Sensitivity of the atmospheric water cycle to corrections of the sea surface temperature bias over southern Africa in a regional climate model

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Received: 15 December 2016 / Accepted: 14 December 2017 / Published online: 28 December 2017
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Abstract

Regional climate models (RCMs) have been used to dynamically downscale global climate projections at high spatial and temporal resolution in order to analyse the atmospheric water cycle. In southern Africa, precipitation pattern were strongly affected by the moisture transport from the southeast Atlantic and southwest Indian Ocean and, consequently, by their sea surface temperatures (SSTs). However, global ocean models often have deficiencies in resolving regional to local scale ocean currents, e.g. in ocean areas offshore the South African continent. By downscaling global climate projections using RCMs, the biased SSTs from the global forcing data were introduced to the RCMs and affected the results of regional climate projections. In this work, the impact of the SST bias correction on precipitation, evaporation and moisture transport were analysed over southern Africa. For this analysis, several experiments were conducted with the regional climate model REMO using corrected and uncorrected SSTs. In these experiments, a global MPI-ESM-LR historical simulation was downscaled with the regional climate model REMO to a high spatial resolution of $50 \times 50 \text{ km}^2$ and of $25 \times 25 \text{ km}^2$ for southern Africa using a double-nesting method. The results showed a distinct impact of the corrected SST on the moisture transport, the meridional vertical circulation and on the precipitation pattern in southern Africa. Furthermore, it was found that the experiment with the corrected SST led to a reduction of the wet bias over southern Africa and to a better agreement with observations as without SST bias corrections.

Keywords Sea surface temperature bias · Southern Africa · Atmospheric water cycle · Regional climate projections · Okavango River Basin

1 Introduction

There is a rising need for regional to local high-resolution climate change information worldwide in the transdisciplinary process of identifying and developing suitable options for climate change adaptation (UNFCCC 2011a, b, 2015). In order to provide this kind of information, a spatial refinement of the existing global climate change projections from general circulation models (GCMs) is required. The major activity in the field of downscaling is currently the ongoing World Climate Research Programme/Coordinated Regional

Climate Downscaling Experiment (WCRP/CORDEX; Giorgi et al. 2009) initiative, in which modelling centres from all over the world contribute, using both, statistical approaches (e.g. Hewitson et al. 2014) as well as classical dynamical models (e.g. Jacob et al. 2014; Nikulin et al. 2012) to provide multi-model multi-scenario multi-method ensembles to be used as input for climate change impact assessment as well as for the development of climate change adaptation strategies.

One common issue for both statistical and dynamical downscaling technique is that they often suffer from deficits, which they inherit from their global models forcing data (e.g. Denis et al. 2002). Although there is a wide range of studies available in literature proving that regional climate models (RCMs) often have the potential to provide an added value when compared to their coarser scale forcing data (e.g. Haensler et al. 2010; Torma et al. 2015), the ability for the models to correct shortcomings in the input is limited and

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depends strongly on the region, the size of the domain as well as the structure and strength of the error itself (Diaconescu and Laprise 2013).

The complex interplay between atmosphere and ocean is a common error source in the fully coupled GCMs (e.g. Wang et al. 2014). A region which stands out in this respect when analysing the latest version of coupled GCMs simulations from the CMIP5 project (Taylor et al. 2011) is the subtropical Atlantic region spanning down the west coast of Africa (Wang et al. 2014; see Fig. 1 for an illustration of the main ocean currents influencing the southern African region). This region includes the Benguela current over which a very large warm bias in SST is present in the models. The cold waters of the Benguela are known to suppress rain formation over the western parts of southern Africa (e.g. Muller et al. 2008). The Benguela current itself is influenced by the Agulhas current in the southern Indian ocean (Veitch and Penven 2017) which itself also has an impact on the rain formation in southern Africa, leading to above rainfall in the summer rainfall region during warmer SST conditions (e.g. Reason 2001).

