

Future Climate Projections in Algeria Using Statistical DownScaling Model

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Future Climate projections in Algeria using Statistical DownScaling Model

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Abstract:

In this study, we perform a statistical downscaling to investigate projected future changes in minimum temperature (T-min), maximum temperature (T-max), and precipitation (PRCP) for the three periods the 2020s (2011–2040), the 2050s (2041–2070), and the 2080s (2071–2100), with respect to the reference period 1981–2010 over Algeria by applying the Statistical DownScaling Model (SDSM). The NCEP reanalysis data and CanESM2 predictors of three future scenarios, RCP2.6, RCP4.5 and RCP8.5 are used for model calibration and future projection, respectively. In order to get realistic results, bias correction was also applied to the climate variables. The evaluation of the SDSM performance indicated that model accuracy for simulating temperatures and precipitation was statistically acceptable. The predicted outcomes exhibit strong warming for both extreme temperatures under the worst-case scenario (RCP 8.5), it is more pronounced for the maximum temperature and over the Sahara region. The results indicate that the highest changes are expected to increase by 3.6 to 5.0°C for the minimum temperature and 5.0 to 8.0°C for the maximum temperature for the strong radiative forcing pathway (RCP8.5) by the end of the century as compared to the reference period. Under the optimistic scenario (RCP2.6), the strength of the warming is projected to increase up to 2.0°C for both extreme temperatures. For the precipitation, the projections indicate for all scenarios a significant decrease in rainfall by approximately 20% over the northwest region and central Sahara, while non-significant change is expected for the center and eastern coastal regions. Conversely, the projections of rainfall under different emission scenarios exhibit an increase (~10–40%) at the central and eastern high plateaus in the north and the extreme west and south of the Sahara. The study reveals several discrepancies among considered stations in the projections of seasonal rainfall under different emission scenarios where most of them exhibit a significant increase of precipitation in summer. Our findings corroborate previous studies by demonstrating that Algeria's climate will warm further in the future. The results might be beneficial for policymakers for planning strategies and may help to mitigate the risks linked to climate change.

KEY WORDS: SDSM · CanESM2 · Algeria · climate change projections · Precipitation · Temperature

1. INTRODUCTION:

North Africa is considered as one of the most exposed regions to negative effects of climate change impacts in the world (IPCC 2014). This region is for several years experiencing extreme temperatures leading to severe droughts and water rarity, extending desertification, loss of marine ecosystems and biodiversity (IPCC 2018). The region is highly exposed to climate change and threatened by extreme heat and water shortages. According to the World Meteorological Organization's (WMO) REPORT of the 2020' State of the Global Climate (<https://public.wmo.int/en/resources/library/state-of-global-climate-2020>), the average global temperature during 2020 is about 1.2 degrees Celsius above that of the pre-industrial period (1850–1900) baseline, classified as one of the three warmest years on record globally. Considering the climate change context, Working Group I of the Intergovernmental Panel on Climate Change (IPCC-WG I) revealed in its fifth assessment report (IPCC 2013), for the extreme radiative forcing scenario RCP 8. 5, an increase in atmospheric temperature expected for North Africa region ranging from 2 to 3 degrees Celsius for the period (2046-2065), and from 3 to 6 degrees Celsius for the long-term period (2081-2100) compared to the 1986-2005 reference one. Therefore, the effects of global warming would be most severely felt by the increase in extreme air temperatures that would intensify the occurrence of extreme events and conditions of heat stress.

Moreover, the north Africa region is classified as a climate change hotspot (Diffenbaugh and Giorgi 2012). In their study, Lelieveld et al. 2016 demonstrate that climate observations and simulations show an upward trend of the heat extremes days and a decrease of the cool days and nights, particularly since the 1970s.

In early July 2018, the heat extended to the North Africa region, with records set at 5 cities in Algeria, the highest being +51.3 °C at Ouargla, classified as a national record (WMO 2019).

However, very few studies have investigated the projected climate simulations under different scenarios over Algeria. Most of the climate projections studies over the country were conducted in a regional context of the Middle East–North Africa (MENA) or Mediterranean regions (Almazroui 2016, Almazroui et al. 2016; Driouech et al. 2020; Goodess et al. 2013).

Zeroual et al. (2019) used CORDEX-Africa regional climate models simulations to assess future changes in the climate zones of Algeria as defined by Koppen–Geiger based on two Representative Concentration Pathway scenarios (RCP4.5 and RCP8. 5) for the period from 1951 to 2098. They found a gradual but significant expansion of the surface area of the desert zone while the rate of expansion of desert climate will increase in the future, particularly during the period from 2045 to 2098 according to projections for the pessimistic emission scenario (RCP8.5).

Although, various research studies applied global and regional model scenarios to simulate future temperature and precipitation changes and to assess impacts at a MENA scale (Bucchignani et al. 2018; Bigio et al. 2011; Sowers et al. 2011; Goodess et al. 2013; Giannakopoulos et al. 2009). Since the last decade, there is an increasing number of MENA studies based on the hub of the Coordinated Regional

Downscaling Experiment (CORDEX: [http://mena-cordex.cyi.ac. cy/](http://mena-cordex.cyi.ac.cy/)), focusing on individual regional model simulation and validation (Zittis et al. 2021; Almazroui et al. 2016; Almazroui 2016; Bucchignani 2016), as well as several future projections and impact assessment studies for the region (Zittis et al. 2021; Driouech et al. 2020; Ozturk et al. 2018).

The most significant results of these studies confirm that precipitation in North Africa is likely to decrease while temperatures are likely to rise. Paeth et al. (2009) showed that according to the Regional Model REMO, the annual total precipitation is projected to decline between 10 and 20%, and the temperature to increase between 2 and 3°C by 2050 under SRES A1B scenario conditions, where more pronounced drying is expected in north-western parts of North Africa.

A part of the Mediterranean region, the Integrated Research Project (CIRCE) models simulations over Algeria as well as most parts of the region were consistent in indicating warming ranging from 0.8 to 2.0°C in winter (DJF) and from 1.2 to 2.5°C in summer (JJA) for 2021–2050 compared with 1961–1990 under the A1B emission scenario (Goodess et al. 2013). In general, the six CIRCE regional and global models used show a tendency towards warmer and drier conditions over the Mediterranean, consistent with earlier studies (e.g. , Giorgi and Lionello 2008) accompanying by a general increase in the number of very hot days and nights, together with longer warm spells and heatwaves.

Driouech et al. (2020) indicate that the projected changes over the CORDEX-MENA domain through contrasting ALADIN-climate regional model for the future period (2071–2100) against the present-day period (1976–2005) under both RCP4.5 and RCP8.5 are statistically significant (at 95% level). The mean temperature will increase around 2°C for RCP4.5 and at least 4°C for RCP8.5 in North Africa (Eastern Morocco and most Algeria). The future scenarios indicate the intensification of heatwaves occurrence over this region particularly in the inland, while the total annual precipitation amounts will decrease from 5 to 20% in the North and increase in nearly all the remaining parts notably in the Sahara exceeding +40%.

Zittis et al. (2021) for a business-as-usual pathway (RCP 8.5), indicate that in the second half of this century, the MENA region including Algeria will experience unprecedented super- and ultra-extreme heatwave conditions. These events involve excessively high temperatures (up to 56 °C and higher) and will be of extended duration (several weeks).

Similarly, Varela et al. (2020) show that maximum temperature is expected to rise throughout the entire MENA region for the 21st century under the RCP 4.5 and 8.5 scenarios. The increment of maximum temperatures is expected to range between 4°C and 7°C, while the mean and maximum intensity of heatwaves is also expected to increase for almost the whole MENA region.

On the other hand, Ahmadalipour et al. (2018) investigate the mortality risk for people aged over 65 years caused by excessive heat stress across the MENA region for the historical period of 1951–2005 and two future scenarios of RCP4.5 and RCP8.5 during the 2006–2100 period. Their results show that without mitigation measures, the mortality risk will be 8 to 20 times higher by the end of the century, compared to the reference period.

The climate change studies aim to determine the changes in the future climate compared to a referenced past period or simulated one, under different radiative forcing pathway scenarios. The used models should be evaluated through their reproduction of the past climate (Collins et al. 2020).

To quantify the impacts of climate change, the outcomes of general circulation models (GCMs) are frequently used to simulate the impacts of increased greenhouse gases on climatic variables. However, these models are limited because of their coarse resolution at a subgrid-scale, and regional and local scale processes are occurring on spatial scales much smaller than those resolved in GCMs.

Scientists employ various techniques to bridge the gap between the resolution of climate models and regional and local scale processes, yielding localized information on future climate behaviours in order to fit the purpose of local-level analysis and planning and to assess the impact of climate change including the application of climate change scenarios to different sectors. These techniques are known as “downscaling”. Furthermore, the benefit of the selected downscaling method could be evaluated once introduced in a practical impact study by assessing the climate risk and proposing adequate implementation measures (Hussain et al. 2015).

Mainly, regional modelers use two categories of downscaling. One approach is dynamical downscaling where outputs from GCM’s are used to drive higher-resolution regional climate models with a better representation of local conditions, but it is computationally expensive. The second approach is statistical which requires less computational effort than dynamical downscaling, where statistical links are established between large-scale climate phenomena and observed local-scale climate, and can therefore replicate finer scales than dynamical downscaling (Fowler 2007). Statistical models are classified under three categories based on the statistical approaches used: Transfer function (Wilby 2002), stochastic weather generator (Semenov 2017) and weather typing (Anandhi 2011).

