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# SIMULATION OF CLIMATE AND ITS IMPLICATION ON AGRICULTURE IN MOROCCO USING STATISTICAL DOWNSCALING

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**Abstract-** ***Assessment of regional climate impact requires high-resolution climate data. We use a Statistical Downscaling Model to develop and implement a methodology for constructing a high-resolution climate projection dataset, based on IPCC scenarios. We use down-scaled temperature and precipitation for different future scenarios and time horizons to assess the impact of climate change on agricultural regions in Morocco. The accuracy of downscaled precipitation and temperature is acceptable. Under the IPCC A2 scenario and for 2020, results indicate annual warming between 0.8 and 1.8°C with warming less than 1.9°C for all seasons. Similarly, annual rainfall decreased by less than 8% with a maximum reduction of 11.4% during the spring. We find that projected rainfall reductions are larger than those made by low resolution multi-model ensemble. Under a warmer climate, projected extreme statistics related to temperature, such as heat-waves, are likely to increase substantially in magnitude and frequency. These projections are useful for the study region where observations are rare and coarse large scale global models do not capture local features. In our study region, the Statistical Downscaling Model appears to be an essential tool for scale-reduction of modelled meteorological information.***

***Results from this study are important for farmers and land and water managers alike to start early planning for cropping and developing adaptation measures including crop replacement and modifications and other means of irrigation and water deliveries, optimal for near future climate conditions.***

***Keywords -*** Climate Change; Global Climate Model; Statistical Model; Meteorological Observations; Agriculture, IPCC scenarios.

## I. INTRODUCTION

Climate change is global in nature, but its potential impact is local and will be felt in towns and villages. The way climate affects a locality depends on its weather patterns and geographic features such as topography, coastal proximity, and land-use and cover. The interactions between weather patterns and these geographic features are complex and when forced by global change may result in outcomes that are not easily predictable using outputs from global scale projections [31].

Climate is changing rapidly and according to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change [22] the warming of the global climate system is unequivocal and is evidenced by observations of increases in global mean air and ocean temperatures, melting of ice and rising average sea level. Over the North African Mediterranean region, the IPCC models agree unanimously on a general warming and drying [22]. This semi-arid to arid region is bordered by the Sahara Desert to the south and the Mediterranean to the north; its climate is characterized by moderately wet and cool winters and dry and warm summers in the north with arid conditions in the south. The rainy season occurs during a short period of the year, generally between late fall and early spring and the vegetation cover is sparse, severely degraded and confined to a narrow strip along the coastal area [36, 6].

Changes in climate are already having a measurable impact on local agriculture and water resources in Morocco [4], a semi-arid to arid country in north west Africa surrounded by the Sahara to the south and East, the Mediterranean to the north and the Atlantic Ocean to its west (figure 1). Climate in Morocco is strongly modulated by the Atlantic Ocean influence along its western coast [18] and by the Atlas Mountains. Precipitations are abundant in mountainous area and moderate west and north of it [15]. Climate in Morocco is also influenced by the evolution of the Saharan Heat Low [29, 38], which is a key feature of the West African monsoon and a key synoptic element over the region which generates warm easterly wind referred to as "Chergui". The destabilization of the mixed layer appears to result from a thermal unbalance between the net radiative heating and the convergence of the eddy sensible heat flux during the formative stage of the thermal low, inhibiting thus convection and sustaining arid conditions [7].

A recent study [5] confirms the modeled increase in temperature and reduction in precipitation over large areas of Morocco and suggests a northward expansion of arid climate characteristics. This may have important implications for the regional climate as the increase in temperature over the region may reach the 2°C upper limit endorsed by the United Nations Framework Convention on Climate Change (UNFCCC) and discussed at the world climate summit [47] sooner than expected.

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The combination of the geographic location, the landscape composition and the complex topography make this region sensitive to climate variations and increase the spatial variability of the response. As such, the region is vulnerable to changes in climate and unless achievable pathways for sustainability, mitigation and adaptation are developed, the region may be subject to large-scale desertification with important socio-economic consequences to local populations. Sustainable adaptation pathways may be developed if the interactions between the land-surface and climate that control agricultural, hydrological and energy cycles are understood and modeled at small spatial scales. Such modeling requires local and regional climate record with fine spatio-temporal resolutions that capture local characteristics [24].

Global models such as those used by the IPCC are useful tools for providing climate information around the globe [22] but at a rather coarse spatial resolution and as such they fail to enable local and regional assessments of phenomena such as the diurnal evolution of the urban heat island or the important daily heat stress-induced inhibition of photosynthetic activity and its impact on the surface carbon, water and energy budgets [6, 21]. This poses a significant obstacle to study local phenomena, such as the local daily temperature range, watershed level fresh water availability and the frequency of extreme events.

Combined to local observations, Statistical Down-Scaling Models (SDSM) (e.g.; [43]) offer a powerful means to correlate coarse climate model projections outputs to moderate resolutions surface observations. The SDSM has been successfully used and tested in a pilot study of rainfall change in the Anti Atlas region of Morocco [42]. In this study, we use an SDSM to develop and implement a methodology for constructing a moderate resolution climate projection dataset, based on IPCC scenarios, suitable for local to sub-regional studies [3]. We then use the dataset to analyse and compare current and future extreme weather events over semi-arid to arid regions of Morocco.

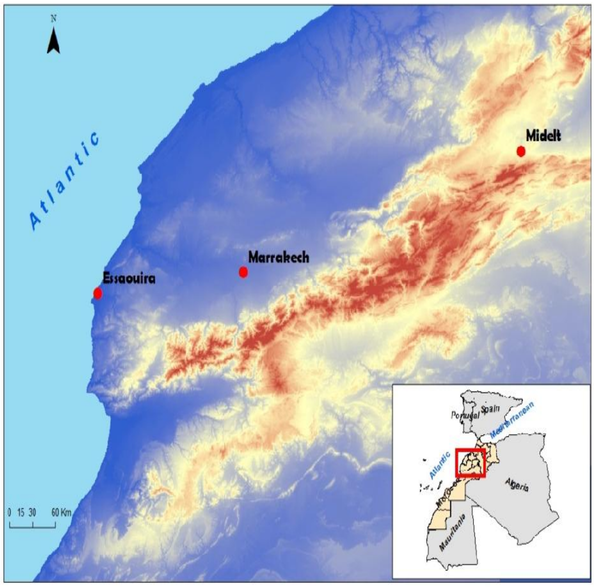


**Fig. 1 Study area.**

## II. MATERIALS AND METHODS

### 1. DATA

In this study we use multi-source dataset consisting of daily observations from meteorological stations representative of a region of interest extending from the western coastal zone through the vast agricultural lands in the Tenzift Al Haouz to the mountainous region of the Atlas [20], combined with the National Center for Environmental Prediction (NCEP/NCAR) re-analysis [25] and climate projections outputs obtained from a multi-model ensemble using IPCC scenarios [12, 19, 35].

- **Meteorological observations**

We use observations from meteorological stations in three large regions; Essaouira representing the maritime climate, Marrakech representing the continental climate prevailing over the agricultural large plains and the station of Midelt representing high mountains climate (Figure 1). The three stations are at an altitude 15m, 466m, and 1515m, respectively and represent three major climatic zones in Morocco. Forty years (1961-2000) observed daily maximum, minimum and mean temperature and precipitation are used to produce climate change projection over the region covering different agro-ecological zones of Morocco.

- **NCEP/NCAR Re-analysis**

The NCEP re-analysis is provided at a spatial resolution of 2.5°x2.5°. The NCEP data is produced using historical, in-situ, satellite and ship observations within a data assimilation system [25] and are available every 6 hours since 1948. For this study, we use daily data between 1961 and 2000 over Morocco. The data was obtained in SDSM format from the Canadian Climate Impacts Scenarios (CCIS) portal [45].

