ORASECOM Document No. 008/2011

SUPPORT TO PHASE 2 OF THE ORASECOM BASIN-WIDE
INTEGRATED WATER RESOURCES MANAGEMENT PLAN
Work Package 4:
Climate Change in the Orange-Senqu River Basin

GCC Downscaling for the Orange-Senqu River Basin

February 2011

ORASECOM

The *Support to Phase 2 of the ORASECOM Basin-wide Integrated Water Resources Management Plan* Study was commissioned by the Secretariat of the Orange-Senqu River Basin Commission (ORASECOM) with technical and financial support from the German Federal Ministry for Economic Cooperation and Development (BMZ) in delegated cooperation with the UK Department for International Development (DFID) and the Australian Agency for International Development (AusAID). The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) implemented the study.

giz | On behalf of Federal Republic of Germany The Federal Government | UKaid from the Department for International Development | Australian AID

Prepared by

wrp A Miya Group Company in association with DMM, Golder Associates, PTK, RAMBØLL, WCE

SUPPORT TO PHASE 2 OF THE ORASECOM BASIN-WIDE INTEGRATED WATER RESOURCES MANAGEMENT PLAN

Work Package 4:

Climate Change in the Orange-Senqu River Basin

GCC Downscaling for the Orange-Senqu River Basin

ORASECOM Document No.	008/2011
Date of Publication:	February 2011
Authors:	Friedrich Wilhelm Gerstengarbe
	Julia Lutz
	Jan Volkholz
Status:	Final Report

APPROVALS

For the Consultants: ______________________________

RS MCKENZIE
Managing Director: WRP Consulting Engineers

For ORASECOM: ______________________________

L THAMAE
Executive Secretary: ORASECOM Secretariat

Study Name	**Support to Phase 2 of the ORASECOM Basin-wide Integrated Water resources Management Plan**
Report Title:	***GCC Downscaling for the Orange-Senqu River Basin***
Submitted by:	WRP Consulting Engineers in association with Golder Associates, DMM, PIK, RAMBOLL and WCE

REPORTS, WPS AND OTHER DELIVERABLES SUBMITTED	**TYPE**	**No.**
Overall Study		
Inception Report	Report	004/2010
Overall Project Executive Summary	Report	013/2011
Work Package 1: WATER RESOURCES MODELLING OF THE ORANGE-SENQU BASIN		
Strengths and Weaknesses of Existing Models	WP	005/2010
Setting up and Testing of the Final Extended and Expanded Models; Changes in Catchment Yields and Review of Water Balance	Report & WP	001/2011
Modelling software and datasets	Software	None
Capacity Building and Setting up the Models in each Country; Process of Continuous Review	WP	003/2011
Work Package 2: EXTENSION AND EXPANSION OF HYDROLOGY OF ORANGE-SENQU BASIN		
Improvements to Gauging Network and Review of Existing Data Acquisition Systems	WP	005/2011
Extension of Hydrological Records	Report	006/2011
Hydrological Database	Database	None
Work Package 3: INTEGRATED WATER RESOURCES QUALITY MANAGEMENT PLAN		
Development of Water Quality Monitoring programme and Data Management Framework	Report	007/2011
Development of Specifications for the Water Quality Model	WP	006/2010
Work Package 4: CLIMATE CHANGE IN THE ORANGE-SENQU RIVER BASIN		
Downscaling Methodology and Ongoing Climate Modelling Initiatives	WP	007/2010
GCC Downscaling for the Orange-Senqu River Basin	***Report***	***008/2011***
Projection of impacts and Guidelines on Climate Change Adaptation Strategies	WP	009/2011
Work Package 5: ASSESSMENT OF ENVIORNMENTAL FLOW REQUIREMENTS		
Literature survey and Gap Analysis	WP	008/2010
Delineation of Management Resource Units	WP	009/2010
Desktop Eco Classification Assessment	Report	016/2010
Goods and Services Report	WP	010/2010
Environmental Flow Requirements	Report	010/2011
Work Package 6: WATER CONSERVATION AND WATER DEMAND IN THE IRRIGATION SECTOR		
The Promotion of WC WDM in the Irrigation Sector	Report	011/2011
Irrigation GIS Database, Interactive Database and Irrigation Scenario Tools	WP	012/2011
Irrigation GIS Database and Interactive Classification Tool	Software	None
Irrigation Scenario Generation Tool	Software	None

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 General

The Orange - Senqu River basin as shown in **Figure 1** originates in the highlands of Lesotho some 3 300m above mean sea level, and it runs for over 2 300km to its mouth on the Atlantic Ocean. The river system is one of the largest river basins in southern Africa with a total catchment area of more than 850,000km^2 and includes the whole of Lesotho as well as portions of Botswana, Namibia and South Africa. The natural mean annual runoff generated within the basin is estimated to be in the order of 11 900 million m^3 based on the 1920 to 2004 period of record. The flow reaching the Orange river mouth has been significantly reduced by extensive water utilization for domestic, industrial and agricultural purposes as well as several major interbasin transfers , both into and out of the Orange/Senqu basin. Based on the most recent assessments, the average annual flow reaching the Orange River mouth is estimated to be approximately 3 700 million m^3 which comprises the environmental requirements of the river mouth as well as the intermittent floods.

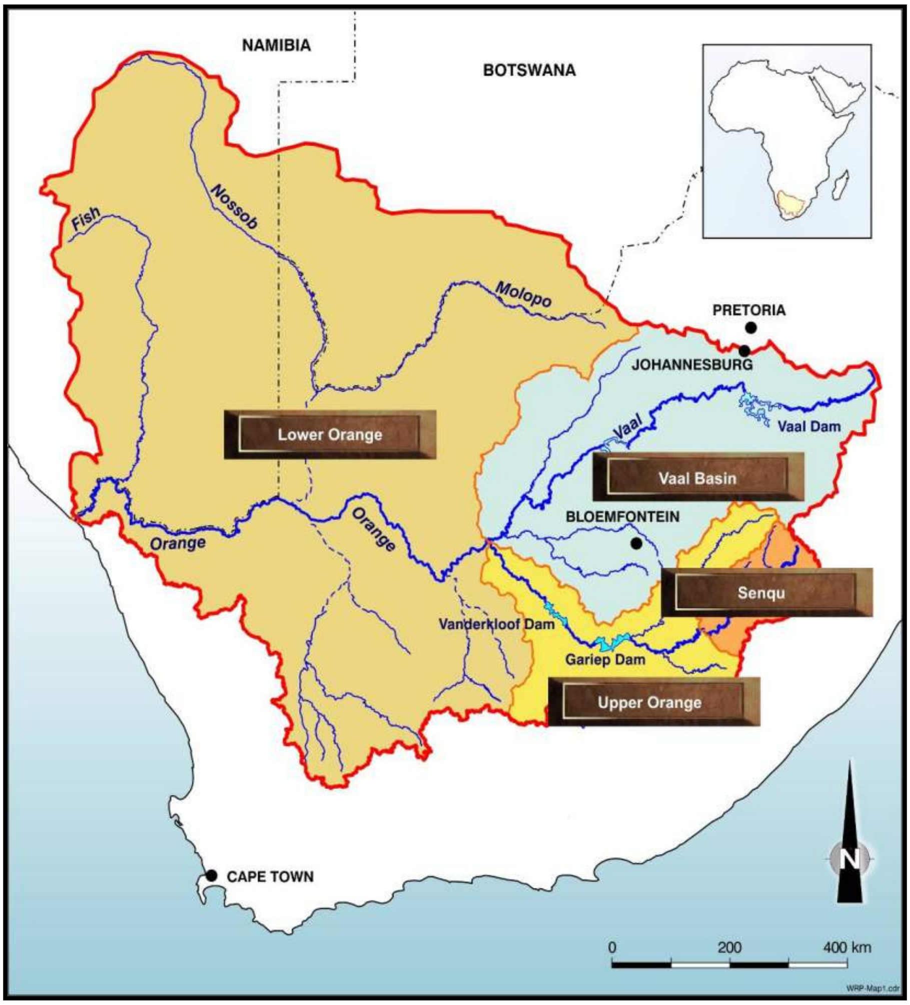

Figure 1: Orange-Senqu River Basin

The Orange-Senqu system is regulated by more than thirty-one major dams with several hundred smaller dams being used to support local demand centres, It is therefore a highly complex and integrated water resource system with numerous large inter and intra-basin transfers. It is one of the most complicated and integrated river basins in the world and is operated using highly sophisticated system models which have been developed over a period of more than 25 years.

1.2 Management and Environmental Issues

1.2.1 General

Management issues, including environmental protection, conservation and sustainable development have to deal with problems relating to, both, water quantity and quality. Potential conflicts between users, pollution sources from industry, mining, agriculture, watershed management practices must all be managed in order to protect ecologically fragile areas. The riparian countries have for some time recognized that a basin-wide integrated approach has to be applied in order to find sustainable solutions to these problems and that this approach must be anchored through strong political will. The development of this strong political will is one of the key initiatives of SADC, in particular the Revised Protocol on Shared Watercourses and the establishment of the Orange-Senqu River Basin Commission (ORASECOM). These initiatives are intended to facilitate the implementation of the complicated principles of equitable and beneficial uses of a shared watercourse system. It is accepted by all countries that the management of water resources should be carried out on a basin-wide scale with the full participation of all affected parties within the river basin.

Water supply in terms both of quantity and quality for basic human needs is being outstripped by the demands within and outside of the basin. Meeting the water supply needs of rapidly growing towns and cities while supplying sufficient water of an acceptable quality to meet existing and proposed future demands is therefore a key challenge for planners and stakeholders in the Orange-Senqu river basin.

1.2.2 ORASECOM

Southern Africa has fifteen trans-boundary watercourse systems including the Orange–Senqu system. The Southern African Development Community (SADC) has adopted the principle of basin–wide management of the water resources for sustainable and integrated water resources development. In this regard, the region recognizes the United Nations Convention on the Law of Non-navigational Uses of International Watercourses, and has adopted the “Revised Protocol on Shared Watercourse Systems in the SADC Region”. Under this Revised Protocol, a further positive step has been the establishment of river basin commissions in order to enhance the objectives of integrated water resources development and management in the region, while also strengthening the bilateral and multilateral arrangements that have been in existence for some time. The Orange–Senqu River Basin Commission (ORASECOM) was established on 3 November, 2000 in Windhoek, Namibia and is a legal entity in its own right.

The highest body of the ORASECOM is the Council consisting of three permanent members, including one leader, for each delegation from the four riparian states. Support from advisors and ad hoc working groups can be established by the council when required. The main task of the Council is to "serve as technical advisor to the Parties on matters relating to the development, utilization and conservation of the water resources in the River System". The council can also perform other functions pertaining to the development and utilization of water resources as directed by the partiers.

1.3 Context of the Study and this Progress Report

1.3.1 GIZ Support to SADC and ORASECOM

The overall goal of the GIZ-supported 'Transboundary Water Management in SADC' programme is to strengthen the human, institutional, and organisational capacities for sustainable management of shared water resources in accordance with SADC's Regional Strategic Action Plan (RSAP). The programme, which GIZ implements on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), and in delegated cooperation with the UK Department for International Development (DFID) and the Australian Agency for International Development (AusAID), consists of the following components:

- Capacity development of the SADC Water Division
- Capacity development of the river basin organisations (RBO) and
- Capacity development of local water governance and transboundary infrastructure.

The activities of this Consultancy, "Support to Phase II of the ORASECOM Basin-wide Integrated Water Resources Management Plan", being undertaken by WRP (Pty) Ltd and Associates, contributes to Component 2 above. The work of Phase 2 comprises six work packages as briefly outlined in **Section** 1.3.2.

1.3.2 Support to Phase 2 of the ORASECOM Basin-wide Integrated Water Resources Management Plan

1.3.2.1 Objectives of the Overall Consultancy

The main objectives of this consultancy were to enlarge and improve the existing models for the Orange-Senqu Basin, so that they incorporated all of the essential components in the four Basin States and are accepted by each Basin State. These models must be capable of providing the current and likely future information needs of ORASECOM. This will involve being able to assess the implications of additional water resource development options to achieve water security in each Basin State – including possible changes to operating rules for water supply and storage infrastructure. This will ensure that ORASECOM is able to demonstrate that its operations are aligned with the principles embodied in the SADC Water Protocol.

1.3.2.2 The Six Work Packages

In order to achieve the above-mentioned objectives, the project included six work packages as outlined in **Table 1-1**. The first of these work packages can be considered as central to Phase 2 of the IWRM Plan and will also be required to develop the final plan in Phase 3 of the project. In Work Package 1, the water resources simulation model (WRYM) was updated and expanded to cover the entire basin for the first time.

Table 1-1 Summary of Work Package Objectives and Main Activities

Work Package	Main Objectives	Main Activities
WP 1: Development of Integrated Orange-Senqu River Basin Model	To enlarge and improve existing models so that they incorporate all essential components in all four States and are accepted by each State	• Extension and expansion of existing models • Capacity building for experts and decision-makers • Review of water balance and yields • Design/initiation of continuous review process
WP 2: Updating and Extension of Orange-Senqu Hydrology	Updating of hydrological data, hands-on capacity building in each basin state for generation of reliable hydrological data including the evaluation of national databases,	• Assessment of Required Improvements to the Existing Gauging Networks. • Capacity Development • Extension of Naturalized Flow Data • Review of Existing Data Acquisition Systems, proposals on basin-wide data acquisition and display system.
WP 3: Preparation and development of integrated water resources quality management plan	Build on Phase 1 initial assessment to propose water quality management plan, based on monitoring of agreed water quality variables at selected key points	• Establishment of protocols, institutional requirements for a water quality monitoring programme, data management and reporting. • Development of specifications for a water quality model that interfaces with the systems models. • Capacity building to operate the water quality monitoring system and implement the water quality management plan.
WP 4: Assessment of global climate change	Several objectives leading to assessment of adaptation needs	• Identification of all possible sources of reliable climate data and Global Climate Model downscaling for the Orange-Senqu Basin • Scenario assessment of impacts on soil erosion, evapotranspiration, soil erosion, and livelihoods • Identification of water management adaptation requirements with respect to expected impacts on water resources • Assessment of major vulnerabilities and identification of measures for enhancing adaptive capacities
WP 5: Assessment of Environmental Requirements	Several objectives leading to management and monitoring system responsive to environmental flow allocations	• A scoping level assessment of ecological and socio-cultural condition and importance • Delineation into Management Resource Units and selection of EFR sites. • One biophysical survey to collate the relevant data at each EFR site and two measurements at low and high flows for calibration. • Assessment of the Present Ecological State and other scenarios • Assessment of flow requirements, Goods and Services, and monitoring aspects.

Work Package	Main Objectives	Main Activities
WP 6: Water Demand management in irrigation sector	To arrive at recommendations on best management practices in irrigation sector and enhanced productive use of water	• Establish a standard methodology for collecting data on irrigation water applied to crops, water use by crops and crop yields; • Document best management practices for irrigation in the basin and finalise representative, best-practice demonstration sites through stakeholder consultation • Consider and assess various instruments that support water conservation/water demand management.

The other work packages are both self-standing and intended to provide inputs to an improved and more complete water resources simulation model for the whole basin. The model will be enhanced by:

- a more complete hydrology (WP2),
- better and more complete water quality information (WP3),
- allowance for climate change impacts and adaptation (WP4),
- inclusion of environmental flow requirements at key points (WP5) and
- modelling of scenarios with improved water demand management in the key irrigation sector (WP6).

1.3.3 Background to Work Package 4 and this Working Paper

1.3.3.1 Work Package Objectives

The Overall objective of Work package 4 is to carry out a detailed assessment of the occurrence, extent and possible effects of climate change in the Orange-Senqu River basin. Sub-objectives include:

- detection of statistically significant change in the climate;
- assessment of to which extent the detected climate change is consistent with the predicted climate change;
- if there is an inconsistency, identification of physically plausible explanations of the detected climate change; and
- assessment of major adaptation needs in terms of water resource management, communities and economic activities, with a view to countering observed and/or expected impacts of climate variability and change on the hydro-climatology and water resources.

1.3.3.2 This Working Paper

This working paper reports back on the major activity undertaken under Work Package 4, namely the Regional Downscaling work.

1.3.3.3 General Aim

In this study, the intention was to downscale the results of global climate simulations according to the SRES A1B emission scenario for the Orange River basin in Southern Africa. The downscaling was carried out by two complementary approaches: One uses the dynamical regional climate model CCLM, whereas second model (STAR II) uses a statistical method.

With this study we aim to provide the scientific-technical basis for planning sustainable water quantity management in the basin.