Statistical Downscaling as epitomized was able to reduce the mismatch between spatial and temporal local and coarse-scale. For example, the Statistical DownScaling Model (SDSM) which is developed based on a transfer function and stochastic weather generator, is intended to bridge the divide between accessibility and sophistication (Wilby et al. 2002; Wilby et al. 2013).

Nowadays, SDSM is broadly adopted due to its reliability, simplicity and great performance as well as the free accessibility of the dedicated software (Wilby et al. 2013; Saidi et al. 2020). The development of the Statistical Downscaling Model (SDSM) as a climate-based scenario generator aims firstly to assess climate impacts towards adaptation planning (Wilby et al. 2014). Since its first release in 2001 and up to 2013, more than 200 research studies using SDSM have been published worldwide (Wilby et al. 2014). Interest in SDSM has been stimulated by citations from the United Nations Framework Convention on Climate Change (UNFCCC) (https://unfccc.int/files/adaptation/methodologies_for/vulnerability_and_adaptation/application/pdf/statistical_downscaling_model__sdsms.pdf), the United Nations Development Programme, and the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4) (Wilby et al. 2013).

The scientific community to downscale different climatic parameters like precipitation and temperature has also used SDSM as a user-friendly software package extensively. Most scientists and researchers used a different kind of statistical models and come to the point that SDSM is one of reasonable and reliable approach among all others (Tahir et al. 2018; Khazaei et al. 2020; Zehtabian et al. 2016; Khan et al. 2006). They indicate that the SDSM is the most capable of reproducing several statistical characteristics of observed data in its downscaled results with a 95% confidence level.

A Decision Centric (DC) version of the Statistical Downscaling Model (SDSM-DC) was recently released, enabling synthesis of plausible daily weather series and exotic variables; this version can also be used for data reconstruction in contrasting climate regimes (Wilby et al. 2014).

Unfortunately, studies on the topic of statistical downscaling methods are almost non-existent in Algeria, when climate change has become a serious challenge and a significant issue for the country. Good knowledge of future climate change scenarios will be of great significance in assessing the risk of droughts, heatwaves, and floods in the future, and the results could further be utilized for planning and the implementation of mitigation strategies.

Moreover, understanding the behaviour of future scenarios of daily extreme temperatures and precipitation distribution in Algeria is critical for economic sectors like agriculture, water resources management, health and tourism; as well as for the design of systems for monitoring climate change. In this scope, this paper aims to quantify the amount and intensity of changes in climate variables and their variations for the 21st century, by (1) evaluating the potential applicability of SDSM for modelling minimum and maximum temperatures as well as precipitation; and (2) examining changes of these climate parameters, between different projected climate scenarios in three periods: the 2020s (2011–2040); the 2050s (2041–2070) and the 2080s (2071–2100) with respect to present period 1981-2010. The results should contribute to the development of downscaling knowledge for the country and provide valuable information at a local scale.

2. METHODOLOGY

2-1. Study area and data

Algeria with its geographical contrasts is located in Northwestern Africa, bordering the Mediterranean Sea between Morocco and Tunisia (Fig. 1). With a surface area of approximately 2.4 million square kilometres, with more than four-fifths of which is occupied by the desert. Three major geographical areas dominate the country from the North to the South: The Tell in the North including the littoral, the High Plateaus (Highlands) and the Sahara in the South. The Tell zone is made up of the hills and plains of 1280 km in length and 100 to 200 km in large (<https://www.inesg.dz/en/about-algeria/geography>). It comprises a fertile region in the north, extending eastward from the Moroccan border, considered as the country's heartland, enclosing most of its cities and population. The High Plateaus zone is made up of plains located between the Tell Atlas in the North and the Sahara Mountains in the south. In the south, the Sahara covers about 2 million km² representing 85 % of the Algerian territory surface. Northern

Algeria is in the temperate climate zone and enjoys a mild, Mediterranean climate influenced notably by the mid-latitude atmospheric circulation variability systems. The geographic properties provide sharp local contrasts in both prevailing temperatures and rainfall behaviour. However, the coastal zone and mountain valleys are characterized by a Mediterranean climate, mild winters, and moderate rainfall. The elevation of the High Plateaus region averages varies between 400 meters in the east and 1300 meters in the west. The highest point in Algeria is located in Mount Tahats of 3000 m altitude in the extreme south of the country.

The mean temperatures observed records during the WMO conventional normal period 1981-2010 revealed that the Algerian coastal region enjoys a pleasant Mediterranean climate, with winter minimum temperatures averaging from 04 to 10°C and maximum temperatures in the summer ranging from 27 and 31°C. The mean total annual precipitation amount in this region varies between 320 mm in the West and about 1000mm in the East. Farther inland, in the winter, the climate is continental and frosty, particularly in the more mountainous areas. The mean winter temperatures are averaging between 01 and 06°C and 32 to 37 °C in the summer. The average rainfall total amount in this part of the country fluctuates from 200 to 600mm. Experiencing a severe, dry and hyper-arid climate, the winter mean minimum temperatures in the Sahara range from 07 to 10°C with extreme highs averaging around 38 to 44°C and reaching 50°C during the summer. Strong winds are usually observed in this zone. Precipitation in this region is scarce and unevenly distributed; the mean annual total varies between 15 and 120mm.

To conduct this study, historical records of observed precipitation (PRCP) and temperature (minimum [T-min] and maximum [T-max]) data of 21 uniformly and well-distributed meteorological stations within Algeria (Table 1) are used. Five stations represent the coastal region, four the high plateaus, five the North of the Sahara and seven representing the large Sahara. Observed daily minimum and maximum temperature and precipitation during the period of 1961–2005 were provided by the Algerian Meteorological Office, a part of the WMO regional basic synoptic network. The location of these stations on the map of Algeria is shown in Fig. 1. Furthermore, all meteorological data used in the study are quality controlled and homogenized.

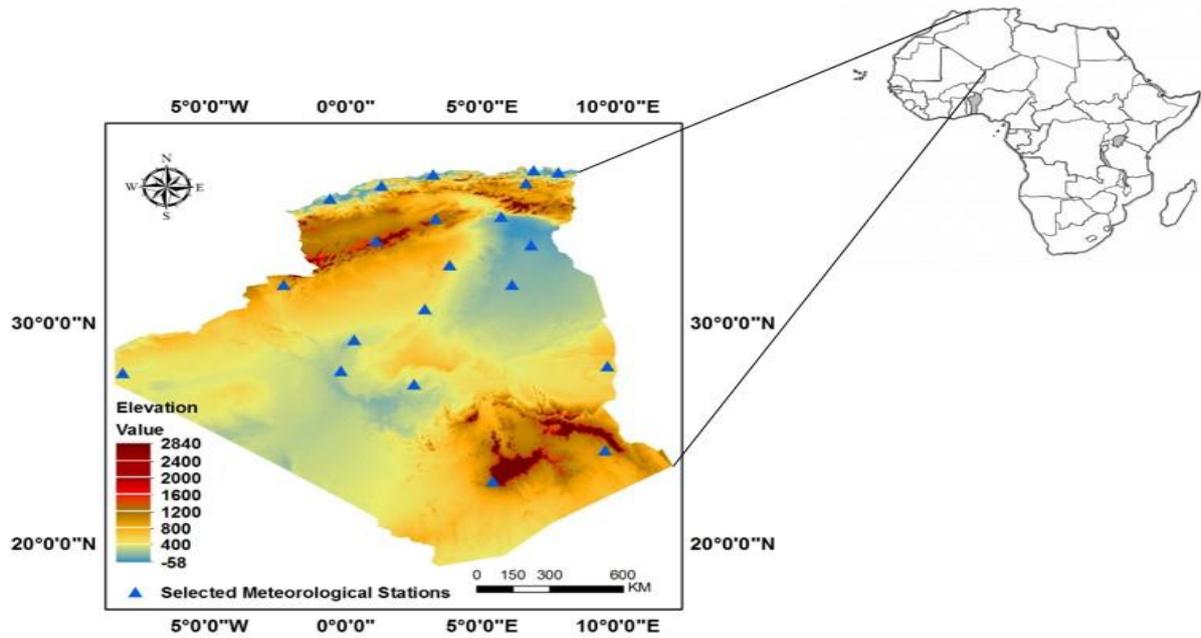


Fig. 1: Location of meteorological stations in Algeria used in the study

Station Name	Latitude (°N)	Longitude East (E) /West (W)	Altitude (m.a.s.l)
Skikda	36.9	6.9 E	2
Annaba	36.8	7.8 E	8
Algiers	36.7	3.2 E	25
Constantine	36.3	6.6 E	685
Chlef	36.2	1.3 E	159
Oran	35.6	0.6 W	90
Biskra	34.8	5.7 E	82
Djelfa	34.7	3.3 E	1185
El-Bayadh	33.7	1.1 E	1341
El-Oued	33.5	6.8 E	69
Ghardaïa	32.6	3.8 E	468
Bechar	31.7	2.3 W	809
Hassi Messaoud	31.7	6.1 E	146
El Golea	30.6	2.9 E	403
Timimoun	29.2	0.3 E	317
In Amenas	28.0	9.6 E	578
Adrar	27.8	0.2 W	279
In Salah	27.2	2.5 E	268
Tindouf	27.7	8.2 W	449
Djanet	24.2	9.5 E	968
Tamanrasset	22.8	5.4 E	1372

Table 1. Geographic coordinates and elevation above sea level (a.s.l) in meters of Climate stations

The Statistical DownScaling Model (SDSM) is used to downscale large-scale variables from the second-generation Canadian Earth System Model (CanESM2) experiments as prepared for the Coupled Model Intercomparison Project Phase 5 (CMIP5) and developed by the Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment and Climate Change Canada. CanESM2 was implemented for the preparation of the IPCC Fifth Assessment Report (AR5).

