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Climate and southern Africa's water-energy-food nexus

In southern Africa, the connections between climate and the water-energy-food nexus are strong. Physical and socioeconomic exposure to climate is high in vulnerable areas and in sectors with crucial economic importance. Spatial co-dependence is high; climate anomalies can be regional in extent and trans-boundary river basins and aquifers transect the region. There is strong evidence of the effects of individual climate anomalies, yet proven associations between rainfall and Gross Domestic Product and crop production are relatively weak. Most nexus studies for southern Africa have been motivated by climate change. Whilst uncertainties remain high, for the southernmost countries the majority of climate models project decreases in annual precipitation, typically by as much as 20% by the 2080s. These changes would propagate into reduced water availability and crop yields. Recognition of spatial and sectoral interdependencies in the nexus should inform policies, institutions and investments for enhancing water, energy and food security and thus support regional prosperity in this climate-sensitive environment. Three key political and economic instruments that mediate nexus interactions in the region could be strengthened for this purpose; the Southern African Development Community, the Southern African Power Pool, and trade of agricultural products amounting to significant transfers of embedded water.

Introduction

Numerous challenges coalesce to make southern Africa emblematic of the connections between climate and the water-energy-food nexus which has important economic influence throughout the region. Physical and socioeconomic exposure to climate is high in vulnerable areas and sectors, such as agriculture, but also in energy generation and mining. For example, almost 100% of electricity production in the Democratic Republic of Congo (DRC), Lesotho, Malawi, and Zambia is from hydropower. Hydropower further comprises a major component of regional energy security through extensive sharing as part of the Southern African Power Pool (SAPP). The region's population is concentrated in areas exposed to high levels of hydro-meteorological variability[1] and Africa's population as a whole is projected to double by 2050[2]. Of the thirteen mainland countries and Madagascar (Table 1) that comprise the Southern African Development Community (SADC), six are defined as low income, three as lower-middle income and four as upper-middle income, according to the World Bank Classification (using 2012 GNI per capita). There are few quantified examples of the linkages between climate and economic activity in the region, though economic modelling studies in Malawi and Zambia indicate that the severe 1992 drought caused an approximately 7-9% drop in GDP and adversely affected household poverty[3]. Importantly, southern Africa's economy is closely linked with that of the rest of the African continent through trade of agricultural and other (frequently primary industry) commodities, acting as an important potential buffer for climate-induced resource scarcity.

Climate variability has important consequences for resource management in the region including for non-equilibrium production systems such as rangeland ecology[4], irrigation[5] and lakes[6]. Hence, southern Africa is a region where seasonal climate forecasts have potential benefit in areas where sustained forecast skill is demonstrated. Seasonal climate forecasting has been the subject of many studies in sub-Saharan Africa[7,8,9]; and the Southern African Regional Outlook Forum (SARCOF) provides advance information about the likely character of seasonal climate. Yet uptake has been very limited, despite over a decade of research on hydrological applications of seasonal forecasts[10] there is limited evidence for their operational use in the water sector[9]. With ongoing climate change, annual precipitation levels, soil moisture and runoff are likely to decrease, while rising temperatures could increase evaporative demand in large parts of the region[11] (Figure 1).

The last decade has seen rapid growth in research and policy interest in natural resource scarcity, with water-energy-food interdependencies increasingly framed as a nexus, or resource trilemma. The Bonn Nexus conference in 2011[10] is notable in this process of recognising the complex interactions between sectors and resource systems and the need to minimise the trade-offs and risks of adverse cross-sectoral impacts[10,12]. The nexus is increasingly prominent on policy-makers' agendas, partly in relation to the post-2015 development agenda for the Sustainable Development Goals[13]. The private sector was another early promoter of the nexus concept[14] due to growing associated risks affecting production security along supply chains, such as (but not exclusively) for water[15]. In southern Africa, for example, South African Brewers SABMiller are seeking better approaches to handling trade-offs between water, energy and food by attempting to make business decisions through a resource nexus lens[16]. Strong co-dependencies at a range of scales give rise to a large number of trade-offs and co-benefits, according to the heterogeneous configurations of societal uses of water across river basins and aquifers. For example, irrigation and other consumptive water uses may bring opportunity costs for downstream energy generation and environmental sustainability such as in the Rufiji and Zambezi basins. Development of new hydropower facilities can increase evaporation and alter river flow regimes, particularly during low flow seasons. The region's many transboundary basins require that trade-offs among upstream and downstream water uses are reconciled between countries.