2 SCENARIO DEVELOPMENT

2.1 Objectives

Different scenarios of global change have been developed in the SRES by the IPCC (see Section 5).

Scenario development distinguishes between contrasting futures: some emphasise economic growth, some give higher initial priority to sustainable development and others distinguish between a globalised and a regionalised world. Here we use the A1B scenario which assumes a globalised world emphasising economic growth.

2.2 Methodological approach

2.2.1 Climate change scenarios

Climate projections with STAR II are based on historical weather records available for the region and on data from the PIK-dataset. CCLM, on the other hand, uses the results of a global circulation model (ECHAM5). The statistical method uses the regional temperature trend supplied by global circulation models (GCMs), and derives changes in other climate variables from patterns between temperature and associated variables recorded in the past. The statistical method was developed and successfully tested within the framework of the GLOWA-Elbe Project.

2.2.2 Main working steps

Step I - preparation: Review and data pre-processing

- Establishing of the climate data base;
- Analysis of recent climatic changes;
- Review of relevant global change studies; and
- Compilation of the spatial data base.

Step II - exploration: Model adaptation and validation

- of the climate models STAR II and CCLM for regional conditions.

Step III - application: Model application for scenario development and regionalisation

- Calculation of climate change scenarios.

3 THE CLIMATE IN THE ORANGE RIVER BASIN

The Orange River has its spring in the Drakensberg Mountains in Lesotho, at an altitude of approximately 3000m above sea level. From here, the river flows 2200km westward to the Atlantic Ocean, passing through different climate types, such as: mountainous areas with high precipitation, dry grasslands and finally arid landscapes (cf. Köppen classification). Three factors determine the climate of Southern Africa: the topology (decreasing from east to west), the oceans and associated currents and the Inter-Tropical Convergence Zone (ITCZ), which is shifting north- and southwards during the year. The shift of the ITCZ implicates two distinct seasons: a dry season from April to September (ITCZ retreats northward) and a wet season from October to March (ITCZ moves southward). Bringing warm and humid air from the Equator to the east coast of Southern Africa, the Mozambique current causes a warm and humid climate in the eastern parts of the river catchment. Meanwhile, the cold Benguela current affects the west coast, causing a dry climate. Thus, there is a strong rainfall gradient from east to west: the mountain regions in Lesotho reach annual precipitation of up to 2000mm, whereas the region around the mouth of the river hardly reaches 50mm per annum. The temperature gradient in the interior of Southern Africa is strong as well. The daily mean temperature ranges from approximately 10℃ in the Lesotho Highlands, to more than 22℃ at the river mouth. This contrast is even more evident when looking at the extreme temperatures. The desert regions at the lower Orange River can reach very high temperatures of about 50℃, while frost days are common in the mountain region.

4 MODELS

4.1 The CCLM (COSMO Model in Climate Mode)

The “COSMO Model in Climate Mode” (CCLM) [2, 3] is a dynamical, non-hydrostatic regional climate model. Like most dynamical climate models, it is an offspring of a numerical weather prediction model. In this particular case it originated from “Lokalmodell” (LM), a model developed and used for numerical weather forecasting by “Deutscher Wetterdienst”. The successor of LM is currently called COSMO. Subsequently, a climate mode was added onto LM in order to leverage the tremendous work already put into LM for climate research. In 2005, CCLM became the official RCM of the German climate modelling community. The different development branches were eventually merged back together in the years 2007/2008, resulting in a unified weather forecast/climate simulation model. The CCLM has now been developed, maintained and used by a growing community of around 40 institutions in Europe, Asia and South America.

Dynamical regional climate modelling originated from the pioneering research such as [4, 5, and 6].

One reason for using a dynamical regional climate model (and for downscaling in general) is the ability to bridge the gap between a GCM and the scale at which climate impact research operates. Whereas a GCM typically has a resolution of more than 100km (e.g. in the IPCC AR4 the GCM resolution was at 110km), a RCM can go down to a resolution of a few tens of kilometres. Using higher resolution model allows local drivers, such as orography, to be captured, which cannot be resolved by the traditional GCMs due to their coarse resolution. Being a regional model, the area simulated by CCLM typically is at the mesoscale, i.e. several 1000km in extent. Examples of areas simulated by CCLM are shown in **Figure 2**.

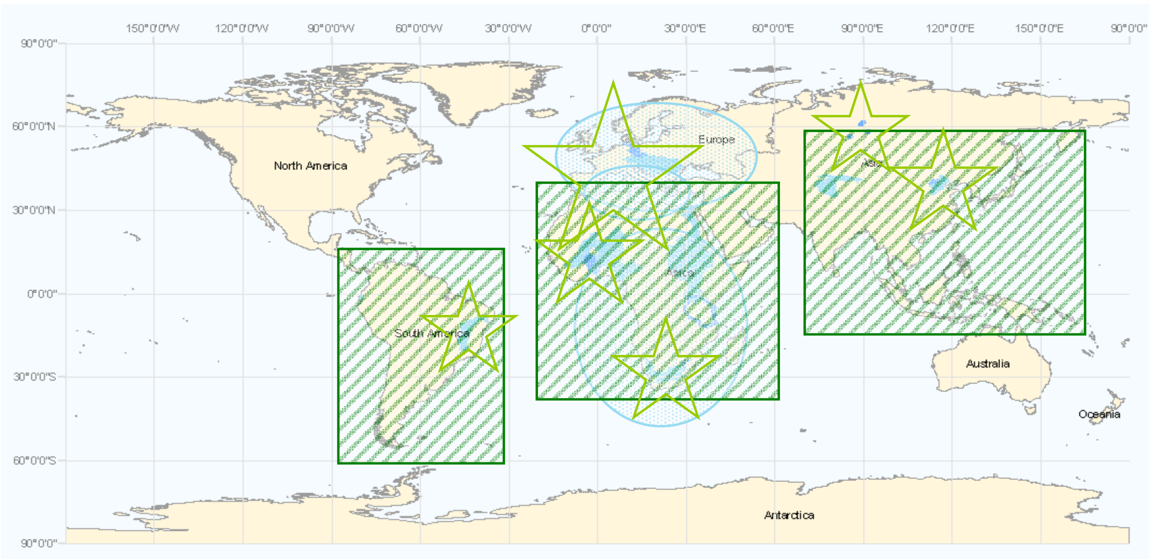

Figure 2: The areas typically simulated by a dynamical RCM. CCLM is applied to various regions such as South America, Africa or parts of Asia. The stars show where STAR II is being used

In order to have evenly-sized grid cells, CCLM uses a rotated latitude-longitude system, in which the “equator” is located in the centre of the simulation area. An example of where the “equator” is located in Europe is shown in **Figure 3**. CCLM is able to simulate time spans from a few days (weather forecasting), up to several decades. The internal time step is dependent on the spatial resolution. For instance, in the run for Africa, it was set to 225 seconds. A dynamical model implements atmospheric physics and solves the resulting differential equations. In particular, CCLM is based on the equation of motion

$$\frac{d\vec{v}}{dt} = -\nabla\Phi - 2\vec{\Omega}\times\vec{v} - \frac{1}{\rho}\nabla p - \frac{1}{\rho}\nabla\cdot T \, .$$

Where $\vec{v}$ stands for the velocity,

Φ for the geopotential,

$\vec{\Omega}$ for the angular velocity of the Earth,

ρ for the density of air,

p for the pressure and

T for the friction-stress tensor.

The equation of continuity is another key ingredient

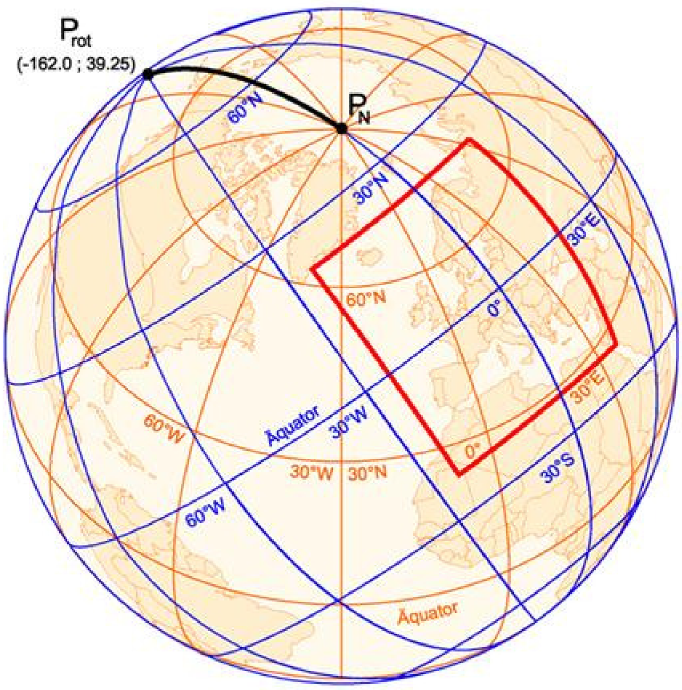

Figure 3: The rotated coordinate system of CCLM in case of a simulation over Europe. Red lines show the conventional latitude longitude system, while the blue lines depict the coordinate system used by the CCLM

$$\frac{d\rho}{dt} + \rho\nabla \cdot \vec{v} = 0$$

Furthermore, we need to take care of the balance of the individual constituents by means of the balance equation

$$\rho \frac{dq^x}{dt} = -\nabla \cdot \vec{J}^x + I^x$$
.

Where ρ signifies the density, q^x the mass fraction of the particular constituent x , and J^x and I^x describe the diffusion flux resp. stand for sources/sinks. The index x stands for dry air, water vapour, liquid water or ice. The final ingredient is conservation of energy (first law of thermodynamics)

$$\rho \frac{de}{dt} = -p\nabla \cdot \vec{v} - \nabla \cdot \left(\vec{J}_e + \vec{R}\right) + \varepsilon$$
.

ρ , t , $\vec{v}$ and p are, just like before, the density, time, velocity and the pressure.

The internal energy, the heat flux , the flux density of solar/thermal radiation and the kinetic energy dissipation due to viscosity, are denoted by the symbols $e, \vec{J}_e, \vec{R}$ and ε respectively.

With this description of the atmosphere we are able to simulate the area in question. The region to be simulated is initialised with values of a GCM, and during the simulation time the boundaries are fed with data from the GCM. Again, typical regions that are simulated are depicted in Fig 1. Every six hours data from the driving GCM is read into the spatial borders of the RCM simulation. This is a one way coupling, meaning there is no feedback from the RCM to the GCM. This shortcoming breaks energy and momentum conservation. It also means that we can never produce better climate projections than the one provided by the driving GCM.

The lower boundary of CCLM is provided by a land surface parameterisation scheme called TERRA-ML.

Unlike statistical RCMs, dynamical RCMs allow for drastic changes in the regional climate. They enable researchers to look into causal connections and into areas where no measurements are taken. However, in reproducing the regional climate, statistical RCM still outperform dynamical ones. Another drawback of dynamical RCM, when compared to their statistical counterparts, is the comparatively large computing power required.

4.2 The STAR (Statistical Analogue Re-sampling) model

The model STAR was developed in different stages over a long period of time, resulting in the version used today [7, 8]. The most recent model version is described below, but one should keep in mind that the model is under continuous development. The following model description is based on the paper by Orlowsky et al. (2007) [8].

As discussed above, the model presented here is based on the assumption that weather states from segments of a past observation period may occur again, or very similarly, during the simulation period. Hence, simulated series are constructed by re-sampling from segments of observation series, consisting of daily observations. The obvious advantage of such re-sampling, is that the resulting series consists of observations of different meteorological parameters of the same day, which are therefore physically consistent, as they were once real world observations. The same holds for the spatial fields of the meteorological variables. The idea is to constrain the re-sampling by a very simple forcing, which can be easily checked for plausibility. As the only external constraints to the simulated series at a given location, the two parameters of a regression line (mean and slope) are prescribed, in which the simulated annual means of a characteristic climate variable, at this location, have to feature. The characteristic variable is to be chosen, such that it captures the essential climate variability of the region of interest. The forcing in this case describes the long-term magnitude and the (linear) increase of the temperature, over a defined simulation period.

Figure 4 illustrates this principle together with its external constraints: given are a time series of observations (for instance: temperature) and a regression line for the simulation period. From the observations, a simulated time series covering the simulation period is assembled using the Monte Carlo method in such a way, that the annual means feature the prescribed regression line as precisely as possible. The black line represents the temperature series from observation period. The prescribed temperature trend for the simulation period is shown in red. The green line represents the simulated temperature series of which the annual means (green dots) are used to produce the green regression line.

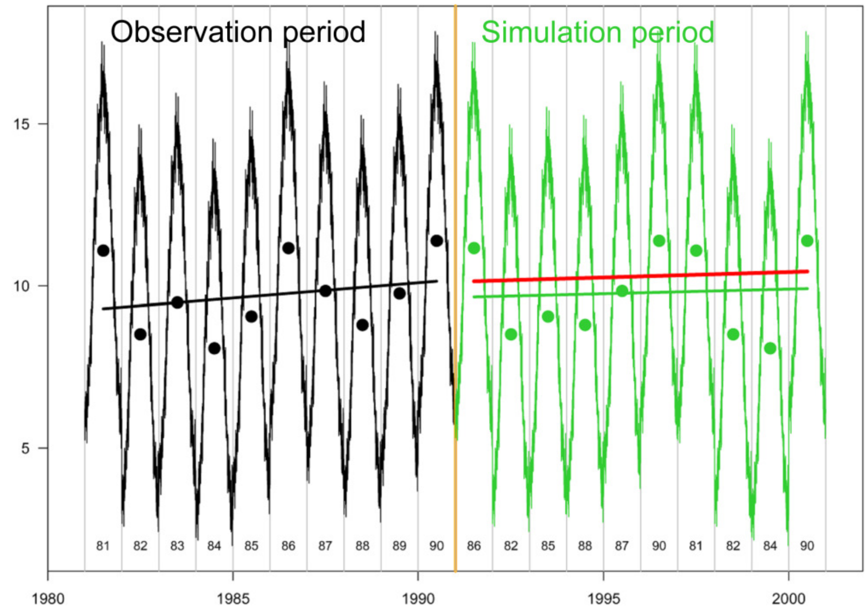

Figure 4: Generating simulated series from segments of observed series.

This kind of forcing does not, of course, completely determine the simulated series. Therefore, a set of heuristic rules for the re-sampling are defined which ensure that the resulting series exhibit realistic properties, such as annual cycles and persistence. Stochastic elements in the re-sampling procedure make every simulated series a realisation of the ensemble of all series compatible to the prescribed regression parameters and the set of heuristic rules. The bandwidth of this population, i.e., the range of possible climate developments under the assumption of the given linear trend of the temperature according to this approach, can be estimated by generating a large number of simulations. This ensemble makes it possible to estimate the uncertainty of the scenario calculation.

Generating a simulation can consequently be seen as a date-to-date mapping, in that each day of the simulation period is assigned a day from the observation period and its concurrent observations. It should be noted that such mapping is equivalent to obtaining simulated series of all observed variables. To explain the principle, a single station version will be used. The date-to-date-mapping is constructed in two steps which operate on the time scale of years and on the shorter time scale of blocks of 12 days (R^{12}-tuple). They are, together with the preparation of the input data, illustrated in **Figure 5**.

Input

In preparation, the observational data are organised in year-wise segments and in sliding R^{12}-tuples. These blocks of the observation period are grouped into classes of similar blocks by means of a combination of hierarchical (Minimal-Variance-Distance; [9]) and nonhierarchical (k-means; [10]) cluster analysis. Each of the resulting clusters is represented by the centroid of its R^{12}-tuples.