Although the mechanism leading to the SST bias is not yet completely clear it seems that at least for the Atlantic region combinations of deficits in the cloud formation and the positioning of the ITCZ (both, over ocean and land) due to a too low horizontal and vertical resolution in the GCMs as well as deficits in the representation of the upwelling mechanism (maybe due to bathymetry) contribute a substantial amount of it (Harlass et al. 2015; Richter and Xie 2008). Recently a study of Cabos et al. (2017) showed that also the underestimation of the South Atlantic anticyclone in the models could be a driver of the warm bias in the SST. As the RCMs for studies over Africa (e.g. CORDEX Africa) get their lower boundary conditions over ocean directly from the GCMs, errors in the GCMs SST simulations directly

enter the RCMs likely to impact the simulation of rainfall and subsequently the hydrological cycle.

The impact of the SST on the simulated precipitation over Africa and especially over southern Africa, which is known to be a region with a strong interaction between SST and rainfall variability (e.g. Reason et al. 2002) has been studied before (e.g. Haensler et al. 2011). It has been shown that the warm bias in SST could lead to an overestimation in rainfall in the RCM simulation. However, it has not yet been conducted a comprehensive analysis of the impact of the SST bias on all parts of the water balance over this region. This analysis is however needed in order to identify and understand the mechanisms in the climate models leading to a change in simulated precipitation patterns. In this study, we have conducted a comprehensive analysis of the water cycle over southern African region, which is extremely vulnerable to changes in the rainfall characteristics (e.g. Schewe et al. 2014). In order to link changes in the water balance to SST bias, we conducted simulations with SST estimates directly taken from GCM as well as bias corrected SST. To be able to quantify how the different systems (Atlantic vs Indian Ocean) impact on the water balance over the southern African region, we disentangle the two main SST bias regions in our simulations. Finally, we use the Okavango River Basin as a case study region to identify the impact of the SST correction on the rainfall characteristics, as the basin has a rather complex hydrological cycle which has been analysed in REMO simulations before (Weber et al. 2014).

The paper is structured as follows: In the following section the model and experiment setup are described. Results of the study are presented in Sect. 3 and a comprehensive discussion of the results and the main conclusions drawn from this study are presented in Sect. 4.

2 Model and experiment setup

In this work, the regional climate model REMO version 2009 (Jacob and Podzun 1997; Jacob 2001) was used to analyse the impact of the SST bias on the atmospheric water cycle. The land surface scheme in REMO was simulated by the physical parameterisation of the global circulation model ECHAM4 (Roeckner et al. 1996) with modifications such as the surface runoff scheme (Hagemann and Gates 2003), the inland glaciers (Kotlarski 2007) and the vegetation phenology (Rechid 2009). The land surface was described by the topography and land-sea distribution based on United States Geological Survey (USGS) GTOPO30 (2002), by soil texture types from the Food and Agriculture Organisation of the United Nations (FAO) data (Zobler 1986) and by a global dataset of vegetation parameters from the Land Surface Parameter (LSP) II dataset of Hagemann et al. (1999) and Hagemann (2002). The soil temperatures in REMO

Fig. 1 Mean sea surface temperature (SST) distribution in (°C) with the Benguela and Agulhas current for southern Africa calculated from ERA-Interim from 1993 to 1997

were simulated by diffusion equations in five discrete layers applying the scheme of Warrilow et al. (1986) and the evapotranspiration was assigned to the vegetation types of the LSPII dataset based on the global distribution of field capacities of Patterson (1990). The sub-grid scale variations of the field capacity over inhomogeneous terrain (Dümenil and Todini 1992) and the sub-grid scale variations of soil saturation (Hagemann and Gates 2003) were taken into account by a surface runoff scheme implemented in REMO.

In the experiments, the global MPI-ESM-LR historical simulation (member r1p1i1) from the Climate Model Intercomparison Project Phase 5 (CMIP5) was used as lateral forcing only at the eight outermost gridboxes of the regional model domain. This simulation was performed with the MPI-ESM (Stevens et al. 2013) containing the global circulation model ECHAM6 coupled with the ocean model MPIOM (Jungclaus et al. 2013). The ECHAM6 model simulated the global atmospheric circulation at horizontal resolution of about 1.8° (T63) and was coupled with MPIOM at horizontal resolution of about 1.5° (GR15). The bias correction of the MPIOM SST was carried out by means of using

daily absolute SST values from the ERA-Interim dataset (Dee et al. 2011). The MPI-ESM-LR historical data was initially dynamically downscaled by the regional climate model REMO at the CORDEX-Africa domain with a horizontal resolution of $0.44^\circ \times 0.44^\circ$ ($50 \times 50 \text{ km}^2$) and, subsequently, at a southern Africa domain of $0.22^\circ \times 0.22^\circ$ ($25 \times 25 \text{ km}^2$) (Fig. 2) using 27 model levels in the vertical. In total, five high-resolution simulations were performed over the South African domain (Table 1).

