Framework for needs-informed research: assessing climate processes

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About FRACTAL working papers

This series is funded by the UK's Department For International Development (DFID) and the Natural Environment Research Council (NERC) through the Future Resilience for African CiTies and Lands (FRACTAL) project, within the Future Climate For Africa (FCFA) multi-consortia programme. The overarching objective of FCFA is to generate fundamentally new climate science focused on Africa, and to ensure that this science has an impact on human development across the continent. FRACTAL's main aim is to advance scientific knowledge on regional climate responses to global change and enhance knowledge on how to integrate this information into decision making at the city-region scale in Southern Africa. These products have been developed to share initial findings from research in the hope of fostering dialogue and eliciting feedback to strengthen the research. The opinions expressed are therefore the author(s) and are not necessarily shared by DFID, NERC or other programme partners.

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Acronyms and abbreviations

CMIP5	Coupled Model Intercomparison Project phase 5
ENSO	El Nino Southern Oscillation
GCM	Global Climate Model
IOD	Indian Ocean Dipole
ITCZ	Inter-Tropical Convergence Zone
LWSC	Lusaka Water and Sewerage Company
MCC	Mesoscale Convective Complex
RCM	Regional Climate Model
SST	Sea Surface Temperature
TTT	Tropical-Temperate Troughs

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1. Introduction

FRACTAL aims to improve understanding of regional climate processes and process change in Southern Africa, whilst taking into account the urban decision context and research to improve understanding of how cities can become more climate-resilient. To meet this aim it is necessary to build a common understanding and develop a consistent approach amongst FRACTAL researchers and institutions.

The project proposal lists three primary climate science related objectives:

1. Understand the climate processes driving the African regional climate system's natural variability and response to global change in recorded history and climate model simulations;
2. Distil defensible, scale-relevant climate information, informed by and tailored to urban decision making and risk management within their regional dependencies;
3. Use pilot studies to enhance our understanding of co-exploration processes with urban partners to integrate climate messages within real-world decisions, and strengthen development pathways to resilience.

To address these objectives, the climate information cluster within FRACTAL is focusing on two research lenses: "needs-informed" and "needs-driven". Needs-informed research is focused on addressing foundational knowledge gaps and developing new methodologies to better understand climate processes and process change relevant to Southern Africa, requiring only minimal framing from users. Needs-driven research seeks to deliver on identified user needs and must therefore explicitly reflect the needs of users in the focus cities, which is the subject of ongoing investigation (e.g. through "city learning dialogues").

This document presents a framework for needs-informed research targeted at addressing objective 1. We outline parallel top-down and bottom-up characterisations of climate processes, where each provides an alternative starting point to pursue needs-informed research. A top-down approach begins by compiling current understanding of the dominant synoptic scale climate processes in the region as well as relevant remote processes and "process chains" that extend beyond the southern African region. Conversely a bottom-up approach begins with an articulation of key climate risks facing the cities of interest, using existing knowledge and preliminary assessment, and relating these to relevant climate processes that influence these risks. Through this parallel approach it is possible to identify key climate processes relevant to Southern Africa and identify scientific knowledge gaps for each city within the context of both present-day variability and future climate change.

Ultimately the framework will inform existing data and model assessments as well as the development of new experiments and subsequent analysis. By assessing the ability of climate models to capture relevant processes, as articulated in this framework document, FRACTAL researchers will be able to better understand the relevance of model outputs for understanding climate processes, and the related uncertainties, and guiding decision making in the cities.