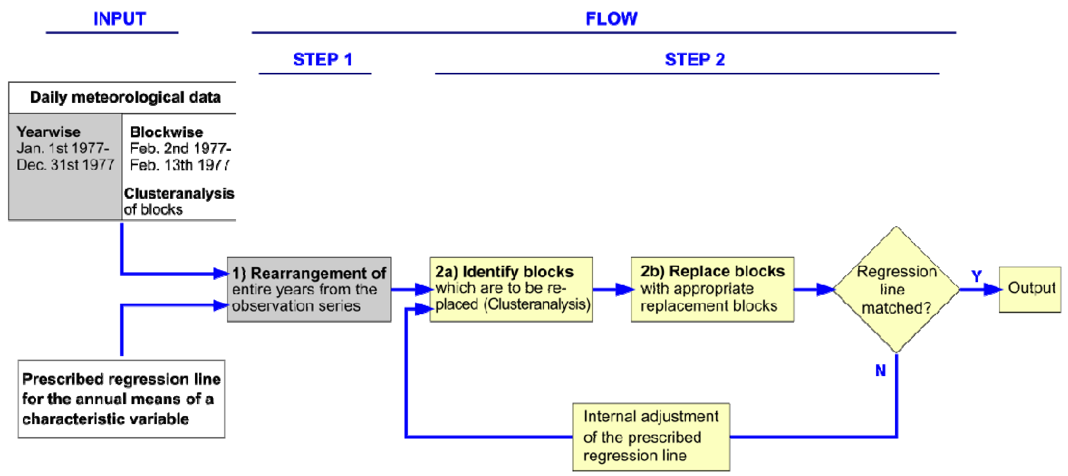

Figure 5: Summary of the generation of the date-to-date mapping

Step 1 (grey shaded in **Figure 5**) generates a simple re-arrangement of entire calendar years from the observation period, thereby producing a mapping which leaves the sequences within the years unaltered. Series generated by this 1st step are sure to exhibit realistic annual cycles and persistence. The series are generated as follows:

The observed series are cut into pieces of one year length. These pieces are randomly re-arranged and a large sample of such re-arrangements is then generated, each consisting of as many years as the simulation period. Such a re-arrangement is shown in **Figure 4**, where for the simulation period 1991–2000 years from the observation period (1981–1990) are randomly re-arranged (note the numbers at the bottom for the period 81/90 indicating the years in real order, those for the period 91/00 show the random arrangement of the observed years). From this sample, the re-arrangement closest to the prescribed regression line is chosen.

Step 2a: The first part of the second step shown in **Figure 5**, consists of identifying blocks which have to be replaced, namely those which contribute too much to the mismatch between the regression line of the series from Step 1 and the prescribed regression line. “Too much” in this context is determined as follows:

From the temperature series of Step 1, a synthetic series is generated by shifting the Step 1-series year by year such that the regression line of the resulting annual means corresponds to the prescribed trend. At this stage, two series of the characteristic variable exist. A few example years are shown in **Figure 6**, green for the series of Step 1, blue for the synthetic series. The figure also shows the annual means (dots) of the respective series. The first mean exhibits realistic annual cycles and persistence; the second, though not very different, fits the prescribed parameters exactly. The given trend is shown in red for the artificial temperature series.

Each of the consecutive 12 days-blocks is compared with respect to these two series. If a block is similar relative to both series, it is kept from the series of Step 1. For the comparison, each of the blocks is assigned the class with the closest centroid, both for the Step 1-series and the synthetic series. The assigned classes are shown in **Figure 7** by the coloured bars at the top, the lower one for the Step 1 series, the upper one for the synthetic series. If the two classes coincide, the blocks are considered to be similar. Otherwise, the block from the Step 1 series is seen as too distant from the synthetic series and therefore is considered to contribute too much to the mismatch between the regression parameters of the two series. In such a case, it is marked for replacement, illustrated in **Figure 7** by the shaded rectangles.

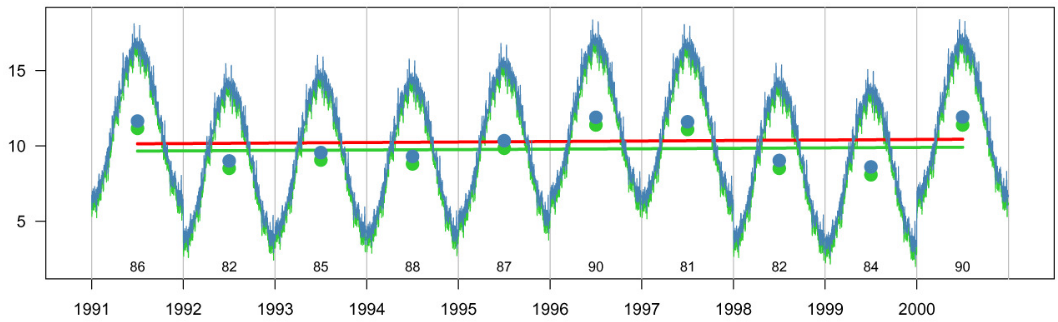

Figure 6: The first approximation (green) as produced by the new string of years.

Step 2b: Each replacing block is randomly drawn from a set reduced by applying several heuristic criteria. These criteria only allow for blocks that bring the regression line of the resulting series closer to the prescribed one, while making sure that the inserted replacement fits well into the parts of the series which have been set already. The candidate set is defined as follows:

1. Choose all blocks from the observation period which belong to the same class as the block from the synthetic series. These blocks will improve the regression line of the simulated annual means.

2. To avoid too frequent reuse of single blocks: only keep unused blocks in the selection.

3. Keep blocks of which the position within the year lies within a ±20 day window around the respective position of the block to be replaced. This ensures that only seasonally matching blocks remain in the selection.

4. Keep blocks which connect well with their already chosen predecessor and, if also already defined, their successor.

This fourth criterion identifies valid blocks by comparing the connecting blocks: that is, the second half of the predecessor together with the first half of a candidate block, to the block of the observation series that starts in the middle of the predecessor. If they both belong to the same class, then the candidate is admissible. For an already set successor, this works analogously.

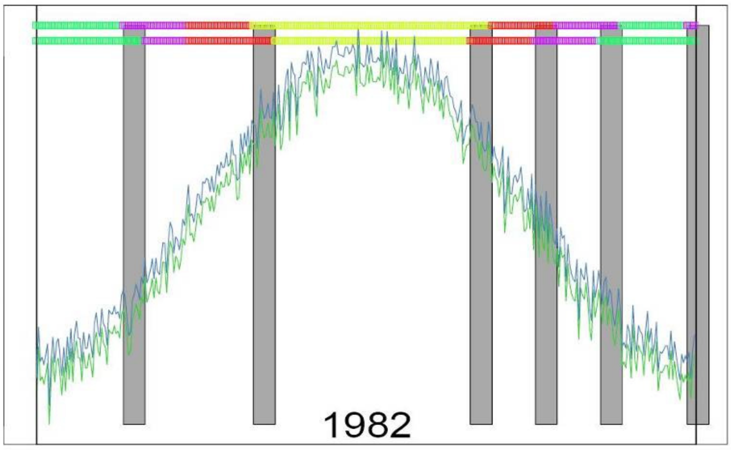

Figure 7: Comparison of the recorded and simulated temperature series

After all ‘‘blanks’’ are filled in this way, the date-to-date mapping of this iteration is fully defined.

Iteration of Step 2: Despite the replacements with blocks improving the regression line, the resulting series may still miss the prescribed parameters. If their effect turns out to be insufficient, the second step is iterated. These iterations are continued until the prescribed parameters are matched within a certain tolerance.

Both, at Step 1 and at the end of Step 2, years or blocks are drawn randomly. This allows any given simulation a stochastic realisation of the population of possible simulations, the range of which can be estimated by generating large ensembles of simulations. The ability to generate large ensembles is a very important feature, as it allows the study of extensions of possible climate developments.

Multi-station simulations

The approach is similar for multi-station simulations, except that it takes place in a parameter space of higher dimensionality. However the ultimate goal, a date-to-date-mapping, is the same. This means that the series of simulated fields consist of spatial fields that were observed during the observation period. They are spatially consistent, thereby also for problematic variables such as precipitation.

Depending on the station density in the region of interest, it can be advantageous to restrict the number of stations actually considered in the construction of the mapping. This can be a practical necessity (e.g. memory limitations), but also helps to avoid the use of redundant information in the case of stations with highly correlated series. Using parameters like mean, variance and trend estimates for precipitation and temperature from the observation series, cluster analysis can identify climatologically similar stations. Choosing for each of the resulting classes, the station which is closest to the respective centroid, a smaller set of stations is obtained, which represents the variability among the stations in a generalising way. For each of the representative stations, regression parameters are prescribed, thereby allowing for the simulation of spatially differentiated developments.

For Step 1 (the shuffled annual segments from the observation series) a large random sample of rearranged annual segments is again generated. From this sample, the realisation is chosen for which the regression lines at all of the representative stations are closest to the prescribed ones. Step 2, that is (2a), the identification of blocks to be replaced and (2b) their replacement, works analogously as for the single station case, except that blocks are now characterised by the characteristic variables of all of the representative stations instead of just one. Consequently, for each of the representative stations, a synthetic series is generated and the blocks of all of these series merged together, are compared via the classification to the blocks of the combined series from Step 1.

If several iterations are needed, the exaggerated trends for the next step are calculated as for the single station case for each representative station individually.

5 DATA AND EXPERIMENT SET-UP

5.1 CCLM

For the simulation over Africa, including the Orange River basin, we chose an area stretching from 42.25°N to 45.75°S resp. from 24.75°W to 60.25°E. The resolution was chosen to be of 0.44° × 0.44° (48km × 48km). Since the equator naturally lies within the simulated area, no rotated coordinate system was necessary. The validation run was for the period from 1971 to 2000. It was driven by an ECHAM5 run that used measured greenhouse gas (GHG) concentrations for the 20th century. The future simulation ran from 2001 to 2100. Again, it was driven by an ECHAM5 run which was based on the SRES A1B scenario [11]. For this analysis we investigated two observables: the 2m temperature and precipitation. The results were finally interpolated to a 0.5° × 0.5° resolution, which allows for easy comparison with observation (CRU) data [12].

5.2 STAR

STAR re-arranges observational station data to generate ensembles of future climate projections. Due to limited availability of station data in Africa, in this study STAR is driven with the daily PIK-dataset as discussed in **Section 5.2.1**. Climate projections from STAR are constrained by a linear temperature trend which is derived from several GCMs for the time period 2011 to 2060. **Section 5.2.2** describes the experiment set-up in more detail. The simulations are carried out for the area encompassing the Orange River basin. It contains 720 grid points with a resolution of 0.5° × 0.5°, ranging from 21°S to 33°S and from 16°E to 31°E (cf. **Figure 8**).

5.2.1 Data

For this study, a daily dataset that was produced at PIK was used. This dataset covers the years from 1958 to 2007. It is available on a regular grid with a resolution of 0.5° × 0.5°. The daily time series of the mean temperature and precipitation are used in the presented work.

Future climate projections are computed for the time period 2011-2060. The required temperature trend for this time period is derived from 22 GCMs [13] which assume the SRES A1B scenario [11]. To this end, the linear increases of the annual mean temperatures are calculated for the grid cells which embed the representative grid points. They range from 1.7K to 2.1K and are much stronger than the ones observed in the training period from 1958 to 2007 (ranging between 0.3K and 1.2K). Actually, in this case [14] the projections do not fulfil the “internal variability conservation” criterion. This criterion says that only if the temperature anomalies of the training series and the future simulated series can be seen as originating from the same distribution, then the variability of the training period data will be large enough to generate series with a given temperature trend without a statistically visible reduction of variability. In various tests Orlowsky found out that this criterion is only fulfilled when the warming in the future period continues with the same strength as in the training period [15]. Thus, the strong trend for the future time period is likely to result in a climate lying outside the training period variability.

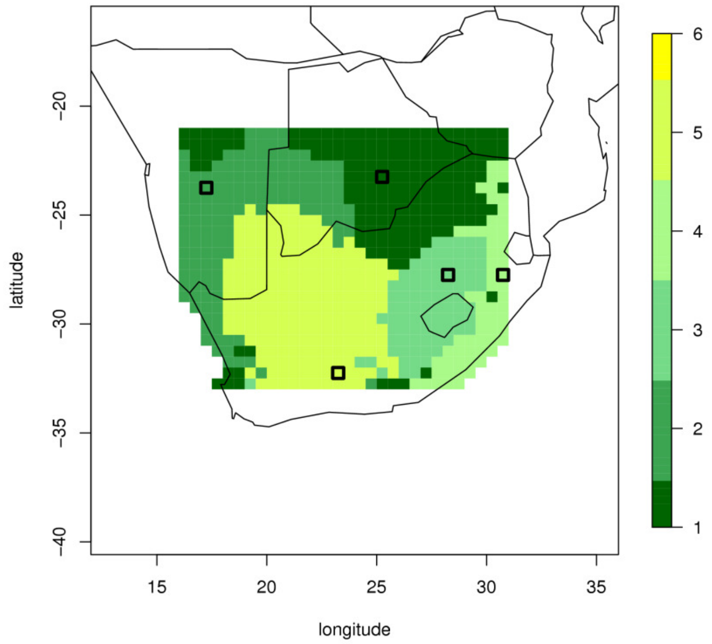

Figure 8: Result of the cluster analysis to determine regions with a similar climate

5.2.2 Experiment set-up

To test the applicability of STAR to the Orange River basin, a cross-validation experiment is carried out. The input data is split into two time periods of 25 years: the input data covering the period 1958-1982 and the validation period covering the period 1983-2007. The climate of the validation period is simulated using the first 25 years and the trend of the annual mean temperature for the subsequent 25 year period. This trend is derived from the data by a regression analysis of the annual mean temperature series at the representative grid points. It ranges from -0.2K to 1.1K. The performance of STAR is evaluated by comparing the simulated climatology with the observed one. However, the annual mean temperature of the input data shows a decrease for the representative grid points, while the annual means for the same grid points mainly increase in the validation period. A successful cross-validation despite this demanding setting, gives strong evidence of the robustness of the projections.

The future climate projections are generated for the time period 2011-2060. Both simulation periods (present and future climate) consist of 100 ensemble members. The cross-validation experiment takes the whole ensemble into account, whereas only three ensemble members are accounted for a detailed analysis of the climate projections. We choose these three realisations according to the annual area averaged precipitation. The 0.05-quantile of the precipitation represents a dry realisation, the median represents a moderate realisation and the 0.95-quantile represents a wet realisation. This approach makes sure that the range of possible climate variations for the future is accounted for.

The simulations for both time periods are based on five representative grid points which are shown in **Figure 8** which also displays the model area.

6 VALIDATION

6.1 Validation of CCLM

As stated previously, we validated the period from 1971 to 2000. In particular, the performance of CCLM with regard to the 2m temperature and precipitation was investigated.

Figure 9 to **Figure 11**, show the results of the validation runs for the 2m temperature. More precisely, the annual averages are shown. The simulation was driven by the results of an ECHAM5 run, which used 20th century GHG concentrations. Overall, we see that CCLM's performance varies considerably throughout the Orange River basin. In some areas, particularly in the Kalahari, CCLM is too cold, while in mountainous areas it is too hot. In some areas, the simulated and observed temperatures match well. For the coastal areas of Namibia, CCLM strongly underestimates the temperature. No clear trend in the performance of reproducing the 2m temperature emerges. Overall, however, the temperature is relatively well simulated.

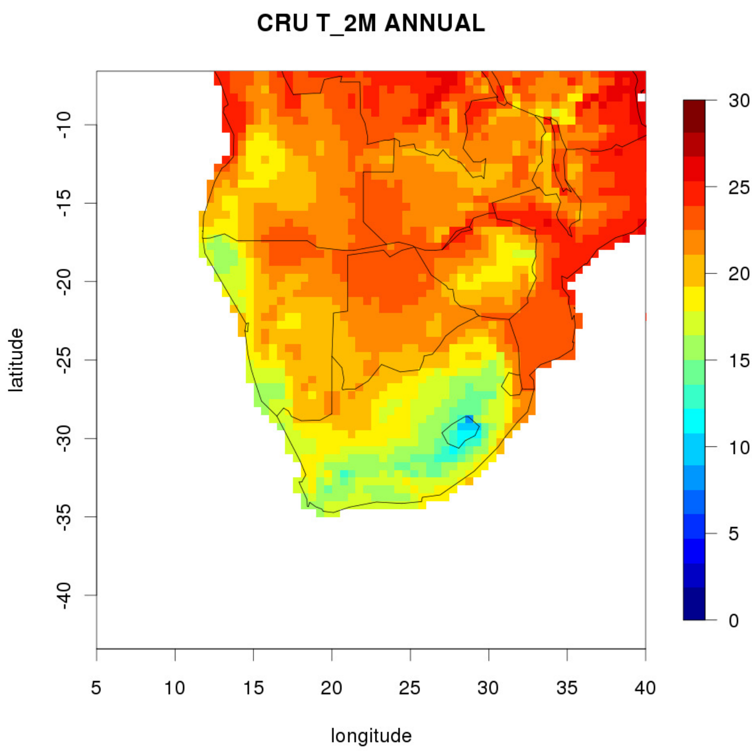

Figure 9: The annual average 2m temperature according to CRU

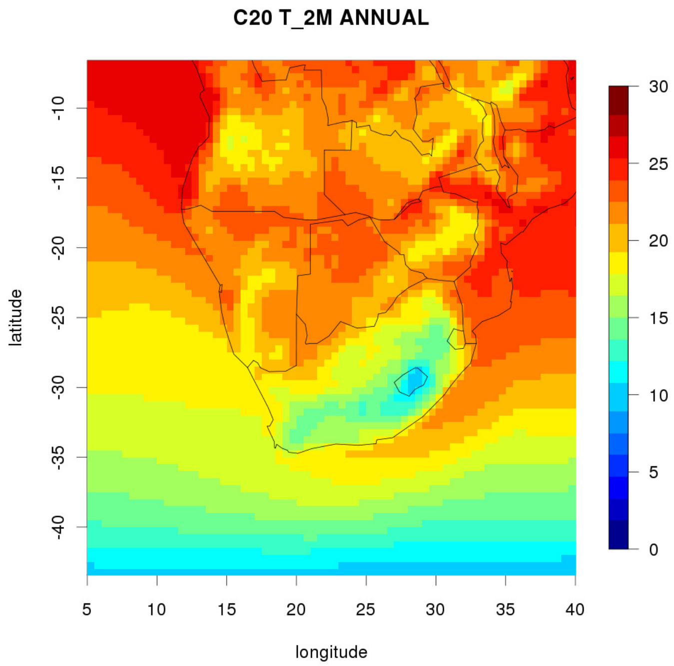

Figure 10: The 2m temperature from 1971 to 2000 as simulated by CCLM.