The control experiment (CTL) used the MPI-ESM-LR historical (member r1p1i1) simulation downscaled by REMO at the CORDEX-Africa domain as forcing data without any SST modifications (Table 1). To isolate the impact of the Atlantic and Indian Ocean SST with their coastal currents on the atmospheric water cycle, two experiments were conducted. In the ATL-experiment, the southeast Atlantic Ocean SSTs were replaced with ERA-Interim while in the IND-experiment, the southwest Indian Ocean SSTs were replaced (Fig. 2). The intersection line of both oceans has been set along about the 34°S latitude in the southeast Atlantic Ocean to avoid cutting the Agulhas current (Fig. 1). In order to prevent leaps in the SST field along the intersection line of both oceans, a linear interpolation of the SST across the intersection line was applied. In the CRP-experiment, the SSTs of Atlantic and Indian Ocean were completely replaced by the ERA-Interim SSTs. Furthermore, in the PTD-experiment a simulation with perturbed atmospheric conditions was performed to estimate the internal model variability of REMO according the method by Sieck and Jacob (2016). This experiment was carried out by starting REMO without corrected SSTs at a different starting point (1st of December 1992) using soil data, which was in an equilibrium regarding temperature and hydrology.

The simulation periods were from 1990 to 1997 and the first 3 years were omitted in the analysis. The spin-up period of 3 years was necessary to reach an equilibrium regarding the temperature and hydrology in the soil. This experiment setup (a RCM forced by a GCM) and the relative short simulation period allow to neglect the strong decadal variability of precipitation in Africa. Nevertheless, to estimate the simulated precipitation variability and observations in the chosen experiment years, a comparison between the

Fig. 2 Model domain showing the ATL and IND ocean areas for the SST replacement

Table 1 Overview of the model experiments

Experiment	REMO forcing data	Replaced ocean SST by ERA-INT	Perturbed atmosphere
CTL	MPI-ESM-LR	No	No
ATL	MPI-ESM-LR, ERA-INT	Atlantic Ocean	No
IND	MPI-ESM-LR, ERA-INT	Indian Ocean	No
CRP	MPI-ESM-LR, ERA-INT	Atlantic and Indian Ocean	No
PTD	MPI-ESM-LR	No	Yes

precipitation produced by REMO and observational datasets from the Climatic Research Unit (Mitchell and Jones 2005) and the Global Precipitation Climatology Centre (CRU TS 3.22) (GPCC V7.5) (Becker et al. 2013) over land was conducted. The analysis shows that the seasonal cycle of the simulated and observed precipitation agrees, but the simulated precipitation is clearly overestimated in all years (Fig. 3). Therefore, we regard the precipitation variability of the chosen years as acceptable for the experiments.

To assess the impact of the inconsistencies between the atmospheric forcing from the GCM and the replaced SSTs taken from the ERA-Interim in the ATL and IND ocean area, the temporal evolution of the MPIOM SST

and the ERA-Interim SST were compared. Both SSTs are in phase and show the same seasonal cycle in the Atlantic and Indian Ocean, but with higher amplitude in the Atlantic Ocean (Fig. 4). The Atlantic SST simulated by MPIOM is distinct higher than the one of the ERA-Interim and moderate lower in the Indian Ocean. Therefore, we consider the differences between the MPIOM SST and ERA-Interim SST as temperature offset influencing the atmospheric GCM forcing. Moreover, because of the fact that the atmospheric forcing from GCM takes only place at the eight outermost gridboxes in the model domain and the capability of the RCM to react faster to SST changes due to the higher spatial and temporal resolution of the RCM, we assuming the inconsistencies between the atmospheric forcing of the GCM and the SST in our experiments of minor importance.

