



# The validation of climate in the wine-growing region of the Western Cape of South Africa

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## Abstract

The Western Cape province, home to the majority of South Africa's viticulture, is highly vulnerable to the effects of climate change. This study validates the Coordinated Regional Climate Downscaling Experiment (CORDEX) temperature and precipitation outputs along with their viticultural bioclimatic indices over the Western Cape for the historic period (1980–2000) as the first step to determining the ability of the models to accurately simulate future conditions. From the results, we observed that the output had a high agreement with observational data in the case of reproducing monthly average temperatures while precipitation outputs show high variability with moderate to high agreement. The performance of the models in simulating the viticultural indices greatly depends on location with some models performing better than others. The results of this study will contribute to current efforts to understand the dynamics of climate change and viticulture in the Western Cape, where extreme events associated with climate change are already affecting farmers and potentially impacting the industry's production and quality.

**Keywords** Regional climate model · Validation · Projection · Warming · Drought · Viticulture

## 1 Introduction

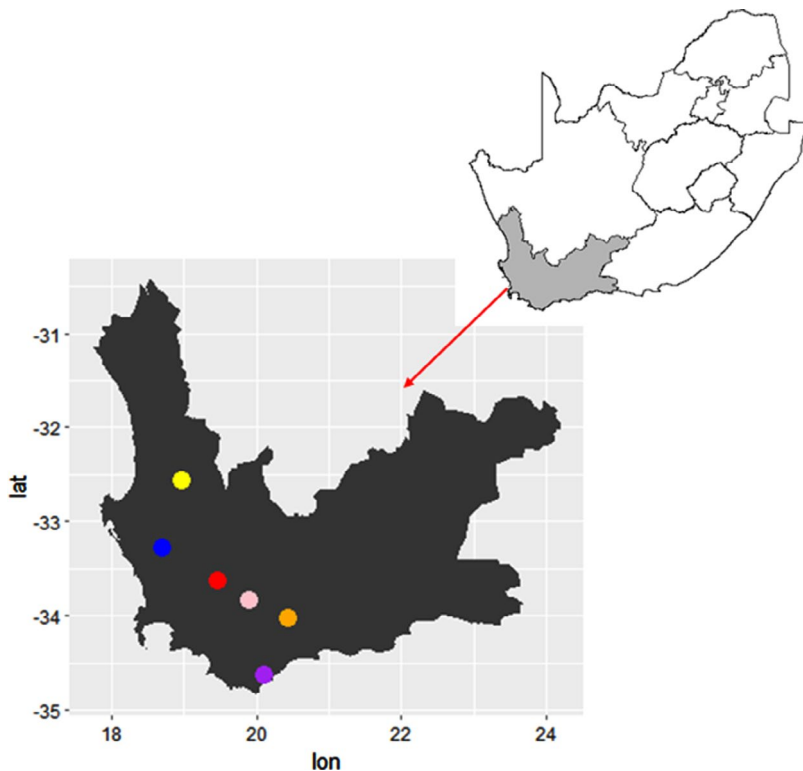
South Africa is among countries that are most susceptible to the severe effects of climate change (Anyanwu et al. 2015). The recent Intergovernmental Panel on Climate Change (IPCC) report has highlighted that the Southern African region is highly vulnerable to the effects of climate change due to its dependence on climate-sensitive

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ecosystem services and limited capacity to adapt to climate change (IPCC 2022),. The vulnerability of the African region prompted the World Climate Research Program to start the Co-ordinated Regional Climate Downscaling Experiment (CORDEX) with the aim of improving and providing accurate regional climate projections for Africa and therefor strengthen the climate research community in the region (Dosio and Panitz 2016). Studies from this initiative have reported that warming is projected to reach around 3 to 4 °C along the coast, and 6 to 7 °C in the interior by the end of the century. Thus, resulting in more frequent climatic extremes which are already occurring in South Africa, the country has experienced droughts and severe water scarcity challenges in recent years due to its natural dryness. The droughts were most prominent in the Western Cape (Fig. 1), wherein prolonged droughts leading to the day zero drought which threatened the complete halt of potable, agricultural and industrial water supply. (Dube et al. 2022). The province has been previously prone to droughts (e.g. previous studies highlighted that the change in climate may increase the occurrence of dry spells as the province is already vulnerable to droughts, there need for improved water management strategies and adaptative governance in the regions will persist (Orimoloye et al. 2022; Otto et al. 2018). The Western Cape Department of Environmental Affairs and Development Planning has extensively researched the



**Fig. 1** The map of the Western Cape within South Africa, highlighted stations with observational data for validation: yellow=Citrusdal Valley, blue=Swartland, red=Worcester, pink=Robertson, orange=Swellendam, purple=Cape Agulhas

effects of climate change on the province and had prepared a climate change response strategy focusing on helping the 9 major sectors to adapt to the rapid change in climate (Pienaar and Boonzaaier 2018). This area is of interest to this study because this is where the majority of South Africa's viticulture is practised. Climate change will have major implications on the agricultural sector, including viticulture (e.g., Zwane 2019). These temperature increases will bring changes in rainfall patterns, which together with the rising atmospheric carbon dioxide levels could shift the distribution of South African terrestrial biomes (Engelbrecht and Engelbrecht 2016).