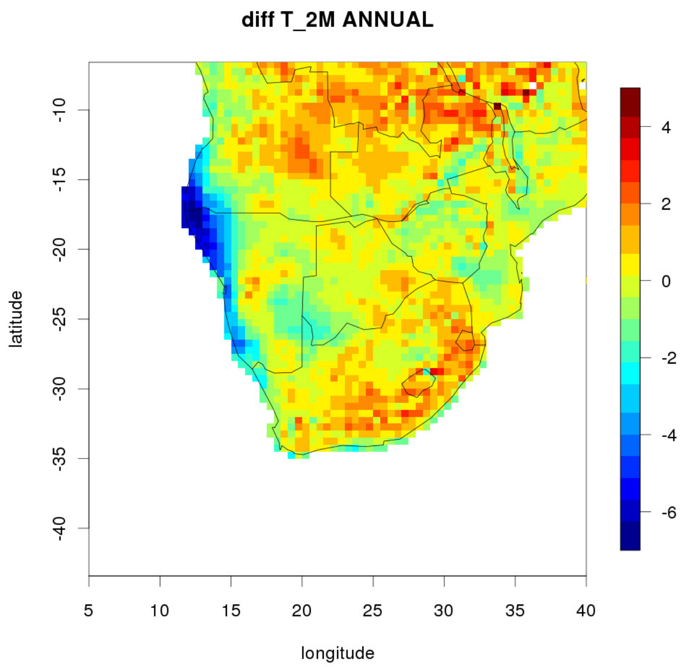

Figure 11: The bias in the 2m temperature in the CCLM simulation

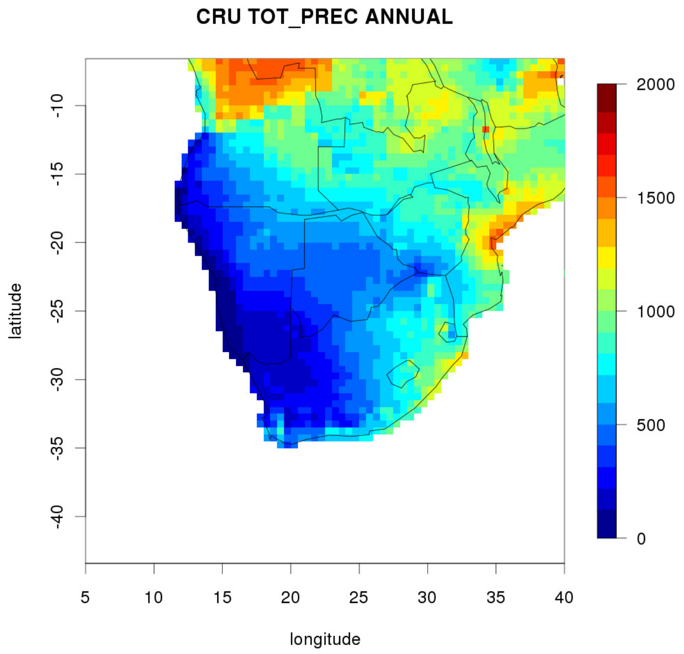

Figure 12: The annual precipitation according to CRU

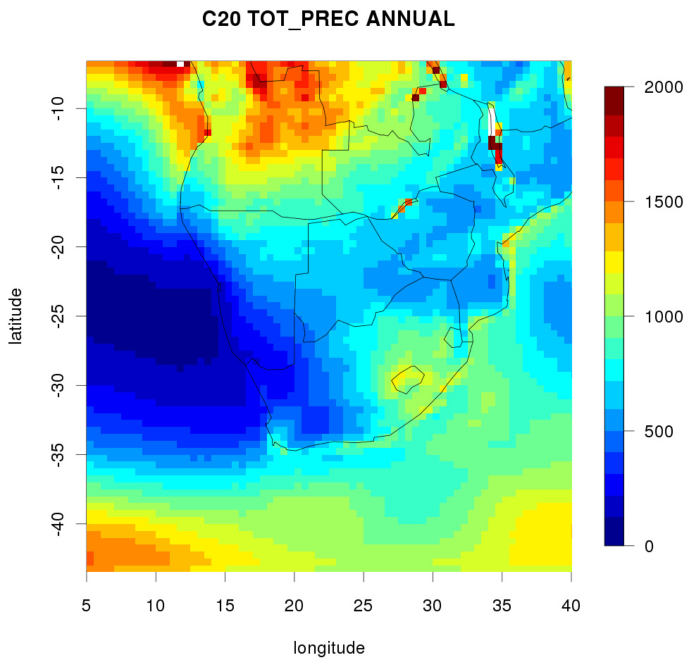

Figure 13: The annual precipitation from 1971 to 2000 as simulated by CCLM.

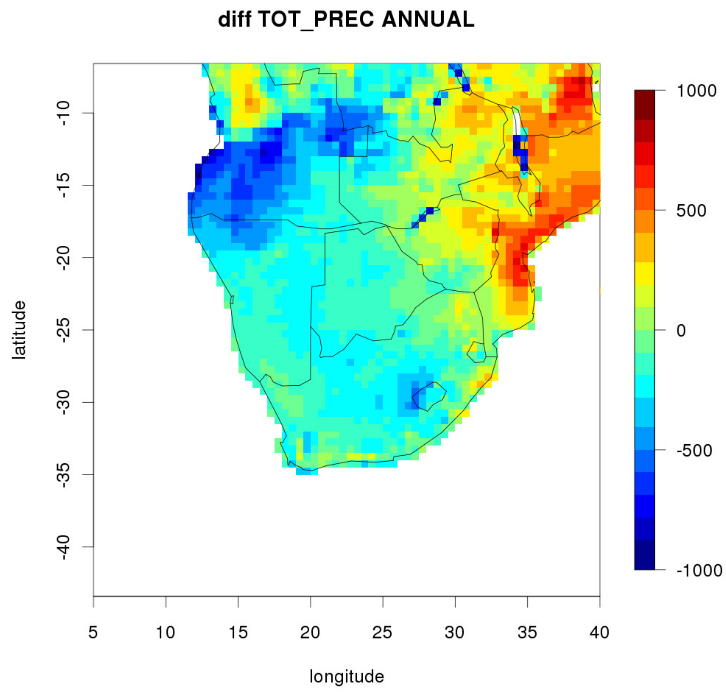

Figure 14: The bias in precipitation in the CCLM simulation for the validation period (1971-2000)

Similarly to the case of the 2m temperature, the results of the CCLM validation are shown with respect to precipitation in **Figure 13** and **Figure 14**. Since the CRU data consist of observations, while the CCLM data shows true precipitation, we “correct” the CRU data by adding 9% to the data, as described in [16]. From the above pictures we see that the precipitation performance of CCLM in the Orange River basin is rather poor. This is in line with the notorious difficulties dynamical RCMs have in reproducing precipitation. Across the whole river basin the precipitation is too low, with a large bias in northern Namibia and in Lesotho. The latter is particularly troublesome since approximately a third of the Orange’s natural runoff originates from Lesotho. So far CCLM does not produce reliable precipitation data in this area. It still needs to be fine-tuned and improved for Africa and, in particular, Southern Africa.

6.2 STAR validation

The high variability of the climate in the Orange River basin is a challenge for every regional climate model, because most models include physical parameterisations that are mainly tested and optimised for one specific climate regime. But, as STAR reproduces only spatial patterns which have been observed before, the simulated spatial variability is expected to be consistent with the observations.

The comparison between the observed and the simulated climate in the validation period (1983-2007) leads to the following results: The agreement between both climates is very close for all statistics analysed (not all are shown here), the observed climate lying always within the range of the different realisations. **Figure 15** shows the long term average of the temperature for the observed series, while **Figure 16** shows the same for the simulated series and **Figure 17** shows the corresponding difference between the simulated and observed series. The long term average of the annual precipitation for the simulated and observed series, and the corresponding relative difference, is displayed in **Figure 18** to **Figure 21**. As can be seen, the simulated spatial pattern for both the temperature and the precipitation, provides an accurate observed pattern. The highest temperatures can be found in the north and northwest of the simulation area, while the lowest temperatures can be found in the east, especially Lesotho. The precipitation decreases from east to west, with the highest values in the southeast and the lowest values at the mouth of the Orange River, at the border between Namibia and South Africa respectively. The low differences between the simulations and observations confirm the strong similarity between them. In case of the temperature, the results of STAR are primarily too cold, with the difference ranging between -0.3℃ and 0.3℃. However, the values are very low (up to -0.1℃) when looking at the average over all realisations, or at the realisation that represents the median. In case of the precipitation, STAR is on average up to 10% too wet. The values of the relative difference of the individual realisations range between 6% and 23%. The highest values can be found in the north, where the annual precipitation is very low, so that relative deviations tend to increase quickly. Compared to dynamical regional climate models, the bias of 10% is considered to be a very realistic value (see for example [17]).

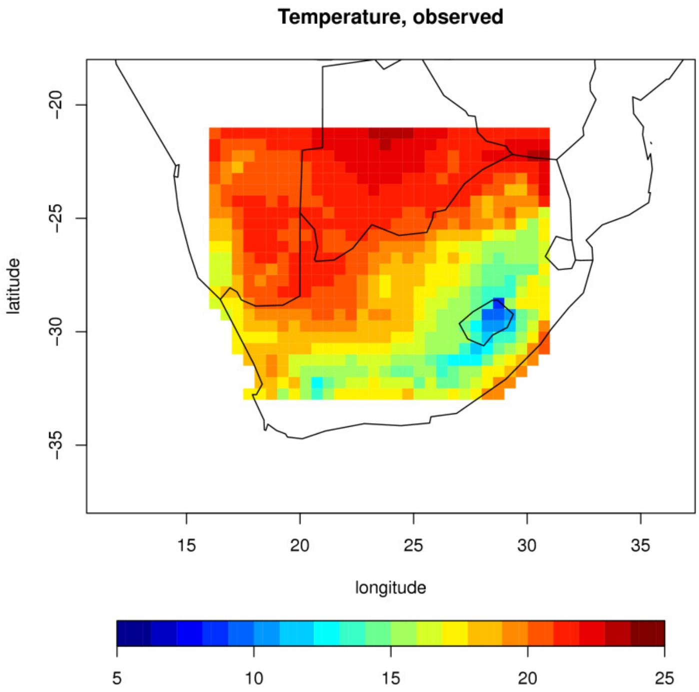

Figure 15: Long term average of observed temperature (1983-2007)

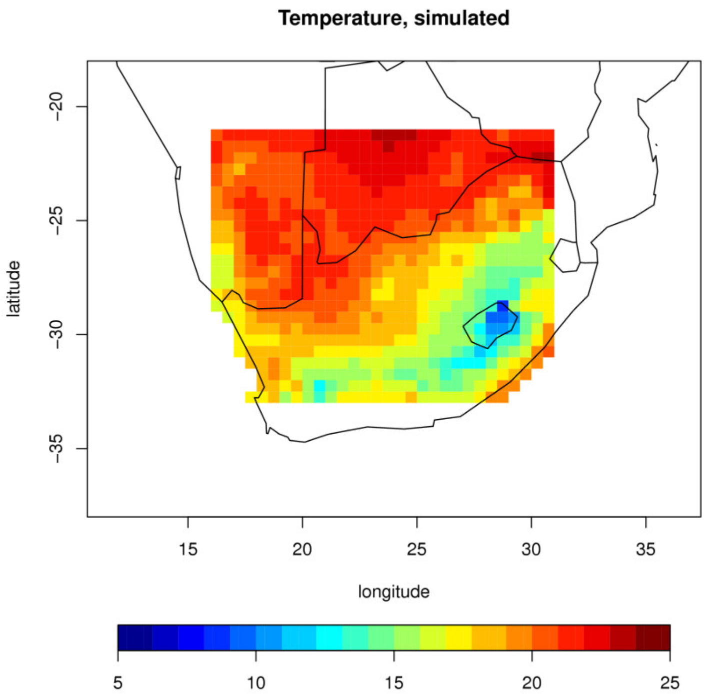

Figure 16: Long term average of simulated temperature in °C (1983-2007)

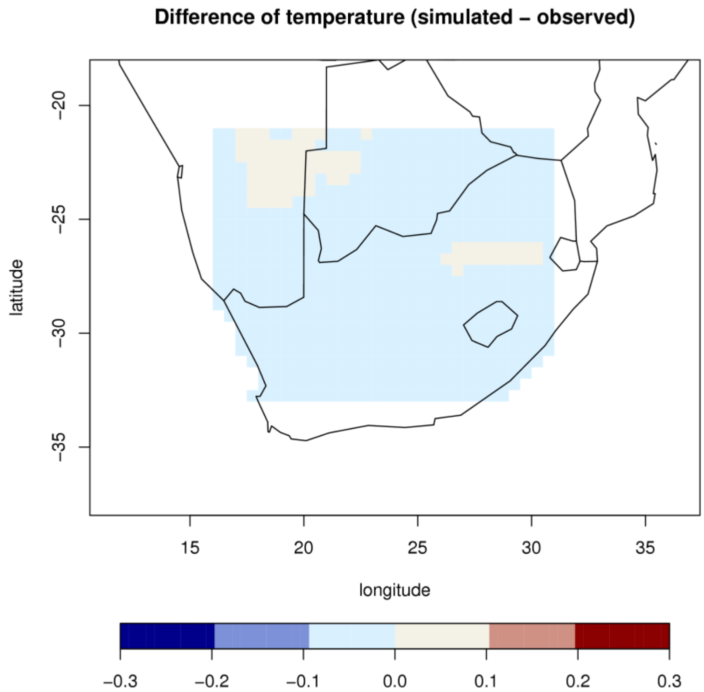

Figure 17: Difference between long term averages of simulated and observed temperature in °C (1983-2007)

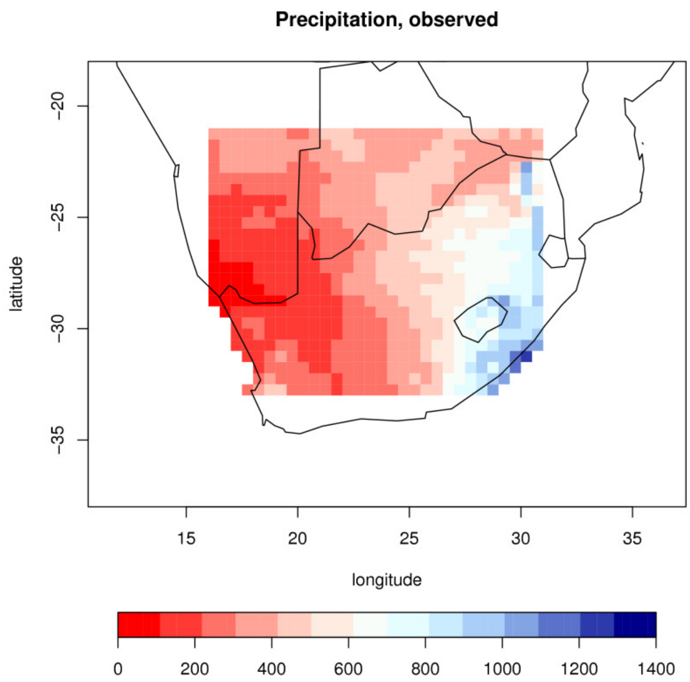

Figure 18: Long term average of observed precipitation in mm (1983-2007)