2. Top-down View of Processes

2.1 Conceptual framing

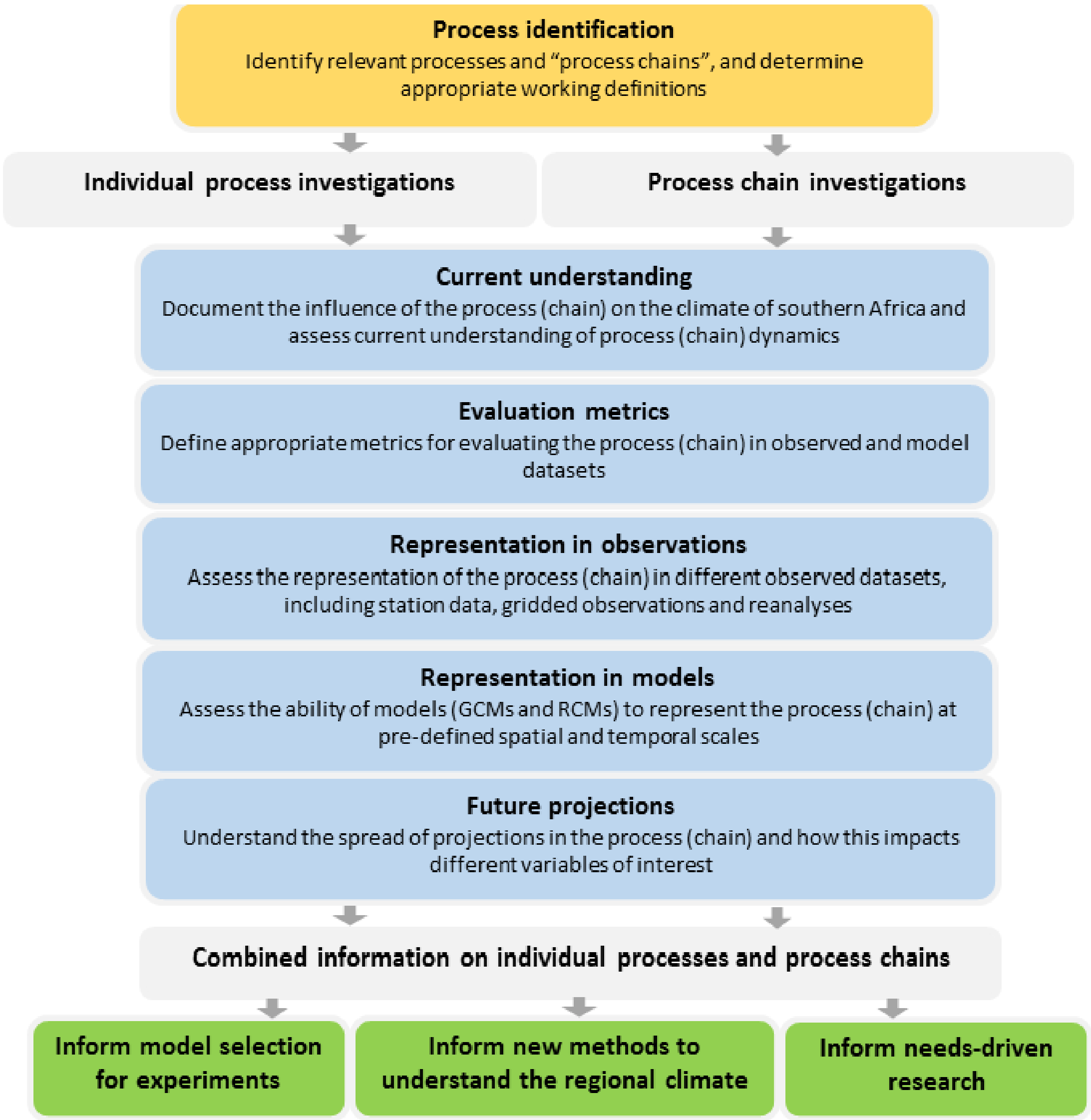

Figure 1: Conceptual diagram of top-down approach to assessing climate processes

The diagram in figure 1 summarises a top-down approach for research to understand climate processes, showing the sequence of steps required to characterise and analyse relevant climate processes and "process chains"; the concept of a process chain acknowledges the interplay of multiple processes across time and space (see section 2.3). The approach starts with the identification of relevant processes and their definitions before dividing into two streams focused on the analysis of 1) individual processes and 2) process chains. Different considerations are then investigated to determine current understanding of the processes, the definition of suitable metrics to assess the processes in different datasets, how well the processes are represented in observations and models, and what the future projections suggest for changes to processes under climate change. Once these have been investigated for each process and process chain, understanding can be brought together to inform future research – i.e. the design of new (downscaled) experiments, the development of new methodologies, and provision of information to other FRACTAL clusters and the city partners.

Process identification

As shown in figure 1, the first step in the top-down approach is to identify the key processes for the focus region. These processes will vary across temporal and spatial scales, and include both local and remote processes.

Some of the key large-scale processes known to affect the climate of southern Africa include:

- **Inter-tropical Convergence Zone (ITCZ) migration** – The timing and intensity of the main rainfall seasons for Southern Africa (typically December to Februaru) are controlled by the ITCZ, with the exception of southwestern part of South Africa which experiences winter rainfall in June to August.
- **Regional Hadley circulation** – A semi-permanent high pressure system (descending branch of Hadley circulation) is found over most of Southern Africa during winter (JJA), influencing the positioning and strength of westerlies, which impacts the timing of maximum rainfall in the southwest winter rainfall region
- **El Nino Southern Oscillation (ENSO)** – This influences the rainfall timing and spatial distribution with drier than normal conditions (wetterr in northern Mozambique) during El Nino, and wetter than normal conditions in most of southern Africa (drier in northern Mozambique) during La Nina

Other relevant large scale atmosphere-ocean processes influencing the region include the Indian Ocean Dipole (IOD), tropical-temperate troughs (TTTs), the Angola low pressure system, mesoscale convective complexes (MCCs), frontal systems, and tropical cyclones.

Smaller scale climate processes, such as convection, mountain winds effects and boundary layer processes will also be important to consider as they modulate the impact of the larger scale processes on outcomes of interest. Each city will have its own set of relevant small scale processes.

2.2. Individual process investigations

This section outlines the key considerations for investigating individual processes according to the framework laid out in figure 1.

Current understanding

Before exploring how well different datasets capture the process of interest, it is important to first compile and document current understanding. This should include details of the dynamics of the process, its behaviour across temporal and spatial scales, and how the process is thought to impact the climate in southern Africa under current forcing and possible future conditions. Determining what is known (and not known) about relationships to specific climate variables and outcomes in the region will provide a benchmark for subsequent research to improve understanding.

Evaluation metrics

Following an analysis of current understanding, the next step in the top-down approach is to determine appropriate evaluation criteria or "metrics" tailored to the specific process in question. Processes can be defined and measured in different ways, and there may be no optimal approach. Therefore, defining and testing a range of metrics may be necessary, allowing subsequent work to include sensitivity analyses that help in articulating confidence in conclusions.

Representation in observations

There are a number of observational and reanalysis datasets available to understand past and present climate conditions. Before analysing the ability of climate model simulations to represent a given process, it is essential to assess the representation of a process in observations. For processes that are defined using multiple variables and/or over different geographical regions, the assessment may need to consider the representation of the process simultaneously across multiple datasets. This analysis will complement the analysis of current understanding to provide a benchmark for assessing the representation of processed in model datasets.

Representation in models

Climate models inherently contain biases in the representation of climate processes and variables. Kalognomou et al (2013) report that model biases found over Southern Africa typically originate from the model setup, circulation anomalies and differences in the simulated moisture transport. These biases can vary across time and space making it difficult to define a single index to measure model fidelity (Kim et al 2014). Understanding the biases is an important precursor for assessing future projections of changes to climate processes.