Winegrape cultivation greatly depends on optimal conditions, however, the projected increase in temperature due to climate change will have implications on the viticultural industry where production and wine quality may be altered (van Leeuwen et al. 2019). Increasing temperatures may make some regions less suitable for vine grape growing and potentially favour areas that were previously not suitable for the production of certain varieties (Malheiro et al. 2010). The change in climate will also result in increased pests and diseases which may affect yields. Viticulture is one of the most important contributors to South Africa's GDP. It was reported to have employed over 266 000 people and generated R 55 billion in 2020.

Therefore, considering the sensitivity of this industry, it is important to understand the severity of climate change in the future so that we can start implementing adaptation strategies as some farmers are already affected by extreme events associated with climate change. Wherein the increase of climate thus far has resulted in a shift in growing seasons (Ausseil et al. 2021). This study will contribute to the current efforts to understand the dynamics of climate change and viticulture as we will validate CORDEX outputs and their bioclimatic indices. Thus, evaluating the ability of the models to accurately simulate future extreme events.

Although many studies focused on southern Africa, by the time of this study, there is no available study focusing on climate change analysis using CORDEX simulations over the wine region of the Western Cape at a finer spatial resolution of  $0.22^\circ$  despite the vast research done on the province following the droughts.

Several studies evaluated the performance of the simulations at a resolution of  $0.44^\circ$  against the Climate Research Unit (CRU) and GPCC observation data over southern Africa (Favre et al. 2016; Abiodun et al. 2019). It was observed that climate models were able to reproduce observed climate trends. Other African studies show that the simulations can maintain the precipitation gradient of their domain from the West to the East in the southern hemisphere (e.g., Kim et al. 2014). However, almost all of them produced a wet bias over drier regions of southern Africa (Botai et al. 2017). The model simulations underestimated the average temperature but the minimum temperature was greatly overestimated, thus indicating a common weakness in the physics parameterization of the models (Panitz et al. 2014). The main objective of this study is to analyse the ability of the Co-ordinated Regional Climate Downscaling Experiment (CORDEX) outputs to accurately reproduce temperature and precipitation over the Western Cape for the historic period (1980–2000), and validate viticultural indices calculated from these outputs against observational data. The three regional climate models used in the CORDEX downscaling experiment focusing on Region 5 include CCLM5-05-15, REMO2015 and RegCM4-7. The simulations are driven by the Nor-ESM1-M, MPI-MPI-ESM-LR and the MOHC-HADGEM-Had-

GEM2-ES (Giorgi et al. 2011; Panitz et al. 2014; Runde et al. 2022) as described by Nikulin et al. (2012). All these simulations are available at  $0.22^\circ$  and  $0.44^\circ$  for the African domain. There is no finer resolution available for Africa due to the large extension of the continent, which limits the simulations. Panitz et al. (2014) indicated that there was no significant change in model performance with a change in spatial resolution. Therefore, we theorise that while the simulation data will provide useful data to help analyse the relationship between climate change and viticulture, the models may not accurately reproduce the climatic conditions of some wine regions due to the complex topography of the province which might result in overestimation of climatic conditions.

## 2 Study area

The study focuses on the wine region in the Western Cape of South Africa (Fig. 1). The province's surface area covers 129,642 km<sup>2</sup>, with a Mediterranean climate. With temperature ranging between 15 and 27 °C and 5–22 °C in summer and winter respectively (Naik and Abiodun 2020). The annual precipitation of the province ranges between 300 and 900 mm (Botai et al. 2017) thus, receives more rainfall than the rest of the country in winter. The precipitation gradient varies within short distances due to the variable topography of the province. The annual rainfall has greatly decreased (30–50%) over the past years, especially during the 2015–2017 drought (Otto et al. 2018). The province is rich in agriculture and fisheries, and the region is rich in vineyards. Major wine regions include Stellenbosch, Paarl and Robertson.

The wine region of the Western Cape was approximately 73 654 ha in 2022 (SAWIS 2022). Five major wine regions were identified by the Wines Of South Africa namely; the Citrusdal Valley, Coastal region, Cape South Coast, Breede River Valley and the Klein Karoo (WOSA 2022), from which 6 wine of origin districts were selected for this study. The province produces approximately 60% of the wines in South Africa, from which 55% were red and 45% were white wines in 2020 (SAWIS 2022). The largest and most dominant wine region according to WOSA is Breedekloof followed by Robertson which currently produces more wine than ever (See Table 1).