The precipitation results of the CTL- and the CRP-experiments were evaluated by means of the observational datasets CRU TS 3.22 and GPCC V7.5. For this purpose, the model data was regridded to the spatial resolution of both observational datasets of $0.5^\circ \times 0.5^\circ$. Moreover, to estimate the impact of the SST bias correction on a specific region being sensitive to precipitation change, the annual precipitation cycle of selected experiments (CTL, CRP and PTD) and observational dataset (CRU TS 3.22 and GPCC V7.5) were analysed over three sub-domains of the Okavango River Basin, which will be described later.

Fig. 3 Field mean of the temporal evolution of simulated precipitation generated by REMO in the control experiment (CTL) (blue) and observed precipitation from GPCC V7.05 (green) and from CRU TS 3.22 (yellow) over land southern of the equator in the model domain

Fig. 4 Field mean of the temporal evolution of simulated SSTs by MPIOM (blue) and from ERA-Interim (red) in **a** Atlantic Ocean (ATL) and **b** Indian Ocean (IND)

3 Results

3.1 Experiments

Initially, the SST from MPI-ESM-LR historical simulation was compared with the SST from the ERA-Interim reanalysis dataset to estimate the SST bias in the forcing data (Fig. 5a–d). Subsequently, the atmospheric water cycles from all experiments were analysed by evaluating the mean vertically integrated moisture transport (Fig. 6a–g), mean meridional circulation (Fig. 7a–d) calculated as the latitudinal mean from 15°S to 0° over the South African model domain, mean daily precipitation (Fig. 8a–e) and mean daily evaporation (Fig. 9a–e). The analysis of the atmospheric water cycle was restricted to the austral summer (DJF) since the major precipitation occurs in this season (Weber et al. 2014). Finally, the CTL-, CRP- and the

PTD-experiments were evaluated using observational data (Figs. 10a–f, 11a–d).

For the assessment of the changes in the atmospheric water cycle caused by SST bias, the deviations of the SSTs taken MPI-ESM-LR historical simulation from the ERA-Interim SSTs are briefly described. The results show a distinct bias both in the Atlantic and the Indian Ocean SST in all seasons (Fig. 5a–d). In particular, the SST of the south-east Atlantic Ocean is clearly overestimated by more than 8 K offshore the Namibian/Angolan coast where the Benguela current is located. Nevertheless, the MPIOM simulates a west-east SST gradient of 1–4 K depending on the season offshore the Namibian coast (not shown). On the contrary, the SST in the southwest Indian Ocean is mainly too cold up to –5 K except for the Agulhas current, which is up to 3 K too warm. The distinct bias in the SSTs, especially in coastal areas, may be a result of the misrepresentation of the coastal currents due to the coarse resolution of the ocean model.

Fig. 5 Mean seasonal sea surface temperature bias (MPI-ESM-LR historical minus ERA-Interim) for **a** Dec.–Feb., **b** Mar.–May, **c** June–Aug. and **d** Sep.–Nov. from 1993 to 1997

Fig. 6 Simulated mean vertically integrated moisture transport ($\text{kg m}^{-2} \text{s}^{-1}$) in austral summer (Dec.–Feb.) from 1993 to 1997. **a** The first row shows the absolute vectors of the CRL-experiment, the second row shows **b** the absolute vectors and **c** the difference vectors of the ATL-experiment, the third row shows **d** the absolute vectors and **e** the difference vectors of the IND-experiment and the last row shows **f** the absolute vectors and **g** the difference vectors of the CRP-experiments

In the ATL-experiment, in which the warm bias of the Atlantic SST has been corrected by the colder ERA-Interim SST, the mean vertically integrated moisture transport (VIMT) is decreased by up to $140\text{--}160 \text{ kg m}^{-2} \text{s}^{-1}$ from

the Atlantic Ocean onshore to Angola (Fig. 6a–c). This is a result of the colder SST leading to a strengthened high pressure system over the southeastern Atlantic Ocean and a strong reduction of ascending air offshore of the Angolan

Fig. 7 Simulated mean meridional circulation (mean over latitudes 0°–15°S) and specific humidity in (g/kg) in austral summer (Dec.–Feb.) of the experiment **a** CTL, **b** ATL, **c** IND and **d** CRP from 1993 to 1997. The vertical velocity has been multiplied by the factor of 350

coast. Both processes together cause a reduction of moisture uptake from the Atlantic Ocean (Fig. 7a, b). Interestingly, the change in the circulation pattern over the southeast Atlantic Ocean causes also a feedback in the circulation pattern over the southwest Indian Ocean, which triggers an enhanced VIMT offshore to northern of Madagascar and a slightly increase onshore to Mozambique southern of Madagascar (Fig. 6a–c).