This model uses different scenarios called Representative Concentration Pathways (RCP). In our study, we will focus on the optimistic scenario (RCP2.6) corresponding to the lowest rates of greenhouse gas emission, the intermediate scenario (RCP4.5) for the intermediate inclined toward optimistic scenario and the pessimistic scenario (RCP8.5) corresponding to the highest rates of greenhouse gas emissions. Observed daily precipitation and minimum and maximum temperature from 21 Algerian meteorological stations and 26 predictors for each station from the corresponding grid box (<https://climate-scenarios.canada.ca/?page=pred-canesm2>) with a resolution of 2.8° latitude by 2.8° longitude (Table 2) from the CanESM2 and the NCEP/NCAR reanalysis data provided by CCCma are used. Compared to GCMs, the NCEP predictors are regularly used due to their accuracy and correctness (in terms of Nash–Sutcliffe Efficiency (NSE) and high correlation) in representing the recent climate (Sachindra et al. 2014). In this study, we selected the same period (1961–2005) and the identical variables from NCEP/NCAR to preserve uniformity with the atmospheric variables generated by CanESM2. We used SDSM 4.2.9 to derivate the future climate projections in 3-time slices for the period 2006-2100 under the RCP2.6, RCP 4.5 and RCP 8.5 scenarios as available with the CanESM2.

After data quality control, different correlation tests were completed by screening the variables in SDSM software between 26 NCEP predictors and the predictands (precipitation, minimum and maximum temperatures). Selection of the identified best performing predictors for a considered predictand is based on the correlation matrix, partial correlation, and P-value results.

No	Predictor	Description	No	Predictor	Description
1	mslp	Mean sea level pressure	14	p5zh	500 hPa Divergence of true wind
2	p1_f	1000 hPa Wind speed	15	p850	850 hPa Geopotential
3	p1_u	1000 hPa Zonal wind component	16	p8_f	850 hPa Wind speed
4	p1_v	1000 hPa Meridional wind component	17	p8_u	850 hPa Zonal wind component
5	p1_z	1000 hPa Relative vorticity of true wind	18	p8_v	850 hPa Meridional wind component
6	p1th	1000 hPa Wind direction	19	p8_z	850 hPa Relative vorticity of true wind
7	p1zh	1000 hPa Divergence of true wind	20	p8th	850 hPa Wind direction
8	p500	500 hPa Geopotential	21	p8zh	850 hPa Divergence of true wind

No	Predictor	Description	No	Predictor	Description
9	p5_f	500 hPa Wind speed	22	prcp	Total precipitation
10	p5_u	500 hPa Zonal wind component	23	s500	500 hPa Specific humidity
11	p5_v	500 hPa Meridional wind component	24	s850	850 hPa Specific humidity
12	p5_z	500 hPa Relative vorticity of true wind	25	shum	1000 hPa Specific humidity
13	p5th	500 hPa Wind direction	26	temp	Air temperature at 2 m

Table 2. CanESM2 and NCEP predictors used in the study

2.2. Description of the SDSM

The SDSM is a hybrid tool combining stochastic weather generator (SWG) and multiple linear regression (MLR) based on downscaling methods (Wilby et al. 2002), requiring two types of daily data: Observed station data representing local climate (predictand) and large-scale atmospheric data (predictors) of a grid box closest to the station. Before model calibration, as pre-processing for the application of the SDSM model, data are quality controlled and checked for any outlier or missing data value. Then, the fourth root transformation has been conducted for precipitation, which is usually a skewed climatic variable to render it normal before using it in a regression equation (Wilby et al. 2002; Mahmood et al. 2013; Huang et al. 2011). In SDSM, there are two methods to optimize the model: (1) ordinary least squares (OLS) and (2) dual simplex (DS). In this study, OLS is used because it is faster than DS and its results are comparable. To select the most potential future climate predictors, different correlation tests were completed by screening the variables in SDSM. Each predictor was selected based on a high correlation with the predictand and the magnitude of its probability (p -value) at a significant level of (0.05). Each of the selected predictors is further assessed for its accuracy using graphical methods such as a scatterplot.

A stochastic component of the SDSM artificially inflates the variance of the generated scenario daily data to compensate for the regression that does not explain all observed variance of the predictand, given to the user in the form of a percentage of explained variance (R^2) and standard error (SE) for the model (Koukidis and Berg 2009). The Weather Generator operation in SDSM generates up to 100 different ensembles of synthetic daily weather data series given observed atmospheric predictor variables. In this study, only 20 ensembles were simulated. The observed historical data used for calibration was for 30 years (1961-1990) and the period from 1991 to 2005 is being used to validate the models. After successful calibration and validation of SDSM, the future climate parameters were simulated separately for all the three scenarios of RCPs (RCP2.6, RCP4.5 and RCP8.5). The correlation coefficient (R), coefficient of determination (R^2), root-mean-square error (RMSE), Nash-Sutcliffe efficiency (NSE) and

RMSE observation SD ratio (RSR) were applied according to (1) through (5) equations and used to test the ability of SDSM to realistically downscale GCM data and to check statistically the performance of historical and simulated data during the calibration and the validation periods.

In these equations, $X(\text{obs}, i)$ and $X(\text{model}, i)$ are, in order, the daily observed and the simulated data at the i th time step. \bar{X}_{obs} and \bar{X}_{model} represent the daily average observed and simulated values, where n is the number of values. Each of these statistical indicators expresses the correspondence or similarity between the observed values and the simulated ones (Golmohammadi et al. 2014; Ashofteh et al. 2015; Tiwari et al. 2020; Shakeri 2020). The coefficient of determination measures the goodness of fit and the RMSE is the criterion for the amount of deviation of the simulated values. The RMSE indicates a perfect match between observed and simulated values when it equals 0 (zero). NSE indicates the ratio of the variance of the observed values to the variance of simulated values. Ideally, $\text{NSE} = 1$ means complete correspondence between observed and predicted values, whereas values between 0.0 and 1.0 are considered as acceptable. The RSR varies from the optimal value of 0 to a high positive one. The lower RSR, the weak the RMSE and the better the model simulation performance. In sum, the greater the value of R , R^2 and NSE and the lower RMSE and RSR indicate the stronger the relationship is between the calibrated and validated time series.

$$R = \frac{\sum_{i=1}^n (X_{\text{obs},i} - \bar{X}_{\text{obs}})(X_{\text{model},i} - \bar{X}_{\text{model},i})}{\sqrt{\sum_{i=1}^n (X_{\text{obs},i} - \bar{X}_{\text{obs}})^2 \cdot \sum_{i=1}^n (X_{\text{model},i} - \bar{X}_{\text{model},i})^2}} \quad (1)$$

$$R^2 = \frac{\sum_{i=1}^n (X_{\text{model},i} - \bar{X}_{\text{obs},i})}{\sum_{i=1}^n (X_{\text{obs},i} - \bar{X}_{\text{obs},i})} \quad (2)$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (X_{\text{obs},i} - X_{\text{model},i})^2}{\sum_{i=1}^n (X_{\text{obs},i} - \bar{X}_{\text{obs}})^2} \quad (3)$$

$$\text{RMSE} = \frac{\sqrt{\sum_{i=1}^n (X_{\text{obs},i} - X_{\text{model},i})^2}}{n} \quad (4)$$

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDE}} = \frac{\sqrt{\sum_{i=1}^n (X_{\text{obs},i} - X_{\text{model},i})^2}}{\sqrt{\sum_{i=1}^n (X_{\text{obs},i} - \bar{X}_{\text{obs}})^2}} \quad (5)$$

2.3. Bias Correction:

To eliminate the biases from the daily time series of SDSM's downscaled data, a bias correction method is performed by applying the two following equations (Salzmann et al. 2007; Mahmood and Babel 2013; Saidi et al. 2020).

$$T_{\text{deb}} = T_{\text{sce}} - (\bar{T}_{\text{con}} - \bar{T}_{\text{obs}}) \quad (6)$$

$$P_{\text{deb}} = P_{\text{sce}} \times \left(\frac{\bar{P}_{\text{obs}}}{\bar{P}_{\text{con}}} \right) \quad (7)$$

Where: T_{deb} and P_{deb} are the de-biased daily time series of temperature and precipitation, respectively, for future periods; T_{SCE} and P_{SCE} represent the daily time series of temperature and precipitation downscaled by SDSM for future periods respectively (e.g., 2011-2100). \bar{T}_{con} and \bar{P}_{con} represent in order the long-term mean monthly values of simulated temperature and precipitation by SDSM for the control period (e.g. 1961–2005). \bar{T}_{obs} and \bar{P}_{obs} represent the long-term monthly mean observed values for temperature and precipitation.

