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CAN CMIP6 CLIMATE SIMULATIONS ACCURATELY REPRODUCE STATION DATA?

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Introduction

The validation of climate models is an important step of regional climate analysis, helping to select best performing models (Getaneh Ayele et al., 2024). CORDEX climate models have been recommended for regional studies in Africa as the models have a high resolution and more ability to reproduce climatology over the complex topography of the African domain (Kassahun et al., 2023). However, the Coupled Model Intercomparison Project (CMIP) within the World Climate Research Programme has recently completed its sixth phase (CMIP6) with some model runs at a higher resolution (0.5-1°) and better parametrizations (Mackallah et al., 2022) than earlier, in CMIP5 (from which global climate model (GCM) runs were used as driving data for Africa-CORDEX). Even though the spatial resolution is still somewhat coarser in CMIP6 simulations than in Africa-CORDEX simulations, new scenarios are available only for CMIP6-models, and more time is needed for downscaling them for Africa. The aim of this paper is to evaluate whether or not the historical GCM runs from CMIP6 outperform the corresponding runs within CORDEX-Africa driven by CMIP5, so the newer versions of GCMs can accurately be used for regional climate analysis.

Studies have highlighted that the performance of climate models differ within regions (e.g. Palmer et al., 2023; Nguyen-Duy et al., 2023). Therefore, it is recommended that specific models are selected for local analysis (Wada et al., 2022) in order to obtain accurate information for policy and impact analysis. This report aims to guide the next phase of our research in model selection for the analysis of the effect of climate change on viticulture in the Western Cape of South Africa. We have previously analyzed the performance of CORDEX data (i.e. regional climate model (RCM) simulations) against the station data provided by the ARC in South Africa (Chauke & Pongrácz, 2024). The model simulations were generally able to reproduce the annual cycle of temperature in the selected districts, with correlation > 0.90 and RMSE < 2°C indicating good performance, however, RegCM4 showed high variability regardless of the driving GCM. On the contrary, precipitation validation indicated high variability between the model simulations and station data especially in Citrusdal Valley, while some stations exhibited better agreement with the station data. The model simulations had a correlation coefficient < 0.7 with exception to performance in Swartland wherein the model simulations indicated a better ability to reproduce precipitation.

Previous studies (e.g. Gwiza & Jarbandhan, 2024) have highlighted a challenge in the validation of climate models against observational data sets due to the lack of sufficient station records in Africa. For example, in the previous study we conducted (Chauke & Pongrácz, 2024), more than 60% of data was missing resulting in exclusion of several districts from the analysis. However, CRU[1] offers reliable data sets that can be used for accurate validation of monthly

[1] Climatic Research Unit (University of East Anglia)

climate data. We validated both the CORDEX-Africa simulations and the most recent simulations from CMIP6 for a broad overview of the performance of climate models in the entire area of South Africa. We found that CMIP6 climate models exhibited an ability to accurately preproduce data in some South African provinces. Therefore, this report evaluates if such performance will be reflected at a district level in the Western Cape where the majority of the country's viniculture is practiced.

Study area

The Western Cape province is located at the southwestern part of South Africa, with a 400 km coastline bordering the Atlantic and Indian oceans. The Western Cape has a Mediterranean climate, which is influenced by both the Indian and Atlantic Ocean. The province has unique and variable topography, which also contributes to its climate. The commercial wine and grape industry have taken over some of the natural vegetation units of the province, thus making it vulnerable to the effects of climate change. Viniculture significantly contributes to the provinces culture and the country's economy; therefore, it is important to understand climatic factors that may threaten quality and yields. The validation of climate model simulations is the first step of determining the models that can accurately capture the complex climate of the region.

Data and methodology

Monthly temperature and precipitation data were downloaded from the CMIP6 data node that is freely available from the Earth System Grid Federation (ESGF) server. The following model simulations are used in this study: HadGEM3-GC31-MM (indicated as HadGEM3 in a short form), NorESM2-MM (NorESM2 in short form) and MPI-ESM1-2-HR (MPI in short form). The observational data was provided by the South African Agricultural Research Centre (ARC), we selected data from Cape Agulhas, Citrusdal Valley, Robertson, Swartland, Swellendam and Worcester. Note that there was no temperature data from Swellendam; however, it is included in the study for precipitation data analysis. The study period covers the historic runs of climate models, more specifically, from 1981 to 2000. We calculated multi-year monthly mean values from both data sets, and extracted the local data from the climate model simulations using the nearest neighbor remapping function in CDO[2]. Then, the data was exported to R and the Taylor diagrams were plotted.

Results and discussion

CMIP6 models have exhibited substantial improvements in capturing local climate patterns compared to its predecessors. These improvements and model set up are observed in the changes in root-mean-squared-error (RMSE), correlation coefficients and standard deviation (SD). However, the performance of the GCM simulations varies with some districts outperforming others.

Temperature

The model simulations exhibit high correlation (> 0.90) with the station data. However, relatively higher RMSE are observed (*Figure* 1). The NORESM2 and MPI simulations improved in terms

[2] Climate Data Operators

of RMSE and SD in Robertson, while some model simulations exhibit slight decrease in correlation, coupled with a decrease in RMSE in the other stations.

