particular has an increased risk of coastal flooding due to its low elevation coastal plain and a potential increase in tropical cyclone intensity (Dzoga et al., 2018).

In this paper, we adopt an expert-driven risk analysis to assess the major climate risks facing southern Africa. The approach used here is taken from the Disaster Risk Reduction (DRR) sciences, where the underlying vulnerabilities in the system and the degree of exposure, sensitivity, and susceptibility combine to influence the risk outcomes (Holloway et al., 2010). Coping capacity (i.e., the ability to adjust and recover or 'bounce back') or the inability of people to adapt or adjust (Cutter et al., 2000, 2003) are central elements of this DRR approach and can further aggravate the climate risks a region faces. Vulnerability and risks are thus driven by the intersectionality of a range of risk drivers and influenced by inherent coping capacity. They are not only as a result of a hazard (e.g. rainfall, temperature etc.), but also socio-economic factors such as [lack of] access to services (education, healthcare, housing, credit, information), social support systems, income and assets.

Hereafter, we demonstrate that climate change acts as a stress multiplier that exacerbates pre-existing systemic and structural socio-economic issues and produces a range of intersectional risk contexts in the region. In profiling these intersectionalities, and interrogating some of the science-policy-practice efforts that may be required to help navigate this complex risk landscape, we aim to highlight the role for appropriate institutional architecture to coordinate and mobilise appropriate action while taking advantage of the region's existing human, science and technological resources to do so.

2. Methods

2.1. Study area

The IPCC distinguishes east and west southern Africa ('ESAF'; 'WSAF'); for the purposes of our research presented here, we consider them collectively. This region includes the following countries: Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, eSwatini (formally Swaziland), Zambia and Zimbabwe (Fig. 1). We exclude Madagascar from our assessment.

2.2. Assessing climate change risks: Approach and method used

Researchers in the Global Change Institute, of the University of the Witwatersrand, many of whom have experience in global risk assessments such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Panel on Climate Change (IPCC), comprised a panel (n = 12) that framed the risk approach and data used in this exercise. In framing the constituting risks, which determine the contours of the overall risk landscape, we used an iterative approach (Fig. 2). We defined 'risk' as the product of the likelihood of a negative event occurring, over the target region and in the defined timeframe; and its consequence if it does occur.

We used a modified Delphi-type consensus approach to evaluate the most critical climate change risks facing southern Africa in the 21st Century (Dalkey and Helmer, 1963; Hsu and Sandford, 2007). This approach has been widely applied in climate change impact assessments (Doria et al., 2009; Markou et al., 2020; Torres and Pina, 2011).

First developed in the 1950's by the United States military ("Project DELPHI") to predict the probability of Soviet attack (Dalkey and Helmer, 1963), a Delphi process seeks to solicit group opinion from a panel of experts, particularly useful as forecasting tool for problems that are complex or are underpinned by large uncertainties (e.g., Egfjord and Sund, 2020). A conventional Delphi process has the following characteristics: i) it is an *iterative* process requiring cyclic (at least 2–4) rounds of consultation on the same topic typically via questionnaire or online survey, ii) maintains *anonymity* of the experts to ensure no bias and/or influence, iii) has *controlled feedback* to panelists via the group coordinator, which once returned to panelists can be used to adjust initial assessments; herein, first round findings shape successive rounds, and iv) is a *group statistical response*, where the structure of the questions ensures that all answers