3. RESULTS AND DISCUSSION

The results indicate that the most relevant atmospheric predictors for both maximum and minimum temperature were: Mean sea level pressure, 850 and 500 hPa Geopotential, 850 hPa Specific humidity and Air temperature at 2 m. Besides these predictors and for the Saharan region, we selected the predictors 500 hPa Relative vorticity of the true wind and 500 hPa Wind direction. However, for the precipitation, the dominant predictor variables were: surface and 500 hPa Specific humidity, surface Meridional wind component, surface Divergence of true wind, 850 hPa Zonal wind component, 500 hPa Meridional wind component and Total precipitation. The highest correlation scores were obtained for the maximum and minimum temperatures while the lowest ones were for precipitation.

3.1. Calibration and validation of SDSM

Using the selected predictors for each predictand, the model is calibrated under unconditional (temperature) and conditional (precipitation) processes on a monthly scale except for the Saharan stations and for precipitation, the model is calibrated on seasonal time scales to increase the number of wet days. For our case, R varies between 77 and 98% for both calibration and validation of minimum and maximum temperatures, while the R2 is ranging between 60 and 96% and the mean of NSE between 0.77 and 0.90 (Table 3.). However, for the precipitation, weaker correlations were found, R and R2 were globally equal to lower than 60% notably for the Saharan stations, where they were less than 30%, this suggests that the model performance is less effective for the precipitation parameter in the Saharan zone. These results corroborate previous studies on modelling daily precipitation (Saidi et al. 2020; Wilby et al. 2002; Gagnon et al. 2005). This is because of the complex characteristics of daily events and to the fact, modeling precipitation is one of the most challenging climate variables and in conditional models,

there is an intermediate process between regional forcing and local station weather which in turn depend on regional-scale predictors such as humidity and atmospheric pressure (Gebrechorkos et al. 2019).

Data of both observed and simulated precipitation and minimum and maximum temperatures during the period 1991-2005 are mapped using the universal Kriging interpolation method with SAGA-GIS software by converting point data to raster data to carry out and to compare the spatial distribution of these parameters over the country (Figs. 2-4). The observed and simulated patterns of minimum (Fig. 2) and maximum temperatures (Fig. 3) illustrate the observed North-South temperature gradient as well as the effect of elevation. The temperatures distribution over the high plateaus is well reproduced. The Saharan region remains the hottest whereas the highlands in Tamanrasset enjoy a temperate climate and fairly mild weather due to its high altitude. The spatial distribution of simulated precipitation produced is significantly consistent with observations (Fig. 4), thus, higher values of precipitation appeared in the far-North-Eastern cities and the coastal central zone, and lower values mainly observed in the South. The simulated downscaled data during the validation period resulted globally in similar spatial patterns compared to observations as they all show obvious variations across the country. Consequently, SDSM provides reasonable downscaling data when using NCEP large-scale predictors representing the observed current climate and can be therefore used to project future climate.

	RMSE		NSE		R (%)		R ² (%)		RSR	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
calibration (1961-1990)										
T-min	2.32-4.45	3.23	0.50-0.89	0.77	77-96	89	60-92	79	0.33-0.70	0.47
T-max	0.83-5.54	3.22	0.48-0.95	0.81	79-97	91	62-95	83	0.23-0.72	0.42
PRCP :										
All stations	0.49-5.34	2.15	-0.06-0.35	0.05	01-59	22	01-35	08	0.81-1.03	0.97
coastal+plateaus stations	2.23-5.34	3.74	-0.01-0.35	0.15	21-59	37	04-35	16	0.81-1.0	0.92
Saharan stations	0.49-1.61	0.97	-0.06-0.07	-0.01	01-30	11	01-09	02	0.96-1.03	1.01
Validation (1991-2005)										
T-min	2.31-3.31	2.93	0.70-0.92	0.84	89-98	95	79-95	90	0.29-0.55	0.39
T-max	1.93-4.78	2.55	0.74-0.95	0.90	87-98	96	76-96	91	0.21-0.51	0.31
PRCP :										
All stations	0.51-4.95	2.38	-0.03-0.35	0.06	01-60	21	01-36	07	0.80-1.02	0.97
coastal+plateaus stations	2.60-4.95	3.81	0.01-0.35	0.14	18-60	36	03-36	15	0.80-1.0	0.92
Saharan stations	0.51-2.03	1.30	-0.03-0.07	0.0	01-27	9	01-07	01	0.97-1.02	1.00

Table 3. Statistical indicators results of SDSM performance for calibration (1961–1990) and validation (1991–2005): Root mean square error (RMSE), Nash-Sutcliffe efficiency (NSE), correlation coefficient (R), coefficient of determination (R²) and RMSE observation SD ratio (RSR).

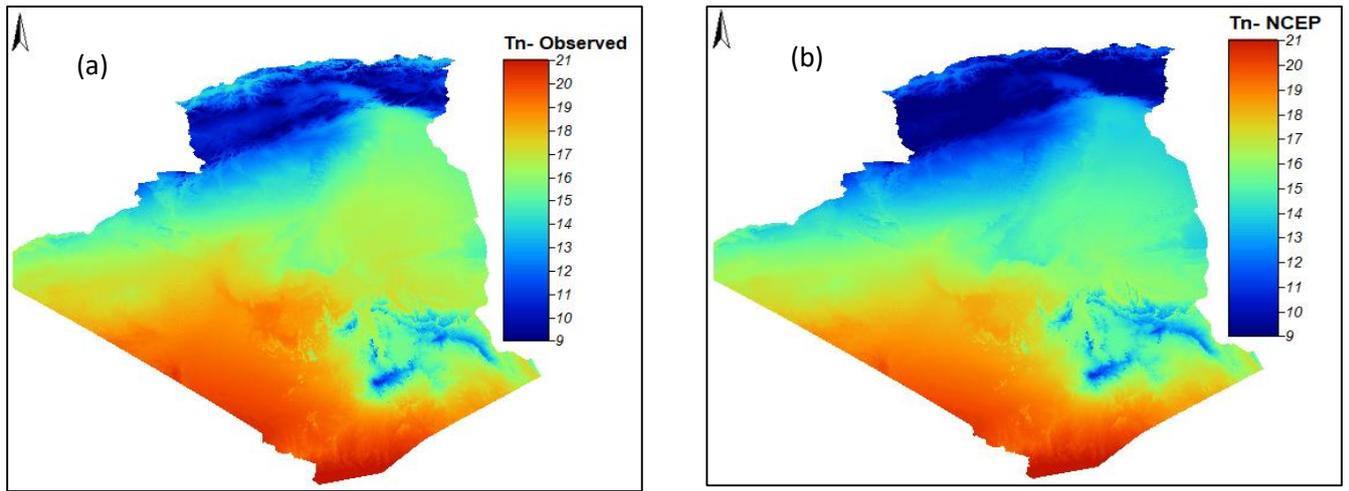


Fig. 2. Spatial variation of T-min ($^{\circ}\text{C}$) of (a) observed versus (b) simulated, generated by SDSM during the validation period (1991–2005) in Algeria.

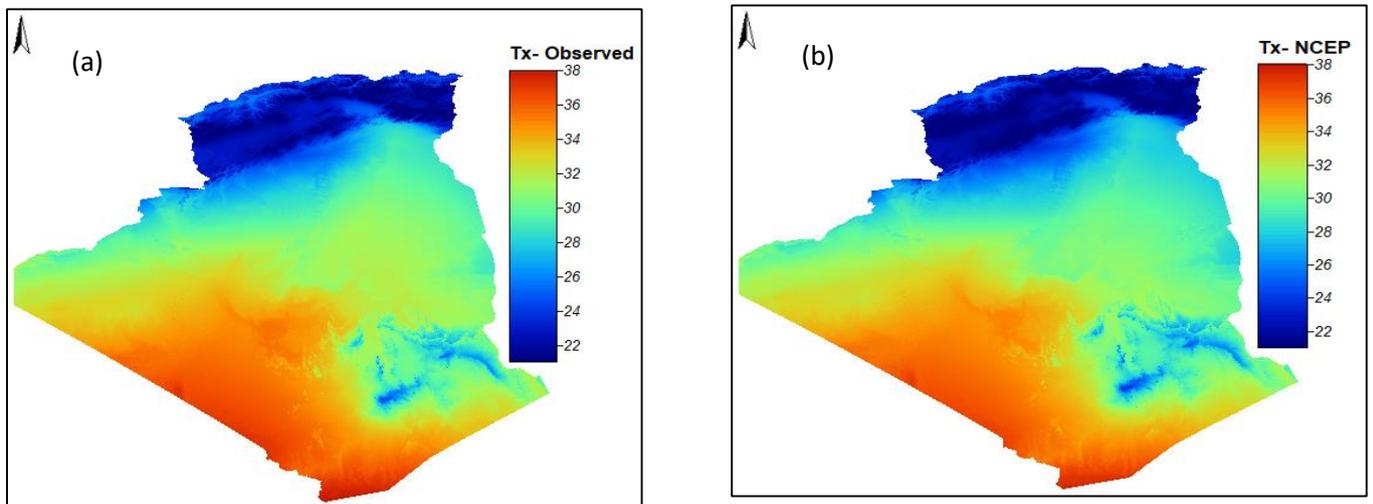


Fig. 3. Spatial variation of T-max ($^{\circ}\text{C}$) of (a) observed versus (b) simulated, generated by SDSM during the validation period (1991–2005) in Algeria.