Future projections

The final step of the top-down approach is to analyse available climate model projections, from Global Climate Models (GCMs), Regional Climate Models (RCMs) and empirical-statistical downscaling, to understand and assess projected changes in key processes and process chains. The analysis should compare information from multiple models and methods to determine whether or not different methods and models provide consistent information or whether there are systematic biases. For example, as depicted in Figure 2, comparing GCM projections (e.g. from CMIP5) to other available information (e.g. recent observed trends, downscaled projections, CMIP3 projections etc) would reveal if and how changes to climate processes and process chains differ across datasets. Such comparisons will inform the emerging research discourse on "contradictions" in climate projections (Team 2010, Pidgeon & Fischhoff 2011) and help to illustrate where these contradictions originate – i.e. to what extent contradictions are scale and/or method dependent. Ultimately this analysis can be used to provide assessments of confidence in projections.

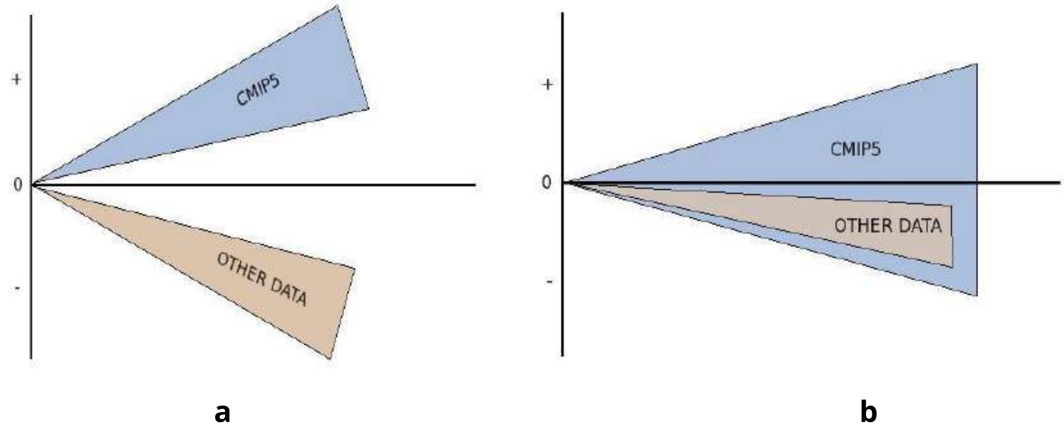

Figure 2: Conceptual diagrams describing possible spreads of climate model uncertainties where different datasets show a) contradicting information and b) consistent information sampling a limited uncertainty range

Compiling information

Table 1 provides a first (incomplete) attempt at using the top-down approach to document and compare different individual climate processes relevant to southern Africa. The table shows the beginning of an assessment of the nine large-scale processes identified, according to key considerations of the framework diagram summarised in figure 1.

ENSO	
Current understanding	Good understanding of Walker circulation and impact on seasonal mean rainfall but limited understanding of how ENSO relates to the IOD
Evaluation metrics	Metrics published in Guilyardi et al. (2012) and, in greater detail, Bellenger et al. (2014), assess CMIP5 models across a number of metrics. These include of ENSO amplitude (NINO3 SST standard deviation), structure (Nino3 vs Nino4 amplitude), frequency (Root Mean Square Error, RMSE, of Nino3 SSTA spectra) and heating source (Nino4 precipitation standard deviation), and additionally several process-based metrics which reflect the role of the atmosphere response to ENSO, and therefore represent an assessment of whether the models capture the key processes required to represent ENSO realistically.
Representation in observations	
Representation in models	Most CMIP5 models realistically capture present-day ENSO characteristics (asymmetry between warm and cold events, two 'flavours' of events in central and eastern Pacific). GCMs and RCMs simulate the impacts of warm and cool ENSO phases on rainfall in Southern Africa but links to central Indian Ocean SSTs and IOD are less well simulated. AOGCMs seem to outperform coupled GCMs in simulating effects of

	ENSO, suggesting poor SST variability contributes to poor teleconnection skill in coupled models.
Future projections	No consistency in projected changes to the location, magnitude, frequency or temporal evolution of ENSO events across CMIP3 or CMIP5. Some show ENSO enhancement and others damping in the 21st century. Aspects of ENSO process chain show robust signals (i.e. expansion of warm pool, weakening of trade winds, decline in stability), but the net effect of these changes is unknown. There is some evidence to suggest teleconnections in the southern ocean (affecting Southern Africa) may shift poleward.
ITCZ migration	
Current understanding	
Evaluation metrics	
Representation in observations	
Representation in models	Depending on the region, GCMs and RCMs capture the timing and intensity of ITCZ migration well, with the exception of far southwestern South Africa (summer rainfall may penetrate too far south).
Future projections	
Regional Hadley circulation	
Current understanding	
Evaluation metrics	
Representation in observations	
Representation in models	RCMs tend to over-simulate the strength of the Hadley circulation during July, inhibiting northward movement of westerlies.
Future projections	

Table 1: (incomplete) Summary information on key climate processes for southern Africa

2.3 Process chain investigations

A weather or climate event that impacts society (e.g. drought or heavy rainfall) results from specific atmospheric and ocean conditions, which occur due to a combination of multiple physical processes. Quantifying how well a climate model represents a single process (e.g. ITCZ) is important, as described in section 2.2, but in linking the process to a climate event/outcome of interest we require a quantification of how much influence this process has within the "chain" of relevant processes.

The concept of a process chain is being developed within FRACTAL as a new way of thinking about interacting climate processes across scales and their combined influence on an outcome of interest. The box below provides a working definition.