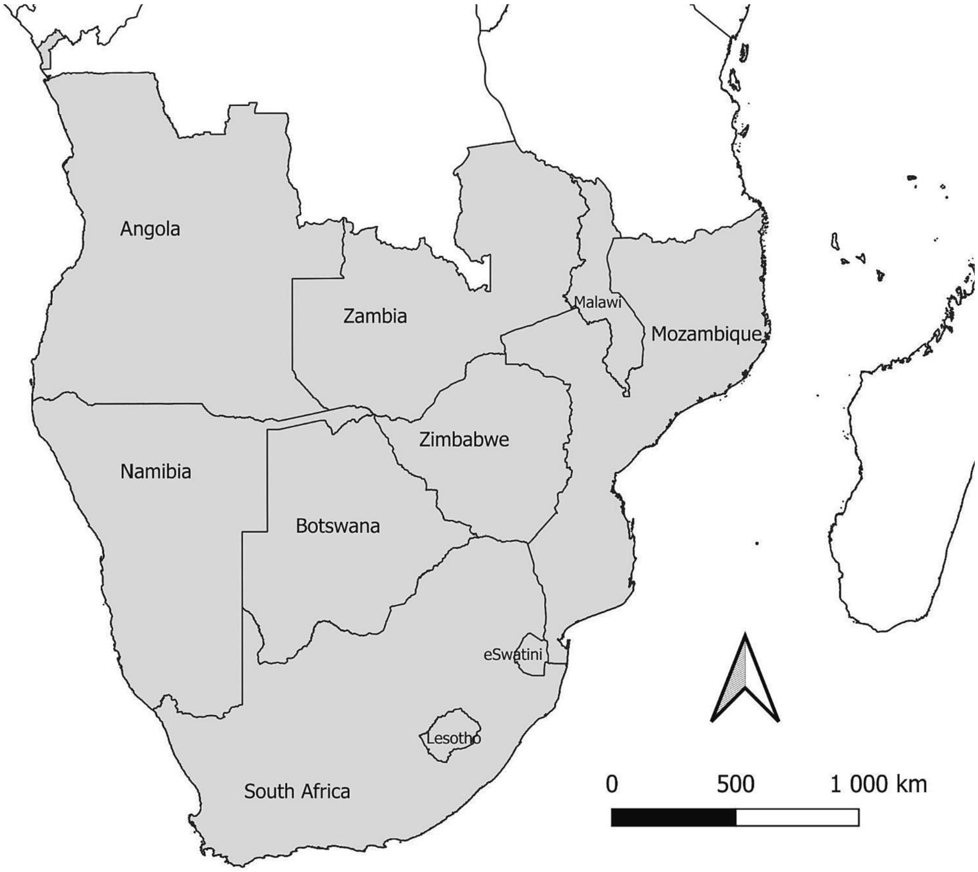
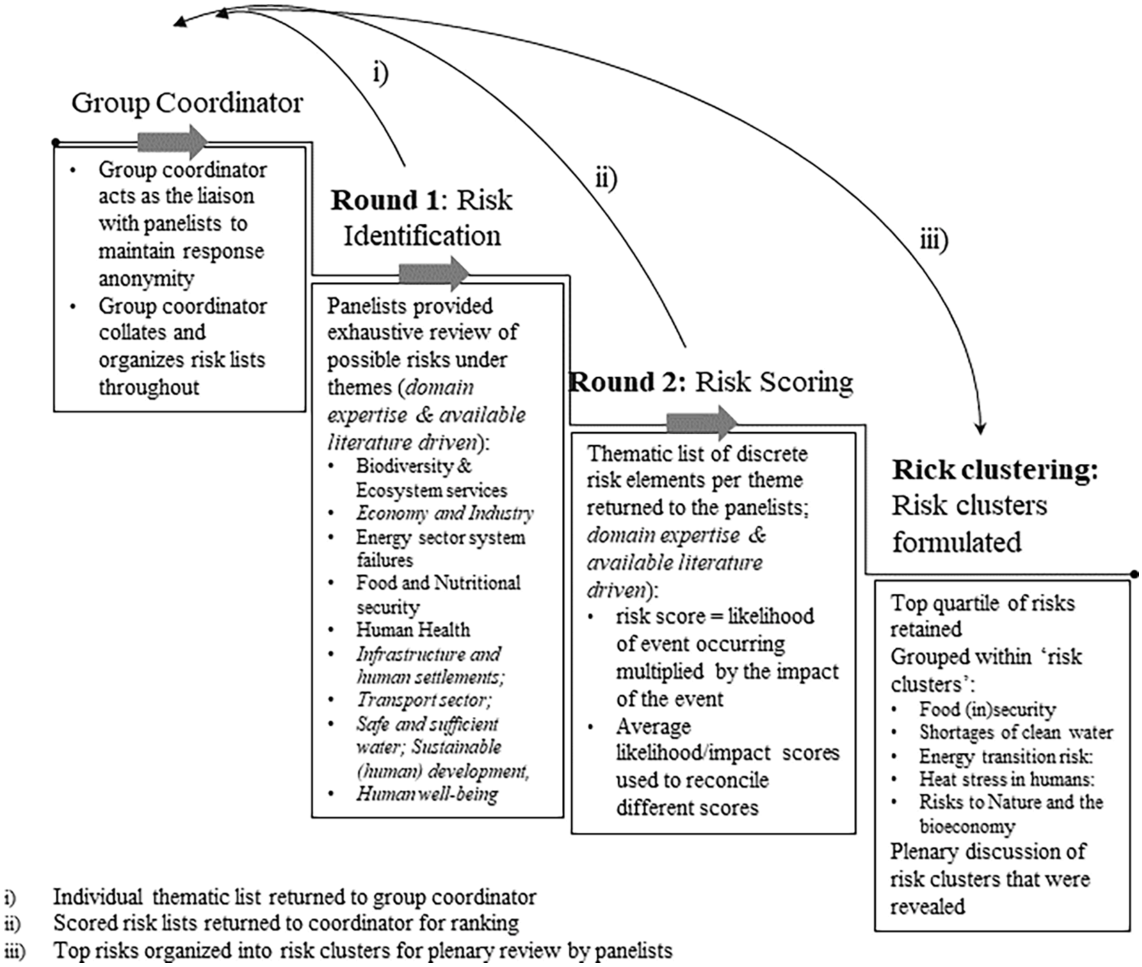


Fig. 1. Geographical region of analysis: Southern Africa.



- Group coordinator acts as the liaison with panelists to maintain response anonymity
- Group coordinator collates and organizes risk lists throughout

Panelists provided exhaustive review of possible risks under themes (*domain expertise & available literature driven*):
- Biodiversity & Ecosystem services
- *Economy and Industry*
- Energy sector system failures
- Food and Nutritional security
- Human Health
- *Infrastructure and human settlements;*
- *Transport sector;*
- *Safe and sufficient water; Sustainable (human) development,*
- *Human well-being*

Thematic list of discrete risk elements per theme returned to the panelists; *domain expertise & available literature driven*):
- risk score = likelihood of event occurring multiplied by the impact of the event
- Average likelihood/impact scores used to reconcile different scores

Top quartile of risks retained

Grouped within 'risk clusters':
- Food (in)security
- Shortages of clean water
- Energy transition risk:
- Heat stress in humans:
- Risks to Nature and the bioeconomy

Plenary discussion of risk clusters that were revealed

i) Individual thematic list returned to group coordinator
ii) Scored risk lists returned to coordinator for ranking
iii) Top risks organized into risk clusters for plenary review by panelists

Fig. 2. Diagrammatic representation of the iterative process of the modified Delphi-type consensus approach utilised.

given can be processed quantitatively and comprise the final answer (Landeta, 2006; Revez et al., 2020). Modified Delphi approaches are less consistent in their application of all of the above criteria, but key remains the role of the group coordinator in the process (Nasa et al., 2021). Our modified Delphi approach was not questionnaire driven, and because the experts were all from one research institute, did not maintain the anonymity of the contributing panelists, but rather of the answers given, with answers returned directly to the group coordinator for sorting.

The first round was one of risk identification organised via the following themes (Supplementary material: Table 1): *Biodiversity & Ecosystem services; Economy and Industry; Energy sector system failures; Food and Nutritional security; Human health; Infrastructure and human settlements; Transport sector; Safe and sufficient water; Sustainable (human) development, & human well-being (incl. poverty, livelihoods, security and youth considerations*). The risk categories followed the taxonomy of the Task Force for Carbon Disclosure (TCFD; https://www.fsb-tcfd.org/). Panelists were tasked with providing an exhaustive review of all potential risk elements under a target theme even if some risk elements may be considered unlikely to materialise. In order to achieve this, they drew on their domain expertise in the risk theme as well as the available literature on climate change impacts in the region, creating a comprehensive risk list of postulated discrete risk elements.