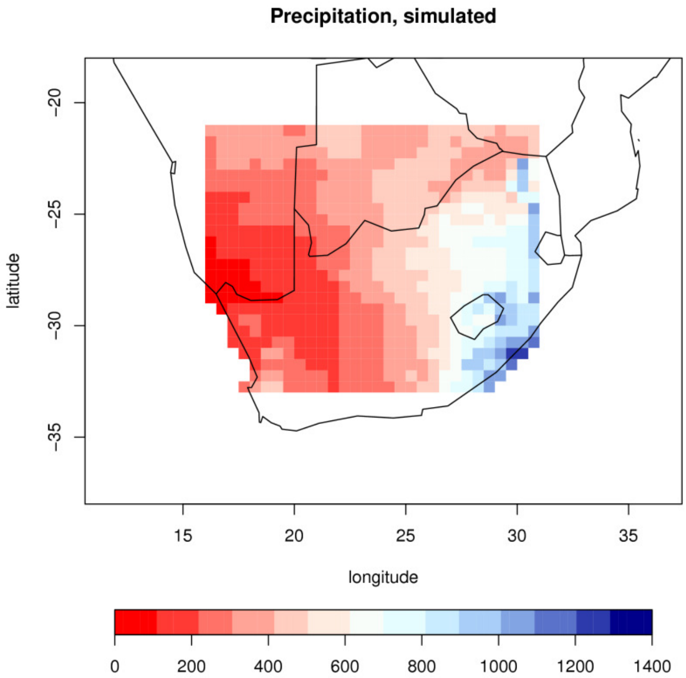

Figure 19: Long term average of simulated precipitation in mm (1983-2007)

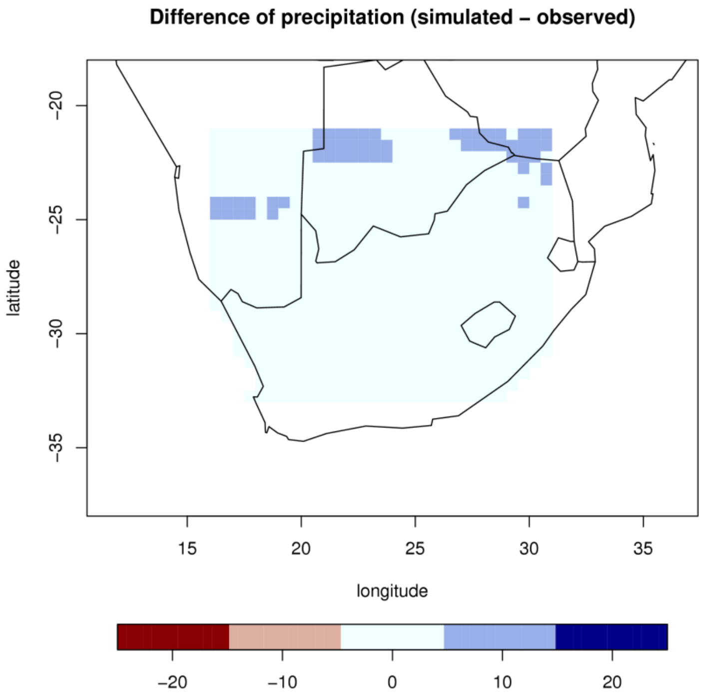

Figure 20: Relative difference between long term averages of simulated and observed precipitation in % (1983-2007)

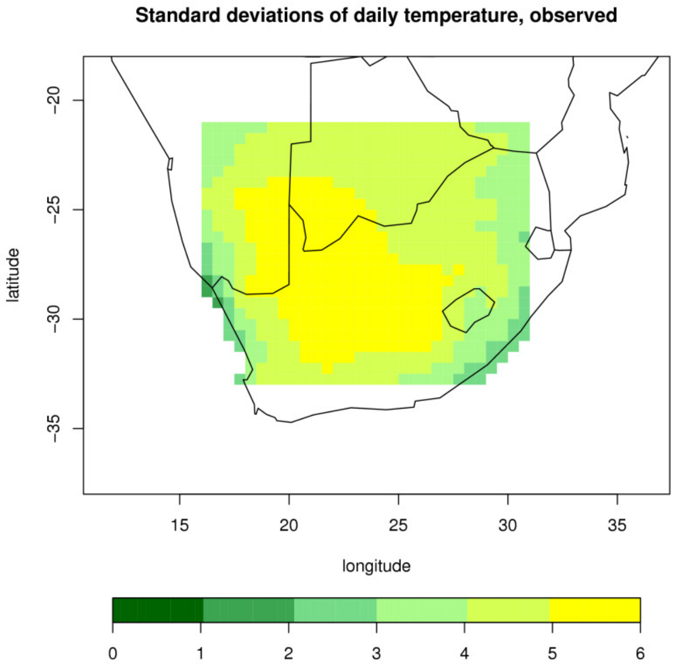

Figure 21: Standard deviations of observed daily temperatures in °C (1983-2007)

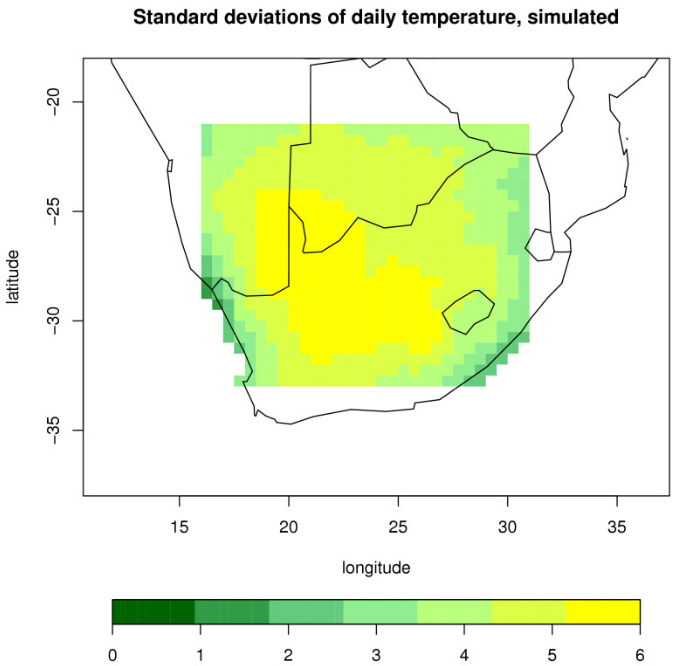

Figure 22: Standard deviations of simulated daily temperatures in °C (realisation that represents the median of the standard deviations)

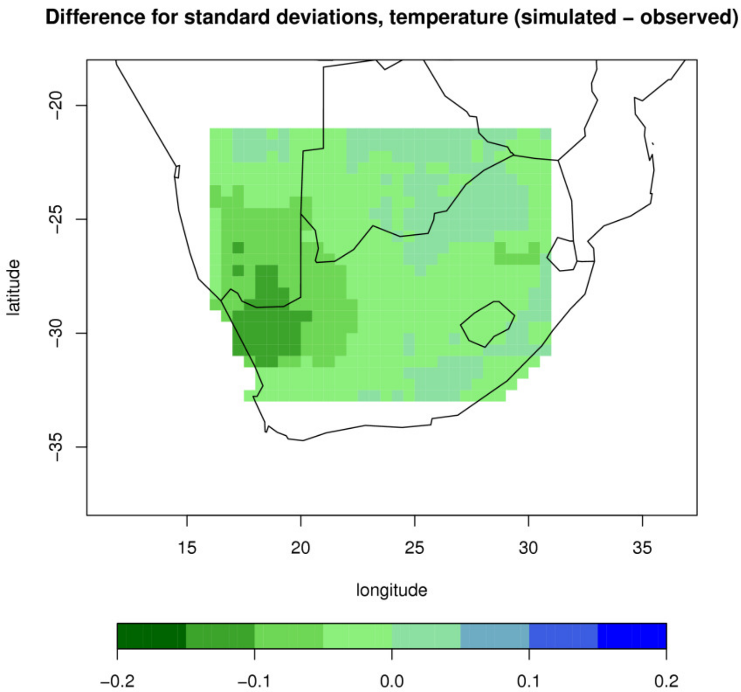

Figure 23: Difference between simulated and observed standard deviations of daily temperatures in °C (1983-2007)

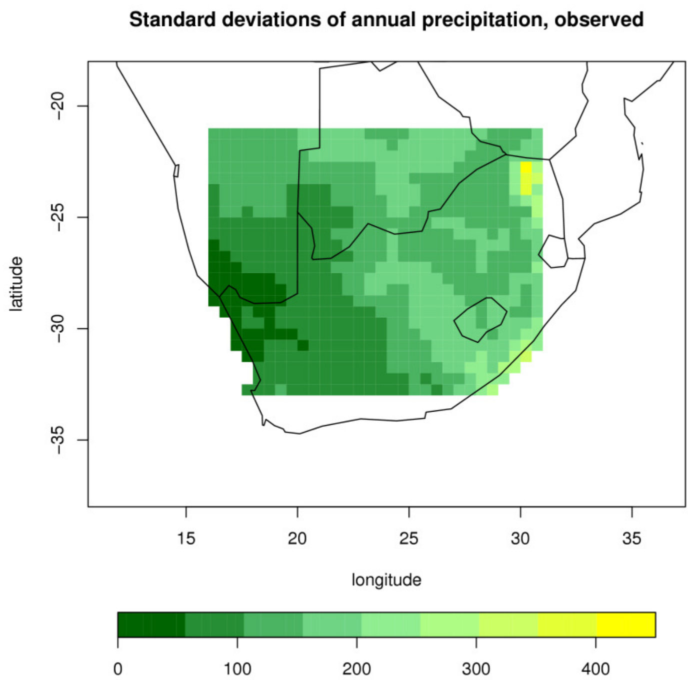

Figure 24: Standard deviation of observed annual precipitation in mm (1983-2007)

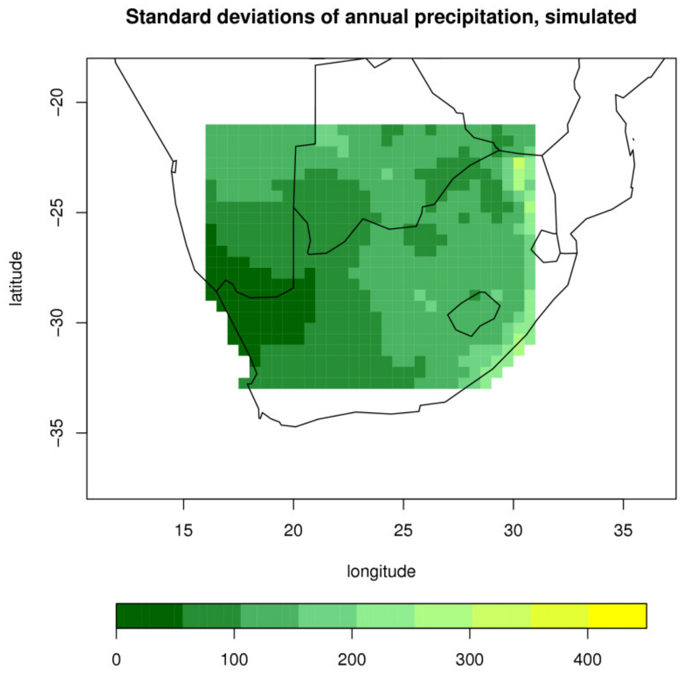

Figure 25: Standard deviation for simulated annual precipitation in mm (realisation that represents the median of the standard deviations)

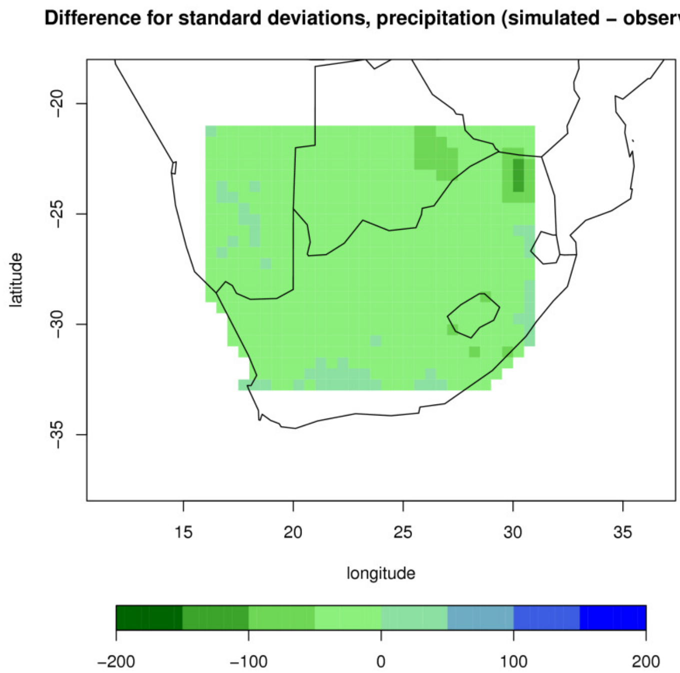

Figure 26: Difference between simulated and observed standard deviations of the annual precipitation in mm (1983-2007)

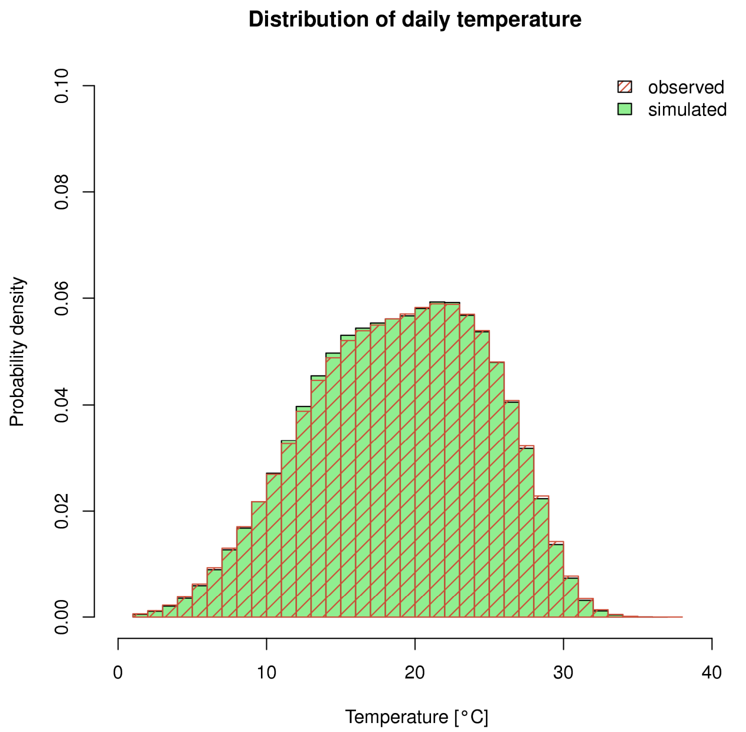

Figure 27: Distribution of the daily temperature in ℃ (1983-2007)

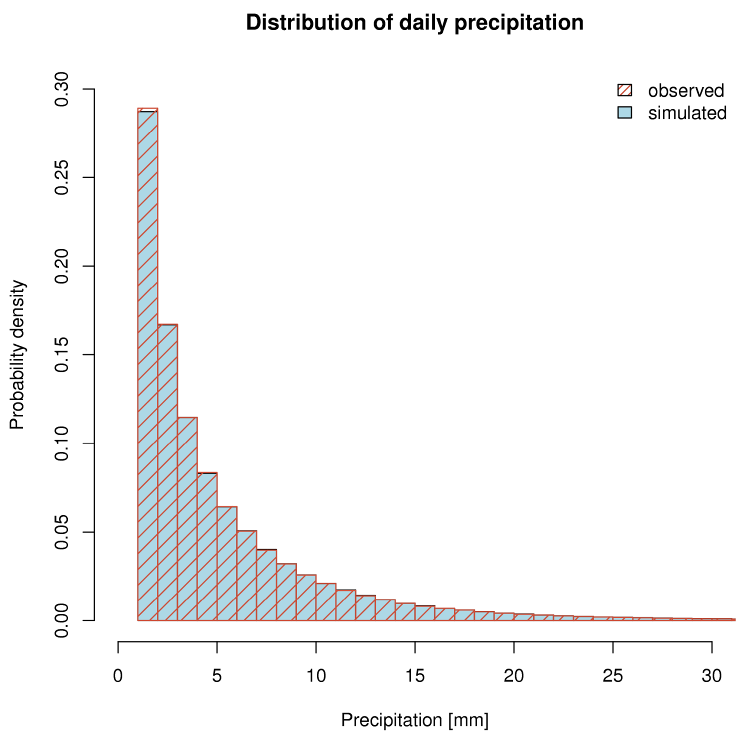

Figure 28: Distribution of the daily precipitation in mm

Figure 21 to **Figure 23** show the standard deviations of the observed daily temperatures and **Figure 24** to **Figure 26** show the annual precipitation. The simulations displayed in **Figure 21** and **Figure 24** (and **Figure 27** and **Figure 28**) are the realisations that represent the median of the standard deviations. The temperatures agree well (correlate accurately) with the highest variances in the centre of the simulation area, and the lowest at the east coast and the mouth of the Orange River. The differences between simulations and observations are low. They range between -0.2℃ and 0.1℃ for the different realisations. But, as they are mainly negative, STAR has slightly lower variances although the general pattern appears to tie in very well. The same can be said for the precipitation. There are low variances at the lower Orange River, especially at the mouth, and high variances in the east of the simulation region. The differences between the simulated and observed values show again that STAR generates lower variances.