"Process Chain"

A sequence of at least three atmosphere and/or ocean processes that results in a weather or climate outcome, where each individual process has a discernible physical influence on (or is influenced by) an upstream/downstream process

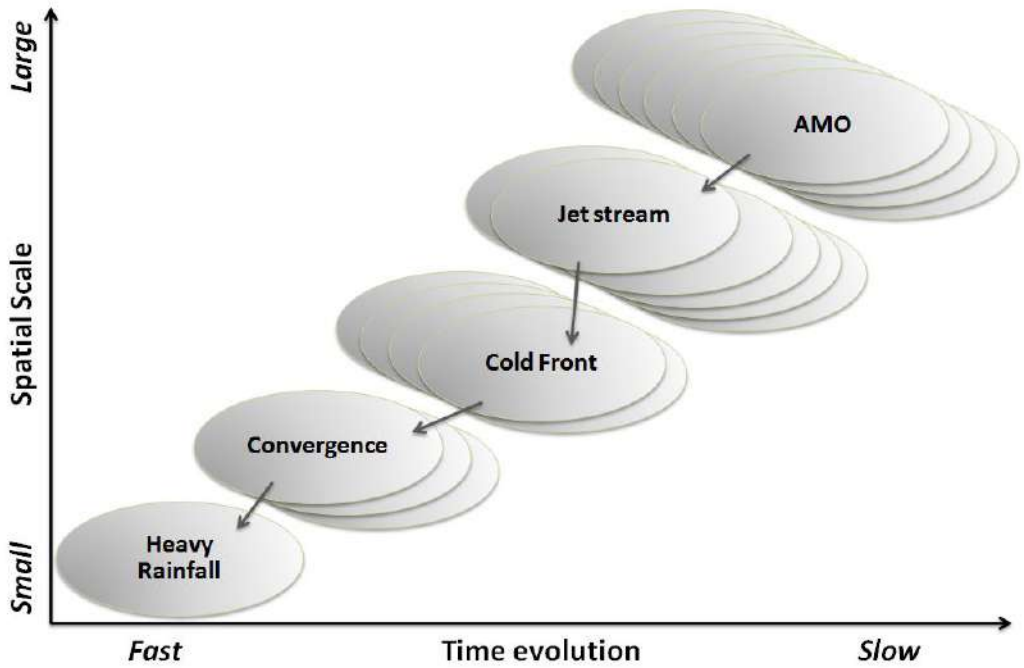

Figure 3: Conceptual diagram of a process chain, taken from a range of processes across time and space scale relevant to an outcome of interest - heavy rainfall

Figure 3 shows a schematic representation of an example process chain related a specific outcome of interest, heavy rainfall. In taking this example further it would be important to better define what is meant by heavy rainfall (e.g. threshold exceedance for a particular time period and spatial scale). However, the example serves to demonstrate that this outcome results from a number of upstream processes. The specific process chain identified, indicated by the arrows and processes identified, could be a dominant process chain affecting the magnitude and/or likelihood of heavy rainfall; other chains are possible but for a useful analysis, the objective is to identify and quantify the dominant process chains.

Once a process chain has been identified, the same steps outlined in the conceptual framework in figure 1 can be used to quantify the nature of the process chain in observations, models and future projections - i.e. following the steps: current understanding; Evaluation metrics; Representation in observations; Representation in models; Future projections.

As an area of research within FRACTAL, this document does not aim to be overly prescriptive in how to frame research on process chains. Using alternative definitions, example and approaches is likely to yield to a richer exploration of this concept as it aims to advance understanding of regional climate and inform resilience building and adaptation decisions.

2.4 Informing future research activities

Inform model selection for experiments

There is scope in FRACTAL to design and produce tailored downscaled climate model experiments. This will be motivated by the needs-driven research activities but the needs-informed lens can be used to provide a suite of options. In particular, prior to addressing explicit user needs it is possible to determine which GCMs are suitable for downscaling based on assessments of their performance and the range of future projection uncertainty.

Owing to practical constraints it is not possible to downscale all available GCM simulations. Therefore a strategic sampling approach is required. Whilst there are different methods of selecting models for downscaing, the approach being suggested for FRACTAL is based on two step process as outlined in McSweeney et al (2015a) and described further in Table 2:

1. Eliminate models that perform poorly when compared to observations
2. From the remaining models, span the uncertainty range associated with future climate projections

Using this approach the emphasis is on removing models that produce unreliable simulations rather than selecting the “best” models, since all models are imperfect and different evaluation methods will reveal different models as being better than others. Using the elimination principle the approach seeks to remove models that cannot capture relevant processes of interest and sample uncertainty from the remaining models, given that the range of futures is ultimately of most interest in the context of adaptation decision making.

Model Performance	Model Projections	
	Outlier	Other models predict similar outcomes
Model suffers shortcoming(s) sufficiently serious to significantly reduce our confidence in its projections (‘Implausible’)	Exclude: we should carefully document justification for this, however, as exclusion will affect the range of outcomes.	Exclude: we can avoid using these models without substantially affecting the range of outcomes.
Model suffers significant shortcomings which we cannot clearly link to	Include: we do not have strong enough evidence to exclude	Exclude: we can avoid using these models without

confidence in its projections. ('Biases/Significant Biases')	these outcomes from the projections.	substantially affecting the range of outcomes.
Model performance is satisfactory ('Satisfactory')	Include	Include

Table 2: Evaluation criteria for model sub-selection, from McSweeney et al (2015a)

Table 3 provides an example summary of model performance from a study in southeast Asia (McSweeney et al 2015b). It shows how different models (only a subset is shown) perform when assessed for their performance in capturing key large scale climate processes relevant to the region. One of the key caveats to any selection activity is the lack of high quality observation datasets at suitable temporal and spatial resolution necessary for model evaluation. Assessing observational datasets, one of the key activities for the climate information cluster, is therefore a critical input to the sub-selection process and experimental design.