Once collated by the group coordinator, the full thematic list of discrete risk elements was returned to the panelists as a second round of review and for scoring, with risks also weighted by the confidence of occurrence (i.e., risk score = likelihood of event occurring multiplied by the impact of the event). We focused on the likelihood and consequence in the mid-term (2041–2060) and scored each risk according to this time frame. Likelihood was judged relative to the risk for the same phenomenon in the absence of climate change. For reference, we use the 'climate baseline' period, 1961–1990. In order to maintain consistency across the wide range of risks considered, we used a shared framework for scoring both likelihood and consequence across all panelists (Table 1).

Each risk theme was assessed by at least two panelists, with a senior domain specialist allocated as oversight. Given that more than one score was received per risk element (i.e., multiple panelists assessing), the average score for likelihood and impact was utilised. The likelihood of the relevant climate events occurring was assessed qualitatively from the multiple lines of evidence available (*Evidence confidence*), as well as the expert rankings of the assessors (*Scorer confidence*). The degree to which the risk can be ameliorated by

Table 1
The risk likelihood and consequence scoring framework used in the assessment of climate-associated risks in southern Africa indicating i) Likelihood, ii) Consequence, iii) Certainty of risk manifesting and iv) Scorer Confidence in risk predictions made.

Word Category	Description	Score
i) **LIKELIHOOD**		
No chance	$0 \leq x \leq 0$	0
Rare	$0.001 \leq x \leq 0.01$	1
Occasional	$0.01 \leq x \leq 0.1$	2
Frequent	$0.1 \leq x \leq 1$	3
Expected	$1 \leq x \leq 10$	4
ii) **CONSEQUENCE OR IMPACT**		
None	$<1\ \sigma$ or less than 0.02% of sector value add, whichever is larger // Less than the non-climate interannual variability (σ) // Less than the inherent variability, therefore undetectable	0
Negligible	~0.05% of sector value add or $<2\ \sigma$, whichever is larger// Up to 2 × the normal non-climate interannual variability// detectable, but not much more than the inherent variability, up to twice the interannual variability, so not at all stretching the coping capacity, just an autonomous adjustment	1
Slight	0.05–0.1% of sector value add // 0.05–0.1% loss of DALY // a measurable impact requiring an adaptive response, but not one that results in a major deviation in actions or reallocation of resources	2
Small	0.1–0.25% of sector value add // 0.1–0.25% loss of DALY // an impact that is noticeable and calls for a bit more of a purposeful response	3
Moderate	0.25–0.5% of sector value add // 0.25–0.5% loss of DALY // definitely substantive, but within the realm of normal coping	4
Substantial	0.5–1% of sector value add// 0.5–1% loss of DALY// big, testing the limits of coping	5
Severe	1–5% of sector value addition// 1–5% loss of DALY// Right at the limits of coping	6
Catastrophic	>5 % of sector value addition// >5% loss of DALY// substantially beyond the limits of coping	7
iii) **CERTAINTY**		
Certain	Already occurring	100%
Very high confidence	High agreement and much data	99%
High confidence	Either high agreement or much data, but medium or low on other axis	95%
Medium confidence	Either low agreement or little data	90%
Low confidence	Low agreement and little data	75%
Certain	Already occurring	100%
Very high confidence	High agreement and much data	99%
None	No better than a random guess	50%
iv) **SCORER CONFIDENCE**		
Hardly know anything	Scorer has extremely limited knowledge of risk domain	1
Bit below average	Scorer has limited understanding of risk domain	2
Average Non-specialist	Scorer is not a domain specialist but has some understanding of risk domain	3
Near Expert	Scorer has specialist and comprehensive knowledge in risk domain but self-assess as non-expert, with understanding that is not as comprehensive as a domain specialist	4
Expert in Risk Domain	Scorer has specialist expert knowledge in risk domain	5

adaptive action was also evaluated. Scored risks were returned to the group coordinator for ranking (Supplementary material: Table 2).

It is acknowledged that some climate change was already experienced before and during this reference period (e.g., Kruger, 2006), but its magnitude is considered small relative to the impending changes in the 21st century. Many of these risks, however, are likely to be already manifested by the near-term (2021–2040) and critical ‘tipping points’ may be reached in the second half of the century (Hoegh-Guldberg et al., 2018). We thus also reflect on the near-term (2021–2040) and long-term (2081–2100) time horizons.

Throughout the assessment process we use the assumption of the IPCC RCP8.5 climate scenario, representing a low mitigation future (associated with the largest risks), widely used in climate change impact research (Hoegh-Guldberg et al., 2018; van Vuuren et al., 2011). This set of assumptions about the future most closely corresponds to the ‘worst case scenario’ and the pathway, in the absence of coordinated and concerted global climate action, on which the world is currently on. Globally if more ambitious climate change mitigation strategies are prioritised (i.e., those consistent with the agreements reached in Paris in 2015), the general pattern of climate change in southern Africa would be much the same up until 2050, just delayed. It is after 2050 that the different development pathways make a dramatic difference. We do however, acknowledge that RCP8.5 is increasingly criticized as unlikely to come to pass – as the devastating increases in weather extremes under continued global warming means it is unlikely that humans will not respond.

After ranking, the top quartile of risks was retained, and the interconnected nature of the top risks were noted. These were grouped into the five risk clusters that are presented (Section 3: Results) and discussed (Section 4: Discussion) hereafter. We present the risk clusters through the lens of the literature as a collective and/or summary narrative of the top quartile of risks that were identified rather than reporting on the individual risk elements themselves.

3. Results

3.1. *The top five clusters of climate risks*

3.1.1. *Food (in)security*

This cluster includes the agriculture and fisheries sectors, their downstream value addition industries, food logistics and retail, nutrition-related health issues and food-related exports and imports. Southern Africa has faltered with respect to progress towards eradicating hunger and malnutrition (Sustainable Development Goal number 2). Undernourishment in the region increased from 4.9 to 8.4% between 2005 and 2019 (~5.6 million people) and is projected to increase to 14.6% by 2030 (FAO et al., 2020), without factoring in the impact of Covid-19, or climate change.