The high correlations between the model simulations and station data indicate a strong agreement and the model's ability to reproduce the overall temperature climatology. However, the substantially high RMSE in CMIP6 simulations compared to CORDEX-Africa simulations indicate that there are greater biases in the model simulations processing temperature (Firpo et al., 2022), therefore, this suggests that CMIP6 data should be used with caution at local scale.

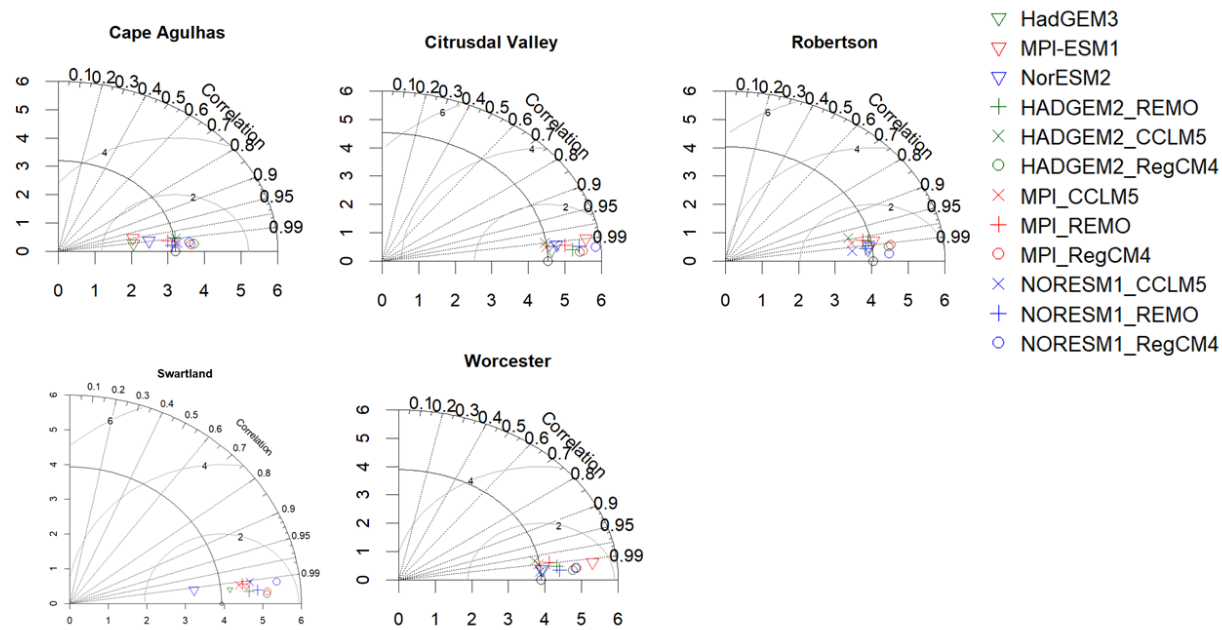

Figure 1: Taylor diagrams depicting the model performance over the selected stations. The model simulations are able to preproduce the general annual cycle of temperature, with r > 0.95 in all stations.

Precipitation

Despite continuous developments and improvements of climate models, precipitation is still difficult to reproduce. Lower correlation and higher variability between the CMIP6 simulations and ARC data can be seen (*Figure 2*) compared to CORDEX-Africa simulations vs ARC data. As reported in previous studies (e.g. Kassahun et al., 2023) the model simulations behave differently in different regions.

Robertson is selected for a more detailed analysis in this report. *Table 1* shows that the NorESM2 was greatly improved to capture local precipitation with lower RMSE (0.36 mm/month) and a slight change in SD. The MPI and HADGEM3 performance did not substantially improve. Even though there are some improvements in RMSE (became lower), the model simulations have a lower correlation with station data (0.44–0.60).

The CMIP6 GCM-simulations exhibit similar behaviour as CORDEX-Africa model simulations in Worcester. However, an improvement in SD and RMSE is observed in HADGEM3 and NorESM2, more specifically a higher SD in HADGEM3 and a lower SD in NorESM2 compared to CORDEX-Africa model simulations. A slight change in correlation is observed (0.6–0.73) in Cape Agulhas with the MPI and NorESM2 showing improvements in

RMSE and variation. The GCM simulations were able to reproduce the overall annual precipitation cycle in Swartland, exhibiting high correlation (0.95), low variations (i.e. SD) and RMSE. The greatest improvement in the GCMs is noted in Citrusdal Valley, where the local precipitation is well captured. On the contrary, poor performance was observed in Swellendam, as previously observed in the validation of CORDEX-Africa model simulations against the ARC station data, this poor performance may be attributed to missing data in the station data.