Model (overall assessment)	Southwest Monsoon	Southwest Monsoon variability	Northeast Monsoon	ITCZ Migration	SSTs	ENSO
ACCESS1.3						
CCSM4						
CNRM-CM5						
EC-EARTH						
FGOALS-g2						
HadGEM2-ES						
MIROC-ESM						
MRI-CGCM3						
Nor-ESM1-M						

Table 3: Example assessment of models for specific processes, from McSweeney et al (2015b): green = satisfactory, yellow = small biases, orange = large biases, purple = implausible, grey = missing analysis (note, more models than shown were assessed in the study)

Inform new methods to understand the regional climate

Research conducted on individual processes and process chains should explore and test new methodologies that advance ways of understanding climate processes driving the African regional climate system's natural variability and response to global change. Developing and testing new methodologies has broader relevance to the climate research community arcoss the world.

Entry points for needs-driven research

The understanding of the urban context is still emerging through project interactions in the focus cities. Through engagement in the cities it is important to establish a clear articulation of what we know, don't know, and could know about relevant aspects of climate variability and change over Southern Africa, and the climate processes responsible. Based on existing knowlegde, there are a number of high probability climate entry points that we can pre-empt for engaging in needs-driven research. These include:

- Basin/catchment scale rainfall (and temperature/evaporation) characteristics
  - Water resource management
  - Riverine flooding
  - Hydro-power
    - Irrigation for food crop production

- Extremes
  - Rainfall extremes driving localised flooding
  - Wind extremes driving coastal storm surge
  - Seasonal variability, mainly dry seasons
  - Combined extremes (rainfall and wind, rainfall and cold, dry and hot)

3. Bottom-up View of Processes

A bottom-up approach to extracting and analysing key climate processes for the focus cities begins with an articulation of key climate risks. Through understanding the climate risks and sensitivities of adaptation decisions, it is then possible to identify which climate processes are most relevant and therefore warrant further investigation within the needs-informed research stream.

In this section, the key climate risks facing each of the Tier One cities are highlighted in turn. The discussion of climate risks and key impacts is based on analysis of the "city background reports" produced at the beginning of the FRACTAL project. Figure 4 summarises the content of this section in a word cloud. To pursue this perspective further requires a more rigorous analysis of existing literature and knowledge.

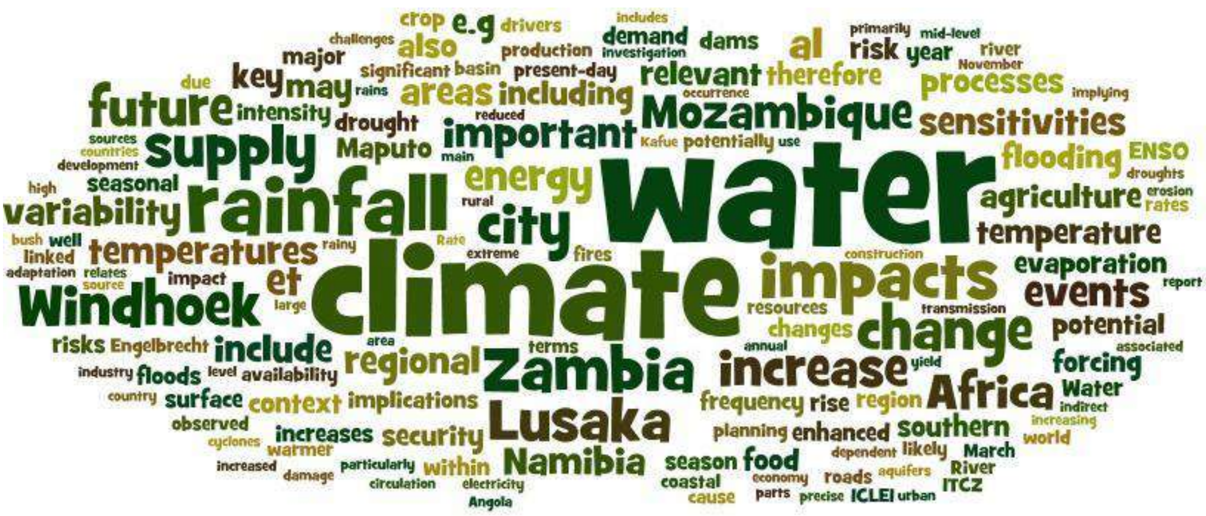

Figure 4: Word cloud using the text from sections 3.1 to 3.3 for the three Tier One cities. The size of the words is proportional to the frequency of their use.

3.1 Maputo

Weather and climate context

The rainy season in the Maputo region lasts from November to March, associated with the annual migration of the ITCZ. January is the warmest month, about 7°C warmer than the coolest month July.

Maputo and the surrounding region has been exposed to droughts. The most severe drought periods were recorded in 1981–1984, 1991–1992 and 1994–1995, while floods were observed in 1977–1978, 1985, 1988, 1999–2000 and more recently in 2007–2008.

During the months of February to March 2000, a combination of torrential rains and tropical cyclones caused the most devastating floods in the history of Mozambique killing 700 people and producing damages worth USD 600 million (Kundzewicz et al., 2002; McBean and Henstra, 2003). Floods in Mozambique are caused not only by rainfall in Mozambique but also by water discharge from dams in neighbouring countries situated upstream, demonstrating the regional co-dependencies.