Previous nexus studies have concentrated on global interdependencies[17], problem framing[18] or case studies of trade-offs and co-benefits in specific systems such as islands[19] and irrigation and hydropower production[20]. Here, we examine southern Africa's nexus through a climate lens and modify Hoff's nexus framework[10] which integrates global trends (drivers) with fields of action, to highlight the role of climate as a driver in southern Africa's nexus (Figure 2). Climate encompasses average (i.e. 30-year) conditions, variability over years to decades (i.e. as observed) and anthropogenic climate change. In terms of the nexus, we consider the main elements of intra-regional linkages in water-energy-food at a national level, while highlighting connections at the river basin scale and drawing attention to some of the many examples of specific trade-offs and synergies. We base our review on published studies, complemented by empirical analysis of available national-level data on climate, water resources, crop production, trade and GDP. We first consider national-level exposure of water, energy and food production to climate variability in aggregate economic terms and analyse the relationship between inter-annual and multi-year climate variability and economic activity, focusing on GDP and agricultural production. We then outline the potential for connecting areas with robust seasonal climate forecasting skill in areas with socially and economically important nexus related activities, and summarise studies that model the impact of anthropogenic climate change on elements of the nexus. Finally, we describe three key intra-regional mechanisms for balancing nexus components and conclude by identifying knowledge gaps in southern Africa's climate and water-energy-food nexus.

National level exposure of nexus sectors to climate

We characterise exposure as the interaction between characteristics of the climate system (particularly inter-annual rainfall variability) and a country's dependence on climate-sensitive economic activities such as the share of agriculture in GDP, the proportion of rain-fed agricultural land and the energy contribution from hydroelectric sources (Table 1, Figure 3). South Africa's GDP is larger than that of the other 12 economies combined. The direct contribution of agriculture to the economy is lowest (<10%) in South Africa, Botswana, Swaziland, Namibia, Angola and Lesotho, 13% in Zimbabwe, and over 20% in the other countries. If agricultural processing were included in agricultural GDP, the shares would be substantially larger in most, if not all, SADC countries. The share of cropland equipped for irrigation is low in most of the region, with the exception of Madagascar, South Africa and Swaziland (Table 1). The contribution of hydropower in energy production is very high overall (Figure 3), but varies considerably across the region, from 1.5% of energy production in South Africa, over 30% in Madagascar, Swaziland and Zimbabwe, to almost 100% in DRC, Lesotho, Malawi, and Zambia. Reliable electricity production is at risk during prolonged droughts, and also during extreme flooding events, when dam safety is an additional risk. Over 90% of South Africa's energy generation is coal-based[21], well above the rest of the region. Coal-fired power plants with wet cooling systems consume far more water than most other energy technologies[22]. South Africa's main energy utility Eskom uses about 2% of the country's freshwater resources, mainly for coal-fired power stations[23]. Coal mining and energy generation from coal both substantially impact water quality and availability[24]. To reduce these impacts, Eskom has implemented a dry-cooling system in two existing power stations and all new power stations will use dry-cooling[23], enabling a 15-fold reduction in water use of power stations.

Overall, there are strong contrasts (Table 1) in energy (8-84% of energy consumption imported) and food (5-90% of cereal food imported) self-sufficiency, and in the sustainability of freshwater use, expressed as freshwater withdrawals relative to total actual renewable water resources (TARWR) (0.1-24%). Countries facing most water shortage, expressed as share of TARWR withdrawn (Table 1), are South Africa (24%), Swaziland (23%), and Zimbabwe (21%), well within categories defined as physically water-scarce (ratio larger than 20%[25]). We interpret this indicator with caution, noting its failure to capture the complex spatial and temporal distribution of water, political-economic access, differences in water needs and socioeconomic capacity to support effective water utilisation[26,27]. Sub-national areas of high demand relative to availability include southern Malawi, Namibia and Botswana. Low ratios of water withdrawal to TARWR (such as 0.05% in DRC[27]) could also indicate economic water scarcity due to inadequate investments to harness and deliver water.

The cereal import dependency ratio (Table 1) reflects the importance of imports in the volume of grains available for consumption in the country (i.e. Production + Imports - Exports). It is particularly high for the small countries of Swaziland and Lesotho, and more strikingly so for larger nations like Botswana (90%), Namibia (65%) and Angola (55%). Dependency ratios are lowest in Zambia and Malawi. Total food aid received by the region (260,000 tons in 2012, Figure S1) was equivalent to about 2-3% of food imported by the region from the rest of the world (9 million tons in 2008). Chronic and episodic food insecurity remain important problems in the region. The causes of inadequate food access are multiple and, at the household and individual level, they are dominated by poverty, environmental stressors and conflict, often underpinned by chronic structural elements in the lives of communities, intensified by sudden shocks which can be climate related such as decrease in cereal availability and food price increases[28,29].