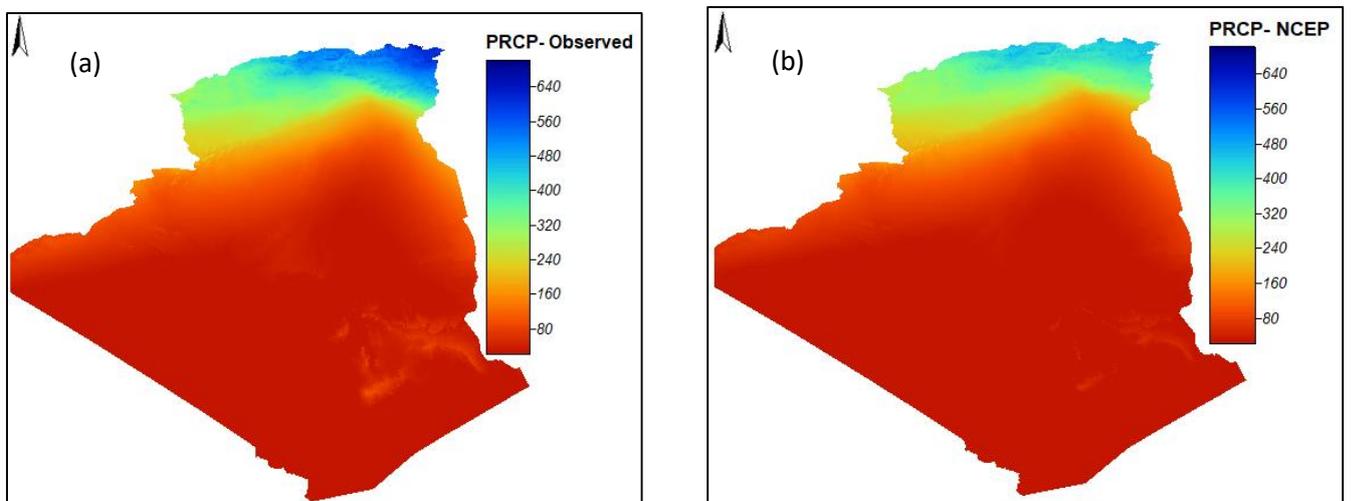


Fig. 4. Spatial variation of annual precipitation (mm) of (a) observed versus (b) simulated, generated by SDSM during the validation period (1991–2005) in Algeria.

3.2. Future Temperature and Precipitation Change Scenarios

The future climate parameters have been extracted based on each model-scenarios and compared with respect to the baseline period 1981-2010 considered as the present climate, using the large-scale atmospheric predictor variables derived by CanESM2 for the three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. Twenty ensembles of synthetic time series at the daily scale were generated for the daily temperatures and precipitation and for each emission scenario of future decades; the average value of these 20 ensembles was used for the appropriate period.

3.2.1. Temperature

Future temperature projections from all downscaled models under different scenarios highlight an increase for both minimum and maximum temperatures in intensity in the country up to the end of the 21st century. Overall, strong warming is projected for the “business-as-usual” Representative Concentration Pathway (RCP 8.5), particularly for the Saharan region. The annual mean of minimum temperatures under the RCP 2.6 scenario is expected to increase by 0.2 to 1.6°C in the 2020s and 1.0 to 2.0°C in the 2050s and the 2080s compared to the baseline period (1981–2010). According to the RCP4.5 scenario, the change ranges from 0.3 to 1.9°C in the 2020s and 1.4 to 2.5°C in the 2050s and 2.0 to 3.0°C in the 2080s. Under the RCP8.5 scenario, it will increase by 1.0 to 2.4°C in the near future (the 2020s) and 2.4 to 4.0°C in the mid-century (the 2050s) and 3.6 to 5.0°C by the end of the century.

Under the most optimistic RCP2.6 scenario and compared to the recent reference period, the annual average of maximum temperatures is predicted to increase for the near future (2011–2040) by 0.3 to 1.9°C and 2.2 to 3°C in the mid-century (2041-2070) and 3 to 4°C towards the end of the century (2071–2100). For the intermediate stabilization scenario (RCP4.5), the mean annual maximum temperatures are projected to rise by about 1.4 to 3.2°C in the 2020s; 2.8 to 4.0 °C in the 2050s and 3.2 to 5°C for the 2071–2100 period. Under the “business-as-usual” pathway (RCP8.5), the rise in the average annual maximum temperature is expected to reach 3.0°C – 4.0°C by the 2020s, and 3.6 - 5.0°C by the 2050s and 5.0 - 8.0 °C by the 2080s. The results show an emergence of unprecedented climate change in projected future temperatures by the end of the century. Thus, the average rate of increase in maximum temperature revealed a dangerous level of warming particularly in the Saharan region under both the intermediate (RCP4.5) conditions as well as for the strong radiative forcing pathway (RCP8.5). We conclude that for Algeria, the development and implementation of adaptation strategies and plans to mitigate climate change risks must be realized with high priority in the near future. We deduced also that the rate of change for the minimum temperature is less than the rate of change for the maximum temperatures. Figs 5 and 6 show the spatial distribution of the projected future change of annual mean of respectively T-min and T-max over Algeria.

For both minimum and maximum temperatures, the coastal region is projected to warm more slowly than the high plateaus and the Saharan zone, due to its proximity to the Mediterranean Sea, a primary factor responsible for reducing extreme heat conditions (Sahabi et al.2017).

The obtained results are globally consistent with those of Zittis et al. (2021) who compared the evolution of daily maximum temperature derived from each of the MENA-CORDEX ensemble members to the reference period 1981-2010. The authors indicate that for a business-as-usual pathway (RCP8.5), in the second half of this century, unprecedented super- and ultra-extreme heatwave conditions will emerge over the MENA region including the Algerian Sahara zone (temperatures up to 56 °C and higher).

Projections over Algeria are also in quite good agreement with the values obtained by Driouech et al. (2020). These results are also in line with those obtained by Bucchignani et al. (2018) who explore future climate simulations with the COSMO-CLM over the 21st century under RCP4.5 and RCP8.5 scenarios. They showed that for an intermediate emission scenario (RCP4.5), the T2m change projections for the period 2071-2100 with respect to 1981-2010 in North-western Africa will be strong (up to 5°C).

Lelieveld et al. (2016) show in their study that the positive trends of the temperature extremes over the MENA region, based on CMIP5 models simulations under RCP4.5 and RCP8.5 are projected to be stronger particularly in summer, with approximately a similar intensity obtained in this study.

Our results corroborate those previously obtained by Almazraoui et al. (2020) who examine projected variations in precipitation and temperature over North Africa using the CMIP6 models simulations for the period 2030–2059 (near term) and 2070–2099 (long term), relative to the present climate (1981–2010). The authors revealed that warming is projected to extend over North Africa until the end of the century. They concluded that projected warming over North-Africa for the near (long)-term period is 1.2–2.1 °C (1.2–2.4 °C), 1.4–2.5 °C (2.3–3.6 °C), and 1.8–2.9 °C (4.1–6.0 °C) under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. Whereas, projected temperature changes over Sahara for the near (long)-term period is 1.2–2.0 °C (1.1–2.2 °C), 1.5–2.4 °C (2.4–3.5 °C), and 1.9–2.9 °C (4.3–6.1 °C) for SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios respectively. During the summer, the projected temperature increases under SSP5-8.5 for more than 6 °C over the North-Africa region and more than 5°C over the Sahara.