As a result of the decreased VIMT and vertical velocity offshore of the Angolan coast, the mean daily precipitation is also clearly decreased area widely by more than –20 mm/day over the southeast Atlantic ocean, but also decreased over Angola and northern Namibia (up to –5 to –10 mm/day) and southwestern Zambia (up to –2 to

–5 mm/day) (Fig. 8a, b). An increase in mean daily precipitation is simulated between the Tanzanian/Mozambican coasts and northern Madagascar over the Indian Ocean (up to 10–15 mm/day) as well as at the equator over the Atlantic Ocean (up to 5 to 10 mm/day) (Fig. 8a, b). The mean daily evaporation and evapotranspiration are decreased (up to –2 to –5 mm/day) over the southeast Atlantic Ocean due to the colder SST and decreased over western Angola (up to –2 to –5 mm/day) and north-western Namibia (up to –1 to –2 mm/day) caused by the reduction of available surface moisture (Fig. 9a, b). Overall, the correction of the warm Atlantic SST bias causes changes in the atmospheric water cycle, which is distinctly attenuated over the southeastern Atlantic Ocean and over southwestern Africa, and slightly

Fig. 8 Simulated mean daily precipitation in the austral summer (Dec.–Feb.) from 1993 to 1997. **a** Absolute values of the control experiment (CTL) in (mm/day) and differences of the experiments **b** ATL, **c** IND, **d** CRP and **e** PTD to the control experiment in (mm/day)

increased between the Tanzanian/Mozambican coasts and northern of Madagascar over the Indian Ocean.

The IND-experiment, in which the cold bias of the Indian SST has been corrected by the warmer ERA-Interim SST, simulates similar changes in mean VIMT over the southwest Indian Ocean as in the ATL-experiment. In detail, the mean

VIMT is enhanced clockwise around Madagascar with a pronounced flow by up to $120\text{--}140\text{ kg m}^{-2}\text{ s}$ offshore the Tanzanian/Mozambican coasts to northern Madagascar (Fig. 6a, d, e). The mean meridional circulation shows a clear increase in ascending air over the southwest Indian Ocean, which can be attributed to the warmer SST (Fig. 7a, c). This causes,

Fig. 9 Simulated mean daily evaporation/evapotranspiration in the austral summer (Dec.–Feb.) from 1993 to 1997. **a** Absolute values of the control experiment (CTL) in (mm/day) and differences of the experiments **b** ATL, **c** IND, **d** CRP and **e** PTD to the control experiment in (mm/day)

together with the enhanced VIMT, a strong increase in mean daily precipitation by up to 20 mm/day over the southwest Indian Ocean, in particular, north-westerly of Madagascar and at the eastern side of Madagascar (up to 10–15 mm/day). Only the middle and the southern part of the Mozambique Channel experiences largely decreased precipitation (up to

– 5 to – 10 mm/day) (Fig. 8a, c). Furthermore, the warmer SST leads to a wide area with increased mean daily evaporation by up to 2–5 mm/day over the southwest Indian Ocean, except for the Agulhas current and westerly of Madagascar showing a decrease (up to – 2 to – 5 mm/day) (Fig. 9a, c). In general, the correction of the cold Indian SST bias induces

Fig. 10 Comparison of simulated precipitation in the austral summer (Dec.–Feb.) with CRU TS 3.22 and GPCC V7.05 data from 1993 to 1997. **a** Absolute values of CRU TS 3.22 in (mm/day), **b** absolute

values of GPCC V7.05 in (mm/day), differences of the experiment **c** CTL and **e** CRP to CRU TS 3.22 in (mm/day), and differences of the experiment **d** CTL and **f** CRP to GPCC V7.05 in (mm/day)

an enhancement of the atmospheric water cycle only over the southwest Indian Ocean, especially around Madagascar.