Yet, the agricultural sector contributes a substantive 17% (28% when excluding middle income countries) to southern Africa's Gross Domestic Product (GDP) (SADC, 2014). Agricultural systems in the region are, however, mostly rain-dependent and underdeveloped as small-scale farmers with limited adaptive capacity make up around 60% of the sector (SADC Secretariat, 2014). This increases vulnerability as people are directly dependent on farming for their livelihoods and lack the adaptive capacity and resources to persist through adverse environmental changes (Pereira, 2017).

Most crops in the region are also already at, or above, their temperature optima, and some are close to their upper limit (Harrison et al., 2011). Already in the near-term, and increasingly so in the mid- to long-term, the increased frequency of droughts and associated heat-waves (Engelbrecht et al., 2015; Niang et al., 2014), is likely to result in greater frequency of below normal crop yield (Leng and Hall, 2019; Ostberg et al., 2018). Under a high mitigation scenario, a case study in Zimbabwe projects maize yield losses of 13% and 20% for the periods 2010–2069 and 2070–2099, respectively, while for RCP8.5, yield loss of 32% is expected at the end of the century (Rurinda et al., 2015). Moreover, in the Olifants River catchment of South Africa, projected yield declines for maize, soya beans, dry beans and sunflowers are 63%, 38%, 42% and 30%, respectively, for the 2070–2099 time period under RCP8.5 with no adaptation measures (Olabanji et al., 2021). Similarly, some research has shown the productivity of wheat across the southern African region to decrease by 35% by 2050 under low mitigation (Nelson et al., 2009). In South Africa specifically – historically one of largest wheat producers in sub-Saharan Africa, second only to Ethiopia (Tadesse et al., 2019) – under warming scenarios of +1 °C, +2 °C and +3 °C relative to historical climate, models project an average wheat yield reduction of 8.5%, increasing to 18.4% and 28.5% as warming continues (Shew et al., 2020). At 3 °C of global warming, translating to 4–6 °C of regional warming in the interior, such warming is thought to represent a tipping point at which cultivation of maize (the staple food in southern Africa) may collapse (Hoegh-Guldberg et al., 2018; Thornton et al., 2011). The same applies to animal production (poultry, dairy and meat; e.g. (Archer van Garderen, 2011; Muller and Botha, 2018; Nesamvuni et al., 2012; Nyoni et al., 2019, 2019; Rust and Rust, 2013), where a 3 °C of global warming represents the tipping point at which the southern African cattle industry may collapse (Hoegh-Guldberg et al., 2018).

Importantly, regional economies are likely to suffer considerable knock-on effects from reduced and less-reliable agricultural production. Small-scale farmers are already reporting a reduction in crop output (Ebhuoma and Simatele, 2017). This situation is attributed to the impacts that climate change has on their productive assets and hence their adaptive capacities and abilities are eroded on a yearly basis. Countries with low GDP and high dependence on agriculture are thought to be the most vulnerable to any changes in climatic conditions, slowing their socio-economic growth and national development (Hoegh-Guldberg et al., 2018; Pretis et al., 2018). Notwithstanding the climate changes experienced thus far, commercial crop production is steadily increasing in Sub-Saharan Africa, thanks to technological improvements and expansion of the area under cultivation (Preston et al., 2011). Cereal production in the SADC region for example, has significantly increased since the 1960's owing to an increase in the area under irrigation (Mpandeli et al., 2018; Nhamo et al., 2019). Yet as water resources and water extraction options become increasingly strained (see Section 3.1.2), maintaining yields becomes equally problematic. The rate of food consumption growth (82% in the past three decades) exceeds the rate of food production growth (9% over the same period), and this is the context for evaluating the anticipated additional burden of climate-related losses, estimated to be 2%–7% in agricultural GDP by 2100 (Thornton et al., 2008). This is indicative of a potential continental-scale food shortage, exacerbated if food production shrinks as a result of declining water availability (Ziervogel, 2018).

To a great extent, SADC countries share these challenges in that they have all instituted some form of social protection schemes to safeguard vulnerable populations from socio-economic hardships. Such social welfare may help ameliorate some of the immediate consequences of climate impacts on household food production (Ziervogel, 2018; Ziervogel et al., 2006), but since these grants already have many uses and users, they rarely meet the nutritional needs of poor families. Additional climate change impacts may further divert social grants from other important household supplies and services (Ziervogel, 2018).

3.1.2. *Shortages of clean water*

The availability of fit-for-use water affects almost all aspects of life and sub-sectors of the economy in southern Africa. Human and animal health requires sufficient access to clean water. Energy production, industrial output and irrigated agriculture are all water-dependent and will be at greater risk in future, with large social-economic consequences (Conway et al., 2015; Hoegh-Guldberg et al., 2018).

Climate change threatens water security in southern Africa in two ways. *Firstly*, the likely lower rainfall totals and increased in evapotranspiration due to rising temperatures may result in reduced streamflow and dam yields (Engelbrecht et al., 2015; Maúre et al., 2018). *Secondly*, higher temperatures and lower flows and stocks in reservoirs will lead to deteriorating water quality (Tantoh et al., 2020). The quality of drinking water may be compromised by excess algal growth and eutrophication as a result of increased water temperature (Whitehead et al., 2009).

The risk of multi-year droughts in the winter rainfall region, such as the 2015–2017 drought, is estimated to already be three times higher than it is supposed to be due to climate change that has already occurred (Otto et al., 2018). Multi-year droughts are likely to occur more frequently over the summer rainfall region as well (Fig. 3), especially once the 1.5 °C threshold in global warming has been exceeded (Hoegh-Guldberg et al., 2018; Maúre et al., 2018). Gauteng Province, the industrial heartland of South Africa, is dependent on inter-basin transfers (including across national boundaries) for its water security. The dams in the system, when 100% full, have capacity to supply the province with water for five years (Otto et al., 2018). Multi-year droughts lasting 3–4 years thus present substantial risks to the system, as was demonstrated by the 3-year drought that culminated in the El Niño event of 2015/16 (Hoegh-Guldberg et al., 2018; Maúre et al., 2018).