Climate signals in the nexus

Multi-year rainfall variability in southern Africa is higher than in many other parts of the world[30]. Inter-annual variability, expressed as the coefficient of variation (CoV), is not particularly high at national scales: < 20% for most countries, except for the driest two countries Botswana and Namibia (Figure 3). However, rainfall displays much greater local variability (local CoV exceeds 20% across much of the SADC region), strong seasonality, and a range of longer periodicities from multi-annual to decadal[31]. At the national level, long-term trends in rainfall between 1901 and 2012 are modest (the linear trend is insignificant relative to the long-term average) without evidence of any clear spatial pattern (Table S1). Linear trends during the last two decades show varied behaviour; three countries with wetting trends above 20% of the long-term mean annual rainfall (Botswana, Namibia and Zambia) and Tanzania with a drying trend of 21% (Table S1). National level analysis is likely to obscure local trends and trend results are highly sensitive to the period chosen for analysis, particularly in regions with strong multi-annual variability.

We use correlation analysis to explore the associations between annual rainfall and national economic activity (GDP annual growth rate) and agricultural production (all cereals and maize - the most significant crop in the region). Fifteen year sliding correlations are used to examine the temporal stability of associations between variables (see SI Methods and data). There are no statistically significant relationships between annual rainfall and GDP growth rate and none of the mean 15-year sliding correlations are significant (Table 2). Correlation of rainfall with total production of cereals and maize shows three countries with significant relationships at 1% level and three at 5% level (although for DRC, it is negative and possibly spurious). The average sliding correlations are somewhat higher (but not statistically significant, Table S2).

Time series data of hydropower production are not publically available and not easily comparable between sites/countries, making it difficult to assess the importance of climate variability as a driver of energy production fluctuations. Electricity insecurity is known to negatively affect total factor productivity and labour productivity of small and medium-sized enterprises but the relationship is as yet not straightforward, with differences between countries and measurement effects[32]. Studies of specific events highlight what are major consequences of some drought-induced reductions in electricity production[33]. Ref. 18 cites examples of drought impact on the Kariba Dam (Zambezi River basin), during 1991-92, resulting in an estimated $102 million reduction in GDP and $36 million reduction in export earnings; and Kenya where, during 2000, a 25% reduction in hydropower capacity resulted in an estimated 1.5% reduction in GDP. A review of the economics of climate change in Tanzania profiled the consequences of drought in 2003, which brought the Mtera dam reservoir levels close to the minimum required for electricity generation[34]. This prompted Tanzania Electric Supply Company (TANESCO) to approach a private provider to use gas turbine units at huge cost. A more recent World Bank estimate put costs of power shortages in Tanzania at $1.7 million per day with an average 63 days a year with power outages[34].

Early warnings from the climate system

Given the linkages between climate and the water-energy-food nexus in the region, seasonal forecast information can play an important role in guiding nexus-related decision-making, depending on forecast skill and utility. Seasonal to inter-annual variability in southern Africa is high, but so is its predictability relative to other regions, depending on location and time of the year[35] and phase of the El Niño-Southern Oscillation[36] (ENSO). This can be seen by considering the association (Figure 4a) between Nino3.4 sea surface temperatures (SST) - as a representation of ENSO - and gridded rainfall over southern Africa south of 15°S[37]. A state-of-the-art coupled ocean-atmosphere model has some skill in predicting seasonal (December to February, DJF) rainfall over the region at a 1-month lead-time (DJF forecasts produced in November, Figure 4b shows areas with statistically significant correlation[36], see SI Methods and data) Stronger ENSO associations and best model performance are found for maximum temperatures (Figure S2). The areas where ENSO impacts significantly and where forecast skill levels are relatively high include the river basins of the Limpopo, Orange, Umgeni and lower Zambezi.