## 3 Data and methodology

### 3.1 Simulation data

The simulated data used in this study was obtained from the Earth System Grid Federation (ESGF) server of the publicly available database of the CORDEX-programme which focuses on regional climate modelling of different domains. The simulation data used in this study covers historical outputs from nine simulations with a horizontal resolution of  $0.22^\circ$  from the CORDEX Africa experiment. The historic simulation data used three Regional Climate Models (RCMs) (i.e., CCLM5, REMO2015, and RegCM4-7) driven by three Global Climate Models (GCMs). The simulated data used in this study are for temperature and precipitation at a daily spatial reso-

**Table 1** CODEX models used in the study

RCM	MOHC HadGEM - CCLM5-0-15	MPI MPI - CCLM5-0-15	NCC NorESM - CCLM5-0-15	MOHC HadGEM - REMO2015	NCC NorESM - REMO2015	MPI MPI - REMO2015	MOHC HadGEM - RegCM4-7	MPI MPI - RegCM4-7	NCC NorESM - RegCM4-7
Institute	KIT and CLM community	KIT and CLM community	KIT and CLM community	Climate Service center Germany	Climate Service center Germany	Climate Ser- vice center Germany	Abulus Salam Center for Theoretical Physics	Abulus Salam Center for Theoretical Physics	Abulus Salam Center for Theoreti- cal Physics
Parameters	Temperature Precipitation Non-hydrostatic	Temperature Precipitation Non-hydrostatic	Temperature Precipitation Non-hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic
Dynamics	Temperature Precipitation Non-hydrostatic	Temperature Precipitation Non-hydrostatic	Temperature Precipitation Non-hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic	Temperature Precipitation Hydrostatic
Realization	rl1pl V1	rl1pl V1	rl1pl V1	rl1pl V1	rl1pl V1	rl1pl V1	rl1pl V1	rl1pl V1	rl1pl V1
Version	V1	V1	V1	V1	V1	V1	V1	V1	V1

lution. The model selection is the dominant source of uncertainty in precipitation simulations especially at a regional scale while the different scenarios are the most important source of uncertainty for temperature simulations when analysing climatic changes at a 100-year scale (Hawkins and Sutton 2009).

### 3.2 Observational data

Daily meteorological data (precipitation, minimum and maximum temperature) measured by ten ground stations from 1980 to 2022 were provided by the South African Agricultural Research Centre (ARC) in CSV format containing the location with specific longitude and latitude. Stations with more than 5% missing data and those that did not have data from the period of our reference period (1980–2000) were excluded from the analysis. Therefore, we selected 6 stations namely, Citrusdal Valley (32°33'59.997"S, 18°59'00.0018"E, 198 m), Swartland (33°16'59.9982" S, 18°42'0.0036" E 177 m), Worcester (33°37'20.6394" S, 19°28'8.04" E, 307 m), Robertson (33°49'59.994" S, 19°53'59.9994" E, 156 m), Swellendam (34°1'59.99" S, 20°27'0.003" E, 125 m,) Cape Agulhas (34°38'0.0064" S, 20°7'0.00044" E, 15 m). Figure 1 shows the representative stations for the data validation wherein the monthly mean temperature of the regions. Similarly, the multi-year monthly mean was calculated from the monthly sum and averages for precipitation and temperature, respectively.

### 3.3 Validation

Masks containing the grid cells of the 16 subregions of the study area were created using bilinear interpolation at a 0.22° resolution and embedded onto the time series of the available simulations using remapping tools on the Climate Data Operators (CDO) provided by the Max Planck Institute for Meteorology (<https://code.mpimet.mpg.de/projects/cdo>). The nearest neighbour interpolation method was used to match the grid points of the simulated data and the actual location of each station selected for the observational data thus, allowing a possibility of smaller error.

Taylor diagrams were generated using R studio to validate the simulated data against the available ARC observational data. Taylor (2001) diagrams contain visualized information on the differences in the root-mean-square error (RMSE), correlation coefficient and standard deviation that are commonly used statistical measures. In addition, the mean bias is calculated separately.

$$RMSE = \left( \frac{\sum_{i=1}^n (S_i - O_i)^2}{n} \right)^{1/2}$$

where  $S_i$  represent simulated data,  $O_i$  is the observational data and  $i$  represents the  $i^{th}$  month.

The Correlation coefficient between the observational data and simulated data is calculated by

$$r = \frac{1}{(n-1)} \sum_{i=1}^n \left( \frac{S_i - S}{\sigma_S} \right) \left( \frac{O_i - O}{\sigma_O} \right) \dots$$

Where the standard deviation is  $\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{n}}$ , where  $x_i$  represents each value from the data set,  $\mu$  is the sample mean, and  $\sigma_o$  and  $\sigma_s$  are respectively defined as the standard deviations of the observational and simulated data,  $n$  is the number of months (i.e., 12 for the whole year).

### 3.4 Calculation of historic biothermal and hydro thermal indices

As viticulture is a climate-sensitive sector, it is important to determine how local climatic conditions influence growth and production. The International Organisation of Vine and Wine assesses the suitability of a region to produce varieties and understand the dynamics of climate and grape cultivation. In this study, we calculated five biothermal viticultural indices including the Biologically Effective Degree Day (BEDD) and Cool Night Index (CNI), Growing Season Temperature (GST), Huglin Index (HI), Winkler Index (WI), and the hydrothermal index of Branas, Bernon and Levandoux (BBLI) were calculated using the Fruclimadpt package in R.