However, the temporal variances of the daily temperature and the daily precipitation in **Figure 26** and **Figure 27** confirm the good performance of STAR. These plots were generated using the daily values of all the grid points in the simulation region. There is good agreement (strong correlation) between simulated and observed temperatures, as well as between the simulated and observed precipitation.

The mean seasonal cycles of temperature and precipitation are displayed in **Figure 29** and Figure 30 for the averaged values over the whole simulation area. The spread of the ensemble is very narrow for the temperature, as this is the forcing variable. The observations are included in the spread and correspond well to the average over all realisations. There is again close agreement between observations and simulations for the precipitation.

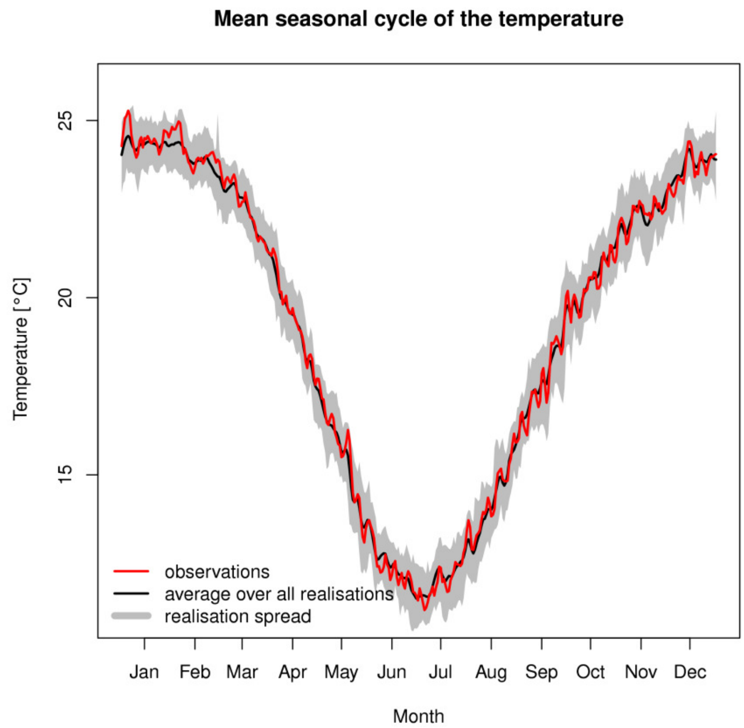

Figure 29: Mean seasonal cycle of temperature in ℃

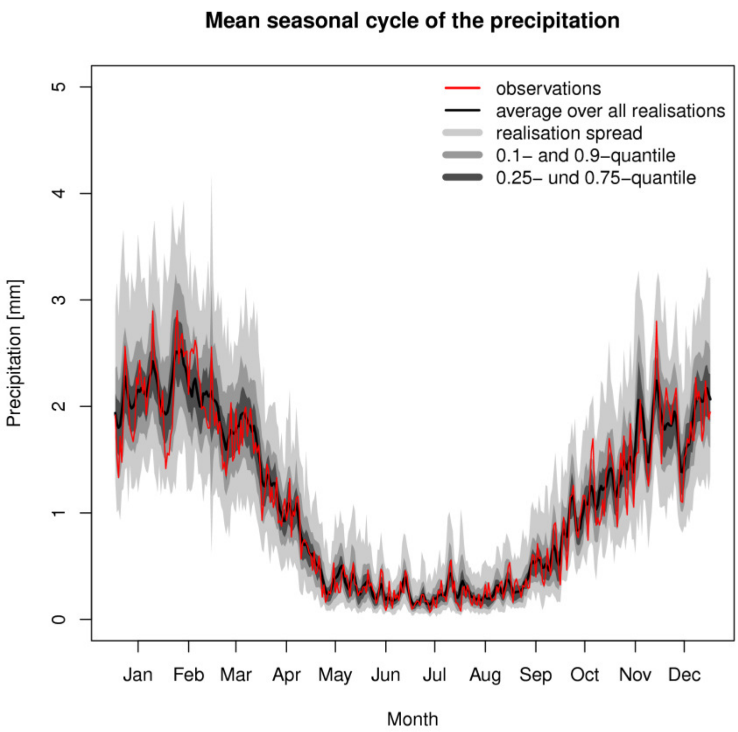

Figure 30: Mean seasonal cycle of precipitation in mm

7 A1B SCENARIO RESULTS

7.1 CCLM

The ECHAM5 results were downscaled for the SRES emission scenario A1B with CCLM as described in **Section 5.1**. In order to determine the change compared to the present climate, the ECHAM5 was run using 20th century GHG concentrations as the baseline. This was undertaken on the assumption that both the past and the future simulations have the same bias. Using this approach should result in a bias cancellation.

As stated above, the SRES A1B emission scenario was considered appropriate for the future [11]. Again, the results from the GCM ECHAM5 were used. These in turn were then downscaled by CCLM from 2001 to 2100. Since the standard definition of a period determining the climate was set to 30 years by the WMO the time slice from 2031 to 2060 was used. The analyses were based on the 2m temperature and precipitation and it should be noted that the dynamic climate models produce “corrected” precipitation, so the values presented are higher than the measured ones [16].

7.1.1 2m Temperature

Overall, we only see an increase in temperature. While the predicted increase for the coastal areas is about 1℃, it is larger for inland areas, in particular for the Kalahari, where it is around 2℃ up to 2.5℃. This result is consistent with the 2m temperature as projected by STAR.

Since the validation for the 2m temperature proved to be realistic, the results for the individual seasons are also presented in **Figure 33 to Figure 40.**

Considering the individual seasons, we see that the projected temperature increase is unevenly distributed across the seasons. In summer (DJF) and autumn (MAM) we see a general temperature increase of more than 2.5℃ in the northern Orange basin and Namibia. The largest increase of 3℃ is predicted for the summer months around the Kalahari Desert. For the autumn and winter seasons temperature increases are predicted although the magnitude of the increase is less extreme. The temperature increase in these cases is more evenly distributed across the basin with predicted temperature increases of between 1℃ and 2℃.

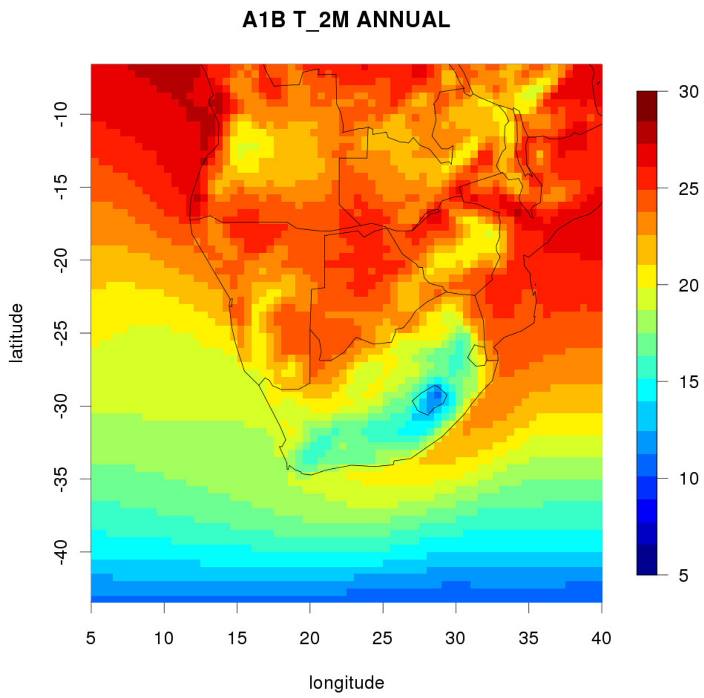

Figure 31: The averaged 2m temperature from 2031 to 2060 according to the A1B scenario

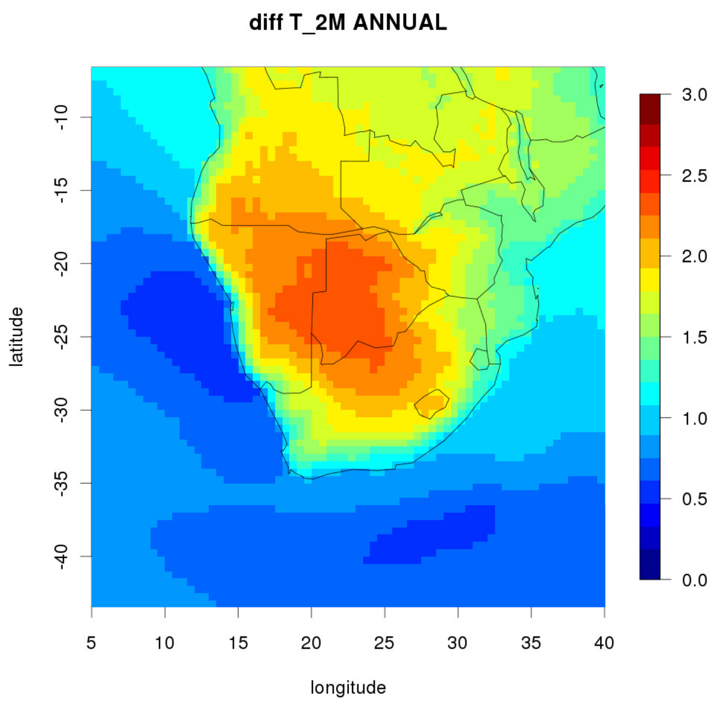

Figure 32: The change in the average 2m temperature 2031-2060 vs. 1971 to 2000

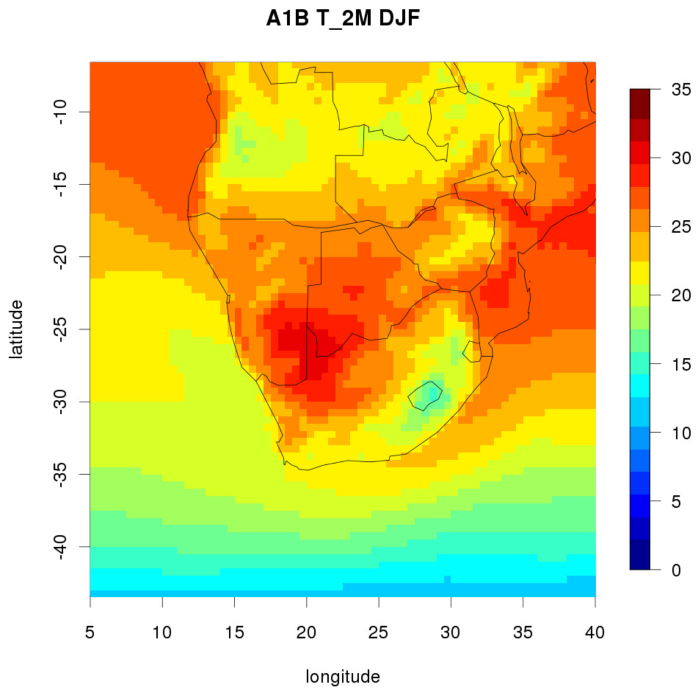

Figure 33: The 2m temperature from 2031-2060 (DJF, austral summer)

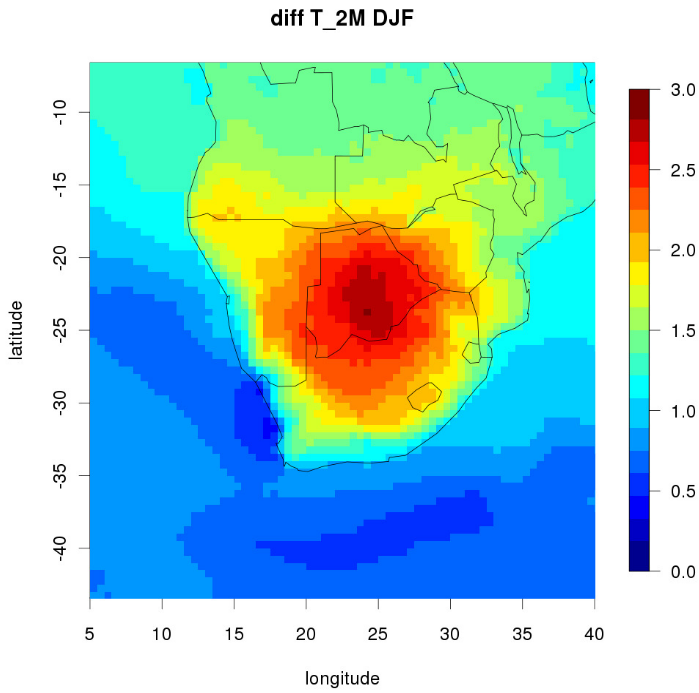

Figure 34: The predicted 2m temperature change (DJF, austral summer). Shown is 2031-2060 vs. 1971-2000

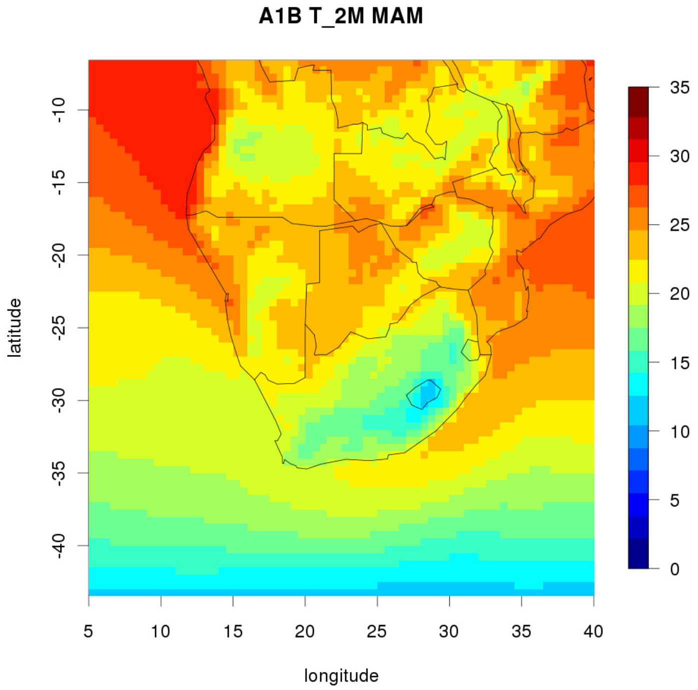

Figure 35: The 2m temperature from 2031-2060 (MAM, austral autumn)

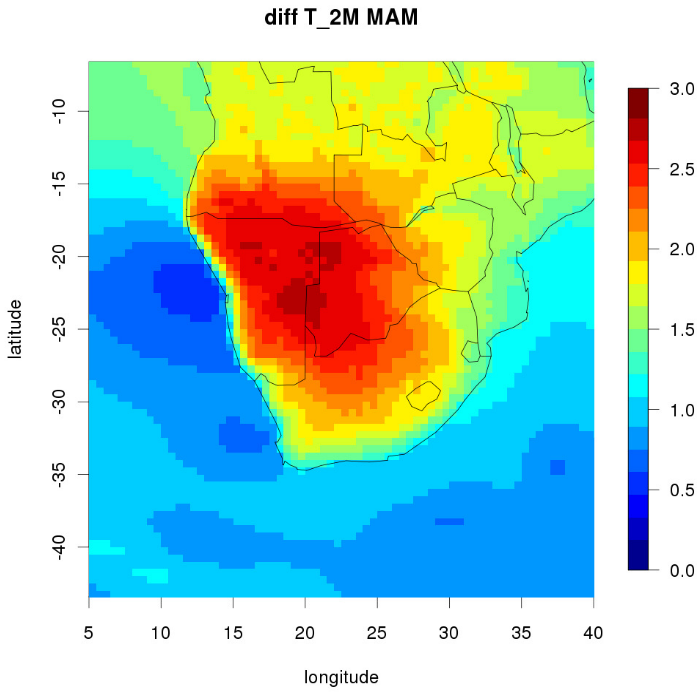

Figure 36: The predicted 2m temperature change (MAM, austral autumn). Shown is 2031-2060 vs. 1971-2000