Lower availability of usable water also threatens human health, agricultural and economic productivity, and the functioning of freshwater and estuarine ecosystems. Urbanization leads to an increasing per capita water demand and consequently, competition for water has and will become acute, not only between cities and their hinterlands, but also between nations (Hedden and Cilliers, 2014; Hoegh-Guldberg et al., 2018). Securing water supply to rapidly growing cities and towns is challenging, given the regional water scarcity. Municipal and district water sources already frequently run dry, leaving insufficient water to support basic household needs for drinking, washing and sewage disposal (Tantoh et al., 2020).

The water supply infrastructure is already inadequate or failing, owing to the weak governance and municipal institutions and the centrally directed legal and regulatory framework that guides municipal management in many southern African countries (Enqvist and Ziervogel, 2019; Robins, 2019; Vogel and Olivier, 2019). This decreases the capacity to cope with water shortages (Tantoh et al., 2020). South Africa could experience a 17% shortfall in water supplies by 2040 if urgent action is not taken (Hedden and Cilliers, 2014). At the household level, acquiring water comes at an increasing opportunity cost to household members as more time, energy and money are spent in this pursuit (Ziervogel, 2018), disproportionately impacting women and girls, who in southern Africa bear primary responsibility for household water collection (Graham et al., 2016).

In rural communities dependent on rivers for domestic water, shortages increase the risk of water-borne diseases during periods of low flow. When borehole water levels fall below pumping specifications failure of groundwater supply results, with the 'young groundwater systems' that are recharged via precipitation most vulnerable to declines in both quantity and quality (e.g. (van Rooyen et al., 2020). There is however some evidence to suggest that groundwater systems in sub-Saharan Africa generally are more resilient to climate change than previously anticipated, with the rise in major rainfall events, e.g. albeit associated with more intense rainfall and

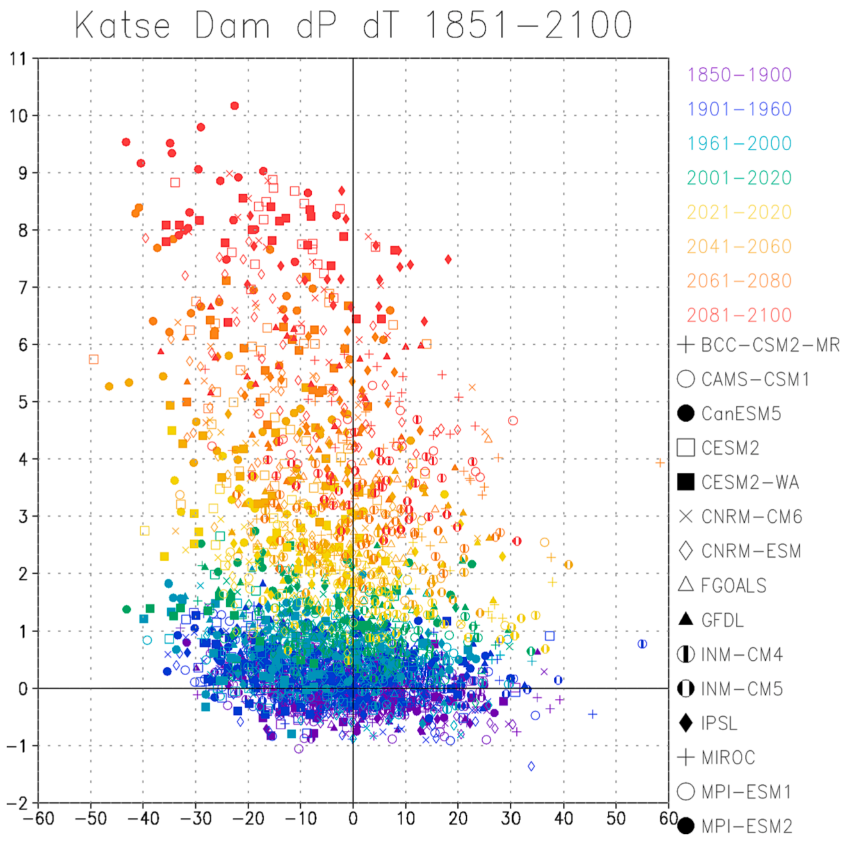


Fig. 3. Projected annual temperature anomalies (°C, y-axis) and rainfall anomalies (% change, x-axis) over the Katse dam catchment in southern Africa, for the period 1851–2100. Anomalies are expressed with respect to the 1851–2100 temperature and rainfall climatologies for an ensemble of Coupled Model Intercomparison Project Phase Six global climate models. In an increasingly warmer word, the climate of the catchment is to shift towards an increasingly drier regime, with more frequent multi-year droughts.

increased flooding risk, potentially increasing groundwater recharge opportunities (Cuthbert et al., 2019).

3.1.3. *Energy transition risk*

This cluster of risks relates to the social and economic costs associated with changing the southern African energy economy from one based primarily on fossil fuels (coal in particular) to one based on low-carbon energy sources. It includes impacts on the coal mining sector, petrochemical industries (i.e., SASOL) and all sectors dependent on affordable, reliable and clean energy. Risk elements include job losses, energy security and progress towards universal energy access.

The global market for coal is expected to shrink over the next twenty years, as the world transitions to low-carbon energy (Huxham et al., 2019). Many end-of-life coal power plants in South Africa will be decommissioned over the next decade, in line with the Integrated Resource Plan 2019. Most will be replaced by cheaper renewable energy technologies, therefore local demand for coal will also fall (Department of Energy, 2019). South Africa could lose up to US $83,7 billion (R1,2 trillion) between 2018 and 2035 as a result of declining coal exports (Huxham et al., 2019).