The calculation of the indices required the daily minimum and maximum temperature and precipitation along with the exact latitude and elevation of each station. The length of day was adjusted according to the latitude. The indices were calculated for the historic simulations and the observational data from the representative stations. The accuracy of the simulated indices was calculated by using the Index of Agreement (IoA) matrix from the hydroGOF package in R. The IoA measures the agreement between simulated observational data sets where the returned matrix ranges between one and zero where 1 assumes a strong agreement and zero is a result of no agreement between the two data sets. The results from the IoA were supported by the calculation of the RMSE to better determine the errors of the simulated data.

The IoA is calculated using the following formula

$$d = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (|S_i - \bar{O}| + |O_i - \bar{O}|)^2}, 0 \leq d \leq 1$$

## 4 Results and discussion

### 4.1 Analysis of data validation

The simulated historic average temperature generally perform well against the observational data in all selected districts (Fig. 2A) due to the good simulation of the annual temperature cycle. The relationship between the simulated and the observational data is evaluated using Taylor diagrams.

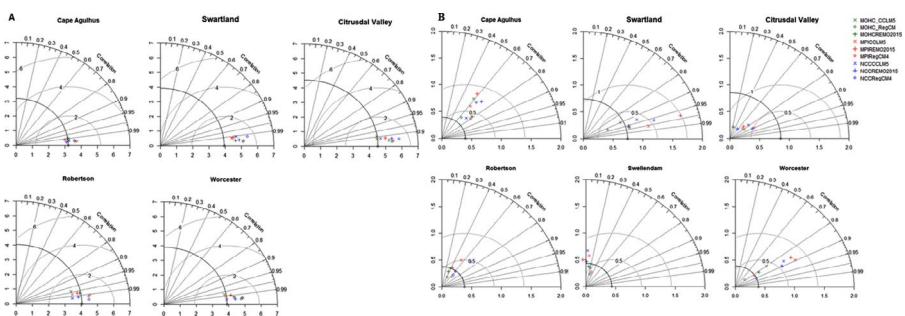
All model simulations exhibit a strong correlation with observational data where  $r$  is greater than 0.99 in 4 of the 5 stations. With the lowest correlation coefficients

observed in Robertson ( $r > 0.95 - 0.99$ ). The model simulations have an RMSE  $< 2$  °C across all stations indicating that temperature data from the simulations represent observations well on an average monthly scale. A slightly higher variability is noted in Swartland and Citrusdal Valley compared to other stations. The RegCM4-7 simulated data show more variability than the REMO2015 and CCLM across the selected stations. Notably, the variability of REMO2015 simulations depends on location, excelling in Cape Agulhas and Robertson but it is an outlier in three other stations.

When validated against observational data, the precipitation data from the 9 historic simulations had the best performance in Swartland. The MOHC-Had-GEM-RegCM4-7, NCC-NorESM-CCLM5, MPI-MPI-CCLM5 and MOHC-Had-GEM-REMO2015 fall within the 0.5 correlation with the observational data in Cape Agulhas (Fig. 2B). Precipitation is considered the most complicated parameter to compute due to variability in topography.

There is a high variability between the simulations and the station data coupled with a low standard deviation in the Citrusdal Valley. More variability between the simulations and observed data is observed in Cape Agulhas, Swartland and Worcester while the remaining three stations indicate some agreement with less variability. The reproduction of the annual precipitation cycle is suboptimal as most of the model simulations exhibit a correlation coefficient ( $r$ ) less than 0.8. From the above results, it is evident that the reproduction of climatic conditions in Swartland is the most accurate. All models in this district fall within  $< 0.5$  mm RMSE between the simulation and observational data and  $r > 0.9$ . This indicates that the model simulations have a potential to reproduce the precipitation cycle in the study area.

Previous African studies have shown a weak relationship between precipitation and observational data (Dosio et al. 2020; Marra et al. 2022; Onyutha 2020). It should be noted that the lack of sufficient observational data in most parts of Africa is a major challenge in validating simulated data (Gbobaniyi et al. 2014). For example, in this study, the station data that was initially used, had more than 60% missing precipitation data for the reference period hence it was excluded from the analysis. The use of satellite data as a means of validation has been widely used, however, the lack of station data in some regions poses a challenge in Africa (Akinsanola and Ogunjobi 2017). Satellite data was not used for the validation in this study due to great differences in horizontal resolution. The model simulations demonstrate a greater



**Fig. 2** Taylor diagrams of monthly mean temperature (A) and precipitation (B) for selected wine sub-regions of the Western Cape for the reference period 1981–2000