The Limpopo river basin is particularly notable as having both high economic productivity and strong ENSO associations and forecast skill. Comprising 408,800km^2, and including the countries of South Africa, Botswana, Mozambique and Zimbabwe, the Limpopo basin is one of the most water stressed in sub-Saharan Africa, and features some of the largest urban conglomerations (including Pretoria, Johannesburg, Gaborone, Francistown and Bulawayo). Irrigation comprises more than 50% of basin water use and other infrastructure (including industry and mining) also highly dependent on basin water. There are significant mining activities in the basin, particularly in South Africa and Zimbabwe[38], that generate major water pollution downstream[39]. The Limpopo is heavily regulated, with extensive plans for further development stimulating increased focus on better monitoring and research for development of the basin.

Finally, although forecast skill is critical, and has potential utility in economic productivity hotspots such as the Limpopo Basin, a range of barriers persist in the region to realizing the benefits of seasonal forecasting. A comprehensive review of seasonal forecasting status in sub-Saharan Africa identified persistent constraints in the use of forecast products, which were generally insufficient to inform response actions, such as production decisions and institutional actions[40]. If these barriers can be overcome, seasonal forecasting has the potential to contribute to smoothing fluctuations in the nexus by informing guidance on the early targeting of or access to agricultural inputs and credit, design of interventions during food crises, and improvements to trade and agricultural insurance[40-42].

Modelling the nexus in a changing climate

The challenges for the water-energy-food nexus posed by inter-annual variability occur in the context of a gradually changing climate. Even if an international agreement to limit global warming to 2°C above pre-industrial conditions is successfully developed, climate models project significant changes that exceed the range of natural climate variability (Figure 1). Most southern African countries warm more than the global-mean in most climate models, with annual-mean temperatures rising by 2 to 3°C in most cases. Precipitation changes are more uncertain, with both increases and decreases possible. Nevertheless, for most countries the majority of models project decreases in annual precipitation, typically by as much as 20% though more for some models and countries. Except for the southernmost countries, there is a tendency for models that warm most to simulate stronger reductions in precipitation, a combination that could have severe impacts across the water-energy-food nexus. Analysis of extreme precipitation in climate models used for IPCC AR4 shows a marked delay in rainy season onset over most of the region and an early end to the season in parts of the region[43].

Most nexus studies for southern Africa have been motivated by climate change and assess biophysical impacts for specific sectors, e.g., rainfall and irrigation water availability on crop production, or river flow changes on hydropower generation. Some crop models simulate sizable yield losses for southern Africa[44], suggesting the region's food system could be particularly vulnerable to climate change[45]. Differences in climate scenarios, impact models, spatial and temporal scales and processes represented, restrict our ability to reliably define impacts for specific sectors and, importantly, secondary effects across the water-energy-food nexus. Nevertheless, an estimate of the range of potential impacts on maize yield (and the wide range in uncertainty) can be determined from the 30-member ensemble of global gridded crop models run by the ISI-MIP programme[46] (see SI). The simulated maize yield averaged across southern Africa decreases by 15.7±16.3% (rain-fed) and 8.3±20.4% (irrigated) by the 2080s relative to the 2000s, i.e. a yield reduction for the median but with a substantial range of different outcomes. The wide range is due to climate uncertainties described earlier and large uncertainties in our understanding of crop response to climate change, particularly the role of elevated atmospheric CO_2 concentration on photosynthesis and crop water use efficiency. Median impacts in the top five southern African producers are relatively small in the 2020s and 2050s, becoming more substantially negative by the 2080s, with a stronger level of agreement in the sign of change among simulations (Figure 5) but an increasing inter-model range. Among these countries, rain-fed cultivation is more negatively impacted, highlighting that water stress is an important limiting factor to crop yield in the region. Along with declining maize yields, average crop water use decreases at a slightly faster rate in both rain-fed and irrigated maize growing areas, resulting in a 5.9±20.7% increase in estimated crop water productivity in rain-fed maize growing areas and a 9.2±17.9% increase in irrigated systems (see SI and Figure S3) by the end of the 21st century.

An ensemble of global hydrological models driven by five climate scenarios from the CMIP5 programme shows reductions in annual discharge from 0 to 50% for the multi-model mean across much of southern Africa, excluding Southwest Botswana[47]. River basin and water management models indicate higher risks for Zambezi hydropower generation[48; 49]; while regional and global water and food models suggest lower runoff raises risks for water and food security in southern Africa in general[50-52].