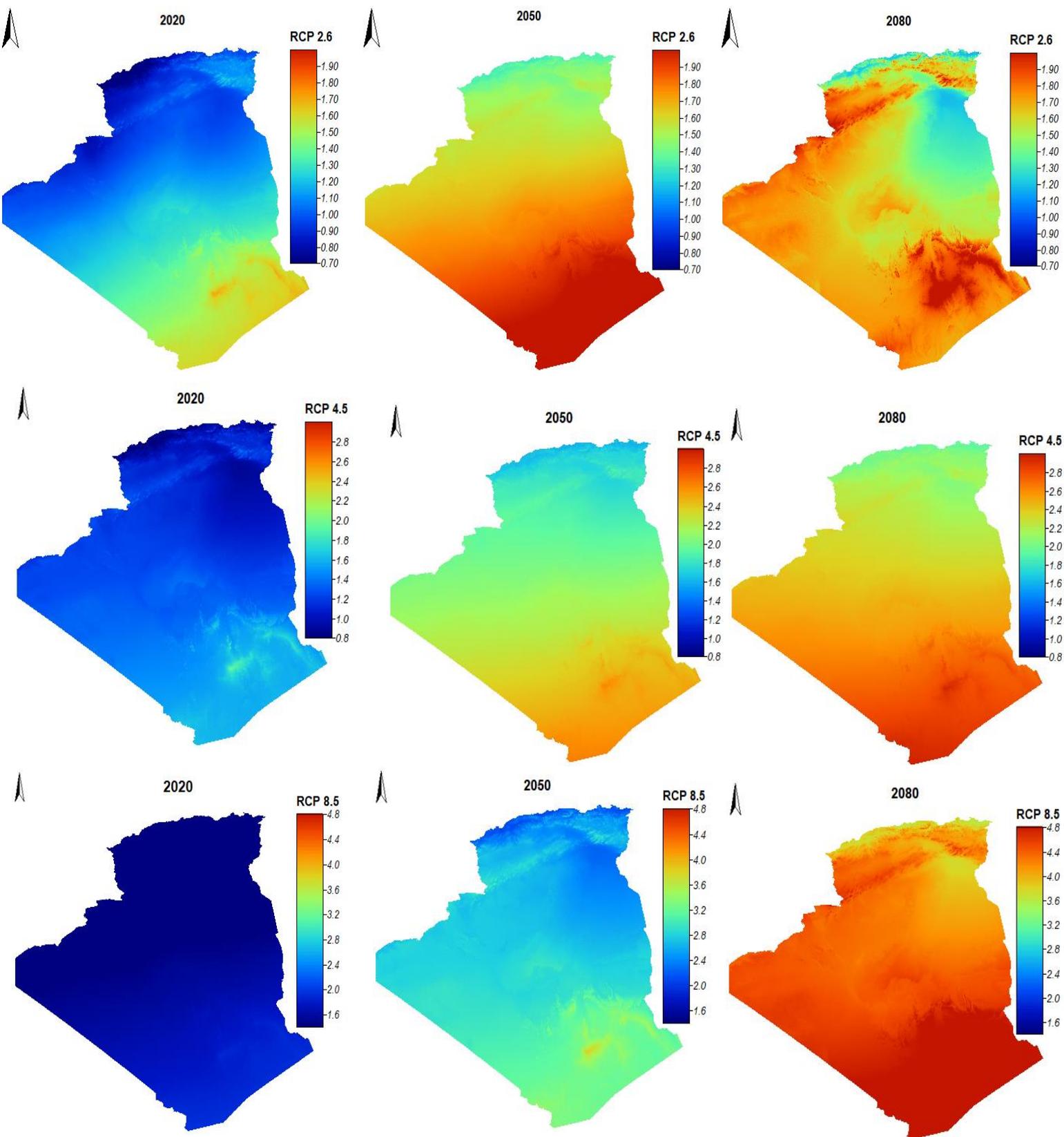


Fig. 5. Projected future change of annual mean of T-min (°C) (2020s, 2050s and 2080s) under RCP2.6, RCP4.5 and RCP 8.5

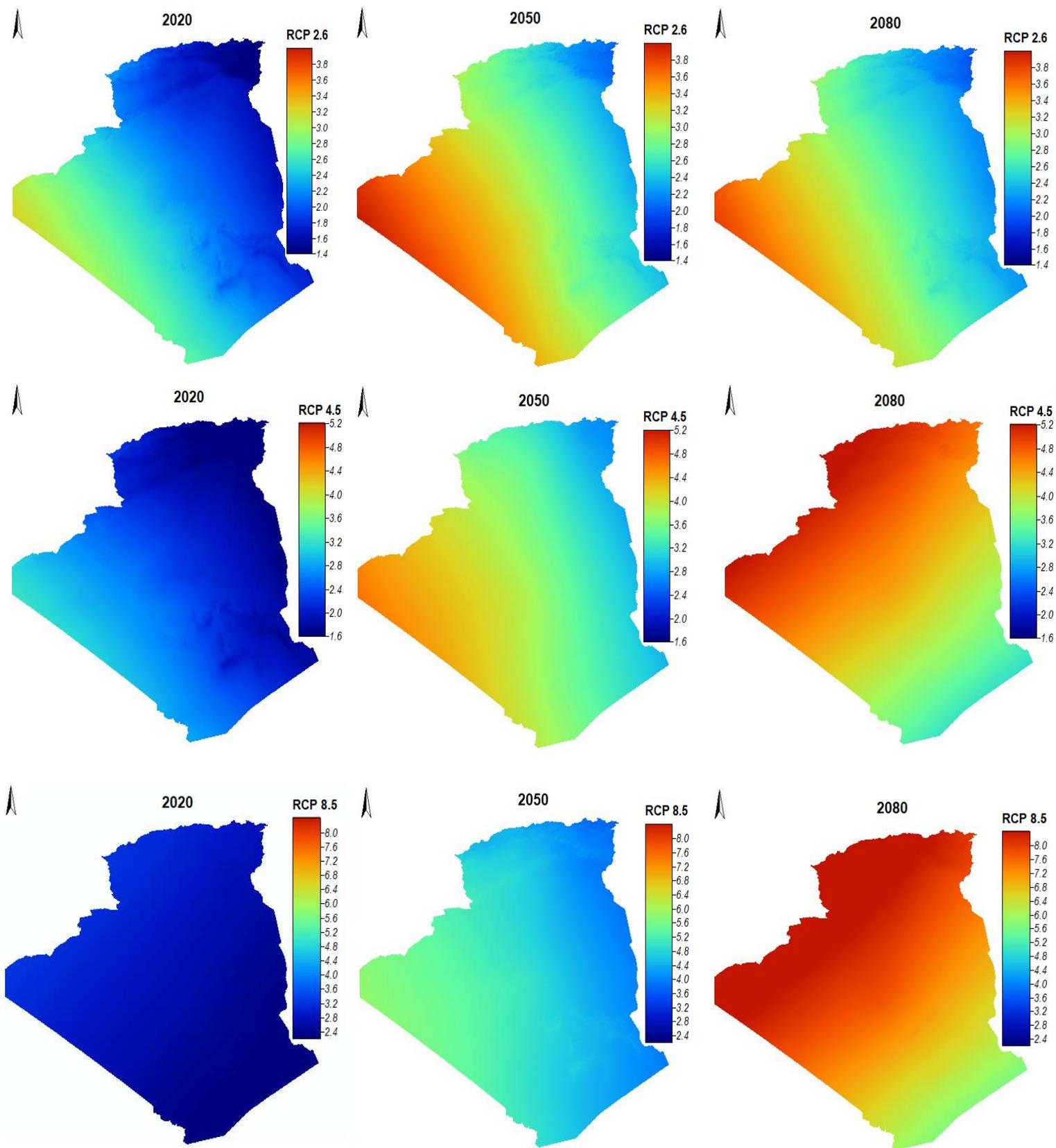


Fig. 6. Projected future change of annual mean of T-max (°C) (2020s, 2050s and 2080s) under RCP2.6, RCP4.5 and RCP8.5

3.2.2. Precipitation

To investigate the future projected precipitation, relative future changes were calculated by normalizing the future change values by the historical values of the reference period to obtain a relative sense of how much the change compares to the recent climatology. Overall, we project mean annual precipitation to increase in the south-western, extreme south-eastern part and the eastern region of North highlands and a decrease in the remaining regions particularly in the north-western of coastal and plateaus regions. Fig. 7 illustrates the spatial distribution patterns of the percentage variations of projected precipitation under different Representative Concentration Pathways during the three-time slices regarding the historical reference period. However, in the 2020s and under all RCP scenarios, the western region surrounding the Mediterranean Sea, the western inland zone and most parts of the Sahara (excepted south-western and extreme south-eastern zones) showed an expected decrease varying between -10 to down -20%. These results are consistent with CIRCE models (Goodess et al. 2013) in indicating a quite large decrease in total annual precipitation for the period 2021-2050 with respect to 1961-1990 over the Gulf of Oran (western coastal region) of about 20%.

Conversely, normal conditions to a small increase of around 10 % are predicted in the central and eastern coastal part while a strong increase in precipitation (reaching 50%) is expected in the precipitation projections over the central and eastern plateaus and south-western and extreme south of the Sahara. However, this latter area is characterized by low annual total precipitation values, leading to high percentage variations in any future period even if absolute changes are weak.

Expected changes in precipitation for the 2050s will be globally similar to that in the 2020s. Yet for the eastern high plateaus region and extreme south of Sahara, there is going to be a greater spatial expanse of strong values in relative precipitation variations (up +35% from historical values), particularly for RCP4.5 and RCP8.5.

Under the “business-as-usual” pathway, projected precipitations for the period 2071 to 2100 are from normal over the North of the Sahara to a substantial increase expected for the remaining parts of this zone (up to 50%), while precipitation reductions (~20%) are projected in the coastal region notably in the west.

These results are consistent with those revealed by Massoud (2020) who investigated the future projected change of atmospheric rivers and precipitation for the MENA region using a suite of models from the CMIP5 historical and RCP8.5. He found out that for changes in mean precipitation, much of the region surrounding the Mediterranean Sea showed an expected decrease (down -30% from historical values) and an increasing trend is expected in precipitation (up +50% from historical values) for southern Algeria and the Arabian Peninsula.

Driouech et al. (2020) revealed in their study a projected drying with RCP8.5 for the future period (2071–2100) against the present-day period (1976–2005) in the Mediterranean area and over the western part of the MENA region including Morocco and Algeria, consistent with our results and those of the

previous studies (IPCC 2013). Their results indicate a reduction of total precipitation amounts varying from -5 to -20% and exceeding -40% in the west of the Atlas Mountains, while the changes in the Sahara Desert correspond to increases exceeding $+40\%$ of the reference period.

Our findings corroborate the study by Paeth et al. (2009) in projecting under A1B scenario conditions a decrease of the precipitation between 10 and 20%, and an increase of temperatures between 2 and 3°C by 2050, with a most pronounced warming in the north-western parts of northern Africa.