City context and sensitivity to climate risks

Agriculture is the main economic activity of the country, especially in rural areas, and is exposed to weather-induced risks such as floods and droughts. Most Mozambicans rely on rain-fed agriculture for their food production needs meaning that information on growing season climate characteristics is particularly important. Cash crops (e.g. cashew, coconut and mango trees) also provide a source of income to people in Maputo, each of which have different climate sensitivities.

Maputo's economy is centred on the harbour, with obvious sensitivities to sea level rise and coastal flooding. The city's three islands located a few kilometres from the coast show clear evidence of climate change impacts, which include the disappearance of mangroves, degradation of water quality in wells, desertification, erosion of sand dunes, worsening wind erosion, loss of coastline and reduction of arable land for domestic agriculture (Broto et al., 2013).

The city is highly sensitive to rainfall in the Limpopo river basin. Water in the basin is a shared resource between three countries, and streamflow in the Mozambiquan section is of direct importance to the water security of Maputo. Different mechanisms (e.g. ENSO) can influence rainfall variability in the Limpopo basin. Understanding the influence of both present-day and future forcing on rainfall variability in the basin will help to inform decisions related to water security in the region. In addition, rainfall variability in northern Mozambique can have an impact on subsistence agriculture (the maize crop in particular) in rural Mozambique and there are implications for rural-urban migration to Maputo. Water supply for the city is primarily obtained from the Umbeluzi River and stored in the Pequenos Libombos reservoir. In wet years Pequenos Libombos might supply ample water, however, supply is greatly reduced during two- or three-year drought series (ICLEI Africa, 2011).

16% of the administrative area, excluding the districts of Katembe and Inhaca, is prone to flooding as a result of heavy rainfall and sea level rise. This has implications for considering coastal and rainfall induced flooding risks simultaneously. Floods in the city may also cause contamination of shallow aquifers, due to pit latrines being flooded or latrines overflowing, with implications for disease spread and health risks.

Mozambique is an energy-rich country. It has gas and coal reserves, hydropower potential on 39 rivers (including the Zambezi, the fifth largest river basin in the world), and a wealth of unexploited biomass, solar and wind resources (ICLEI Africa, 2011). Mozambique is in the difficult position of having to export electricity from Cahora Bassa via the South African Eskom transmission system, and re-import it for use in the south and Maputo, presenting interesting energy challenges and co-dependencies for transmission with the associated climate sensitivities. The most significant industry in Maputo is the Mozal aluminium smelter, which primarily exports aluminium to other countries, and it is highly energy intensive, with implications for energy security and demand.

The Mozambican Government considers disaster risk reduction as an important component of climate change adaptation. Its policy is based on the premise that by 2100, temperatures have increased between 5 and 6°C, resulting in severe droughts, cyclones and floods (INGC, 2009). The city is also planning for preventing and combating uncontrolled bush fires, a key risk in some areas.

The Master Plan for Prevention and Mitigation of Natural Disasters includes disaster risk mapping for planning and monitoring purpose, which therefore is a key source of climate risk information for planning. Phase 1 of the Pilot Programme for Climate Resilience (PPCR) (2010) includes an in-depth assessment on the potential climate change impacts in Mozambique for the next 50 years, which is currently under preparation. The Urban Master Plan of Maputo Municipality (PEUMM) has identified sensitive areas of Maputo City which are vulnerable to extreme events related to climate change and provides guidelines for future urban development interventions.

Key climate risks facing the city

- **Tropical cyclones:** Changes in the frequency, intensity, tracks and rainfall associated with landfalling tropical cyclones
- **Rainfall variability and change:** Variability in mean and extreme rainfall, both within the city and in surrounding regions which directly affect the city (e.g. flooding associated with high streamflow) or indirectly affect the city (e.g. rainfall supporting agriculture for food supply to the city)
- **Temperature increases:** Increasing temperatures and the implications for different sectors (e.g. food production, heat stress impacts of health)
- **Sea-level rise and coastal erosion:** rising sea levels must be analysed within the context of population displacements and enhanced urbanisation

- **Contaminated and decreased water resources**
- **Loss of biodiversity, ecosystems, natural and marine resources**

3.2 Windhoek

Weather and climate context

Namibia (and Windhoek) receives rainfall in the summer, from November to March, associated with the seasonal migration of the ITCZ. Key drivers of seasonal and annual variability include ENSO and its interactions with the Angola Low, as well as the other large scale modes of variability (e.g. southern annular mode) and influences from the south Atlantic Ocean. There is a teleconnection between ENSO and rainfall over eastern and northern Namibia (influencing Windhoek water security) and questions regarding the stability of this teleconnection under climate change.

Future temperature increases will impact livestock and crop yields in Namibia, including the Windhoek region. The physical processes relevant here are those responsible for the relatively high rate of temperature increase that are observed over the western parts of southern Africa, including Namibia and Windhoek. Current theory (e.g. Engelbrecht et al. 2009 and Engelbrecht et al. 2015) relates observed rapidly increasing regional temperatures to an intensification of the regional Hadley circulation, and increases in the frequency of occurrence and intensity of mid-level high-pressure systems over subtropical southern Africa.

City context and sensitivity to climate risks

Windhoek faces significant challenges in terms of clean water access as it is located far from any perennial water sources and has low levels of rainfall each year for the replenishment of the water supply (Cashman et al., 2014). The main sources of water supply to the central area of Windhoek include surface water obtained from the Von Bach, Swakoppoort and Omatako dams, groundwater abstracted from 50 municipal production boreholes, and reclaimed water from processing sewage. Turpie et al. (2010) states that the dams supplying water to Windhoek all fall into the area worst affected by reduced surface water, linked to climatic changes. Understanding local scale processes and climate sensitivities if therefore important for long-term water resource planning in the context of climate change.