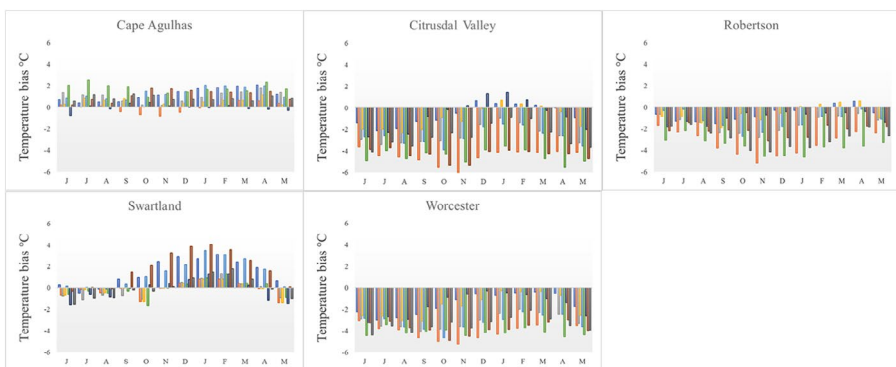


capacity to reproduce temperature in this region compared to their ability reproduce precipitation. Naik and Abiodun (2020) demonstrated that the CORDEX simulations at  $0.44^\circ$  resolution could reproduce CRU observational data over the Western Cape thus suggesting that the data is reliable.

The simulated temperature biases vary by region, resulting in both underestimation and overestimation. While model simulation performance varies across all districts, MPI-MPI/RegCM4-7 and MOHC-HadGEM-RegCM4-7 had the lowest biases throughout the annual cycle. Temperature is overestimated; with biases ranging between  $0.5$  and  $3^\circ\text{C}$  and  $1$ – $5^\circ\text{C}$  in Cape Agulhas and Swartland, respectively (Fig. 3). Temperature is underestimated in Robertson, Worcester and Citrusdal Valley corresponding with the variability observed in the Taylor diagrams. The highest temperature bias ( $-6.05^\circ\text{C}$ ) occurred in Citrusdal Valley in the case of underestimation.

It is observed that in most of the regions, the higher temperature biases occur in the summer half-year than the winter with biases ranging between  $-1^\circ\text{C}$  and  $-4^\circ\text{C}$  while in Worcester temperature bias in JJA ranges between  $-2.5^\circ\text{C}$  and  $-4.5^\circ\text{C}$ . Robertson has the lowest underestimation biases in JJA where the bias ranges between proximately  $-0.1^\circ\text{C}$  and  $-3.5^\circ\text{C}$ . Model behaviour in these regions shows positive biases in DJF and generally the summer half-year even though there is a great difference between model behaviour with biases ranging between  $1^\circ\text{C}$  and  $-4^\circ\text{C}$  in all regions but in Worcester, temperature bias ranges between  $0^\circ\text{C}$  and  $-5^\circ\text{C}$ . Swartland and Cape Agulhas show different model simulation behaviour than other regions which suggests an overestimation of their temperature in the area for the historic period wherein the biases range between  $-1$  and  $2.5^\circ\text{C}$ . Swartland shows an overestimation between  $-0.8$  and  $4^\circ\text{C}$  in DJF while Cape Agulhas shows an overestimation of  $0.5$  and  $2^\circ\text{C}$  in that DJF months and shows great fluctuations. In all of the areas, there are great differences between the simulated historical data and the station data for the reference period.

The simulations follow a natural annual cycle of the Western Cape, with higher precipitation in JJA and lower precipitation in the summer half-year. There are significant precipitation biases are observed in the winter half-year when precipitation



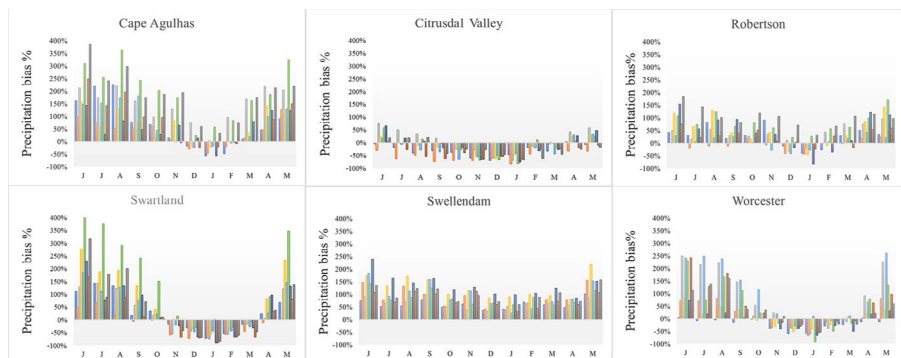
**Fig. 3** Monthly temperature bias of the simulated historic data against the observational station data for the 1980–2000 period. Note that the horizontal scale covers the year from the winter (JJA) to autumn (MAM) of the Southern Hemisphere

is expected to be high in the region. Other studies (e.g., Hernández-Díaz et al. 2013; Panitz et al. 2014; Ayugi et al. 2020) also noted larger precipitation bias over the African continent where greater biases were observed in the wet season. Our results show that the precipitation from the simulated historic precipitation against the observed station data is significantly biased in the wet season JJA (Fig. 4). The highest biases are observed over the Cape Agulhas, Swartland and Worcester with precipitation biases ranging between 0% and 400% during the winter season. It is observed that the NCC-NorESM-CCLM5 simulation exhibits high biases and overestimation in Swartland. While the least overestimation during the wet season (JJA) is observed in Citrusdal Valley, suggesting that the models have a better ability to simulate precipitation over Citrusdal Valley in JJA with the lowest biases recorded, reaching 0% in July according to the NCC-NorESM-CCLM5.