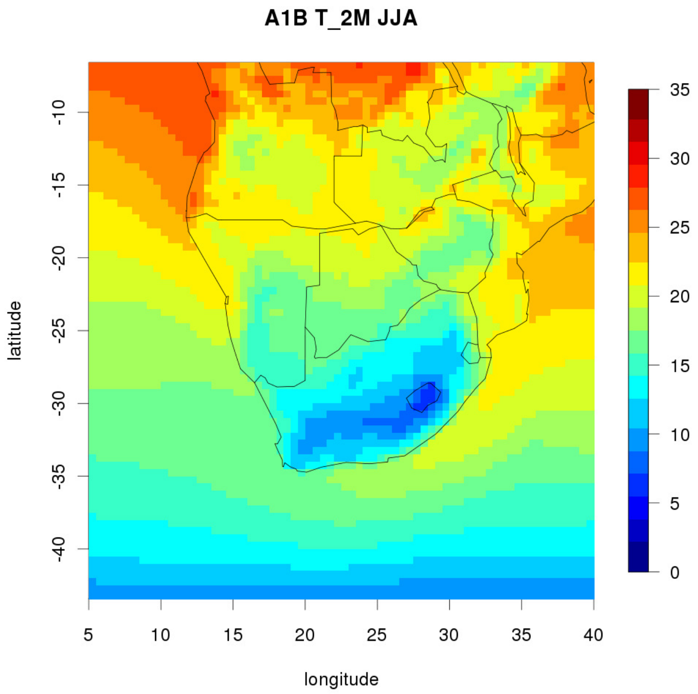

Figure 37: The 2m temperature from 2031-2060 (JJA, austral winter)

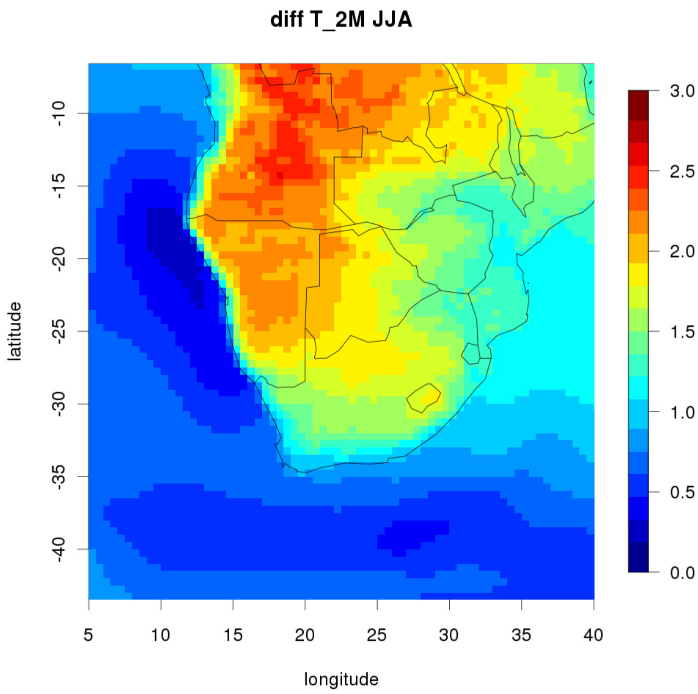

Figure 38: The predicted 2m temperature change (JJA, austral winter). Shown is 2031-2060 vs. 1971-2000

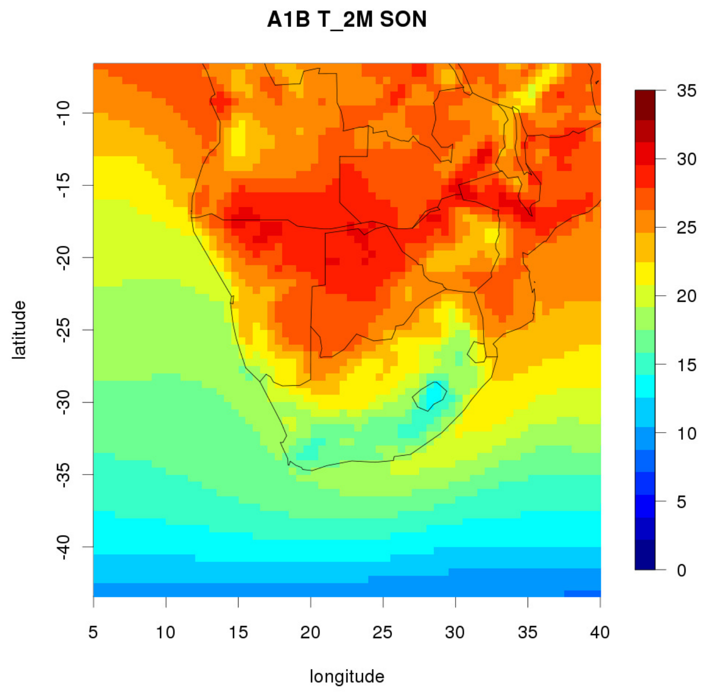

Figure 39: The 2m temperature from 2031-2060 (SON, austral spring)

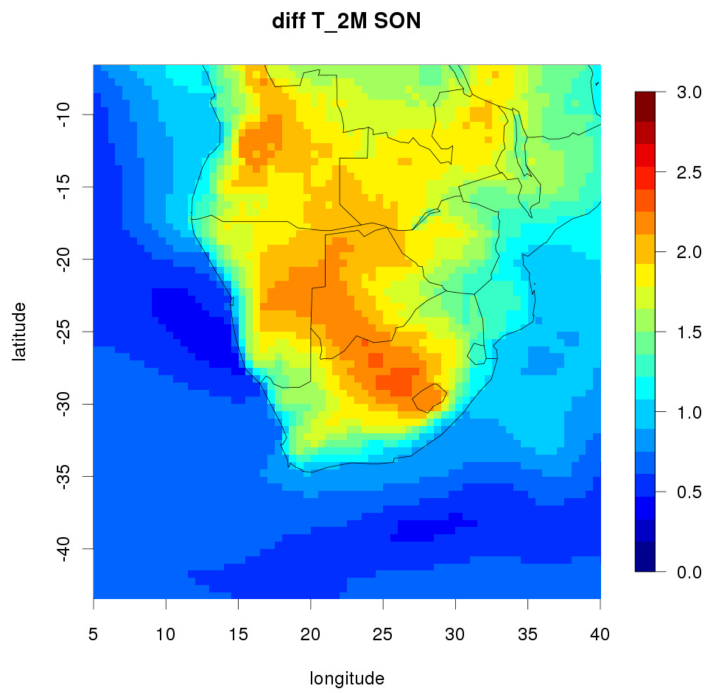

Figure 40: The predicted 2m temperature change (SON, austral spring). Shown is 2031-2060 vs. 1971-2000

7.2 CCLM Precipitation

Since the validation for the CCLM precipitation was not considered to be at a high level of reliability, only the annual results are shown in **Figure 41** and **Figure 42** which show the CCLM projections which suggest an overall decrease in precipitation. The predicted changes in precipitation are even greater than the predicted changes in the dry realisation of STAR, and the spatial distributions do not correspond well with each other. The statistical downscaling predicts no change, or even an increase, in the crucial area of Lesotho, while the CCLM suggests a clear decrease in precipitation for Lesotho. The largest decrease in precipitation is predicted for the dry areas of Namibia and east of the Kalahari and these are also the areas where the CCLM validation produced the largest biases.

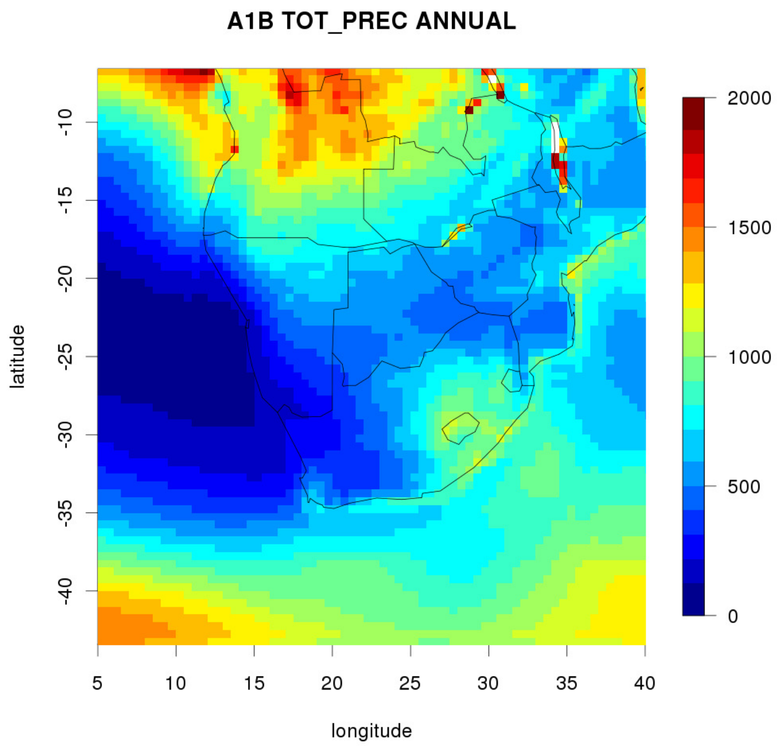

Figure 41: The annual precipitation from 2031 to 2060 according to the A1B scenario

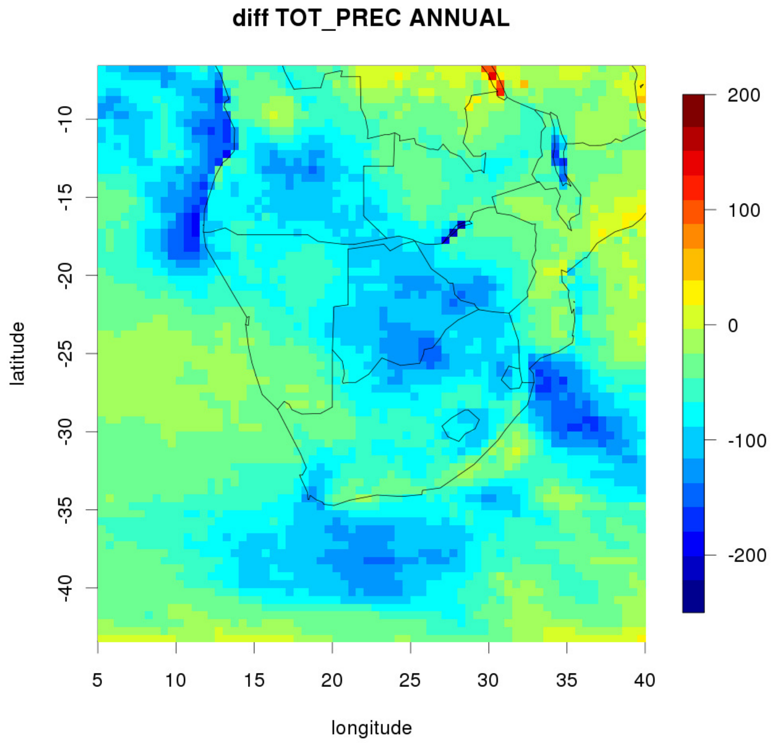

Figure 42: The change in the annual precipitation according to the A1B scenario. Shown is the comparison 2031-2060 vs. 1971-2000

7.3 STAR

Since the validation process suggests reliable and robust results, STAR can be used for future climate projections, despite the fact that the variability criterion (see **Section 5.2.1**) is not completely fulfilled.

To extract the future changes in temperature and precipitation in the Orange River basin, the projections for the time period from 2051 to 2060 are compared with the observations. It should be noted that only three realisations are considered namely: wet, dry and median. (see **Section 5.2.2**).

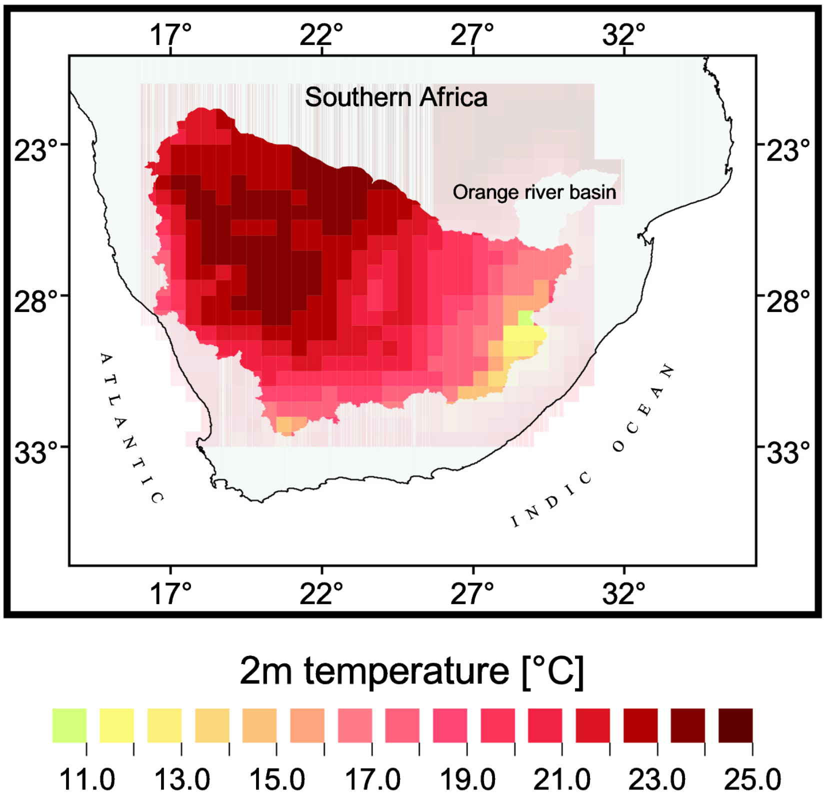

Figure 43: Long term average of temperature for the time period from 2011 to 2060

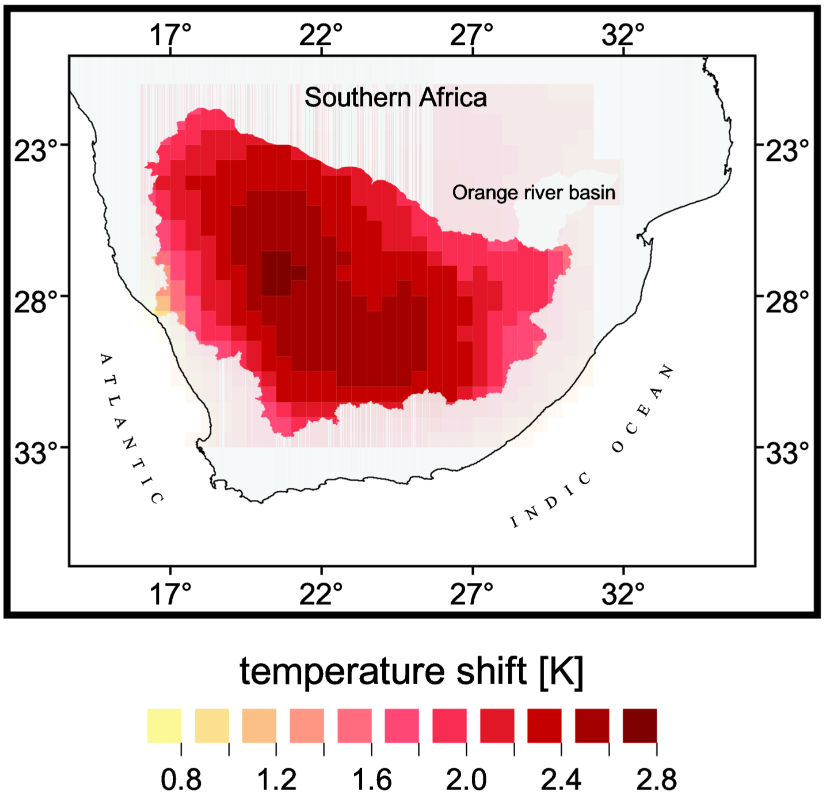

Figure 44: Difference between 2051-2060 and 1958-2007

Figure 43 shows the temperature for the median realisation, averaged over the whole future time period. **Figure 44** displays the difference between the predicted temperature averaged over 2051-2060 and the recorded temperature averaged over 1958-2007. The temperature in the river basin is predicted to increase by between 2.4℃ and 2.6℃, especially in the centre of the basin. Changes of less than 1℃ are predicted at the mouth of the Orange River.