In the CRP-experiment, in which the SST biases of both the Atlantic and the Indian Ocean were corrected,

the mean VIMT is distinctly decreased by up to 120–140 kg m⁻² s from the Atlantic Ocean onshore to Angola and strongly enhanced by more than 180 kg m⁻² s northerly of Madagascar offshore to the Indian Ocean. Moreover, the

Fig. 11 Simulated and observational mean daily precipitation in (mm/day) over three sub-domains of the Okavango River Basin from 1993 to 1997. **a** Location of the Okavango River Basin with the orography in (m) and the sub-domains **b** SD1, **c** SD2 and **d** SD3

mean VIMT is slightly increased by up to 100 to $\text{kg m}^{-2} \text{ s}$ southerly of Madagascar onshore to Mozambique (Fig. 6a, f, g). The modifications in the mean meridional circulation are a combination of changes in the ATL-experiment with a strong reduction of ascending air offshore of the Angolan coast and of the changes in the IND-experiment with strong increase in ascending air over the southwest Indian Ocean, which is more pronounced in the lower atmosphere (below 400 hPa) as in the IND-experiment (Fig. 7a–c). The mean daily precipitation is area widely decreased over Angola, Namibia, southern Zambia, Botswana, South Africa and western Madagascar between -0.5 and -10 mm/day (Fig. 8a, d). According to the reduced moisture availability caused by the decreased precipitation, the mean daily evapotranspiration is also decreased between -2 and -5 mm/day over western Angola, northern Namibia, parts of Botswana and South Africa (Fig. 9a, d). Altogether, the correction of the SST bias both in the Atlantic and the Indian Ocean in the CRP-experiment generates a superposition of the results from the ATL- and the IND-experiment with regionally attenuations and intensifications of the atmospheric water cycle.

In order to assess the changes in the atmospheric water cycle caused by the internal model variability, a perturbed simulation was carried out in the PTD-experiment. In this simulation, almost no changes in the mean VIMT are noticeable compared to the changes resulting from the SST bias corrections (not shown). The mean daily precipitation shows a small-scale noise of positive and negative deviations from the CTL-experiment which are characteristic for precipitation (Fig. 8a, e). Furthermore, almost no changes in mean daily evapotranspiration are recognisable in this experiment (Fig. 9a, e). In total, the changes in the atmospheric water cycle caused by the SST bias correction are more pronounced than the one caused by the internal model variability.

3.2 Evaluation of precipitation

To estimate the impact in the simulated mean daily precipitation in the austral summer (Dec.–Feb.) by the application of the SST bias correction, an evaluation of the precipitation results from the CTL and CRP experiments using the CRU and GPCC dataset has been carried out. By

applying two different observational data in this analysis we would like to take into account the scarcity of station data in several regions of Africa which affect the generation of observational gridded datasets (Nikulin et al. 2012; e.g. Akinsanola et al. 2016). The results show that the mean daily precipitation is clearly overestimated over southern Africa and Madagascar without SST bias correction (Fig. 10a–d). However, by applying the SST bias correction, the wet bias is strongly reduced over southern Africa (Fig. 10a, b, e, f). Over western parts of Angola, at the coast of Namibia and over South Africa, the wet bias is partly turned into a dry bias. In summary, the SST bias correction causes remarkably improvements in the simulation of the mean daily precipitation over southern Africa.

3.3 Precipitation sensitivity over the Okavango River Basin

The impact of the SST bias correction on the regional scale is analysed using the annual precipitation cycle over three sub-domains of the Okavango River Basin (Fig. 11a). The sub-domains are chosen according to the topography and climate along the river. Sub-domain 1 (SD1) (lon. 15.75°E–19.71°E, lat. 15.49°S–12.19°S) encompasses the northern part of the river basin with the Angolan highlands being the source region of the Okavango River. Sub-domain 2 (SD2) (lon. 16.63°E–21.69°E, lat. 17.91°S–15.49°S) covers the downstreams areas of the river between the Angolan highlands and the Angolan/Namibian border, and sub-domain 3 (SD3) (lon. 16.19°E–28.51°E, lat. 25.17°S–17.91°S) contains the southern part of the river basin with the Okavango River Delta and the Kalahari Desert.