The country is dependent on the seasonal rains for rain-fed agriculture and the recharging of dams and aquifers. Understanding short-term rainfall variability is therefore important for managing water demand and supply. Development and climate change induced changes to water availability in dams, aquifers and along the Orange River pose significant challenges to water security. Moreover, as temperatures in Namibia increase as a result of global warming, increased evaporation will reduce surface water availability affecting the supply of fresh water. At the same time ongoing development, growth in consumption and an expected increase in irrigation projects will increase water demand. Understanding the spatial differences in observed and projected temperature changes, and how this relates to rates of evaporation, is therefore important for climate change adaptation.

Flood and drought events cause significant damage to infrastructure and impact agriculture; floods and droughts are expected to increase in frequency and intensity in the coming decades. Sea level rise threatens coastal towns such as Walvis Bay and impacts on coastal towns may have indirect impacts on Windhoek.

Namibia is heavily dependent on natural resources, and particularly relies on mining to support its economy; mining activities are dependent on sufficient water supply. Windhoek uses energy from coal-fired and hydroelectric plants, both of which have climate sensitivities. Overall, Namibia has an energy deficit and must import energy from South Africa, implying the need to consider remote climate risks. Whilst the government's goal is to reduce dependence on imported energy, there are no stated objectives to increase renewable sources of energy. However, there is likely to be a growing demand for renewables implying the need to understand the influence of climate variability and change on wind potential and solar irradiance.

Pendleton et al. (2012) found that there is widespread food insecurity in the informal areas of Windhoek, where only 8% are food secure and 50% of households are severely food insecure. Reasons include the lack of adequate food storage and basic services. Namibia also imports food from South Africa, again implying remote climate risks. Initiatives to decrease vulnerability to climate change include conservation agriculture, which aims to increase the productivity of subsistence farmers (National Planning Commission, 2012).

Key climate risks facing the city

- **Increasing temperatures and evaporation:** this will affect available surface water availability both in the city and in surrounding regions affecting agriculture and water supply
- **Rainfall variability and change:** changes in mean rainfall will affect the water supply from dams and aquifers, and changes in extreme rainfall leading to altered flooding and drought risks facing the city and surrounding region
- **Changes in wind and solar insolation:** any changes could have positive or negative impacts on the burgeoning renewables sector

3.3 Lusaka

Weather and climate context

Seasonal rainfall is driven by the southward migration of the ITCZ (Nov to March). The interannual variability in rainfall in Zambia is linked to ENSO, and southern Zambia (including Lusaka) typically experiences drier conditions in an El Nino year and wetter conditions in a La Nina year.

Current theory (e.g. Engelbrecht et al. 2009 and Engelbrecht et al. 2015) relates rapidly increasing regional temperatures to an intensification of the regional Hadley circulation, and increases in the frequency of occurrence and intensity of mid-level high-pressure systems over subtropical southern Africa.

City context and sensitivity to climate risks

Future temperature increases will impact livestock and crop yields in Zambia including the Lusaka region. This may well be a key issue for Lusaka – if rapidly rising surface temperatures (likely occurring in association with enhanced evaporation and decreased soil moisture) and more heat-wave days are to impact on maize production in rural Zambia, urbanisation may be a consequence. The physical processes relevant here are those responsible for the relatively high rate of temperature increase that is observed over the western parts of southern Africa, including parts of Zambia.

Mega-fires in a warmer regional world – and their frequency of outbreak under climate change – is a key issue for Zambia, and it links to the further question around tree-grass interactions in the African savannah. CO2 fertilization will plausibly favour trees over grasses in the Zambian savannah, leading to bush encroachment – potentially a negative impact in terms of grazing potential and the inputs required to harness agricultural land. On the other hand, more frequent fires will favour grasses, potentially limiting bush encroachment, but with potentially negative impacts on livestock production and agriculture. However, a large percentage of fires are human-induced, and this frequency can be reduced.

Severe flooding has been identified as the single most challenging weather hazard facing the City (Simatele, 2010). The flooding events are primarily linked to high rainfall events in the rainy season.

The Lusaka Water and Sewerage Company (LWSC) supplies potable water to the city. Demand currently outsrtips supply, exacerbated by losses (estimated to be 46%) due to leakages, bursting of old pipes, illegal water connections and vandalism (ICLEI Africa, 2013). Approximately 43% of the city's drinkable water comes from the Kafue River (ICLEI Africa, 2013). Water from the Kafue River is increasingly in demand, with commercial plantations using large quantities for irrigation. For example, a major user is the Nakambala Sugar Estate (Zambia Sugar Plc), one of the largest companies in Zambia employing 2,000 permanent staff and over 4,000 seasonal staff. According to its 2015 annual report, in the last financial year it generated approximately $365M, which is 2% of the national GDP. The company uses approximately 0.657 km^3 of water per year to harvest the sugarcane crop, which is equivalent to 6.5% of the total river flow into the Zambezi. Changes to rainfall and evaporation in the Kafue basin could therefore have major implications for water supply to Lusaka and the surrounding region, the commercial plantations in the region, and the ecosystems which depend on the river. Water supply from LWSC is also impacted by flooding events with can cause contamination of water when pit latrines overflow, increasing the likelihood of diseases spreading through high-density urban areas, and cause damage to the pipe network.

The city's most important source of revenue (50%) comes from property rates. Direct and indirect climate impacts on property rates is therefore of interest to city planners. The precise climate sensitivities, drivers and processes that may be relevant for Lusaka would require more investigation.