- **Climate projections outputs**

This data is obtained from a multi-model ensemble produced using three General Circulation Models (GCMs); 1) the Hadley Centre Model HadCM3 [12], 2) the CGCM2 [33] and CGCM3 [26], the second and the third generation of coupled global climate models of the Canadian Centre for Climate Modeling and Analysis, respectively [45, 46]. Climate outputs from this multi-model ensemble are generated under the IPCC A2 and B2 emission scenarios [34] for the 21st century. It is widely accepted that Morocco’s surface climate will follow a trajectory confined between these two scenarios [20].

Model individual biases are acknowledged to be important contributors to climate projections uncertainties. To reduce projections uncertainty, a simple ensemble mean (SEM) is used to characterize the three model projections. Although it is difficult to reproduce the present climate in any single model, the multi-model ensemble mean is known to effectively improve the model projection by reducing characteristic biases and uncertainties of any individual model (e.g.; [28, 8]).

### 2. MODEL

The Statistical Down-Scaling Model (SDSM) version 4.1 of Wilby et al. (2002) [43] is used to construct datasets of mean, maximum, minimum daily temperature and precipitation amounts for the period 1961-2099. The technique consists of deriving empirical relationships between local variables of interest over the region, such as daily temperature and precipitation, and large-scale atmospheric predictors, such as sea level pressure, humidity and wind speed, generally supplied by low resolution climate models. A major advantage of SDSM is that continuous daily weather series can be produced for the length of the study period- 1961-2099. These series enable detection and interpretation of emerging trends out of inter-annual variation signals in meteorological variables such as temperature and precipitation. However, this scale-reduction is only possible at locations where high-quality, homogeneous observation stations are available for calibration. Therefore, data quality assurance and checking constitute critical steps in the down-scaling process. In this study, all observations data are screened for outliers and suspicious values. The SDSM was calibrated using large-scale predictor variables sourced from the NCEP re-analysis [25]. Allowing for missing or unreliable data, observations from three meteorological stations are used as the SDSM predictands for calibration and validation. The number and kind of predictor variables used in the SDSM calibration from the low resolution model are different for each meteorological station and for each parameter and depend on the performance of each predictor variable in the initial screening processes, that is characterized by the percentage of explained variance [43, 9]. In this study, the SDSM is calibrated over the period 1961-1980 and validated over the period 1981-2000. For temperatures, the model is calibrated separately for each month while for precipitations the model is calibrated for each season based on a conditional process consisting of intermediate steps between regional forcing and local weather whereby the local precipitation amounts depend on wet and dry-day occurrence, which in turn depend on regional–scale predictors such as humidity and atmospheric pressure [44].

The Weather Generator in the SDSM generates ensembles of synthetic daily weather series given daily observed (or re-analysis) atmospheric predictor variables. The procedure enables the verification of calibrated models (using independent data) as well as the synthesis of artificial time series for subsequent impacts modeling [43]. In our study the number of ensemble members synthesized is 20 members. The down-scaling model skill is assessed using a range of diagnostics, including monthly and annual means, daily time series analysis, and annual maximum. Down-scaled climate change projections were prepared using output from the multi-model ensemble indicated in section 2.1 for the period 2001-2099. The downscaling approach of the SDSM is applied (and validated) separately for each of the 3 GCM control runs used. Then, the 3 validation results are averaged to obtain the multi-model mean performance. The necessary predictors and predictands variables used in the SDSM for the three stations Essaouira, Marrakech and Midelt are summarized in table 1.

**TABLE 1 Downscaling predictor variables for daily mean, maximum and minimum temperature and precipitation at each site. Key to predictors: MSLP (mean sea level pressure), U* (zonal component of airflow), F* (strength of airflow), Z* (vorticity), H* (geopotential height), R* (relative humidity), S* (specific humidity). Elevation of predictors: *SUR (near surface), *850 (at 850 hPa pressure level), *500 (at 500 hPa pressure level).**

| **Sites** | **Mean temperature predictors** | **Maximum temperature predictors** | **Minimum temperature predictors** | **Rainfall predictors** |
|---|---|---|---|---|
| **Marrakec** | MSLP,<br>H850,<br>H500 | MSLP,<br>H850,<br>H500 | MSLP,<br>H850,<br>H500 | MSLP,<br>Z500,<br>F850,<br>R500 |
| **Essaouir** | MSLP,<br>H850,<br>H500,<br>USUR | MSLP,<br>H850,<br>H500,<br>USUR | MSLP,<br>H850,<br>H500,<br>USUR | Z500,<br>F850,<br>R500,<br>SSUR,<br>H850 |
| **Midelt** | MSLP,<br>H850,<br>H500,<br>Z500 | MSLP,<br>H850,<br>H500,<br>Z500 | MSLP,<br>H850,<br>H500,<br>Z500 | Z500,<br>F850,<br>U850,<br>R500,<br>SSUR |

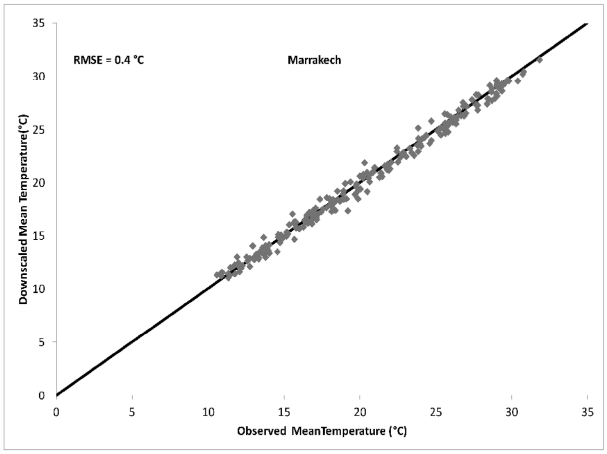
## III. RESULTS AND DISCUSSIONS

### 1. DOWNSCALING OF THE PRESENT DAY CLIMATE

In order to test and validate the model, we use select sites with available observations to assess its performance and accuracy in reproducing observed present day climate signatures. The SDSM is tested using daily mean, maximum and minimum temperature, precipitation and other climate indices over the semi-arid coastal, continental, and high mountains areas of Morocco represented respectively by Essaouira, Marrakech and Midelt.

- **Temperatures**

Although statistical down-scaling is difficult in arid regions [13], the SDSM performed relatively well across the variety of stations in the test period 1981-2000 using NCEP predictors as input in the calibrated model (figure 2, 3 and 4). This provides some assurance, but not absolute confidence, in the robustness of the model and the accuracy of its outputs. We use the root mean square error (rmse) as a standard measure of the differences between values predicted by the model and the values actually observed. The rmse penalizes large differences much more than the smaller ones and serves to aggregate the magnitudes of the errors in predictions for various times into a single measure of predictive power. The SDSM reproduces the observed monthly mean temperature with an rmse of 0.40, 0.58 and 0.65 °C in Marrakech, Midelt and Essaouira, respectively (figure 2-a, 3-a and 4-a). For the extreme temperatures, the rmse is 0.58, 0.67, 0.76 °C for the maximum temperature (figure 2-b, 3-b and 4-b) and 0.60, 0.62, 0.77 °C for the minimum temperature (figure 2-c, 3-c and 4-c) in Marrakech, Midelt and Essaouira, respectively. Similarly, the model reproduces the seasonal mean temperatures with a maximum error of 0.49, 0.58, 0.69 °C during spring time in Marrakech, Midelt and Essaouira, respectively (table 2). In all cases, including downscaling of the extreme, the downscaled temperature rmse is less than 0.8°C. This degree of accuracy is generally acceptable for the assessment of the water and energy exchanges in most agricultural measurements and practices such as assessing the amount of water requirement or the evaporative efficiency during irrigation or selecting plant species for low and high temperature tolerance [20].