In SD1, covering the mountainous source region of the river with the most amount of mean daily precipitation, the CTL- and the PTD-experiment produce almost in all months noticeable more precipitation compared to the observations, whereas the phase of the annual cycle fits roughly with the observational reference dataset (Fig. 11b). The simulated precipitation of the SST bias corrected CRP-experiment shows a good agreement with the observations except for September and October, which seems to be a model specific issue. Similar results are found in SD2, which is covering the intermediate basin area and in SD3, which includes the Kalahari Desert with the lowest amount of mean daily precipitation (Fig. 11c, d). In both sub-domains the simulated precipitation in the experiment with the corrected SST gives the best fit to the observational reference dataset compared to the experiments with the uncorrected SST bias. This analysis for a specific river basin demonstrates the strong sensitivity of the SST bias correction on the precipitation, in particular, for those regions with a high precipitation amount.

4 Discussion and conclusion

A set of sensitivity experiments was conducted to analyse the impact of the sea surface temperature (SST) bias correction on the atmospheric water cycle over southern Africa using the regional climate model REMO. In each experiment, the global MPI-ESM-LR historical simulation (member r1p1i1) from the Climate Model Intercomparison Project Phase 5 (CMIP5) was dynamically downscaled by REMO at the CORDEX-Africa domain with a horizontal resolution of $50 \times 50 \text{ km}^2$ and, subsequently, at a southern Africa domain of $25 \times 25 \text{ km}^2$. The SST bias correction was carried out using the SST from the ERA-Interim dataset (Dee et al. 2011) for the southern Africa domain. A distinct SST bias was found both in the Atlantic and the Indian Ocean SST in all seasons. In the southeast Atlantic Ocean the SST is clearly overestimated of more than 8 K in the area of the Benguela current offshore the Namibian/Angolan coast, which is a similar bias from most coupled general circulation models (GCMs) in the CMIP5 model sets (Toniazzi and Woolnough 2014). The SST in the southwest Indian Ocean is mainly underestimated partially up to -5 K except for the Agulhas current showing overestimation up to 3 K . In total, five different simulations were performed with REMO at the southern Africa domain and analysed from 1993 to 1997. The results show that the SST bias correction has a distinct impact on the atmospheric water cycle over southern Africa, which is stronger than the internal model variability.

The bias correction causes a colder SST in the southeast Atlantic Ocean and mostly a warmer SST in the southwest Indian Ocean affecting the circulation pattern over the southern African continent. In detail, the colder Atlantic SST induces a reduction of ascending air offshore the Angolan/Namibian coast due to a strengthened high pressure system over the south-eastern Atlantic Ocean and a decreased vertically integrated moisture transport (VIMT) from the Ocean onshore to the continent. Over the southwest Indian Ocean the ascending air is increased due to the warmer SST. As a result of these circulation changes, mean daily precipitation over Angola, Namibia and western Madagascar is strongly decreased, and Botswana and South Africa undergo also dryer conditions. Moreover, the experiments identify the southeast Atlantic Ocean as main driver for the changes in the atmospheric water cycle which may be caused by the strong SST bias of more than 8 K. These findings coincide with the GCM experiments by Eichhorn and Bader (2017), which show an intensification/weakening of ascending air in the Atlantic Walker Circulation Cell with a positive/negative Atlantic SST bias. The work of Cabos et al. (2017) demonstrates by applying the coupled regional

