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Analysis of observed climate trends and high resolution scenarios for the 21st century in Morocco

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Abstract
In spite of its geographical situation on the Atlantic and Mediterranean coast, Morocco is one of the most arid areas of the world; it experiences highly variable rainfall and recurrent droughts. Predictions of climate change consequences on several socio-economical fields in Morocco are very alarming. In fact, climate trends observed in Marrakech and Essaouira through the study of meteorological data since 1961, could identify a clear trend towards higher temperatures and lower rainfall. Moreover, the review of recent climatic conditions and future climate change projections could confirm the same result over all the Moroccan territory. A geographic information system (GIS) is used to spatialize these changes in the country. Comparing annual temperatures and precipitations over two decades (1971-1980 and 1998-2007) revealed a global warming in 29 meteorological stations, especially on two broad areas North and South of Morocco. In these areas, the increase of temperatures reached 4°C and the decrease in annual rainfall reached up to 42 mm. Future climate projections were generated with the statistical technique of downscaling SDSM (Statistical Downscaling Model) and climate change scenarios from atmospheric general circulation models. Simulations within the horizons 2040, 2070 and 2099 showed a situation of an overall increase in temperatures that reaches respectively 1°, 1.9° and 3.6°C; and a respective decrease in precipitation of 4.4%, 11.9% and 22.3%. Hence, more increasing climatic, hydrological and agricultural droughts are anticipated in Morocco by the late 21st century.

1. Introduction
Global warming is the observed century-scale rise in the average temperature of Earth's climate system [1]. It is one of the most complex challenges of the 21st century. No country is immune to its effects and no country can deal alone with its controversial political decisions, underlying technological changes and other issues inextricably linked with serious consequences across the globe. At the same time as the planet warms, rainfall patterns change and extreme events such as droughts, floods and forest fires become more frequent [2].
Since the late 1970s, the occurrence of drought years increased in North-West and West Africa presenting a major constraint to the future development of these regions [3]. In Morocco, a country located in North-West Africa on the Atlantic and Mediterranean coast, the climate is controlled by two main climatic zones: the Mediterranean Northern coastal regions and the Southern interior regions, which lie on the edge of the hot Sahara desert [4]. The latitudinal extension, the geographical and hypsometric diversities and the ocean opening also play a role in determining climate types. As a matter of fact, drought has always been present in the history of Morocco, but during the recent decades it has forcefully become a structural element of the country’s climate. Morocco is currently experiencing the longest dry period in its modern history, which is characterized by a decrease in precipitation and a clear trend of rising temperatures [5]. This fact is also confirmed by [6], who predict a decrease in surface runoff and precipitation and an increase of temperatures. The same conclusion is indicated by the Intergovernmental Panel on Climate Change (IPCC). According to the IPCC climate change scenarios, a decrease of up to 20% in rainfall is predicted by the end of this century in Morocco. The increase in temperature is expected to reach 2.5 °C to 5.5 °C under the same scenarios [7].
To this end, the approach of this study is to highlight features that characterize the variability of bioclimatic zones in Morocco by studying recent meteorological data (temperature and precipitation) and analyzing the climate change indicators, in order to fill the gaps in the literature related to climate change scenarios and impacts, as few

studies have examined Morocco as a case study. The purpose is to generate high resolution climate scenarios for the 21st century in Morocco using an appropriate model: the Statistical Downscaling Model (SDSM). In fact, SDSM is designed to implement statistical downscaling methods to produce high-resolution monthly climate information from coarse-resolution climate model (GCM) simulations, using weather generator methods to produce multiple realizations of synthetic weather sequences.

2. Experimental details

2.1. Data types and sources

2.1.1. Observed station data

Meteorological data that we used are provided by different synoptic weather stations covering all the territory of Morocco and parts of Mauritania to have more observations over the Sahara region. These data consist of daily series of temperature and precipitation from 29 meteorological stations that were chosen for this study for the period 1961 to 2007. This period was chosen because it offers available data for all the main meteorological stations with a regular monitoring. They were selected for the reliability of their data, the length of their series and their representation of several agro-climatic zones of the country (Fig. 1).