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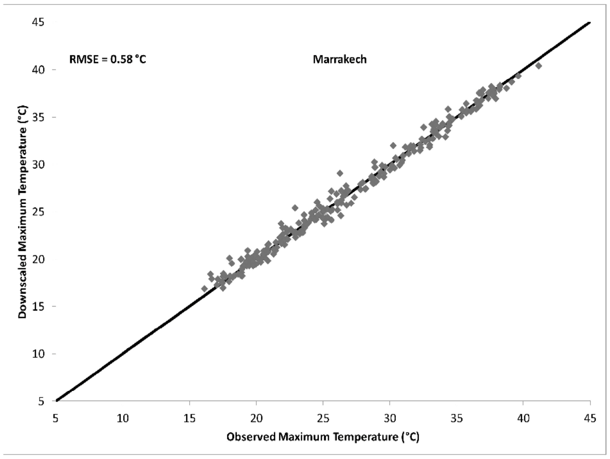

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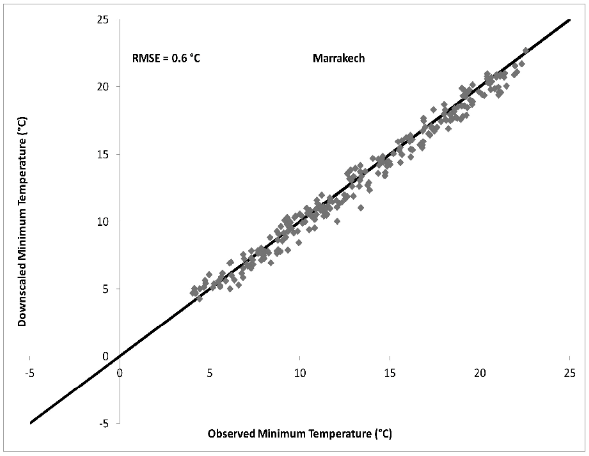

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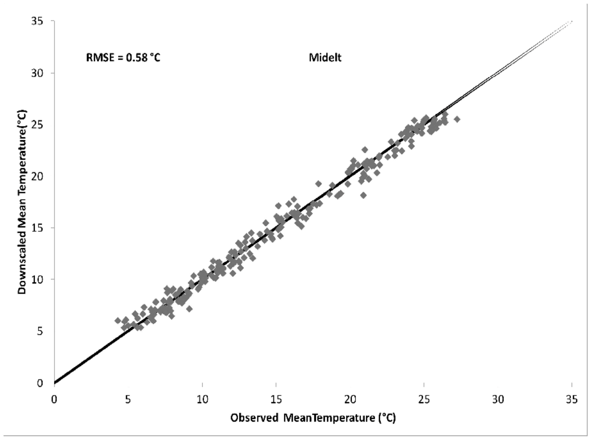
Fig. 2 Scatter plot of observed and downscaled monthly mean (a), maximum (b) and minimum (c) temperature from NCEP at the station of Marrakech between 1981 and 2000.



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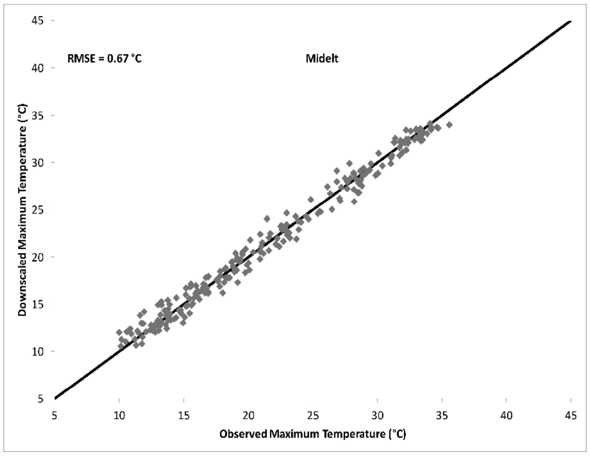

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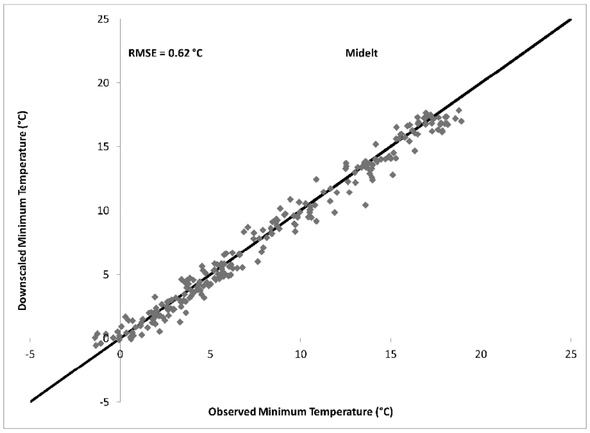

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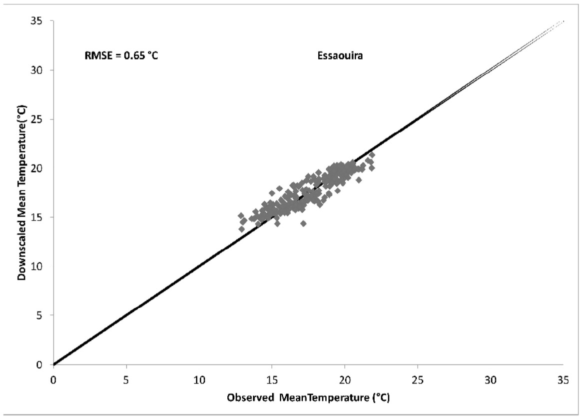
**Fig. 3 Same as figure 2 except for Midelt.**



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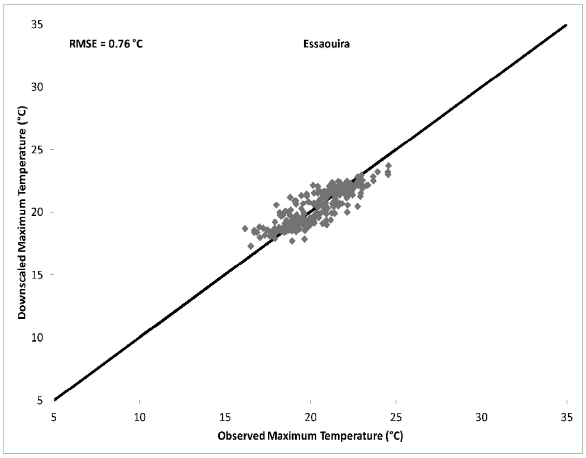

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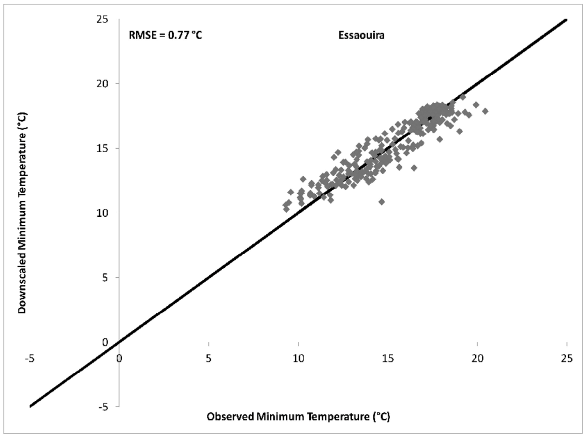

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**Fig. 4 Same as figure 2 except for Essaouira.**

**TABLE 2. Root Mean Square Error (RMSE) between the observed and downscaled seasonal mean temperature from NCEP at Marrakech, Midelt and Essaouira between 1981 and 2000.**

| RMSE (°C) | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| **Marrakech** | 0.49 | 0.35 | 0.31 | 0.25 |
| **Midelt** | 0.58 | 0.46 | 0.34 | 0.32 |
| **Essaouira** | 0.69 | 0.66 | 0.62 | 0.60 |

The calibrated model was also validated using predictors data from multi-model ensemble mean (control run conditions) as inputs between 1981 and 2000 [8]. Table 3 shows the rmse between observed monthly mean temperatures and those downscaled using the multi-model ensemble mean. The model reproduces the observed monthly mean temperature with a rmse of 0.45, 0.61 and 0.66 °C in Marrakech, Midelt and Essaouira, respectively. The maximum root mean square error occurs in the coastal stations of Essaouira with 0.78 and 0.79 °C for the maximum and minimum temperature, respectively (table 3).