South Africa, Botswana, Mozambique, eSwatini and Zimbabwe all have significant coal sectors (UNU-INRA, 2019). Most of the electricity in the Southern African Power Pool is generated from coal (74%) with the rest generated through hydro power (20%), nuclear (4%) and diesel and gas (1.6%) (Wright and van Coller, 2018). Pressures on the coal sector are already evident. Large coal mining companies have begun to dispose of their coal assets (Exxaro, 2020; UNU-INRA, 2019). The many sectors linked to coal, such as logistics, railways, port and shipping companies, petrochemical and metallurgical industries face similar risks, especially if they are export-oriented. Local job losses are expected to trigger new waves of migration to cities and to other parts of the region where there are economic opportunities (Bohlmann et al., 2019). In 2018, the coal sector in South Africa employed over 85 000 people and supported other industries to the value of $4.1 billion, about 1% SA GDP (Huxham et al., 2019).

The solar and wind power resources in the region are potentially sufficient to meet future needs. The large-scale roll-out of decentralised, clean energy technologies such as wind and solar will create new jobs, industries and livelihood opportunities across southern Africa, but most of the new jobs will require higher-skilled workers (South African National Energy Association (SANEA), 2020). There are new economic opportunities associated with the metals and manufacturing needed to support the low-carbon technologies and their battery storage requirements. Therefore, a low-carbon energy future is both technically and economically feasible, but a transition risk emerges if the growth in the clean energy value chains is not matched to the declines in the coal sector.

Southern African countries do not have the financial or technical resources for immediate switching to cleaner fuels and renewable technologies (UNU-INRA, 2019). Poor sovereign credit ratings due to poor governance, weak institutions and high political risk limits the ability of most southern African countries to secure low-interest development loans and attract private companies to invest in such projects. Only 3% of the global green climate finance intended for this purpose has trickled down to Africa (UNU-INRA, 2019). In the meantime, southern African countries continue to invest in long-lived coal mining and coal power plants, exposing their economies to the risk of stranded assets in the future (UNU-INRA, 2019).

The energy transition is now inevitable, for economic as well as climate change reasons. Risk mitigation requires that the transition occurs in such a way that vulnerable workers and low-income households are not unfairly impacted, bearing in mind that failure to make the transition carries even larger risks, to many more people and to the economy as a whole (Wright and van Coller, 2018).

3.1.4. *Heat stress in humans*

With increasing temperatures, exposure to heat extremes, particularly in the form of heat waves (prolonged periods of high temperature) is set to worsen in southern Africa (Engelbrecht et al., 2015; Garland et al., 2015; Nana et al., 2019; Perkins-Kirkpatrick and Lewis, 2020). Heat stress in the exposed population has significant ramifications for morbidity, health care systems and economic productivity. Death rates spike when temperature rises above 35 °C for several days in a row (Ebi et al., 2017). Animals, including both warm-blooded and cold-blooded species, are also susceptible to heat stress, with major implications for livestock agriculture (Davis, 2011), dairy production and biodiversity conservation.

The southern African economy remains highly dependent on physical labour and outdoor activity, for instance in the agriculture, construction, mining, forestry, and tourism sectors. A considerable portion of the population is engaged in the outdoor informal sector (Bonnet et al., 2019). Here the health-related risks and productivity costs of heat exposure and working in direct sun, are high (Ngwenya et al., 2018). Occupational protective equipment often adds to the heat burden. Physical labour capacity halves for every 2 °C rise (Ebi et al., 2017), and exposure to heat stress increases the risk of injury and accidents in the workplace (Rother et al., 2020).

Learners in schools in the region are already compromised at high temperatures, exacerbated by poorly constructed, crowded and badly ventilated classrooms. Learners report feeling tired and have difficulty breathing at temperatures greater than 32 °C (Bidassey-Manilal et al., 2016). By 2030, the working hours lost to heat stress are anticipated to be equivalent to 18 000 full time jobs across southern Africa (compared to 6 000 in 1995) (International Labour Organization, 2019). The impacts of increased temperature suggest declines of greater than 50% on GDP per capita across southern Africa by 2100, relative to a world with no climate change (Burke et al., 2015). Attempting to 'catch up' the lost productivity after episodes of extreme temperatures pass is of limited benefit (Burke et al., 2015).

Humans and other organisms have a limited capacity to adapt physiologically to hotter temperatures, but the rate of warming currently being experienced is far more rapid than at any time in our evolutionary history (Garland et al., 2015). Heat-related illness are in general, underdiagnosed (Mora et al., 2017). Chronic heat exposure is linked to increased risk of long-term diseases, often involving multiple organ systems (Rother et al., 2020), which when diagnosed are not then attributed to heat. Thus, fatalities in Africa associated with severe heat are not attributed as such (Harrington and Otto, 2020), thus policies and institutional advisories remain largely reactive. They are often limited to short-lived behavioural adaptions, such as adjusting work schedules to cooler parts of the day, ensuring hydration and appropriate sun protection (e.g., (Nana et al., 2019).

Increased use of air conditioners and fans can help people to remain cool and productive, but the estimated energy costs of cooling are considerable for the African continent: $51.3 billion with +2 °C rise (2005–2035) and $486.5 billion for a +4 °C rise (2005–2076) (Parkes et al., 2019). Since much of the energy currently comes from coal-based sources (see Section 3.1.3), adaptations involving energy-intensive cooling may be maladaptive as a climate change response.

3.1.5. Risks to nature and the bioeconomy

Species richness in southern Africa is disproportionately high given its land and ocean area. However, a potentially catastrophic loss of biodiversity is on the horizon, partly caused by climate change (Trisos et al., 2020). Protecting this diversity from human-caused climate change is both a moral and an economic imperative. Loss of biological diversity alters the functioning of ecosystems and their ability to provide society with the goods and services needed to prosper, as well as to adapt to the changing climate (Cardinale et al., 2012). Examples of economic sectors sensitive to biodiversity loss include horticulture (especially through loss of pollinators), tourism, wild game farming industry, traditional medicine use, wild-harvested flowers, and fisheries.