Figure 1: Location of the synoptic weather stations in Morocco

2.1.2. NCEP Re-analysis

The NCEP Re-analysis data are the result of an American project between NCEP (National Center for Environmental Prediction) and NCAR (National Center for Atmospheric Research) for the purpose of providing new atmospheric re-analysis by using historical data and assimilation systems and producing an analysis of the current state of atmosphere. The NCEP Re-analysis involves the recovery of land surface, ship, rawinsonde, pibal, aircraft, satellite and other data [8]. This atmospheric re-analysis is produced with 2.5°x2.5° resolution since 1948. However, in this study we are only interested in the period 1961-2007.

2.1.3. HadCM3 climate change scenarios

HadCM3 scenarios (Hadley Centre Coupled Model, Version 3) are scenarios that account for a description of the possible future climate based on assumptions about the future climate of Earth, the future levels of global population, economic activity and greenhouse gas emissions. The projections are calculated by climatologists from atmospheric models that convert assumptions of greenhouse gas emissions (including CO_2) into climate projections [9-10-11]. For this study, we used two climate change emission scenarios A2 and B2 (Fourth Assessment Report of IPCC) from the English model HadCM3. The IPCC describes both scenarios as follows:

A2: A differentiated world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in continuously increasing population. Economic

development is primarily regionally orientated, and per capita economic growth and technological change are more fragmented and slower than other storylines.
B2: A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. This is a world with continuously increasing global population at a lower rate than in scenario A2, intermediate levels of economic development. Although this scenario also is orientated toward environmental protection and social equity, it focuses on the local and regional levels.

2.2. Methodology

In the first part of this work, the study is focused on the observed climate trends and variability at only two meteorological stations: the continental station Marrakech (8°W; 31°37'N) and the coastal station of Essaouira (9°46'W; 31°30'N). The aim of this part is to characterize and compare the recent climate change that affected these two cities since 1961 and the eventual impacts on natural resources through analyses of temperature and rainfall evolutions and calculation of climatic and extreme indices.
The rest of the study covers the entire territory of Morocco. The main purpose is to take stock of the recent climate situation in the country and climate changes that might occur in the future. To facilitate interpretation of results and be able to visualize the entire area of Morocco, spatial data analysis required the use of a geographic information system (GIS). The spatial representation of data is performed with the use of appropriate software and adequate interpolations, namely Kriging and Spline methods for temperature and precipitation data.
As for climate predictions, they are generated with the statistical technique of downscaling SDSM (Statistical Downscaling Model) developed by the Environmental Agency of England and climate change scenarios from atmospheric general circulation models. SDSM uses empirical relationships between observed variables and large scale variables (NCEP and HadCM3 data). The ultimate goal is to construct high-resolution climate change scenarios with a daily time step. As described in Fig.S1, the data used for modeling are daily temperatures (maximum and minimum) and precipitations, NCEP re-analysis and low resolution climate change scenarios from the English model HadCM3 [12].

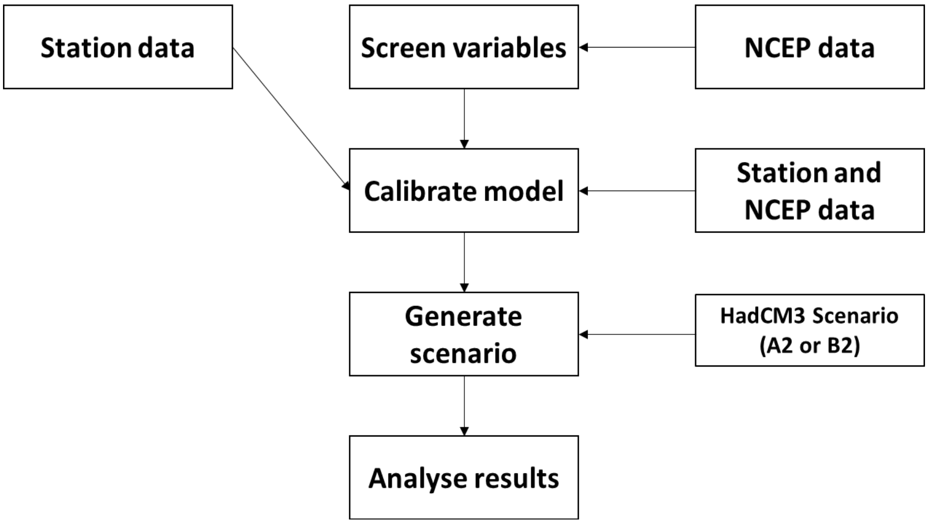

Figure S1: The mean operations used by SDSM model to construct high resolution climate change scenarios