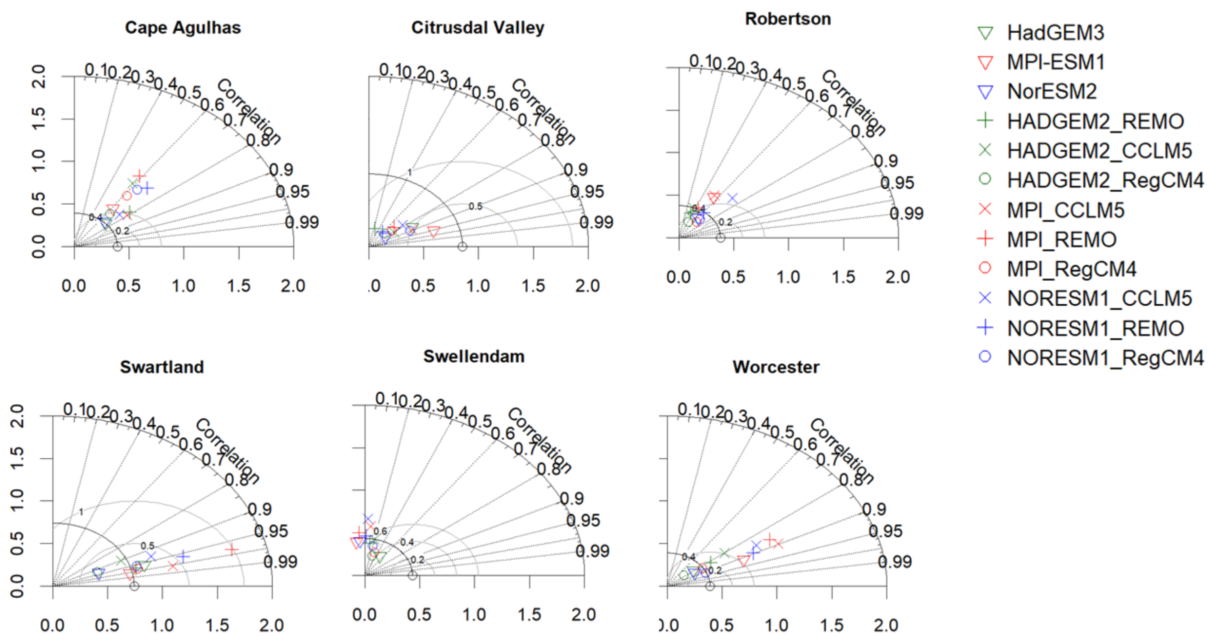

Figure 2: Taylor diagrams depicting variable model performance in simulating precipitation over the selected stations.

The models exhibit an overall improvement, however, they still struggle to reproduce local precipitation in areas of complex topography (Gan & Yang, 2023). Among the GCMs the NorESM2 and MPI show that their set up was improved to reduce the errors (RMSE) in the models at local scale. However, the CMIP6 model simulations still provide valuable information regarding overall precipitation for agricultural studies requiring a careful analysis. Therefore, we recommend the HADGEM3 simulation in Robertson, Worcester, Cape Agulhas and Swellendam, and MPI simulation for Citrusdal Valley and Swartland for local precipitation analysis. We recommend the use of HADGEM3 in Citrusdal Valley, Swartland and Cape Agulhas, moreover, MPI in Robertson and NorESM2 may also so be used in Worcester and Robertson for precipitation analysis using the GCMs. However, it is important to use more than one model simulation for a thorough analysis in order to take into account uncertainties from different sources.

We still recommend the use of CORDEX-Africa model simulations for local temperature analysis because even though the CMIP6-simulations are able to capture the overall temperature climatology with high correlations, they have higher errors compared to CORDEX-Africa models (which may produce more accurate predictions as a consequence of lower RMSEs).

Table 1: Summary statistics for model performance in simulating precipitation over Robertson: Centered RMSE (cRMSE), correlation coefficient (r) and the standard deviation (SD) difference between model outputs and observational data.

	cRMSE	***r***	**SD difference**
HadGEM3	0.365	0.441	-0.082
MPI-ESM1	0.481	0.552	0.202
NorESM2	0.311	0.596	-0.090
HADGEM2_CCLM5	0.424	0.365	-0.005
HADGEM2_RegCM4	0.347	0.420	-0.182
HADGEM2_REMO	0.395	0.352	-0.074
MPI_CCLM5	0.499	0.548	0.223
MPI_RegCM4	0.287	0.651	-0.137
MPI_REMO	0.408	0.447	0.018
NORESM1_CCLM5	0.480	0.722	0.310
NORESM1_RegCM4	0.289	0.656	-0.090
NORESM1_REMO	0.330	0.614	-0.007

Conclusion

The CMIP6 models exhibit improvements in the GCMs' performances, however, the models vary individually and across districts. Therefore, it is important to select the best performing models based on the actual target region. While CMIP6 simulations may provide new insights due to the new SSP[3] scenarios (O'Neill et al., 2017) applied to the predictions, the inclusion of CORDEX-Africa model simulations is still important for local studies, which requires more details and more precision for decision making. The RCMs have a higher resolution and better parameterizations for near-surface mechanisms for regional climate analysis. These new scenarios will eventually be available with higher resolution (i.e. GCM simulations downscaled via RCMs), so they can be used in the future.

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[3] Shared Socioeconomic Pathways

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