**TABLE 3. Root Mean Square Error (RMSE) between the observed and downscaled monthly mean, maximum and minimum temperature from the multi-model ensemble mean at Marrakech, Midelt and Essaouira between 1981 and 2000.**

| RMSE (°C) | Mean temperature | Maximum temperature | Minimum temperature |
|---|---|---|---|
| **Marrakech** | 0.45 | 0.62 | 0.64 |
| **Midelt** | 0.61 | 0.7 | 0.66 |
| **Essaouira** | 0.66 | 0.78 | 0.79 |

- **Precipitations**

Figure 5 shows the downscaled monthly total precipitations using the NCEP and the multi-model ensemble compared to ground observations for the test period 1981-2000. Using predictor variables from NCEP reanalysis, the SDSM reproduces the monthly rainfall pattern with a rmse of 4.8, 3.5 and 4.7 mm in Marrakech, Midelt and Essaouira, respectively (figure 5 a,b,c). However, when using predictor variables from the multi-model ensemble control runs, the model reproduces the monthly rainfall with an rmse of 5.1 for Marrakech, 4.2 for Midelt and 5.6 mm in Essaouira (figure 5). It is worth noting that the performance of the SDSM to downscale the monthly total precipitations using the multi-model ensemble is close to that obtained using the NCEP reanalysis. Indeed the difference in monthly root mean square errors obtained using the NCEP reanalysis and the multi-model ensemble mean is only 0.3, 0.7 and 0.9 mm.month-1 for Marrakech, Midelt and Essaouira, respectively. A standard T-test shows that these differences are not different in the statistical sense. These results suggest that precipitations obtained through the SDSM using multi-model ensemble mean forcing are of the same accuracy as those obtained from reanalysis and provide confidence in using the model for future projections. Similar to temperature, the accuracy of the SDSM downscaled precipitation is acceptable for most studies of the water, energy and carbon assessment in agricultural practices and modelling over the region [20].

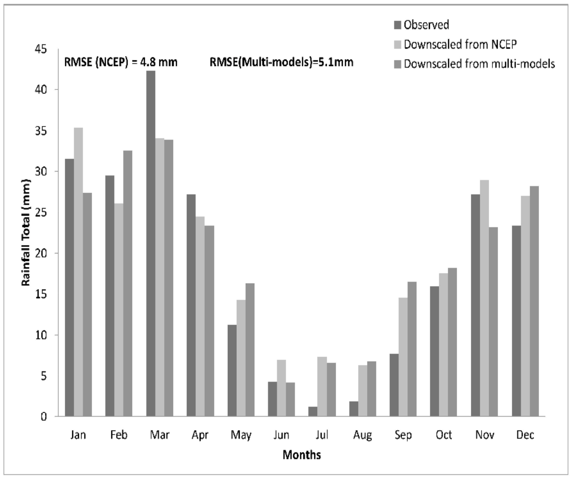


Fig. 5a Observed and downscaled total monthly rainfall (mm) at Marrakech for the test period 1981-2000 in reanalysis conditions using NCEP and in control run conditions using the multi-model ensemble.

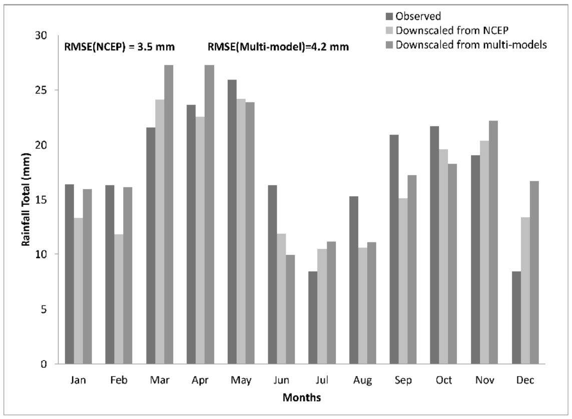


**Fig. 5b Same as figure 5a except for Midelt.**

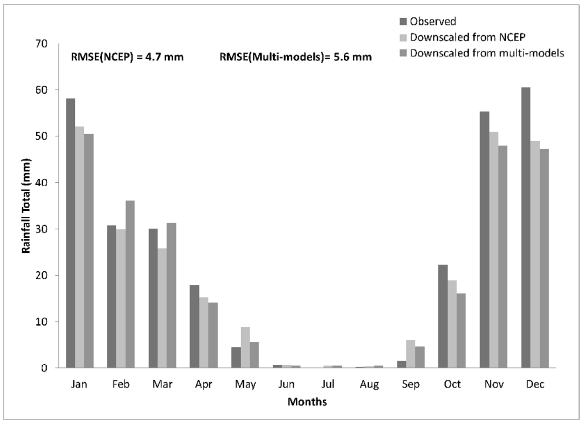
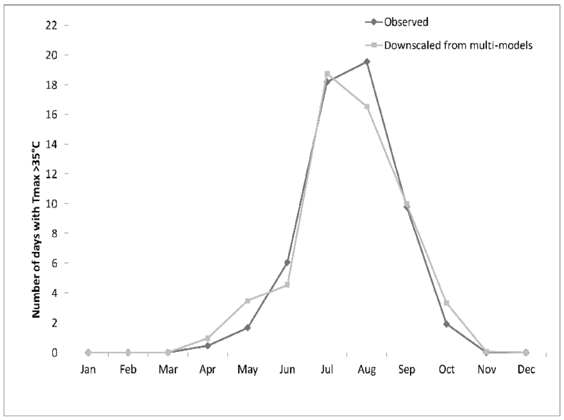


**Fig. 5c Same as figure 5a except for Essaouira.**

- **Extreme indices**

In order to test the SDSM with extreme indices projected in part 3.3 of this paper (see also definitions in part 3.3), we compare the extreme indices obtained, for the test period 1981-2000, from downscaled NCEP and multi-model ensemble mean to the indices obtained using observations. Figure 6 and 7 shows the downscaled heat indices and heat waves from the control multi-model ensemble compared to the observations for the test period 1981-2000 in Marrakech and Midelt. The model reproduces the heat indices with a rmse of 0.9 and 0.4 day (figure 6 and table 4) and the heat waves with an rmse of 0.5 and 0.3 wave (figure 7 and table 4) in Marrakech and Midelt, respectively.



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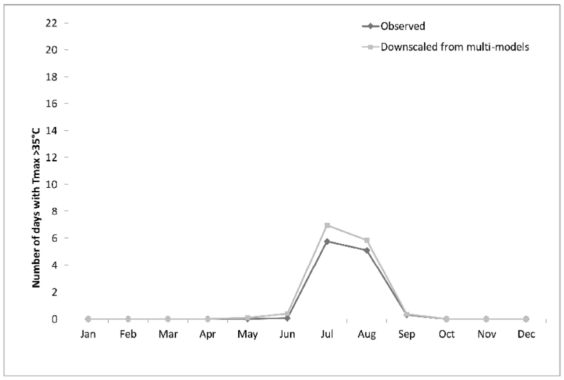

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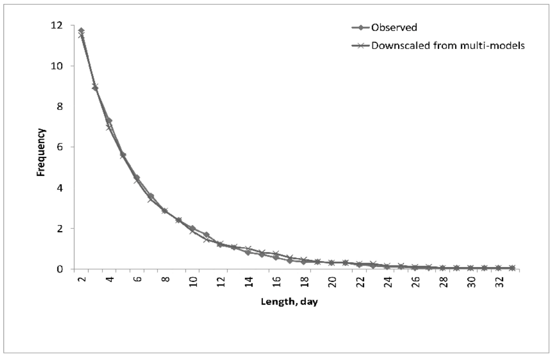
**Fig. 6 Observed and control multi-model ensemble downscaled heat index at Marrakech (a) and Midelt (b) for the test period 1981-2000**.