Taylor et al. (2012) used the CMIP5 ensemble to project precipitation under the RCP8.5 scenario. They predicted very likely decreases in mean annual precipitation over the northern Africa region in the mid and late 21st century periods.

The revealed results are consistent with those concluded by Almazraoui et al. (2020) who analysed projected precipitation changes in North Africa for the period 2030–2059 (near term) and 2070–2099 (long term), relative to the baseline 1981-2010 using the CMIP6 models. They projected a robust reduction in precipitation for this region during the twenty-first century. The precipitation change is expected to vary during near (long)-term period between -13.1 to -0.7% (-17.2 to -3.0%), -14.8 to -1.5% (-22.9 to -4.5%), and -18.3 to -5.7% (-36.1 to -15.3%) under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. They concluded that the CMIP6 model ensemble projects more precipitation over the Sahara as compared with CMIP5.

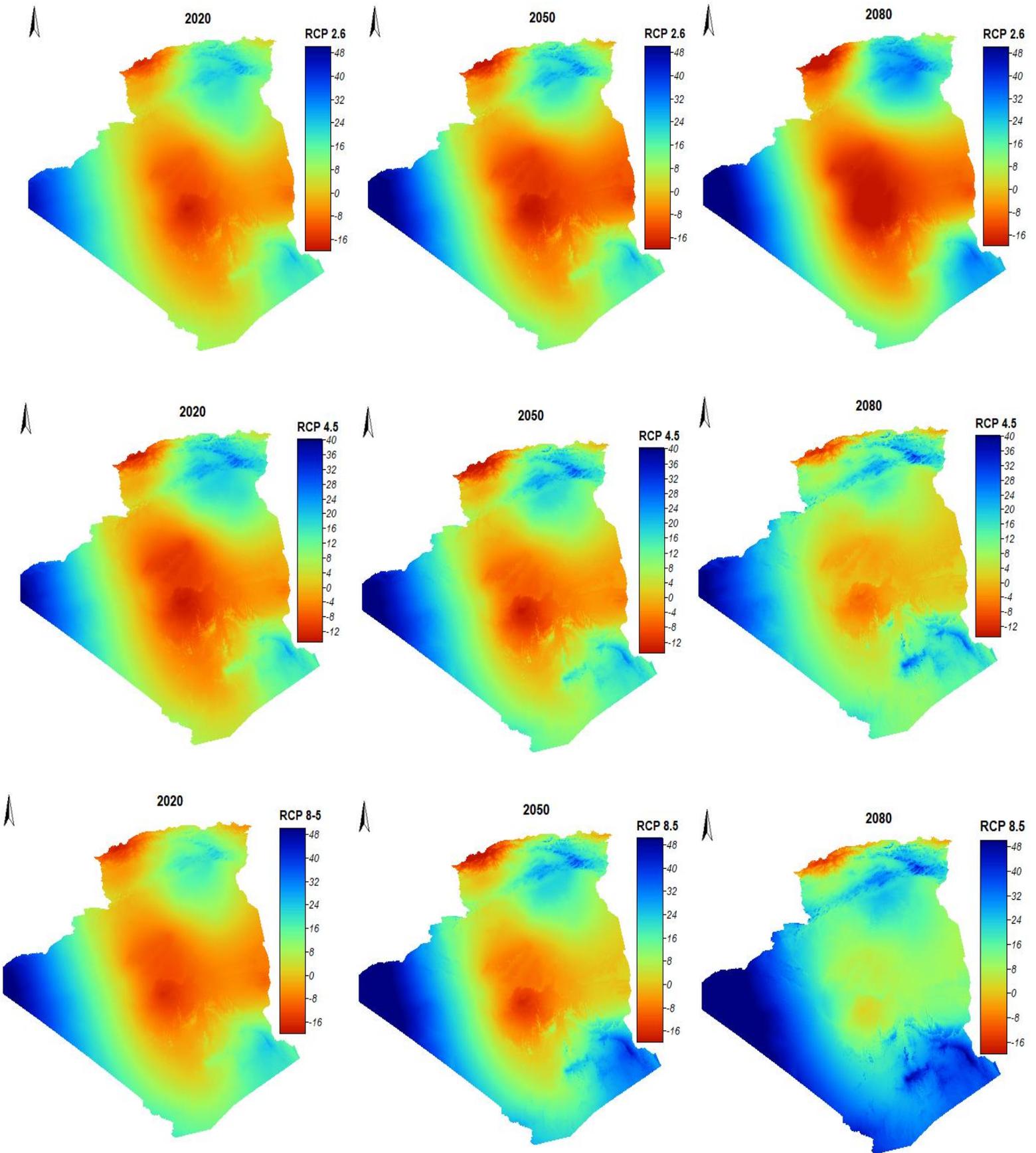


Fig.7. Projected future change (%) of annual PRCP (2020s, 2050s and 2080s) under RCP2.6, RCP4.5 and RCP8.5

4. Comparison of projected seasonal precipitation change in selected stations:

To assess the precipitation changes at a seasonal scale, five meteorological stations established in five important Algerian cities are selected due to their importance economically and demographically and representing different climate regimes: Two coastal cities, Algiers in the center, and Oran in the west; Constantine which is in the northeast highland; Bechar in the northwest of the Sahara and Tamanrasset in the extreme south of the country. Fig.8 a,b show that for all scenarios, Bechar, Algiers and Constantine will experience a strong positive change of the precipitation in summer during the 2020s, the 2050s and the 2080s, while, there will be a decline in precipitation in Autumn for Bechar and in Winter for Constantine. Furthermore, the highest seasonal predicted change is for Constantine in summer with +140% under the RCP8.5 scenario by the 2080s as compared to the reference period 1981-2010. For the Constantine and Bechar stations, a non-significant trend is projected at the annual scale.

In Oran, scenarios exhibit a decreasing precipitation trend for all seasons and in the 2020s, the 2050s and the 2080s. This decrease is more stressed during summer with -30 to -70% under respectively RCP2.6 and RCP4.5 and -40 to -90% for RCP8.5 and that during the 3 selected time slices. However, specifically for the rainy season from autumn through winter, the precipitation is expected to fall to approximately -30 to -80% in this city.

Drying conditions are projected with all scenarios in Tamanrasset in winter and summer. The reduction of seasonal precipitation amounts in this region varies for all scenarios respectively, from -25% in summer to -50% in winter from now to the end of the century. In contrast, precipitation will increase by up to 20 and 30% during spring and autumn for the entire projected period. At the annual scale, we expect rainfall in Tamanrasset to be normal to slightly below normal (-5%) as compared to the baseline period.