Climate change undermines biodiversity in several ways. Impacts include changes to the species populations themselves, their abundance, distribution and their phenology (the timing of critical events like egg laying and flowering). A very large fraction of South Africa’s biological diversity cannot persist in its current locations under climate change (Wilson, 2019). Population-level changes disrupt the communities of species to which they contribute and propagate to the ecosystem level (for a review see (Wilson, 2019). There is robust evidence showing direct negative climate change impacts on species in southern Africa, both for observed past impacts and projected future impacts (IPBES, 2018).

Pollination by insects supports US$361 billion (~R60 trillion) in crop production worldwide (Klein et al., 2007). The deciduous fruit industry in the Western Cape in South Africa is heavily reliant on pollination services from managed honeybees and is worth R9.8 billion per year alone (Melin et al., 2014). Loss of pollinators can lead to widespread losses of other species and even ecosystem collapse.

Ocean warming, ocean acidification, changes in ocean circulation and sea level rise will impact fish stocks, and the fishers who depend on them, in a several ways (Dzoga et al., 2020). These include changing distribution and abundance of estuarine-associated and offshore species, changes in squid and fish spawning and a possible increase in frequency and duration of West Coast rock lobster mass strandings (Dzoga et al., 2020). Increased conflict over international fisheries could arise (Mendenhall et al., 2020). The aquaculture industry is also impacted by high water temperature, acidification, and algal blooms (Augustyn et al., 2017). The coastal, offshore and inland fisheries (both commercial and subsistence) of southern Africa make an important contribution to nutritional security in the region. However, aquatic ecosystems are also critical in providing a host of non-food ecosystem services, including ecotourism.

Perversely, the environmental impacts associated with tourism, such as air travel and the construction of infrastructure in wild areas, significantly add to climate change and habitat loss pressures (Amusan and Olutola, 2017). Nature-based tourism may be threatened by an increasing reluctance to incur the carbon cost of travel, or by unpleasantly hot and dangerous climates in some destinations.

3.1.6. Other risks that matter

Just because a risk element has not been highlighted in one or more of the above clusters does not mean that it is inconsequential for the affected locations, populations and sectors. An example is the likelihood of increasingly severe storms, which affect both coastal and inland areas. They can be life-threatening and locally or even regionally devastating. An important recent example is tropical

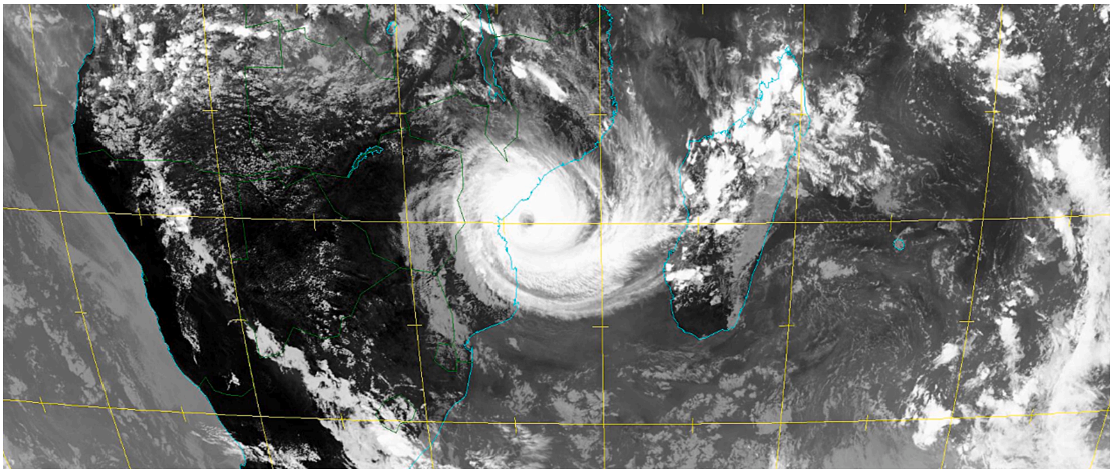


Fig. 4. Eumetsat infrared satellite image showing intense tropical cyclone Idai making landfall at Beira in Mozambique, around midnight on the 14th of March 2019. It is estimated that more than 2000 people lost their lives in the path of the storm, making it the worst flood disaster in the historical record in Africa south of the equator.

cyclone Idai that resulted in more than 2000 people losing their lives in March 2019 as the storm tracked over Malawi, Mozambique and Zimbabwe (Fig. 4). This is the worst flood disaster in southern Africa in the historical record, and occurred within the context of observed upward trends in the occurrence of intense tropical cyclones, both globally and in the southwest Indian Ocean (Hoegh-Guldberg et al., 2018).

The insurance damages from severe storms amount to billions of Rands in South Africa, but in the context of the entire region, they are less damaging than the more systemic risk clusters identified above. Risk elements that were not specifically included within the identified clusters include amongst others; increasingly large wild fires, changes to the distributions of agricultural pests, alien species as well as human and animal disease risk (e.g. (IPBES, 2018; Mordecai et al., 2020; Ryan et al., 2020; Wilson, 2019). Although not exclusively identified as high-risk elements, these risks are interlinked to the main risk clusters identified above.

A host of allied business and financial risks may also increase given climate change (TCFD, 2017). Within the TCFD, for example, climate risk taxonomy there are further risks to be considered by southern African enterprises, such as the legal and reputational risks of not talking action to reduce climate change consequences after having been made aware of their existence.

4. Discussion

4.1. Adaptation to climate change

There are many technical solutions to the risks outlined above, but these are typically expensive and only function up to a point where the risks become unmanageable. That is, there are limits to adaptation. Success stories in sustainable inclusive and fair climate adaptations are few, and tend to be partial, incremental, and reactive adaptations. Much more emphasis on addressing the deep-rooted causes of the challenges, using a proactive, transformative approach, is needed (Feola, 2015; O'Brien, 2011).