atmosphere–ocean version of REMO that the SST bias along the Angola-Benguela front zone can be reduced when the South Atlantic anticyclone is prescribed. This indicates an atmosphere–ocean feedback of the SST bias in this region. In our experiments, using approx. 25 km horizontal resolution compared to approx. 50 km applied by Cabos et al. (2017), we found an increase of the mean sea level pressure over the south-eastern Atlantic suggesting a strengthening of the anticyclone when the Atlantic SST warm bias was corrected (not shown). Consequently, there is also an ocean–atmosphere feedback of the SST bias, which may be worth investing further. Eichhorn and Bader (2017) found a shift of the annual-mean precipitation maximum from the west to the east Atlantic caused by a slow-down of the zonal overturning circulation, which can not be clearly answered by our experiments due to the smaller model domain. However, our experiment using the corrected Atlantic SST bias produces a distinct increase in precipitation at the equator in the austral summer (Dec.–Feb.). The findings are also supported by the results from Rouault et al. (2003), wherein a relation between southeast Atlantic warm events and above average African precipitation over the southeast Atlantic and western Angola/Namibia in observational and reanalysis data were found. Similar results were obtained by Hansingo and Reason (2009) using a global circulation model, which produces anomalous precipitation along the Angolan and northern Namibian coast by imposing increased Atlantic SST offshore Angola in the forcing data. Furthermore, this work also coincides with the results of Paxian et al. (2016), wherein West African rainfall predictions could be improved by reducing the tropical Atlantic SST bias when regional predictions were coupled to a global ocean model. We have shown that the usage of a regional climate model with higher resolved atmospheric processes in combination with corrected SSTs lead to more realistic representation of the atmospheric water cycle similar to results of Paeth et al. (2017).

A comparison of simulated daily precipitation with the observational datasets of CRU and GPCC indicates a clear reduction of the wet bias over southern Africa when the SST bias has been corrected. On the regional scale, the simulated annual precipitation cycle over the Okavango River Basin is also distinctly affected by the SST bias correction and shows better agreement with observations as without an SST bias correction. Thereby, the impact of the bias correction is more pronounced in areas with higher precipitation amount than in areas with lower ones.

This work demonstrates clearly the sensitivity of the SST bias correction on the atmospheric water cycle in a regional climate model. The advantage of these experiment setups is the usage of SST corrections derived from reanalysis data compared to artificial imposed perturbed SST, which may

cause unclear results (Williams et al. 2010). However, there are some caveats in the applied experiment setups. Firstly, the regional climate model allows no interactions between the ocean surface and the lower atmosphere, which are possible in coupled regional atmosphere–ocean models. These interactions are important in oceanic upwelling regions, such as in the Benguela upwelling system, where wind modifications in a regional ocean model cause large changes in the surface current and upwelling (Small et al. 2015). Furthermore, Ratnam et al. (2015) show in their work, that the usage of a coupled regional ocean–climate model produces a good agreement in simulated precipitation with observations over southern Africa. Secondly, it has to be kept in mind that the applied method of the SST bias correction causes some inconsistencies between the corrected SSTs and the atmosphere in the RCM. These inconsistencies are strongest in the eight outermost gridboxes of the model domain, which are used as lateral forcing in REMO, and weakens within the model domain in which the atmosphere can react freely to the SST. Thirdly, the achieved improvements in simulating the atmospheric water cycle using a corrected Atlantic and Indian SSTs are only valid for this region and experiment setup, and may differ in other experiments configurations as found by Paxian et al. (2016). Finally, in this work only one regional climate model was applied for downscaling five years global model forcing data. To achieve more confidence in the findings, it would be appropriate to repeat the experiments with an extended simulation period and with an ensemble of different regional climate models.

The outcome of this research shows that the SST bias stemming from GCMs in the Atlantic and Indian Ocean has to be taken into account in the creation of climate projections for southern Africa. Therefore, an SST bias correction is strongly recommended when a regional climate model is used without a coupled ocean model to downscale climate projections. This can be done with the anomaly approach in which the SST bias is eliminated by systematically impressing an increased or decreased SST on the forcing SST for each timestep (Haensler et al. 2011). Another, more physical method is to apply a coupled regional atmosphere–ocean model, which can represent the coastal SST more properly by a higher spatial resolution and, which allows interactions between the ocean surface and the atmosphere (e.g. Ratnam et al. 2015; Sein et al. 2015). With higher resolution and proper representation of the air–sea interactions, the atmospheric water cycle in southern Africa could be well-simulated.

Acknowledgements This work was realised as part of the research project “The Future Okavango” funded by German Federal Ministry of Education and Research (BMBF). The REMO simulations were performed at the German Climate Computing Center (DKRZ) through support from the BMBF. Furthermore, the authors would like to thank

the anonymous reviewers and the colleagues of the Climate Service Center Germany (GERICS) for their constructive support.

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