The economic dimensions of the nexus in southern Africa can be studied using general equilibrium models that translate biophysical impacts into economic outcomes. This approach simulates economies as adapting to shocks, albeit imperfectly, through market and resource adjustments. Incorporating economic adaptation generally leads to smaller impacts than those from biophysical studies. Global models rarely separate southern Africa from sub-Saharan Africa, leaving country-level studies as the region's main evidence base. Historical climate variability imposes high costs on low-income agrarian economies[53; 54] and climate change is likely to have adverse effects on food security[55-58]. However, long-term change in annual precipitation and temperature may impact less than historical variability until 2050[53, 3]. Historical data show substantial variability in smallholder farm yields and incomes. Increase in future variability of smallholder farm yields from climate change and its propagation into increased variability in farm incomes is likely to increase food insecurity risks for farmers who are already at high risk[59]. Although most studies focus on agriculture[60; 61], this is not always the main impact channel. For example, nexus studies find that road damages from flooding and weather stress are equally or more important drivers of the economic losses associated with climate change in Mozambique and South Africa[60]. More integrated multi-sector/country-level studies are needed to guide adaptation responses.

A second strand of economic research focuses on climate and energy policy. A high proportion of SADC greenhouse gas emissions are from South Africa due especially to its reliance on coal-fired power. Curbing these emissions may reduce national income and employment, because financing domestic renewable options requires higher electricity tariffs[62; 63]. Lifting South Africa's restrictions on hydropower imports would reduce investment costs and economic losses[64]. Climate change will have considerable indirect impacts on electricity generation, with positive feedback mechanisms because higher water and air temperatures make cooling processes in coal-fired power plants less effective and potential reductions in water availability during longer dry periods[23], this could result in an overall reduction of power plant efficiency and higher carbon emissions. Within its climate change strategy, Eskom aspires to diversify its energy generation mix to lower carbon-emitting technologies[65]. Solar photovoltaic and wind energy are considered to be the most viable renewable options in terms of water withdrawal and consumption compared with biofuel and hydropower[24]. Biofuels may reduce the region's imported fossil fuels and reduce rural poverty, but have potential food security trade-offs[66]. Research indicates that continued climate change, economic development and urbanization will strengthen inter-dependencies in the water, energy and food nexus in southern Africa and that climate and associated energy policy will further reinforce the costs of trade-offs and complementarities across the WEF nexus, especially so if expansionist regional hydropower and biofuel strategies are adopted.

Intra-regional instruments for the water, energy and food nexus

Southern Africa can be characterised as a single economic block of strongly interlinked economies where water, energy and food flow between producers and consumers, while also displaying considerable heterogeneity in its natural resource endowments and infrastructure distribution, its socio-political cohesion and its economic development. For both the region and individual nations, this implies significant challenges in attempting to balance supply and demand while maintaining coherent policies towards integrated management of water-energy-food resources. The region is well placed to transfer resources intra-regionally to meet energy and food shortfalls. However, rising demand for electricity, food and water throughout southern Africa may sharpen the region's sensitivity to climate-induced shocks. Fifteen trans-boundary river basins transect the region, including the large Congo and Zambezi basins, shared by nine and eight countries, respectively, as well as many smaller shared catchments. Surface catchments are underlain by an estimated 16 trans-boundary aquifers[67].

The origin of the southern African economic block can be tied to the dominant position of South Africa and its history alongside other ex-South African and British colonies such as Swaziland, Zimbabwe, Botswana, Namibia and Zambia. South Africa in particular has great cultural, economic and political influence over its neighbours making its role as a source (and sometimes a sink) of energy, water, and food hegemonic[68]. This alliance and influence is also evidenced via the SAPP (South Africa has 77% of SAPP's installed power supply capacity[69]), and the SADC and other agreements.

In responding to the distribution of and demand for water-energy-food resources, three key instruments have emerged. First, the SADC, based in Botswana, addresses how member countries sharing rivers might resolve water allocation priorities through a Protocol on Shared Watercourses[70; 71]. The presence of significant water demands arising from irrigated agriculture and the Gauteng urban industrial complex in South Africa has led to relatively sophisticated water sharing agreements such as the Joint Development and Utilization of the Water Resources of Komati River Basin[72] and Lesotho Highlands Development Project respectively. Large-scale dams and inter-basin, often trans-boundary, transfers form part of national water-energy-food security strategies (ref. 73 reports 27 existing ones)[73]. South Africa and Zimbabwe, which have the largest numbers of dams, use these predominantly for irrigation and water supply, whilst Mozambique, which has one of the largest total dam capacities, concentrates on hydropower production (Table S3). Notwithstanding these institutional and physical structures, however, in some instances water sharing still suffers from a lack of institutional integration (particularly between agricultural and water institutions) and incomplete efforts to increase stakeholder participation and decentralise water management (ref. 74; reviewing South Africa, Zimbabwe and Mozambique)[74]. Coordination during flood events can also be challenging, for example the persistent 2010/11 summer rainfall in the Zambezi River Basin catchment area resulted in high water levels of Lake Kariba. Opening of spillway gates raised downstream water levels increasing flooding and compromised effective reservoir management at Cahora Bassa further downstream in Mozambique[75].