All model simulations exhibit great fluctuations with a clear positive bias in all districts excluding Citrusdal Valley during the wet season.

Notable bias fluctuations are observed in Cape Agulhas, there throughout the winter half-year with a steady increases from March, however, it reaches a peak in June (between 150% and 350% bias) and August (between 50% and 300% bias) followed by a sharp decrease in July.

Similar cycles of biases were observed in Swellendam and Worcester in some model simulations, particularly in Worcester with the lowest precipitation biases occurring in the summer half year. The least overestimation during the wet season (JJA) is observed in Citrusdal Valley, suggesting that the models have a better ability to simulate precipitation over Citrusdal Valley in JJA with the lowest biases recorded, reaching 0% in July according to the NCC-NorESM-CCLM5. However, this area is generally rather too dry in the model simulations. A clear negative bias is observed in most districts. Wherein precipitation is underestimated in Cape Agulhas, Swartland and Citrusdal Valley with between  $-100\%$  and  $0\%$ . The results indicate that the historic simulations have less ability to take into account the variable orography within the selected observational stations. Based on the monthly bias results, we validated the daily temperature and precipitation measured to closely evaluate model agreement during the growing season. The growing season in the southern hemisphere is



**Fig. 4** Annual cycle of the precipitation bias of the simulated historic data against the observational data set for the 1980–2000 reference period

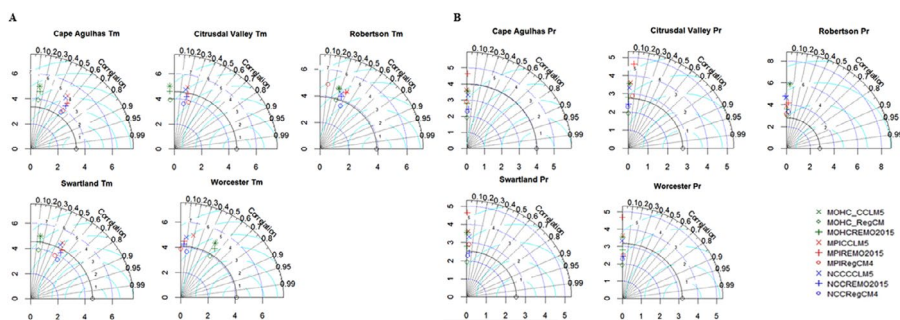
between October and March. The growing season performance greatly differs from the annual results in both parameters (Fig. 5).

There is a very low correlation between modelled temperature and observational data with the highest correlation observed being 0.6 in Worcester, followed by Cape Agulhas and Swartland. The models tend to overestimate the temperature; differences in resolution on the probable reason for such high differences. A significant difference is noted in the ability of the models to reproduce precipitation during the growing season, wherein there is no agreement (Fig. 5B). The growing season is naturally a dry period in which very little to no precipitation is expected, however, it is observed that the models overestimate precipitation during this period.

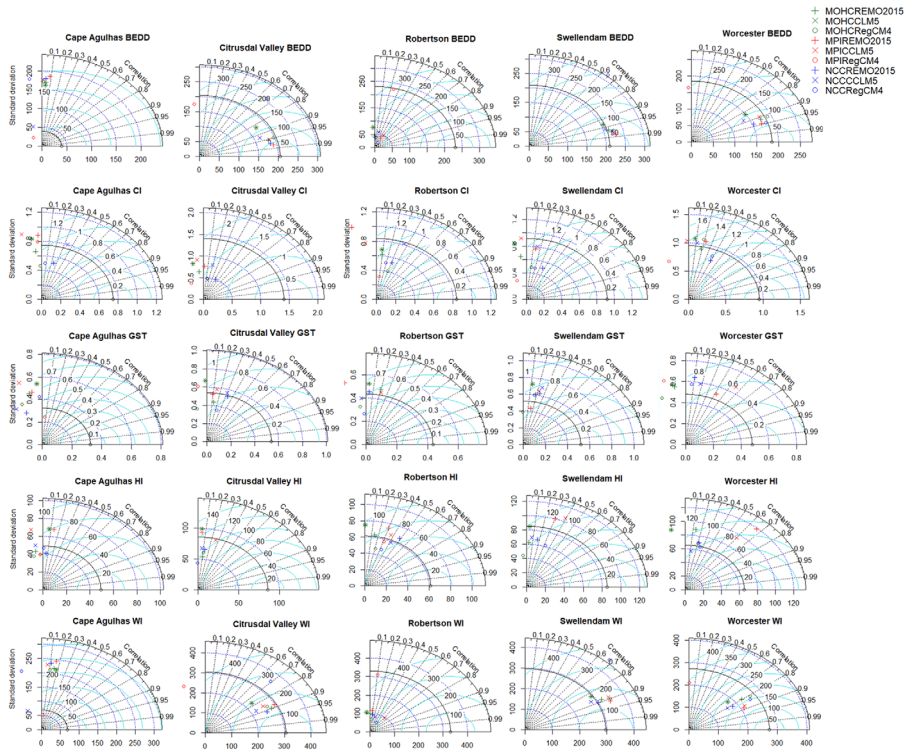
## 4.2 Analysis of simulations validation of vinicultural indices