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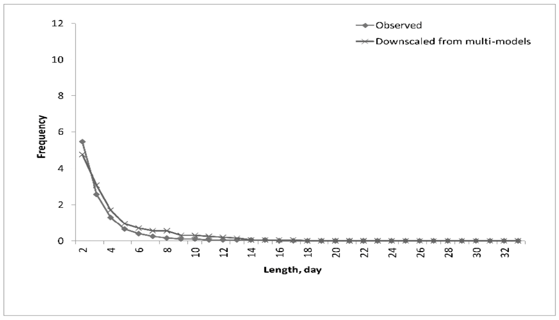

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Fig. 7 Same as figure 6 except for the heat waves.

Similarly, the model reproduces the cold indices and cold waves with an error less than 0.8 day and 0.5 wave, respectively (table 4). For the Maximum Wet Spell (MWS) and the Maximum Dry Spell (MDS) the rmse is less than 2.6 and 2.9 day.

For the indices downscaled using the NCEP reanalysis, the root mean square errors are summarized in table 4. In general, the root mean square errors obtained when using the NCEP reanalysis are a little smaller than those obtained from the use of the multi-model ensemble control run.

**TABLE 4. Root Mean Square Error (RMSE) between the observed and downscaled extreme indices from the multi-model ensemble and NCEP at Marrakech, Midelt and Essaouira between 1981 and 2000. Essaouira is not concerned by heat indices and heat waves (maximum temperature does not exceed the 35°C threshold);HI: Heat Index, CI: Cold Index, HW: Heat Waves, CW: Cold Waves, MWS: Maximum Wet Spell, MDS: Maximum Dry Spell.**

| RMSE | | HI | CI | HW | CW | MWS | MDS |
|---|---|---|---|---|---|---|---|
| **Marrakech** | **NCEP** | 0.7 | 0.5 | 0.4 | 0.5 | 2.1 | 2.3 |
| | **Multi-model** | 0.9 | 0.8 | 0.5 | 0.5 | 2.5 | 2.8 |
| **Midelt** | **NCEP** | 0.4 | 0.3 | 0.3 | 0.4 | 1.2 | 1.5 |
| | **Multi-model** | 0.4 | 0.4 | 0.3 | 0.3 | 1.5 | 1.7 |
| **Essaouira** | **NCEP** | - | 0.4 | - | 0.5 | 2.3 | 2.5 |
| | **Multi-model** | - | 0.6 | - | 0.4 | 2.6 | 2.9 |

## 2. CONSTRUCTION OF SITE-SPECIFICS CLIMATE CHANGE PROJECTIONS

We apply the SDSM to derive climate data projected by the low resolution multi-model ensemble under the A2 and B2 emission scenarios for the period 2001-2099. Change statistics are computed for 3 future time horizons, 2020HR representing the period (2011-2040), 2050HR (2041-2070) and 2080HR (2071-2099) with respect to the 30 years baseline (hereafter REF) extending from 1961 to 1990 [22]. We illustrate and discuss results for 3 important climate indicators over the region of interest: temperature, rainfall and extreme weather events as characterized by heat and cold indices and rainfall extremes.

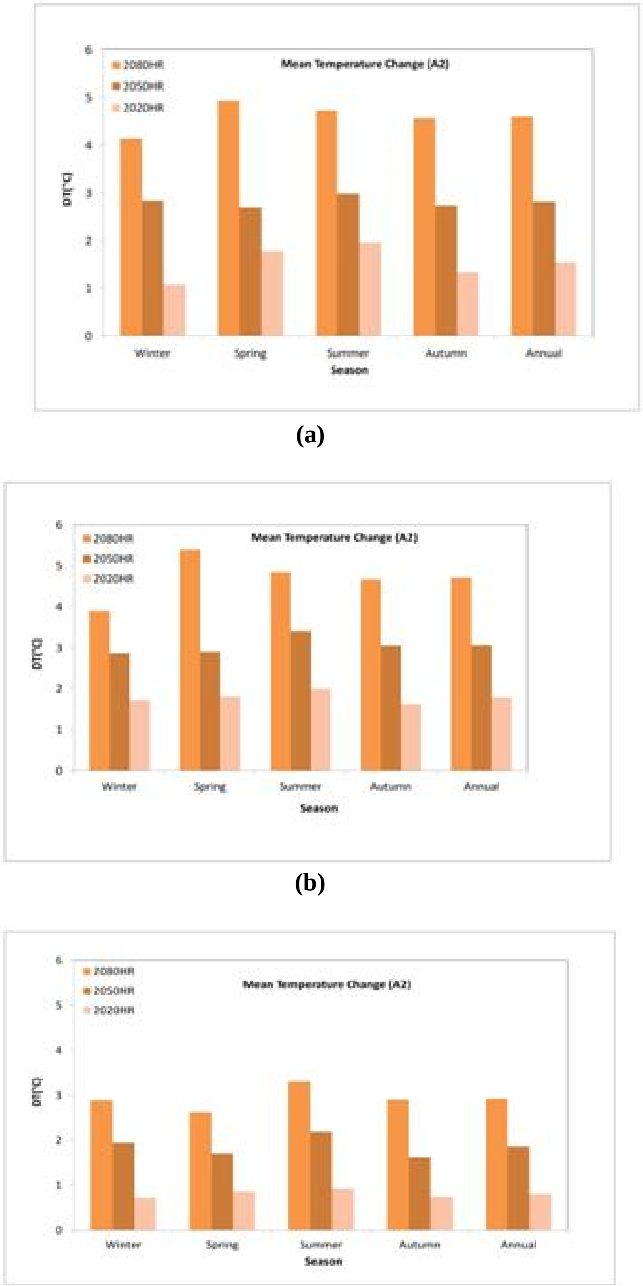
Heat and cold indices are important as they relate to human health and comfort [40] and may affect agriculture, while rainfall extremes directly relate to drought and flood and may affect ecosystem resilience in semi-arid regions.

Future projections are discussed for three regions: Marrakech, Midelt and Essaouira representing our region of interest (figure 1). The region of Marrakech is a semi-arid continental climate and belongs to a large watershed, Tensift Al Haouz, located north of the foothills of the snow-capped Atlas Mountain with an important socio-economic development. Midelt, located in the north-east of Morocco has a mountainous climate. Midelt functions as the market for an extensive agricultural region surrounding the Moulouya River and bounded on the east and west by dry plains. This region is known to produce apples, walnuts, apricots, plums, pomegranates, wheat, corn and a wide variety of garden vegetables. It is an important local economic region quite vulnerable to extreme weather events such as droughts and floods.

On the other hand, Essaouira located in coastal mid-western Morocco represents a large and fertile transition zone influenced by the maritime air and favourable for large scale agricultural activities. The regions of Marrakech and Essaouira are of particular interest to our research study because they are pilot regions chosen by governmental programs for implementing pilot projects related to water and agriculture development that requires detailed information about future local scale climate. Although our study uses projections to the 2080 horizon, our analysis focuses more on the near term time horizon of 2020HR.