Second, the SAPP is a remarkable alliance of 12 energy-generating bodies from 12 countries inter-connected through a grid to help smooth spatial and temporal shortfalls in electrical capacity. It was established in 1995 by the member governments of SADC (excluding Mauritius) to develop an interconnected electrical system, coordinate and enforce common regional standards, harmonise relationships, develop expertise across member utilities, and promote sustainable development[76]. The SAPP electricity generating mix in 2012-13 was 54,923 MW, comprising a significant proportion from hydropower (17.4%), but dominated by coal (72.9%). The network is intended to function as a competitive market in which surpluses and deficits are resolved via trades and negotiations and therefore has potential to serve as a buffering mechanism for climate-induced river basin scale electricity insecurity.

Third, food trade in southern Africa naturally results from regional variability in production, especially of maize. Large and efficient producers in South Africa induce a trade surplus with other SADC members. Importantly, trade of agricultural products corresponds to significant transfers of embedded water resources, or “virtual water trade” (VWT, see SI Data and Methods). Water resources embedded in South Africa’s regional food exports (0.9 km^3 in 2008, Figure 6a)[77] account for half of the total intra-regional flow (1.9 km^3). The dominant link is from South Africa to Zimbabwe, with a volume of 0.4 km^3/y of virtual water, followed by Mozambique to Malawi (0.3 km^3/y). Zimbabwe is the region’s major virtual water importer, importing 0.66 km^3/y from other southern African nations. Considering all international food trade, southern Africa is largely a net importer of virtual water. Indeed, international imports from outside the region (9 million tons of food, or 10.8 km^3 of virtual water) dominate the VWT flows of southern Africa (13.5 km^3/y, Figure 6a, b). In return, smaller volumes to outside the region are exported mainly from South Africa (0.4 km^3/y), followed by Namibia (0.2 km^3/y) and Botswana (0.2 km^3/y). About 7% of South African virtual water exports via food are irrigation-based (blue) water embedded in maize (0.066 km^3), representing almost all of the intra-regional blue VWT (0.067 km^3)[78]. This small percentage reflects the dominance of rain fed (green water) agriculture in the region. Although strong open trade is an important tool to alleviate climate-induced food deficits[79; 80], and virtual water trade openness tends to reduce undernourishment[81], southern African countries have varying levels of trade connectivity and trade link strengths, both for intra- and extra-regional food trade links. Thus, the potential benefits of food trade to alleviate production shocks are likely uneven across the region, and require further investigation.

Informal border trade has become a regular feature of the region’s maize economy since market reform in the 1990s. Estimates suggest that up to 150,000–250,000 tonnes of maize flow from Mozambique to Malawi during years of good production in Mozambique and high demand in Malawi[82]. These important informal imports play a crucial role in alleviating food shortages. Informal traders are less encumbered by trade regulations than larger formal grain traders, and hence can respond to arbitrage opportunities more quickly[83]. Trade could play a greater role in the response to food crises than it has in previous decades, though Zambia and Malawi frequently impose maize export bans during crisis years[83]. One of SADC’s main goals for regional integration is to promote trade across member countries. Efforts are ongoing to reduce major existing barriers, such as trade regulations and lack of reliable transportation infrastructure[84], notably via the Protocol on Trade[85], including facilitation of customs processes, and a regional infrastructure plan for the transport sector[86].