Historic daily meteorological variables were used to calculate vinicultural indices as defined by the International Organization of Vine and Wine (OVI). The Cool Night index, GST, Huglin index, Winker index and Bran's index were calculated and compared to observational data for their growing season which is from October until March. It should be noted that bias correction methods were not used prior to the calculation of the indices in this study in order to understand the original output and performance of the RCMs. The Taylor diagram results (Fig. 6) show that Citrusdal Valley and Robertson had a better performance in reproducing observational data with better correlation between all models and the observational data while it is observed that MPI-RegCM4-7 performs slightly better than other models in Cape Agulhas.

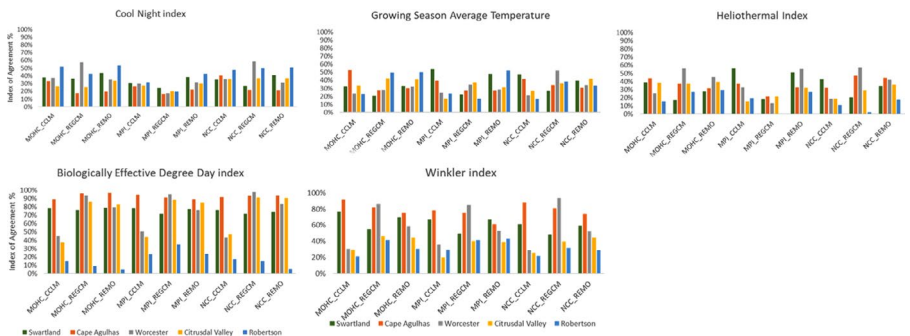
The Index of Agreement (IoA) was used to measure the similarity between the observational and simulated data (Fig. 7) and the corresponding RMSE is taken into consideration to observe the error between the observational data and the simulated data. Based on the index of agreement (IoA) it was observed that each model's ability to reproduce climatic conditions varies with region as moderate to poor model performance is observed in the Cool night index (CI), and the Huglin index (HI). Results for the Cool Night index observed that the agreement is variable across all selected vinicultural wards, with the highest IOA being 0.585 in Worcester and RMSE of 1.46. Poor agreement is observed in all models as they resulted in Low IoA



**Fig. 5** Taylor diagrams of daily temperature (**A**) and precipitation (**B**) for selected wine wards of the Western Cape during the growing season (October – March) of the reference period 1981–200



**Fig. 6** Taylor diagrams of biothermal indices for selected wine subregions of the Western Cape for the reference period 1981–2000



**Fig. 7** Overall bioclimatic model agreement percentage during the 1980–2000 reference period

and High RMSE, suggesting that the models are not able to properly reproduce the CI recorded by the observational data. The poorest agreement is noted in the MPI REMO and MPI-RegCM4-7 across all wards compared to other models as the corresponding RMSE is the highest. Despite poor model agreement, the NCC-NorESM-REMO2015 had the highest model agreement. It is possible that since the daily data

does not represent the nightly measurements but overall, 24/hr data, it could have a significant influence on the results of the cool night index.

While the results of the HI IoA show that model performance didn't vary in each region, for example, MOHC-HadGEM-CCLM5 and NCC-NorESM-CCLM5 had a higher agreement in Swellendam and Cape Agulhas respectively while MPI RegCM and NCC-NorESM-REMO2015 had better performance in Worcester and Citrusdal Valley. However, none of them reached the moderate (50%) agreement with other models (e.g., MOHC-HadGEM-RegCM4-7) generally having higher error than other models. While the MOHC-HadGEM-RegCM4-7 and MPI-CCLM5 showed a better performance. Low RMSE ranging between 75% and 170% in Cape Agulhas, Swartland and Worcester suggests that the models could have the ability to accurately reproduce data. However, they do not have the ability to predict the overall trend during the growing season.

Better model performance is observed in the reproduction of the BEDD, Growing Season temperature (GST) and Winkler index (WI) where all models had the best performance in Swellendam and Cape Agulhas. Model performance varies wherein MPI-RegCM4-7 was the best performing in Cape Agulhas while NCC-NorESM-RegCM4-7 had a substantially lower agreement. However, there is no outperformance in the reproduction of BEDD as models' performance varies with region.

While the GST had up to 54% agreement, wherein the best model performance occurred in Swellendam, Cape Agulhas and Robertson while Worcester where MPI-CCLM5 had the highest IoA and Citrusdal Valley had the poorest performances by NCC-NorESM-RegCM4-7 and MPI\_REMO. Model performance varies with each ward as the lowest and highest RMSE values are observed for different models in different regions. All the RegCM-driven models have the highest RMSE. Based on the IoA and RMSE results, the models can accurately reproduce the GST however, there is high variability.