Figure 45, **Figure 47** and **Figure 49** show the long term average of the precipitation for the future time period and the corresponding difference to the recent climate is displayed in **Figure 46, Figure 48** and **Figure 50**. The Dry realisations are represented in **Figure 45** and **Figure 46** while the median realisations are shown in **Figure 47** and **Figure 48** with the wet realisations shown in **Figure 49** and **Figure 50.** They all suggest a general decrease of precipitation. The dry realisation shows the largest changes, reaching values of down to -140mm per annum in the northeast of the river basin. However, an increase of precipitation of between 20mm and 60mm per annum is predicted for the southeast portion of the basin in Lesotho. This increase is even more pronounced in the wet realisation, where it also stretches further north into the Vaal River catchment. In this realisation the precipitation decrease is more moderate, with values of down to -80mm per annum. The median realisation shows a precipitation decrease of down to -60mm for the river basin.

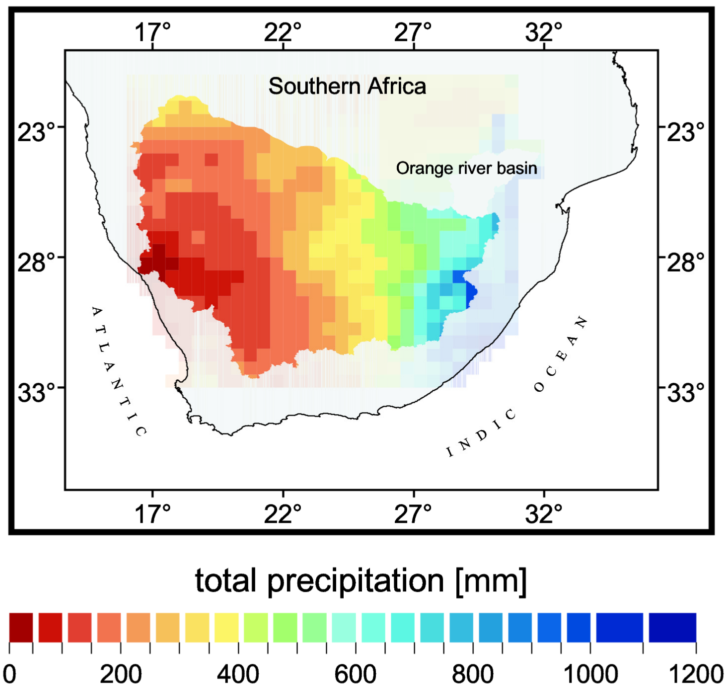

Figure 45: Long term average of precipitation for the time period from 2011 to 2060 (dry realisation)

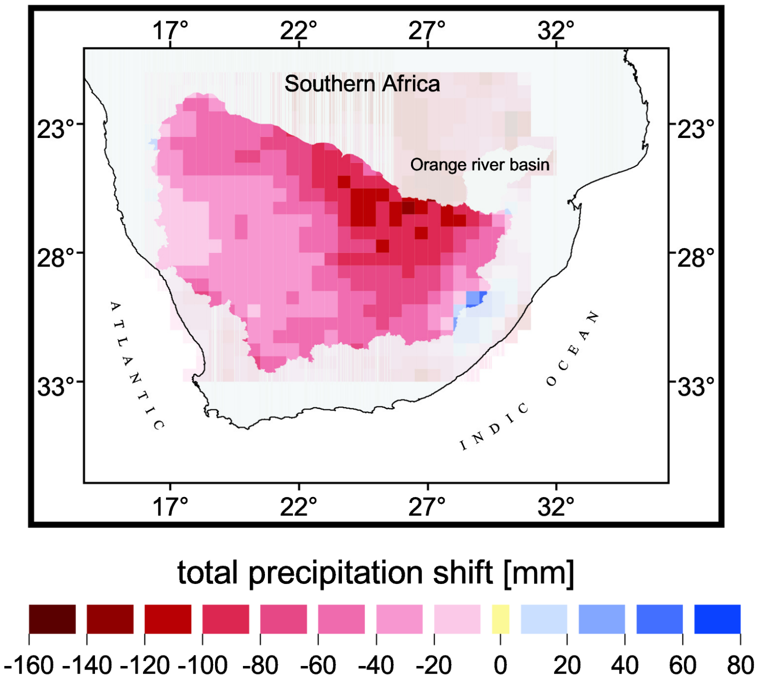

Figure 46: Difference between 2051-2060 and 1958-2007 (dry realisation)

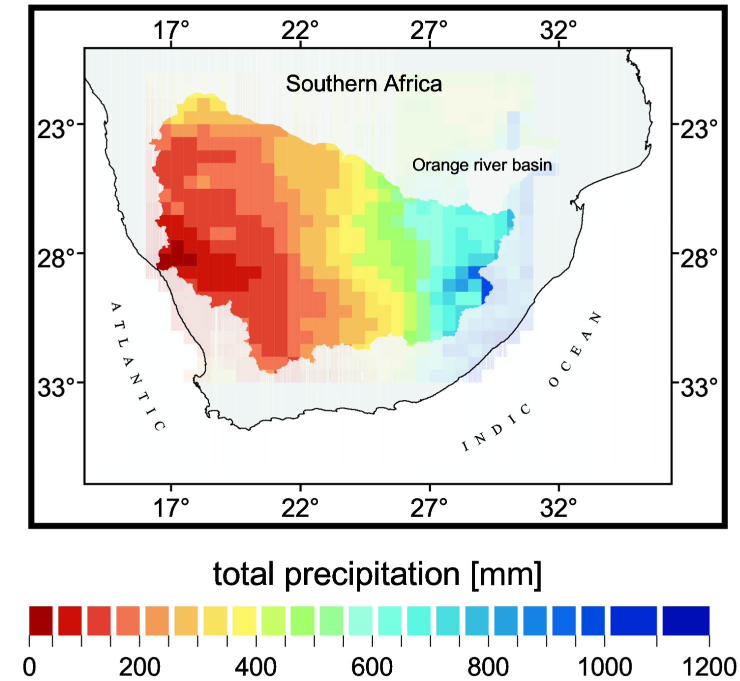

Figure 47: Long term average of precipitation for the period from 2011 to 2060 (median realisation)

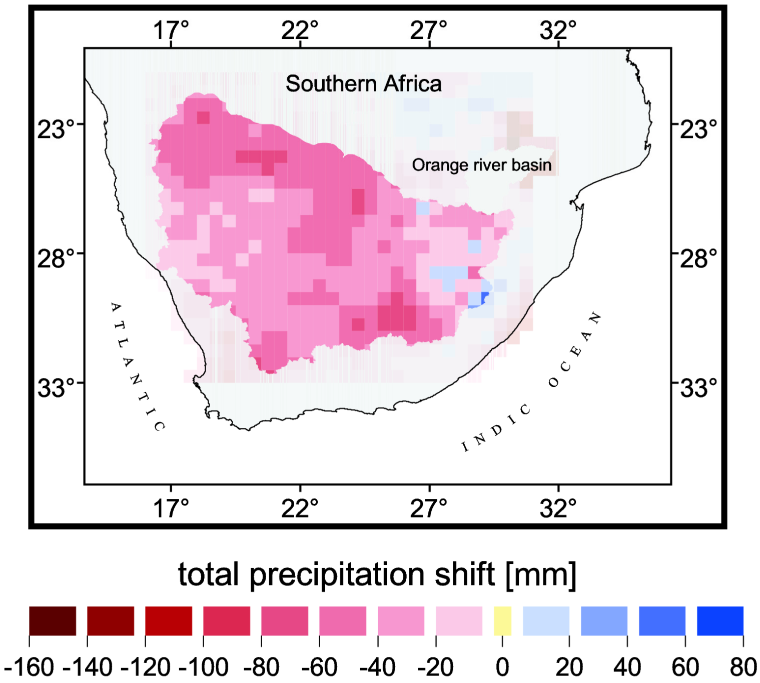

Figure 48: Difference between 2051-2060 and 1958-2007 (median realisation)

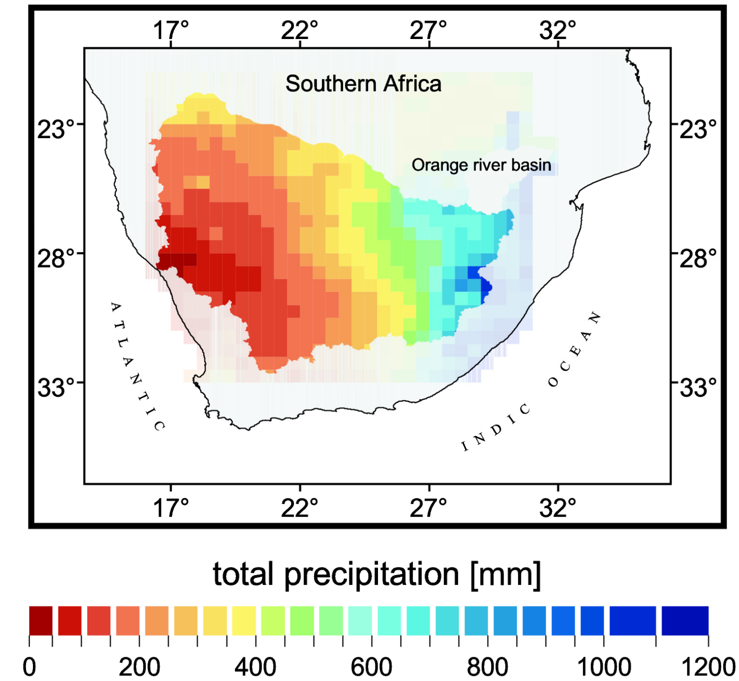

Figure 49: Long term average of precipitation for the period from 2011 to 2060 (wet realisation)

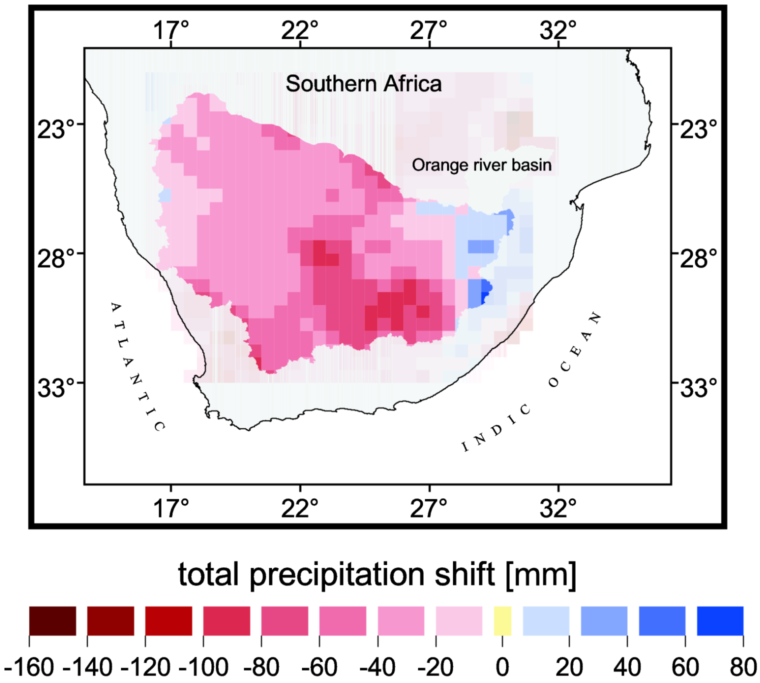

Figure 50: Difference between 2051-2060 and 1958-2007 (wet realisation)

8 CONCLUSIONS AND OUTLOOK

The regional climate models CCLM and STAR were used in order to determine characteristics of the future climate in the Orange River basin, up to the year 2060. Both represent complementary approaches to regional climate modelling, STAR being a statistical model, and CCLM being a dynamical model. For the validation period, STAR produced excellent results, both for the 2m temperature and the precipitation. On the other hand, CCLM produced acceptable results for most of the basin in case of the 2m temperature. However, on the coastal zones of Namibia it failed to yield realistic results or to reproduce realistic precipitation patterns. In particular for the crucial area of Lesotho, the precipitation was strongly underestimated.

For the period up to 2060, CCLM predicts a temperature increase for the whole basin. For parts of the basin, the temperature increase is projected to be larger than 2℃. The strongest increase is predicted to occur in summer and autumn. For the precipitation, CCLM predicts a decrease throughout the river basin, but due to the validation results, this prediction is not considered to be reliable.

STAR was used to generate future projections of temperature and precipitation for the Orange River basin based on the mean temperature trend for the time period from 2011 to 2060. This was extracted from several GCMs (based on the SRES A1B scenario). An ensemble of future climate projections was computed yielding the following results:

According to the median realisation (see Section 5.2.2) the 2m temperature in the Orange River basin will increase by over 2℃, with the strongest increase in the centre of the basin (especially in the southern Kalahari) and the weakest at the mouth of the Orange River. The same realisation results in a weak decrease of annual precipitation (down to -80mm per annum) for most of the Orange/Senqu river basin. The precipitation decrease is evenly spread across the basin. Regarding the dry realisation, there is a decrease of precipitation for the largest part of the river basin, especially in the area of the Vaal River, with values decreasing down to -140mm per annum. To the contrary, the wet realisation results in a decrease of precipitation for the largest part of the river basin, with its maximum around the Gariep Dam (down to -100mm per annum). Note that all three realisations agree in an increase of precipitation in eastern Lesotho and in the east of South Africa, reaching values of up to 80mm per annum.

Both 2m temperature projections from STAR and CCLM are consistent. They largely concur in magnitude and spatial distribution.

Several improvements over the obtained results are conceivable. CCLM could be fine-tuned for the region. Technical improvement to CCLM could also be carried out, such as improved convection schemes etc. An improved CCLM could be used for focusing on particular areas of interest as well, which could then be simulated with a higher resolution than 0.44° × 0.44°. Another possible approach to the simulation of the climate in the Orange River basin would be to carry out long term simulations by STAR. These could be complemented by short term CCLM runs, in order to produce extreme event ensembles. New and improved SRES emission scenarios, as well as new GCM runs for the IPCC AR5 are also due this year (2011), providing the basis for better regional climate projections.

9 REFERENCES

1. WRP (Pty) Ltd (2009). Phase 1 of the ORASECOM basin-wide integrated water resources management Plan.

2. Böhm, U., Kücken, M., Ahrens, W., Block, A., Hauffe, D., Keuler, K., Rockel, B., and Will, A. (2006). CLM - The Climate Version of LM: Brief Description and Long-Term Applications. COSMO Newsletter 6:225-235.

3. CCLM community (2008). Regional climate modelling with COSMO-CLM (CCLM). Meteorologische Zeitschrift 17.

4. Giorgi, F. (1990). Simulation of regional climate using a limited area model nested in a general circulation model. Journal of Climate 3: 941-963.

5. Giorgi, F., Marinucci, M. R., and Visconti, G. (1990). Use of a limited area model nested in a general circulation model for regional climate simulations over Europe. Journal of Geophysical Research 95, 18: 413-431

6. Giorgi, F. and Mearns, L. (1991). Approaches to regional climate change simulation: A review. Reviews of Geophysics 29: 191-216.

7. Werner P. C., Gerstengarbe F.-W. (1997). Proposal for the development of climate scenarios. Climate Research 8: 171-182.

8. Orlowsky B., Gerstengarbe F.-W., Werner P. C. (2007). A resampling scheme for regional climate simulations and its performance compared to a dynamical RCM. Theoretical and Applied Climatology 92: 209-223.

9. Steinhausen D., Langer K. (1977). Clusteranalyse – Einführung in Methoden und Verfahren der automatischen Klassifikation. Walter de Gruyter, Berlin.

10. Hartigan J. A., Wong M. A., (1979). A K-means clustering algorithm. Applied Statistics 28: 100-108.

11. Nakicenovic N. et al. (2000). Special report on emission scenarios: A special report of working group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK.

12. Mitchell T. D., Jones P. D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climate 25, 6: 693-712.

13. Solomon S. et al. (2007). Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK.

14. Orlowsky B., Fraedrich K. (2008). Upscaling European surface temperatures to North Atlantic circulation-pattern statistics. International Journal of Climatology 29: 839-849.

15. Orlowsky B. et al. (2010). Future climates from bias-bootstrapped weather analogues: an application to the Yangtze River basin. Journal of Climate 23, 13: 3509-3524.

16. Richter, D. (1995). Ergebnisse methodischer Untersuchungen zur Korrektur des systematischen Messfehlers des Hellmann-Niederschlagsmessers. Berichte des Deutschen Wetterdienstes, 194.

17. Roesch A. et al. (2008). Analysis of CCLM model biases in relation to intra-ensemble model variability. Meteorologische Zeitschrift 17

ORASECOM