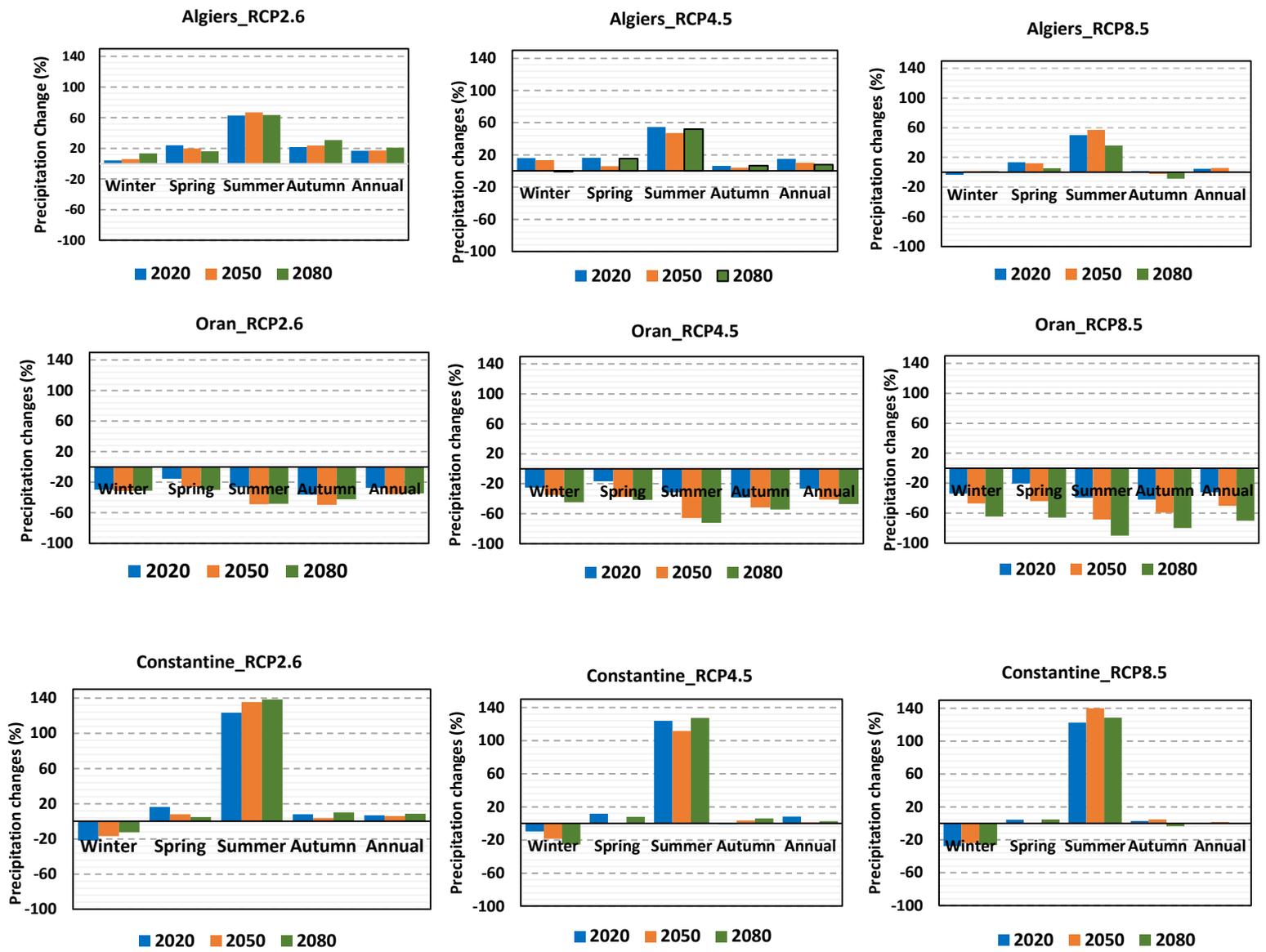


Fig. 8a. Future change in seasonal and annual precipitation across Algiers, Oran and Constantine under the RCP2.6, RCP4.5 and RCP8.5 scenarios in the 2020s, the 2050s and the 2080s as compared to 1981-2010 baseline

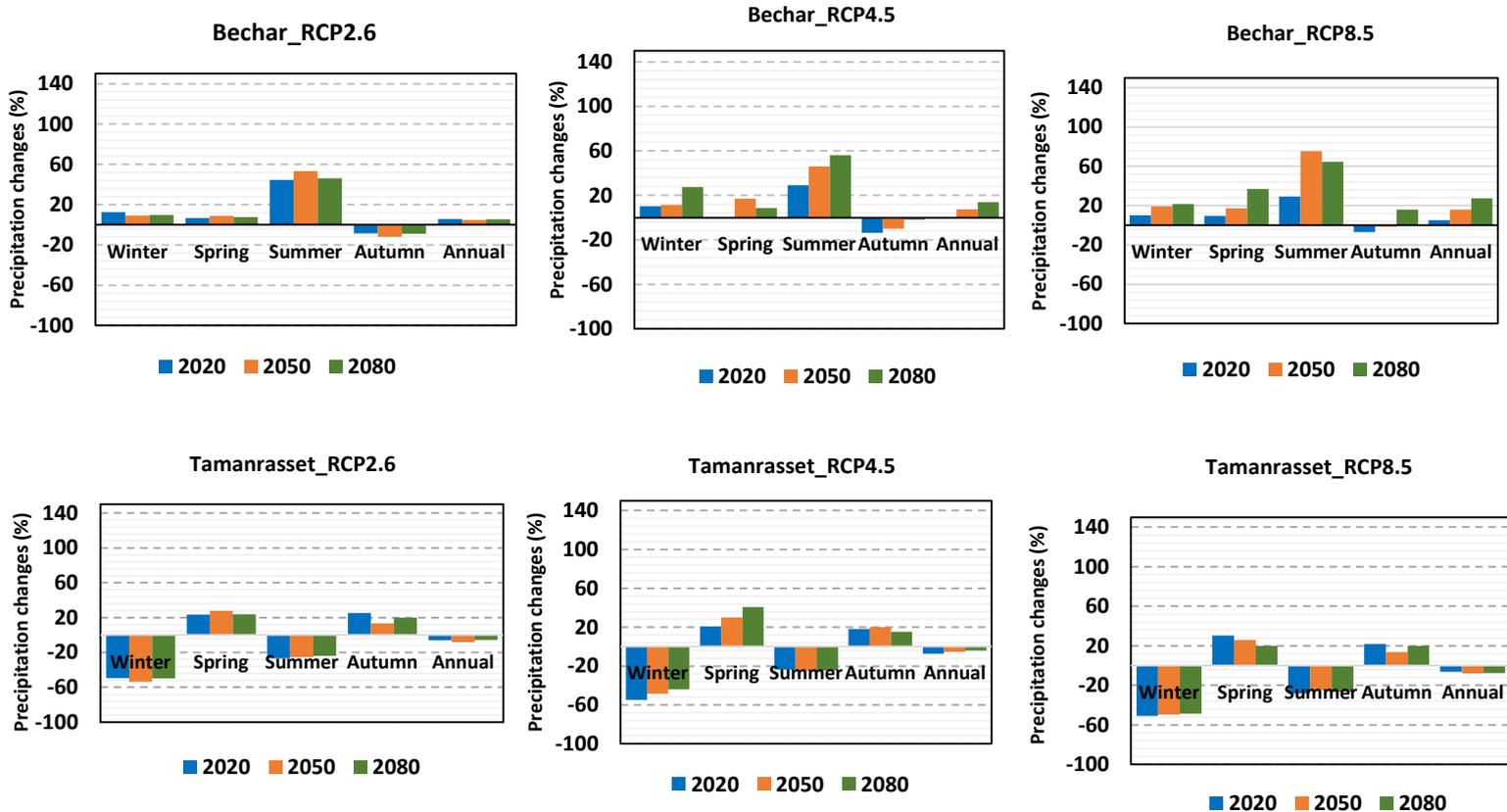


Fig. 8b. Future change in seasonal and annual precipitation across Bechar and Tamanrasset under the RCP2.6, RCP4.5 and RCP8.5 scenarios in the 2020s, the 2050s and the 2080s as compared to 1981-2010 baseline

5. Conclusion:

This study provided a picture of the climate change projections of temperature and precipitation in Algeria, based on large-scale climate variables derived from the second generation Canadian Earth System Model (CanESM2) experiments as prepared for the CMIP5 project and downscaled by using the SDSM tool. Although the SDSM model is being widely applied throughout the world as a statistical downscaling tool, this study reports the first application of SDSM in Algeria. We assess in this work the performance of SDSM in simulating climate variables during calibration and validation periods. Despite the less effectiveness of the model in simulating well the precipitation parameter over the Saharan zone because of the complexity of the variable and a lack of climatological and meteorological stations in the region, SDSM could reproduce the observed temperatures and precipitation during both calibration and validation phases.

The study shows that the magnitude of the warming at the end of the century relative to the baseline period (1981–2010) highly depends on the emission scenario considered. Overall, for the future climate of the domain, the warming trend is observable for the maximum temperatures than the minimum

temperatures especially for the worst-case scenario (RCP 8.5). It is more pronounced over the Sahara than in high plateaus and coastal regions.

Under the RCP8.5 scenario, the minimum temperature over Algeria will increase up to 2.4°C in near future (2011–2040), 2.4 to 4.0°C in the mid-future (2041–2070) and 3.6 to 5°C for the far future (2071–2100) periods. For the maximum temperature, this increase will be stronger, varying between 3 to 4°C in the 2020s, 3.6 to 5.0°C in the 2050s and from 5 °C up to 8 °C in the 2080s. Under the "business as usual" scenario, the warming is expected to be therefore 2 to 3 times higher in the late twenty-first century.

The future pattern of rainfall under all scenarios is constantly decreasing over the western coastal and western high plateau regions. The expected decrease is varying between 10 to down 20% relatively to 1981-2010 period. Inversely, normal conditions to an increase by up to 50% are respectively projected for the Northeastern and southern regions in Algeria.

The study evaluates the precipitation change at a seasonal scale over the five selected stations representing different climate in different regions of Algeria. When compared to the reference period, a significant increase in precipitation across all three future scenarios is projected during the summer except the western coastal region and extreme southern Sahara. The Northwestern of Algeria will be affected by a strong reduction in precipitation during the entire seasons, which contributed appreciably to magnifying drought over this region. Shifting in the wet season is shown in the Northeast in Algeria where the precipitation amount is projected to be greater during the summer and below in winter relative to the baseline period. Therefore, it can be concluded that in Algeria, winter is globally expected to become dryer as compared to the recent climate.

Consequently, the results obtained in this study are in quite agreement with previous studies conducted in the context of the north-African and Mediterranean regions. Since for a business-as-usual pathway and by the end of this century, the expected strong warming will obviously make heatwaves hotter, longer, and more frequent. Climate change is therefore expected to be felt more severely in Algeria given the high exposure fragility and low adaptive capacity. Enhancing resilience, engaging adequate mitigation measures, and integrating the climate information delivery in development policy and planning processes to both assess and monitor the impact of climate change, should be accomplished with great priority in the coming decades. Despite the ability of SDSM to simulate the climate, a comparative study considering several different climate model outputs is strongly recommended to provide greater confidence in the projected climate variables.

Declarations:

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- **Conflicts of interest/Competing interests:** The author declares no conflict of interest
- **Availability of data and material:** The CanESM2 predictors are downloaded from the website (<https://climate-scenarios.canada.ca/?page=pred-canesm2>). The meteorological data are provided by the Office National de la Météorologie – Algeria
- **Code availability:** SDSM tool available for free at: <https://sds.org.uk/software.html>
- **Author contribution:** Sahabi- Study concept and design, perform Data Collection, Analysis, Interpretation and Manuscript writing
- **Ethics approval:** Not Applicable
- **Consent to participate :** Not Applicable
- **Consent for publication:** Not Applicable

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