### Temperature projections

Local seasonal and annual changes in the mean temperature for the region of Marrakech are shown in figure 8-a. For scenario A2, the 2020HR modeled increase in mean temperature is less than 1.9°C for all seasons with less than 1.3°C for the fall (SON) and winter (DJF) and an overall mean annual warming of 1.5°C. The largest increase in the mean temperature is expected during spring (MAM) and summer (JJA). The 2050HR modeled increase in mean temperature is about double that of 2020HR but still not much greater than 2.8°C. For 2050HR, the warming reached 2.8°C in winter, 2.7°C in spring, 2.9°C in summer and 2.7°C in the fall. However, the 2080HR resulted in much higher temperature increase with the largest increase of 4.9 and 4.7 projected during spring and summer, respectively. As expected, scenario B2 (not shown) resulted in slightly weaker temperature increases than A2 for all seasons and all time horizons albeit with the same pattern of changes. This was expected as the forcing in scenario B2 is much weaker than that of A2 [34].



**(a)**

**(b)**

**(c)**

Fig. 8 Mean seasonal and annual temperature changes for 2020HR, 2050HR and 2080HR with respect to the baseline (REF) 1961-1990 at Marrakech (a), Midelt (b) and Essaouira (c) under A2 scenarios.

Even though changes in temperature at Midelt and Essaouira (figure 8-b and 8-c) are projected to follow the same trajectory as those in Marrakech (figure 8-a) under the same forcing, the magnitude of the annual mean warming is 1.8 and 0.8 at Midelt and Essaouira for the 2020HR, respectively. It is important to note the large increase in the temperature in the Mountainous region of Midelt and its potential impact on agriculture. The region of Essaouira, modulated by the oceanic effect recorded the smallest warming.

**TABLE 5. Comparison between downscaled values and interpolated values of annual temperature changes (°C) from multi-model ensemble for 2020HR, 2050HR and 2080HR with respect to the baseline (named as REF) 1961-1990 at Marrakech, Midelt and Essaouira under A2 scenarios.**

| | **2020HR** | | **2050HR** | | **2080HR** | |
|---|---|---|---|---|---|---|
| | **Downscaled** | **Interpolated** | **Downscaled** | **interpolated** | **Downscaled** | **interpolated** |
| **Marrakech** | 1.5 | 0.7 | 2.8 | 2.5 | 4.6 | 3.4 |
| **Essaouira** | 0.8 | 0.3 | 1.9 | 1.3 | 2.9 | 2.3 |
| **Midelt** | 1.8 | 1.4 | 3 | 2.6 | 4.7 | 3.7 |

Table 5 shows a comparison between downscaled and interpolated annual mean temperature changes from multi-model ensemble. For the 2020HR, the interpolated annual mean temperature change is less than the downscaled by 0.8°C in Marrakech, 0.5°C in Essaouira and 0.4°C in Midelt. The differences between downscaled and interpolated annual temperature changes reach a maximum of 1°C and 1.2 °C in Midelt and Marrakech by the 2080HR. This local amplification observed in the downscaled temperature in comparison with the interpolated temperature shows the added value of the SDSM process to produce more realistic temperature projections useful to local adaptation strategies for agriculture and water use.

- **Rainfall projections**

Figure 9-a shows seasonal and annual rainfall changes relative to the baseline at Essaouira under A2 scenario and for the 3 time horizons. In general, the multi-model ensemble mean projects a decrease in local precipitation for both scenarios and at all time horizons. In Essaouira, for the 2020HR, the A2 scenario resulted in an annual decrease in rainfall of less than 8% with a maximum reduction of 11.4% occurring during the spring. It is important to note that the largest decrease in rainfall occurs in the middle of region's growing season and is likely to have the largest impact on crop growth and yield. A much larger decrease is expected over the region for the 2050HR, where reductions up to 32% compared to the baseline were simulated for the fall season. The decline in rainfall is projected to be even higher towards the end of the century, 2080HR, with decreases of over 43% during fall and spring (figure 9-a). Similar to the impact on

temperature, the less severe B2 scenario (not shown) results in a slightly smaller decrease in rainfall compared to A2 for the three future horizons in the region of Essaouira.

Changes in rainfall in Marrakech and Midelt (figure 9-b and 9-c) are projected to follow the same trajectory as those of Essaouira (figure 9-a) under the same forcing; the magnitude of the rainfall reduction in Midelt is however much less than that projected for Essaouira.

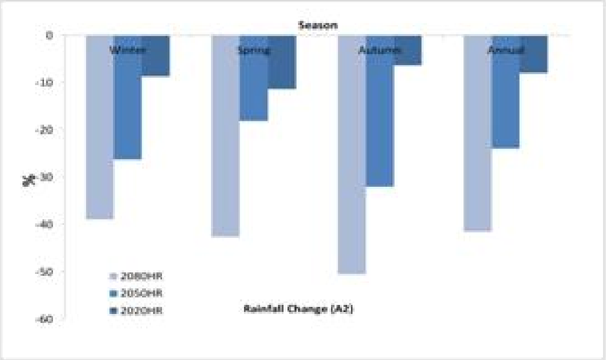


Fig. 9a Seasonal and annual rainfall changes relative to the baseline in percent for 2020HR, 2050HR and 2080HR at Marrakech under A2 scenario (summer is not shown because the rainfall is very low or null).

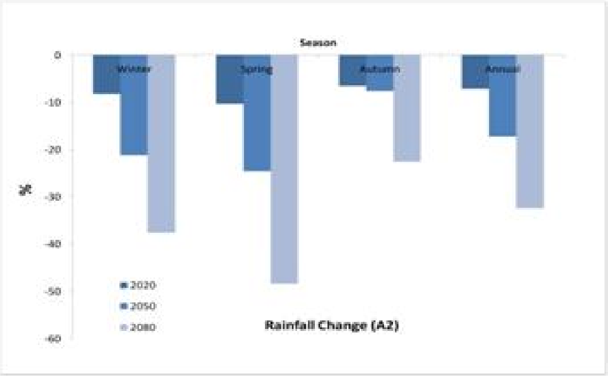


**Fig. 9b Same as figure 9a except for Midelt.**

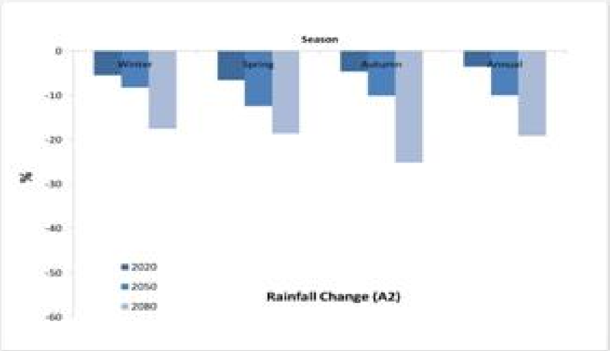


**Fig. 9c Same as figure 9a except for Essaouira.**

A comparison between downscaled and interpolated rainfall changes from multi-model ensemble shows that the annual mean rainfall change from the interpolated multi-model ensemble mean does not exceed 7%, 16% and 27% for 2020HR, 2050HR and 2080HR, respectively for all study regions, while the corresponding annual mean rainfall change estimated using the SDSM can reach 8%, 24% and 42% for 2020HR, 2050HR and 2080HR, respectively.

Results from this analysis indicate also that the projections of rainfall made at low resolution over Morocco by the IPCC models [22] in which the average reduction does not reach 20% by the 2080HR are much less than the projections of rainfall reduction obtained in this study which are estimated to reach up to 42% for annual change and 50% for seasonal change in some regions of Morocco (figure 9). This illustrates that even with a small bias; the SDMS provides a more detailed rainfall variation, much needed for monitoring agricultural and irrigation practices at local scales and assessing potential drought and flood associated with extreme changes in rainfall pattern.

The probabilistic distribution function of monthly rainfall intensity for REF (1961-1990), 2020HR, 2050HR and 2080HR in Midelt clearly shows that the distribution of the maximum monthly rainfall is expected to decrease as climate changes in the future horizons (Figure 10). The probability distribution functions of monthly rainfall intensity in Marrakech and Essaouira (not shown) have a similar pattern than those of Midelt. These results suggest that the impact of climate change on precipitations over the study region not only induces changes in annual rainfall amounts but also in rainfall distribution.