For solutions to be successful, a 'systems view' and the complex interlinkages between climate change and socio-economic development must be addressed (Adger et al., 2009; Boas et al., 2016; Fazey et al., 2016; Kates et al., 2012). Southern African countries must take urgent action to manage these risks through the implementation of well-designed, cross-cutting climate adaptation policies. In-region, greenhouse gas emission reduction actions (climate 'mitigation') will by themselves have only a tiny impact on global warming, but are necessary to support the global mitigation effort, without which adaptation becomes unattainable. Southern African countries have already indicated their commitment to combating climate change through their Nationally Determined Contributions to the Paris Agreement (NDCs), in which there is a heavy focus on adaptation.

Notwithstanding all these efforts, climate finance, a lack of access to updated climate information and weak governance have all been identified as major stumbling blocks impacting the ability of African countries to undertake low-carbon and climate resilient development (Africa NDC Hub, 2018; Maúre et al., 2018). Planning in climate-sensitive sectors, for example, in agriculture and tourism is guided by outdated climate information (Maúre et al., 2018; Nhemachena et al., 2020). Southern African countries must invest in the infrastructure and research initiatives to make climate information services available and accessible to all who need them.

Transboundary, cross-sectoral climate impacts in southern Africa also require Southern African Development Community (SADC)-wide and inter-sectoral cooperation. Networked regional governance approaches have been shown to assist complex climate decision making (Tosun and Schoenefeld, 2017). Such platforms already exist, including SADC and the African Union's Comprehensive Framework Programme on Climate Change in Africa, but may not be effective and relevant as platforms for action. For instance, the regional SADC policy on climate change predates the Paris Agreement, and has not been updated since (SADC, 2012).

Climate finance will also be critical to the success of any adaptation or mitigation actions by southern African countries. Africa will require over US$ 3 trillion in conditional and unconditional financing to implement the NDCs (Nwamarah et al., 2018). Current climate finance trickling down to Africa is insufficient to meet the needs on the ground, especially for climate adaptation (Nakhooda et al., 2011). In financial year 2015/2016, average climate finance flow to Sub-Saharan Africa was about US$12 billion (Nwamarah et al., 2018). The synergies between climate adaptation and sustainable development in southern Africa mean that the concept of 'additionality' as a funding principle for climate finance is potentially an access barrier for southern African countries. While additionality is meant to ensure that climate finance advances climate objectives rather than being diverted to traditional development programmes, well-designed infrastructure development projects should integrate climate adaptation measures - for example, urban planning must also include improving storm-water drainage in response to expected increases in extreme rainfall events. Which interventions are considered additional is not always clear in the African context.

Our approach to risk as used in this paper uses a particular framing, one lens, and we acknowledge that other relevant approaches exist (Beck et al., 1992; Simpson et al., 2021). Risk in such a framing is influenced by a range of factors including 'high modernity' whereby factors such as our political framings and technological 'progress' (e.g., artificial intelligence; emerging energy developments) are all considered as influencing the risk landscape. In such framings, the focus is not only on climate as the exogenous risk driver to the system. Rather climate is seen as one risk driver unveiling the risks and vulnerabilities already embedded in the system, where several endogenous risk drivers (including science and technology) are also configuring and shaping risks. The critical role of the cultural and contextual milieu, thus, including the political, drivers of marginalization and precarity, and whose 'framing counts' and is valued all play additional key, pivotal roles in shaping risks that climate, as a hazard, often unveils (e.g., Jasanoff, 2010; Scoones and Stirling, 2020; Wynne, 2002).

Such a more nuanced risk assessment, while factored into some of the examples we refer to in this paper, deserves much more detailed assessment than this paper achieves. This paper undertakes an assessment of risks for southern Africa and *begins* profiling some of the intersectionalities and framing of risk in the region but, critically to our mind, it departs from a strong 'climate as hazard approach' when framing risks in the region and therein adding value. In this manner, the inherent vulnerabilities and *starting context* for the sub-region are forefronted but we acknowledge that each risk identified requires much more careful interrogation.

5. Conclusions

The interconnected and cross-sectoral nature of the climate risk domains we identified presents a challenge for governance. The success of some of the measures discussed in this paper depends on the existence of strong, well-resourced, well-coordinated and influential governance mechanisms and state institutions (Africa NDC Hub, 2018). There is no shortage of knowledge, ideas and skills reserves to manage climate risks in southern Africa and coordinate a meaningful response to the crisis. Yet implementation of policies and plans is made uncertain due to short-term political cycles and lack of resources, accompanied by shifting political priorities and a lack of political will (Africa NDC Hub, 2018).

Strong champions are also needed, either in the guise of institutions (state or otherwise) or powerful individuals. Southern Africa has these actors. Waiting on a global response and the implementation of single successful agreement to catalyse an appropriate regional response, we argue, is misguided. The value of self-organised cooperation among smaller groups of key actors in climate governance and adaptation, the success of which depend on the perception of risk, are now gaining traction (Ostrom, 2010; Pacheco et al., 2014; Tosun and Schoenefeld, 2017). Regionally, champions can facilitate a shift in perception amongst decision makers and highlight the urgency of implementation of climate adaptation and mitigation measures, in tandem with economic development plans.

More systemic 'nexus approaches' and other systems approaches are also needed to create integrated frameworks that can address multiple goals while optimizing co-benefits (van Vuuren et al., 2017). The focus should be on investigating the many synergies that exist among solutions. Improving the use efficiency of land, energy and water resources (Bartos and Chester, 2014; Nhemachena et al., 2020), for example, can assist in enhancing robust responses to climate and related risks.

Managing complex risks in an ever-changing world is not an easy task. Several efforts, however, are already underway including some of the large global assessments (e.g., IPCC, IPBES, DRR global assessment reports). Waiting on governments and various international agencies to show us the way, while useful in some instances, may not be the only options to consider. In addition, we suggest that more consistent and systematic approaches, focusing on more regional and local assessments, are needed to regularly assess our environmental and related societal risks. These need to include a range of approaches and responses (e.g., science based, transdisciplinarity, integrative risk reviews, social learning etc.), that should be encouraged. By beginning such an assessment, as presented in this paper, the possibilities of various focus areas requiring more interrogation can begin to emerge and provide opportunities for taking this work further.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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