The Models had a good performance in reproducing the Winkler index in all regions (50-93% IoA) but in Citrusdal Valley, where the IoA was less than 45%. The NCC-NorESM-RegCM4-7 had good performance in Robertson and Worcester, it also performed better than other models in Citrusdal Valley even though the models have higher IoA, their corresponding RMSE, is higher in some regions indicating that even though the models are able to accurately produce the WI, there is high variability and lack of ability to follow the general climatic trends in some regions (i.e., Citrusdal Valley).

The hydrothermal index calculated for this study is the BRANAS index, a precipitation-based index which is calculated using precipitation, evapotranspiration and wind speed. Temperature was used to calculate evapotranspiration and wind speed was recalculated automatically assuming their constant wind speed of 2. The IoA was less than 50% in Worcester and Cape Agulhas, while the IoA in Swellendam ranged from 25 to 75%. Higher RMSE values are observed in other regions, indicating low agreement. There are significant differences between them in the performance of each model across different wards. NCC-NorESM-CCLM5 was the best performing with an agreement of 50% in Cape Agulhas followed by MPI-CCLM5 in Robertson. While the MOHC-HadGEM-CCLM5 had the lowest IoA in all wards. There is a significant difference between the index of agreement between the vinicultural indices

and the interannual temperature and precipitation Index of agreement because the indices were calculated from daily data which has high variability while the interannual averages are more robust and followed expected trends.

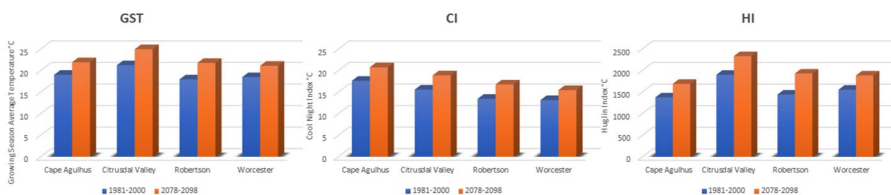
### 4.3 Analysis of change in viticultural indices

The ensemble of indices was calculated for the end of the century (2079–2098) under the RCP8.5 scenario. The viticultural indices results (Fig. 8) indicate a significant change in viticultural climatic conditions wherein an increase of 2.6 to 3.8 °C during the growing season between the reference period and the end of the century during the century which will in turn affect phenology and may alter harvesting times. The increase in GST will also cause an increase in the cool night index by 2 to 3 °C with the highest increase in night-time temperature observed in Robertson (an increase of 19.85%), followed by Citrusdal Valley (17.52%). A general increase in night-time temperature may affect grape maturation.

The Huglin index is the most studied and plays a role in determining the suitability of a region. There will be a shift in viticultural regions, for example, (Fig. 8) shows that Cape Agulhas and Robertson will likely benefit from the change in climatic conditions, both regions will shift from being less suitable for vine grape growth to being cool and temperate regions respectively making them more suitable to grow varieties such as Pinot noir, Cabernet Sauvignon and Merlot at the end of the century under the business-as-usual scenario. While the most extreme change will occur in Citrusdal Valley where regional classification will change from temperate to temperate warm. This could have both positive and negative effects as the cultivation of grape varieties is highly dependent on optimal conditions, thus making it harder to support the growth of varieties that were previously grown in the area, however, bringing an opportunity to grow new varieties.

## 5 Conclusions

There was high variability between the simulated precipitation and the station data from the ARC, thus explaining the large differences and high biases between the data, in contrast, the temperature simulated over the selected stations was well reproduced for the historic period. Precipitation is a more complex parameter than temperature therefore, it is more challenging to validate in cases of large missing data. Spatial differences also account for the large biases observed in precipitation during the grow-



**Fig. 8** The change in viticultural indices at the end of the century

ing season. Inconclusive precipitation validation could lead to increased uncertainty in modelled simulations and can thus mislead policymakers. The vinicultural indices validation indicates that model performance depends on location and a specific index. The overall results indicate that the NCC-NorESM-CCLM5 and MPI-CCLM5 have a good ability to reproduce the CI, GST, HI and WI while the MOHC-HadGEM-RegCM4-7 had poor agreement in all regions and indices. The evaluation of vinicultural indices is affected by topography, soil type and other local factors such as the weather conditions during the growing season. Further research is needed to highlight the factors that influence the dependence of viticulture on climate. The changes in vinicultural indices correlate with the increase in temperature over the western Cape region will require grape farmers to adapt to the changes such as potential changes in harvest times and wine quality. The aim of the study was to evaluate the performance of the CORDEX Africa experiment models during the historic growing season. This study could be of value to the scientific community as it follows the necessary steps for data validation. The limitations of the study were predominantly driven by substantial gaps in the locally based observational data. It is important that we carry out another study to validate the data against other observational sources such as satellite data. The next phase of the study is to determine how projected future changes in climate will influence the extreme events over the different parts of the wine-growing region and assess the suitability of each ward in future scenarios.

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**Author contributions** We applied the SDC approach for the sequence of authors. Material preparation, data collection, analysis and the first draft of the manuscript were performed by HC and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Supervision: RP.

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## Declarations

The Authors declare no conflict of interest and we have no financial relationships that may have inappropriately influenced this article.

**Competing Interests** Authors declare no competing interest.

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