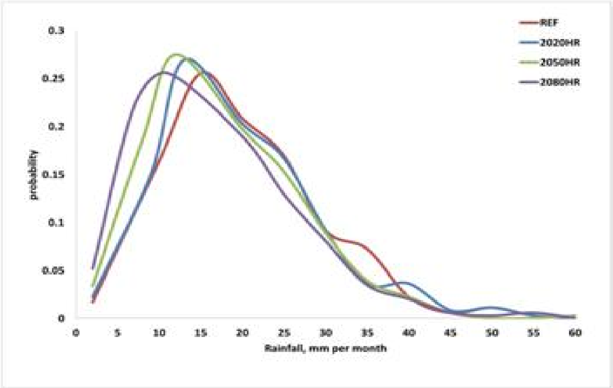


Fig. 10 Probability distribution functions of monthly rainfall intensity for REF (1961-1990), 2020HR, 2050HR and 2080HR in Midelt.

Results from this rainfall analysis suggest that the local and regional impacts of climate change under scenarios A2 and B2 may have important implications for the agricultural economy of the region. Not only will the projected maximum rainfall decrease occur over fertile agricultural lands, but it will also occur during the seasons where rain is needed the most, fall and spring. In Morocco, large part of agriculture is winter to spring rain-fed cereal culture which is sowed in early fall and relies mainly on the autumn to early spring rainfall. These projections may be useful for farmer and policy makers to start early planning of adaptation measures including crop rotation, replacement and modification and other means of irrigation and efficient water use and delivery systems [30]. However, there is a high natural variability in the seasonal rainfall totals and the modelled rainfall trends should be considered with caution [27].

## 3. EXTREME WEATHER EVENTS

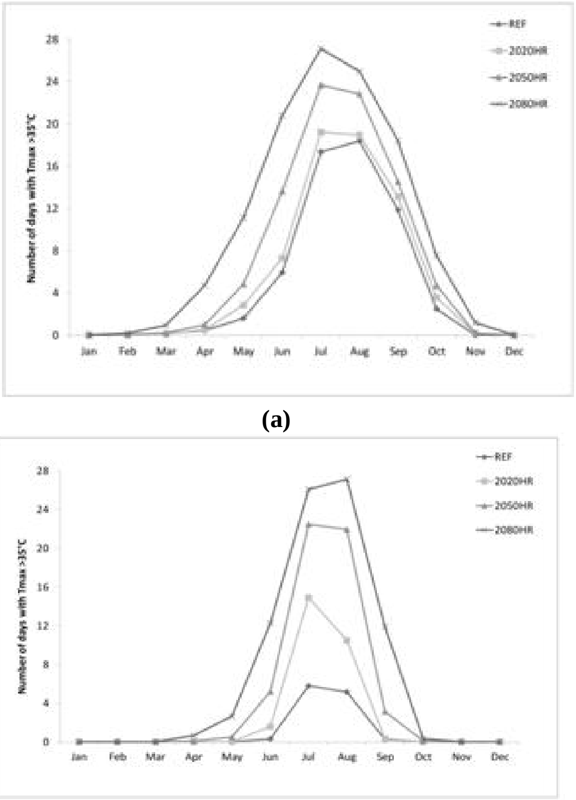
To illustrate the usefulness of the SDSM to the local and regional future changes in weather extreme events, we generate daily climate data using the same three time horizons and baseline for the regions of Marrakech, Midelt and Essaouira using the same methodology described in section 2.2.

- **Heat and cold indices**

Following [39], we define the heat index as the number of days per months with a maximum temperature exceeding a certain threshold Thigh and the cold index is defined as the number of days per months with a minimum temperature below a low temperature threshold Tlow. These indices are calculated for the study region for which the climatological Thigh and Tlow are set to 35°C and 15°C, respectively [14]. For Marrakech, the temperature range between Thigh and Tlow represents the optimum physiological temperature range for most local plants grown in the region, which consists of irrigated leguminous and other leafy crops. The average heat index estimated for the baseline period of 1961-1990 taken as reference (REF) and the three future horizons 2020HR, 2050HR and 2080HR for Marrakech under the A2 scenario is shown in figure 11-a. For the 2020HR, there is not much difference with the baseline; nevertheless there is sensible increase in the heat index from May to October. On average for July and August, a heat index exceeding the 35°C threshold is projected to occur 61.3 % (19 days) for the 2020HR, 74.2% (23 days) for the 2050HR, and 83.9% (26 days) for the 2080HR compared to only 58% (18 days) for the reference period.

This is a significant increase in the number hot days during the summer time which may have important consequences on both agriculture and human health. At 19 days per month during the hottest month of the year, the heat index in Marrakech is considered high and may constitute a serious public health concern as it is likely to increase situations of strings of high heat days similar to those during the European heat wave of 2003 [11]. These severely hot weather withered crops, dried up rivers and fueled wild fires across large regions of Europe. The region of Tensift Al haouz is much more vulnerable to heat than Europe as its mean temperature during the summer months is already high and most of the time abnormally high and dry. For Midelt (Figure 11-b), with a cooler climate, the difference in the heat index is already apparent in the 2020HR, similar to Marrakech the largest difference with the baseline occurs between May and September. However, our analysis suggests an important lengthening in the period of heat index with much larger values for 2050HR and 2080HR. The lengthening of a high heat index period is expected to shorten the natural vegetation growing season and may increase the water requirement for irrigated agriculture in the region.

On the other hand, the cold index drops significantly for the three time horizons and more so during winter months (January and February) for all study regions (not shown).



**(a)**

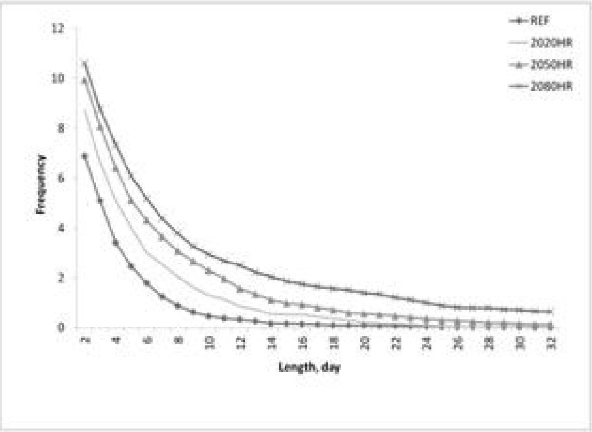
**(b)**

Fig. 11 Monthly heat index (see text for details) calculated for the baseline (REF) 1961-1990, 2020HR, 2050HR and 2080HR at Marrakech (a) and Midelt (b) under A2 scenario.