Lusaka is a transport hub for Zambia with four main roads into/out of Lusaka. High volume road transport in Zambia is vulnerable to climate hazards and damage to the major arterial roads could significantly impact the economy. Short term impacts include flooding events making roads impassable and affecting road construction/improvement projects. Long-term impacts include ongoing (and potentially) increased maintenance to deal with deteriorating roads from surface water (again linked to seasonal rains) and cracking/melting due to heat extremes, which are most likely to occur in advance of the rainy season (September to November) and appear very likely to increase in the future.

Construction is a key industry in the city, especially with many new major private sector retail, business and residential developments, though poorer areas of the city are seeing lower levels of private investment. Climate impacts on the construction industry include direct impacts on operations - e.g. extreme weather events delaying construction - as well as indirect impacts on the availability and costs of labour, construction materials and other supply chains. The precise climate sensitivities, drivers and processes that may be relevant for Lusaka would require more investigation.

Malaria risk is not prominent in affluent areas of the city but where stagnant water is able to build up, typically in informal settlements after heavy rain events, malaria remains prevalent and is a major challenge for the city. Warmer temperatures during the cold season could result in higher survival rates for Anopheles mosquitoes, so an increase in winter temperatures (May to August), particularly night-time lows, could increase the prevalence of malaria. However, rainfall and evaporation remain the most important factors as they directly influence the amount of stagnant water. The balance between potential changes in rainfall, evaporation and winter temperatures, in addition to the non-climatic factors (e.g. better drainage) will be key for understanding future changes to malaria risk in the city and surrounding region.

In urban areas, 60.4% of households depend on wood fuel, mostly charcoal, for energy to cook. Lusaka Province has the highest use of electricity for cooking, at 40.2 % (Central Statistical Office, 2007). Therefore, climate impacts on the availability of wood fuel as well as electricity generation and transmission will have consequences for city residents.

Key climate risks facing the city

- **Flooding:** this has been highlighted as a major issue for the city, particularly as Lusaka is a major transport hub
- **Increasing temperatures and evaporation:** changes to the temperatures will have multiple impacts across a range of sectors, from energy to agriculture

- **Rainfall variability and change:** changes to mean and extreme rainfall will have impacts on water supply and agriculture in the city and surrounding region
- **Wildfire:** current risks will likely be exacerbated by rising temperatures and potential changes to rainfall
- **Malaria prevalence:** a number of climate variables are relevant, including rainfall and evaporation, but primarily increasing night-time temperatures.

4. Linking Top-down and Bottom-up Perspectives

In connecting the top-down and bottom-up perspectives, it is possible to determine which processes and process chains are relevant to each city, given the climate risks that each city faces. Table 5 attempts to relate the processes identified and described in section 3 to the key climate risks identified in section 4 – the table is not exhaustive.

	Wildfire	Flooding	Drought	Water Availability	Growing Season Length	Heat Stress	Wind Damage	Sea Level Rise
ENSO								
ITCZ migration								
Regional Hadley Circulation								
IOD								
TTTs								
Angola low								
MCCs								
Frontal systems								
Tropical cyclones								

Table 5: Subjective summary of relationships between climate processes (rows) and climate risks (columns) for the three Tier 1 cities. For each climate process-risk combination the cell is divided into five sub-columns: Column 1 (left) = Lusaka, Colum 2 (left centre) = Maputo, Column 3 (centre) = Windhoek. The depth of the colour is proportional to the relevance of the process-risk combination, white indicating no relevance (or physical connection) and dark red indicating a strong relevance.

The challenges presented for ongoing research in the climate information cluster include: 1) how to categorise and include smaller scale local climate processes and feedbacks; 2) how to articulate process chains and relate them to the risks or climate outcomes in each of the focus cities; and 3) what kind of understanding is required to inform the co-production of decision-relevant climate information to address the burning issues identified in each city? For example, focusing on flooding in Lusaka, how does ENSO, the ITCZ, the Regional Hadley Circulation and the IOD relate to more local climate-related processes in Lusaka, how can the concept of a process chain be articulated to relate flooding and climate processes in the context, and how can of knowledge on such relationships is needed to improve flood-related adaptation decisions?

5. Conclusions and next steps

FRACTAL aims to advance the understanding of the regional climate system in southern Africa and improve methods for analysing climate data to deal with uncertainties. At the same time, the climate information cluster is responding to the needs of the urban decision-making context and communities responding to risks associated with climate variability and change. It has therefore been necessary to articulate a common framework to guide research activities to ensure that the science remains coherent while attempting novel approaches. This framework document provides a basis for undertaking needs-informed research activities in the climate information cluster to address the aims of the project and specifically objective 1 stated in the introduction.

Through presenting “top-down” and “bottom-up” characterisations of climate processes, this framework provides a starting point to pursue needs-informed research. Focusing on processes and process chains, and combining scientific approaches with information about city-specific risks, the framework can be used to anchor research taken by different institutions in the climate information cluster. Ultimately this framework will inform the development of approaches and metrics to undertake model assessment. It is plausible that studying the processes identified, and assessing the ability of climate models to capture the process chains, will be of direct value to the different cities in terms of understanding uncertainties and guiding decision making.

Next steps

Subsequent research activities should focus on the following areas:

- Articulate different examples of process chains in southern Africa, focusing on specific climate outcomes of interest to the cities and drawing on current understanding of climate processes and interactions across spatial and temporal scales
- Strengthen understanding and quantification of the reliability of different observational datasets for analysing historical climate processes, process chains, and how they may have responded to climate change
- Design a suite of possible experiments using different models and downscaling methods to examine key processes and process chains to advance understanding of process (chain) change under future climate scenarios
- Review literature to complete the tables in the top-down perspective of climate processes and thus identify the key knowledge gaps for further targeted research
- Learn from the city learning labs to determine which climate risks identified in the bottom-up approach are most critical from a development and adaptation perspective

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