Conclusion and outlook

Climate plays an important role in determining medium-term water availability, potential agricultural production, and some components of energy production and demand. Climate variability drives fluctuations in WEF elements with secondary effects across the whole nexus (Figure 1). Exposure and sensitivity to climate variability and climate change are high across nexus sectors that include substantial areas of economic activity in southern Africa and there is strong evidence of the effects of individual climate events. For example, South Africa, experienced a 7% drop in GDP in the 1983 El Niño year, and climatic fluctuations resulted in GDP variations of up to US $5 billion[87]. The 2000 floods in Mozambique led to devastating impacts on livelihoods, electricity supplies and basic infrastructure[88]. Yet our analysis of associations between rainfall, GDP and crop production using available data shows mostly weak correlations. This is likely to be partly a function of scale, where national and annual scales obscure stronger relationships that may exist at finer levels of analysis. Data availability (e.g. absence of publically available hydropower production time series) and quality also play a role. The country climate estimates are based on sparse station coverage for many countries in the region, particularly since the 1980s[37] and recent scrutiny of GDP data for sub-Saharan Africa has highlighted lack of transparency in data sources and collection methods, lack of metadata and lack of detail on methods of aggregation[89]. This leads to differences between GDP estimates, non-random errors, adjustments to historical data, and inhomogeneity in time series. National statistical offices are woefully under-resourced in sub-Saharan Africa. The need for good quality data is paramount and urgent, to underpin reliable modelling of the physical and economic dimensions of the nexus and for defining baselines and indicators as the global community approaches agreement on the Sustainable Development Goals[90].

River flows in the region are strongly linked to seasonal rainfall and temperature variations, and the information reviewed here provides evidence that seasonal forecasting of river flows in some basins has application potential. However, the benefits from seasonal forecasting for reducing net food and energy imports through enhanced agricultural and hydropower production/energy mix have yet to be studied and, even more importantly, implemented in practice. For the future, climate models show fairly strong agreement that the southern countries in the region may become drier and the secondary impacts though very uncertain, are likely to be significant across the water-energy-food nexus.

Water, energy and food are linked across different scales in southern Africa. Spatial co-dependence is high and climate anomalies can be regional in extent, for example ENSO related droughts and river basin scale floods. At the national level, water and energy are closely coupled through significant hydropower production in several countries. Water for biofuels and cooling for electricity generation remains relatively modest except for cooling in South Africa. Water and food linkages are strong, through green water requirements in rain-fed agriculture and through irrigation (blue) water, which account for most freshwater consumption in the region. Food and energy linkages are growing due to increasing irrigation, mechanisation, and fertilization of agriculture, while biofuel development remains low. The rapidly growing demand for energy by industry and mining, rapidly growing urban areas, and agricultural intensification are likely to impose increasing strain on the water-food-energy nexus. At the regional level, nexus linkages are strong, due to multiple shared major river basins and aquifers, the SAPP power-sharing infrastructure, and intra-regional food and embedded water trade. These linkages are enhanced by governance mechanisms such as the SADC, which has established protocols on shared water, energy, and food security, a regional seasonal climate forecasting forum (SARCOF) and initiatives on trade and the green economy.

Debate is ongoing about whether there is anything new about the nexus that distinguishes it from earlier integrative framings[91,92]. Some argue that a nexus framing is better at uncovering more effective approaches and methods for cross-sectoral integration by examining trade-offs and co-benefits, and through linking disparate knowledge sets and improving governance[91]. However, entrenched vertically structured government departments and sector-based structures of agencies, policies and regulatory mechanisms complicate coordination and remain challenges to cross-sectoral integration[91-93]. The political economy of governance and operation is also challenged by regional and intra-regional institutional capacity and power imbalances. Our review suggests that climate change, combined with increasing demand associated with wider socio-economic development pathways, will intensify interdependencies in the WEF nexus, particularly shorter-term pressures associated extreme events. We have outlined some of the main interdependencies and key regional institutional and policy structures in southern Africa. There is a need to map these structures at finer scales, to understand where trends and shocks have been managed effectively in the past, and to identify measures that enhance successful cross-sectoral approaches. In a highly climate-sensitive environment such as southern Africa, emerging strategies - such as those under SADC - will only bear fruit if recognition of co-dependencies and inter-relationships in the nexus provides the basis for credible and well-monitored actions.

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Main Tables and Figures

Figure 1: Average annual total precipitation (1961-1990) and multi-model ensembles of projected changes in national-average annual precipitation (y-axis, pre, as a fraction of 1961–1990 mean) and national-average annual-mean temperature (x-axis, tmp, °C change from 1961–1990 mean), estimated for a global warming of 2 °C using a pattern-scaling approach[94]. The three ensembles are CMIP3 (21 models: open colored symbols and pink shaded distribution), CMIP5 (20 models: filled colored symbols and brown shaded distribution) and QUMP (17 versions of the HadCM3 model with perturbed physical parameter values: black symbols and blue shaded distribution). The shaded distributions are fit to the data to represent the bivariate ±2 standard deviation ranges and have been included to facilitate comparison of the model ensembles rather than to represent probabilistic projections of climate. Black dots and black fitted distributions illustrate the ranges of internal variability of 30-year mean climate simulated in a 1000-year control simulation of HadCM3, for comparison with the projected changes in climate.