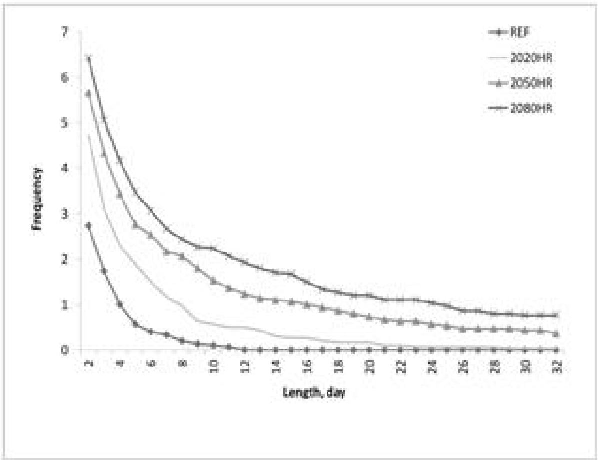
- **Heat-waves and cold-waves**

A heat wave is a prolonged period of excessively warm weather, which may be accompanied by high humidity. While definitions vary [32], a heat wave is measured relative to the prevailing regional weather and relative to normal temperatures for the season. The definition recommended by the World Meteorological Organization (WMO) is when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5 °C, the normal period being 1961–1990 [17]. For Morocco, using the same normal period (1961–1990), a heat-wave is defined as a continuous period of 2 days or more with daily maximum temperature exceeding 35°C. Similarly a cold-wave is defined as a continuous period of 2 days or more with daily minimum temperature below the 15°C [14]. Using the climate change scenarios for the 3 time horizons discussed above along with the baseline (REF) data, we computed the expected frequency of heat waves of various lengths in the regions of Marrakech and Midelt (figure 12). The 2020HR, 2050HR and 2080HR climate change scenarios resulted in a significant increase in length and frequency for heat waves. For example, for the 2020HR, heat waves with lengths of 5-days are expected to occur four times a year in Marrakech and twice a year for Midelt. This is a high frequency of occurrence, especially in Marrakech and could have a serious impact on human health and agriculture. According to the United States National and Oceanic and Atmospheric Administration (NOAA), at 35°C the heat index, an index that combines air temperature and relative humidity in an attempt to determine the human-perceived temperature, is 42°C and 55.5°C at 50% and 75% relative humidity, respectively [48]. This could be a serious health concern for the region of Marrakech whose monthly average relative humidity ranges between 48% in July and 87% in October [15]. For the same time horizon in Midelt, heat waves in excess of 5-days are expected to quadruple in frequency from their normal reference value of 0.5 per year (Figure 12.b). In this less populated, highly agricultural hinterland the economic consequences of increased heat waves frequencies could be severe. Heat waves reaching up to 17 and 29 days in length with a frequency of at least once a year have been simulated for 2050HR and 2080HR in both regions (figure 12).

Cold-waves on the other hand showed a decreasing trend in the study region (not shown). For example, cold waves of 5 days or more have decreased in mean frequency from 4.5 days in the baseline period to 3, 2 and 0.6 days in 2020HR, 2050HR and 2080HR, respectively for all study regions.



**(a)**



**(b)**

Fig. 12 Expected frequencies of heat-waves of various lengths for the baseline (1961-1990), 2020HR, 2050HR and 2080HR for the region of Marrakech (a) and Midelt (b) under the A2 scenario.

- **Maximum Wet and Dry Spell**

According to DMN (2007), the Maximum Wet Spell (MWS) is the maximum period of consecutive days with precipitation greater than 1 mm. The Maximum Dry Spell (MDS) on the other hand has a similar definition as the MWS but with precipitation less than 1mm [2]. Changes in the mean length of maximum dry and wet spells were computed by comparing daily time series of precipitation during the agricultural season (October-April) from SDSM for the 2020HR, 2050HR and the 2080HR and are shown in figure13 for Essaouira. The length of the MWS is projected to decrease with the change in climate while the MDS is expected to increase. During the agricultural season, down-scaled results indicate a decrease in MWS of 8, 21 and 42% from the baseline for 2020HR, 2050HR and 2080HR, respectively while the length of the MDS is projected to increase by 9% for the 2020HR and 46% for the 2080HR (figure13). For Marrakech and Midelt (not shown), the MWS and MDS are projected to follow the same trajectory as those of Essaouira but with more accentuated trend in Marrakech than in Midelt.

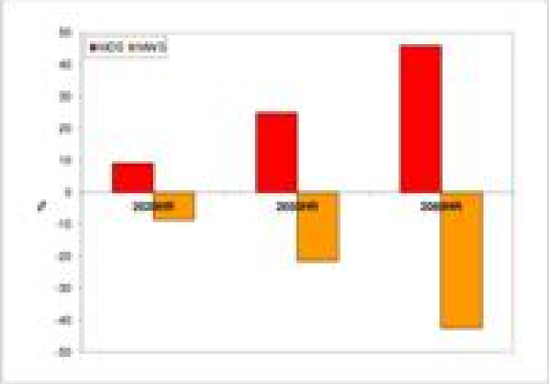


Fig. 13 Percentage changes in Maximum Wet Spell (MWS) and Maximum Dry Spell (MDS) for the agricultural season (October-April) for the 2020HR, 2050HR and 2080HR at Essaouira under A2 scenario.

All extreme indices discussed in this section depend directly on the evolution of temperature and rainfall. However, as discussed in part 3.2, there is a local amplification observed in the downscaled temperature in comparison with the interpolated temperature inducing an amplification of heat indices and heat waves and a reduction of cold indices and cold waves over the study region. For Maximum Wet and dry Spell, the local amplification observed in the downscaled rainfall in comparison with the interpolated rainfall (see part 3.2) induces an amplification of downscaled Maximum dry Spell and a reduction of the length of downscaled Maximum Wet Spell.

## IV. CONCLUSIONS

We use a statistical model to construct daily climate projections suitable for climate impact assessment. The methodology is based on a Statistical DownScaling Model (SDSM) calibrated using large-scale predictor variables sourced from the NCEP/NCAR re-analysis and ground observations obtained from 3 synoptic meteorological stations over Morocco and spanning the period 1961-2000. The synoptic stations are representative of three regions of interest in Morocco's economy. The technique involves deriving physically-sensitive empirical relationships between local variables of interest such as daily precipitation and temperature and large-scale atmospheric variables supplied by coarse resolution global climate models. This methodology is computationally inexpensive and climate scenarios could be produced regionally. In the present study, down-scaled climate change projections were prepared for 3 regions using output from three available climate models with sensibly different physical parameterizations HadCM3, CGCM2 and CGCM3, under the A2 and B2 emissions scenarios for the period 2001-2099. This multi-model ensemble helped to reduce individual models biases. Results show that the accuracy of the SDSM down-scaled precipitations and temperature is acceptable for most agricultural practices and modelling assessment studies with RMSE less than 0.65°C for the mean temperature projection and 4.8 mm.month-1 for precipitations over the 3 study regions.

For their geographic locations and economic importance, the regions of Marrakech, Midelt and Essaouira have been selected for illustration and discussion and daily variables representing future scenarios were generated and used to analyze weather changes and extreme events.

Under scenario A2, temperature projections for the 2020HR show an increase in mean temperature less than 1.8°C for all seasons with an overall annual increase of 1.9°C. However, important implications may be drawn for the regional climate as the 2°C warming threshold endorsed by the United Nations Framework Convention on Climate Change may be reached sooner than expected over the study region. On the other hand, rainfall projections resulted in an annual decrease of about 8% with a maximum reduction of 11.4% during spring. These reductions are estimated to reach up to 50% in some regions of Morocco by 2080HR. We find that SDSM projected rainfall reductions are larger than those made by low resolution models used in the IPCC fourth assessment report in which the average reduction does not reach 20% over the region of Morocco.

The 2020HR, 2050HR and 2080HR climate change scenarios resulted in an increase in length and frequency of extreme weather events. Indeed, heat waves durations reaching up to 17 and 29 days have been simulated for 2050HR and 2080HR, respectively. Cold-waves on the other hand showed a decreasing trend. The heat waves analysis indicated a significant increase of days with high temperature during the summer time which may have important consequences on both human health, natural (trees and other short vegetations) and managed (agriculture) ecosystems. The length of the Maximum Dry Spell (MDS) is expected to increase with increased warming while the Maximum Wet Spell (MWS) is expected to decrease.

These projections are useful for the study region where observations are rare and coarse resolution large scale global models do not capture local features. In these regions, the SDSM appears to be an essential tool for scale-reduction of modelled climate information.

Results from this study are most important for farmers and land and water managers to start early planning for cropping and developing achievable adaptation measures including crop replacement and modifications and more efficient means of irrigation and water deliveries, optimal for near future climate conditions. Our results also suggest serious health challenges as temperature increase in near term future.

## ACKNOWLEDGMENT

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