Figure 2: Modified version of nexus framework of Hoff[10] integrating global drivers with fields of action, to illustrate the main timescales of climate as a driver in southern Africa.

Figure 3: National rainfall variability and socio-economic exposure to hydro-climate; a – c individual countries, d: Average, minimum and maximum of 13 countries. Sources: Rainfall interannual variability (CoV,%), [37]; Hydropower share in energy production (%), [95]; Agriculture (crop & livestock production, forestry, hunting, and fishing) value added share of GDP (%), [95]. Note: missing data for agricultural GDP in Malawi.

Figure 4: Kendall's tau correlations a) between concurrent DJF Nino3.4 SST and DJF rainfall for the 30 years from 1982/83 to 2011/12; and b) between ECHAM4.5-MOM3-DC2 downscaled seasonal forecasts for DJF produced in November and observed DJF rainfall (Source: ref. 36). See SI Methods and data.

Figure 5: Simulated climate change impacts on rain-fed and irrigated maize yield in the top-five producing countries of southern Africa for the near, medium and long-time horizon under RCP 8.5. The bottom and top of the box are lower and upper quartiles, respectively; the band near the middle of the box is the median value across each set of simulations, which comprises an ensemble of 30 impact simulations (see ref. 46).

Figure 6: Water resources transfers (km^3) through food trade (a) among southern African nations (b) and the rest of the world (RoW) in 2007. Ribbon colors indicate the country of export. Sources: trade data [96], hydrology with H08 global model [97-98], in ref. 77.

Country	GDP (10^9 current US$)	GDP per capita (current US$)	Energy imports (% consumption)	Freshwater withdrawal (% total actual renewable water resources)	Cereal import dependency ratio (%)	Area equipped for irrigation (% cultivated land)
	Economy	Economy	Energy self-sufficiency	Water Sustainability	Food self-sufficiency	Water-food
Angola	115	5,540	32	0.48	55	2
Botswana	14.5	7,250	63	1.6	90	1
DRC	18	420	5	0.05	37	0.1
Lesotho	2.3	1,130	*	1.4	85	1
Madagascar	10	440	*	4.9	10	31
Malawi	4.2	270	*	7.9	6	2
Mozambique	14.4	570	21	0.4	31	3
Namibia	13.4	5,930	84	1.6	65	1
South Africa	382	7,310	46	24	19	13
Swaziland	4.1	3,290	*	23	79	26
Tanzania	28	610	13	5.4	13	2
Zambia	20.6	1,460	14	1.5	5	6
Zimbabwe	12.5	910	10	21	52	5

*Data unavailable

Table 1: Economic indicators and climate sensitive economic activities across water, energy and food. Sources: GDP (2012), [95]; Energy (2012), [99]; Water use (2000-2005), [77,100]; Food trade (2007-2009), [96], Irrigation (1960-2005), [77,100].

Country	Corr full record – GDP Growth	Sliding corr mean – GDP Growth	Sliding corr min – GDP Growth	Sliding corr max – GDP Growth
Angola (1986-2012)	0.19	0.06	-0.12	0.26
Botswana (1961-2012)	-0.06	0.04	**-0.77**	*0.62*
DRC (1961-2012)	0.18	0.10	-0.50	0.44
Lesotho (1961-2012)	0.17	0.10	-0.29	0.50
Madagascar (1961-2012)	-0.14	-0.12	-0.43	0.25
Malawi (1961-2012)	0.21	0.23	-0.15	0.47
Mozambique (1981-2012)	0.11	0.22	-0.1	*0.63*
Namibia (1981-2012)	0.15	-0.07	-0.32	0.24
South Africa (1961-2012)	0.08	0.36	0.02	**0.7**
Swaziland (1971-2012)	-0.02	-0.04	-0.27	0.33
Tanzania (1989-2012)	-0.07	0.03	-0.06	0.14
Zambia (1961-2012)	0.09	0.19	-0.31	**0.68**
Zimbabwe (1961-2012)	0.01	0.05	-0.46	**0.64**

Table 2: National-level correlation coefficients between annual GDP percentage growth rate (calendar year) and rainfall (October year-1 to September current year). Mean, maximum and minimum correlations from 15-year sliding Correlations significant at 1% level are bold, and at 5% in italics. Sources: GDP [95], rainfall [37].