3. Results and Discussion

3.1. Recent changes in climate and extreme events in Marrakech and Essaouira

Marrakech and Essaouira are characterized by irregular temperatures. However, the difference between maximum and minimum temperatures is obviously greater in Marrakech confirming the continental character of this city (Fig. 2). Moreover, the trend lines indicate an increase of temperatures in both stations. Average annual temperatures have actually increased by 1.4°C in Marrakech and 0.6°C in Essaouira between 1961 and 2007. On the other hand, precipitation is even more variable than temperature. This irregularity depends on atmospheric circulations (including the movement of Azores High towards South-West and the installation of depressions on the Moroccan offshore), which would produce interesting rainy disturbances over the country [13]. Analysis of the annual data series also revealed that the annual precipitation is highly variable and irregular from one year to another. Nevertheless, as shown in Fig. 2, there is an overall trend toward decrease in annual rainfall heights. The rainfall decline is about 50 mm for Marrakech and 20 mm for Essaouira over the period 1961 – 2007.

- *Standardized precipitation index*

The Standardized Precipitation Index (SPI) is a tool which was developed primarily for defining and monitoring drought. It allows a characterization of rainfall deficits for a given period for any rainfall station with historic data [14]. It can also be used to determine periods of anomalously wet events. In fact, the SPI reflects the impact of drought on water resources availability. It is particularly calculated when the precipitation is not normally distributed [15-16]. As shown in Tab. S1, a classification of drought levels can be established thanks to SPI values [17].

The SPI can be calculated with the formula: $SPI = (Pi - Pm) / \sigma$

With: Pi: Precipitation of year i;

Pm: Average precipitation of the whole study period;

σ : Standard deviation.

In our case, SPI values indicate a downward evolution for both cities. The trend lines are obviously suggesting an evolutionary trend towards drought in Marrakech, more than in Essaouira (Fig. 3). Although SPI values are highly irregular, it is also clearly noticeable that the occurrence of droughts became increasingly more frequent after the year 1980, especially in Marrakech. This observation demonstrates longer periods of intra annual drought and therefore an increase of their persistence time.

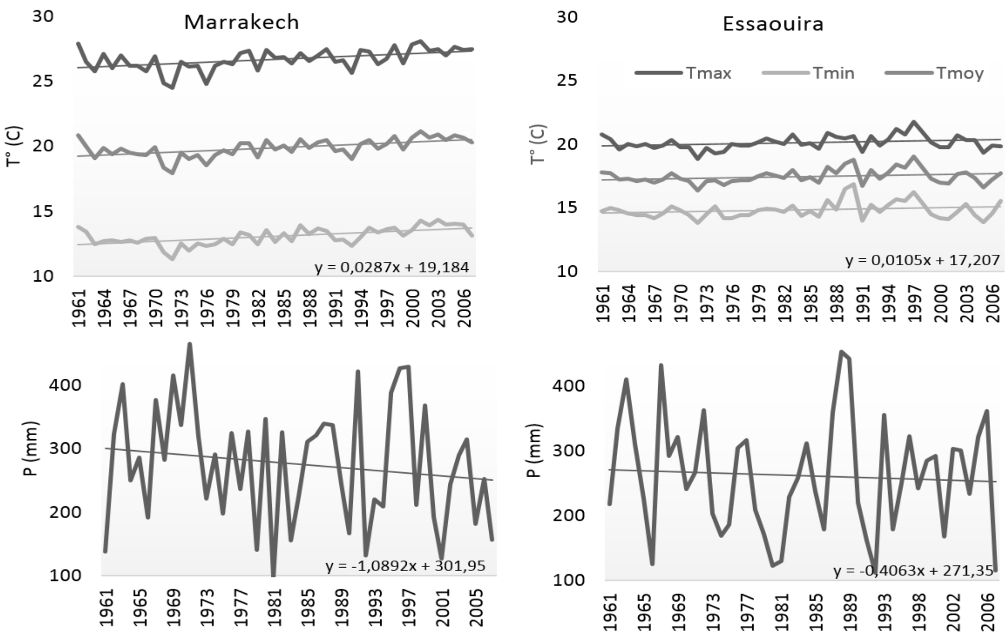

Figure 2: Annual trends of temperature and precipitation in Marrakech (left panel) and Essaouira (right panel)

- *Frost days (FD10) and summer days (SU30) indices*

The frost days index (FD10) corresponds to the total annual number of cool days, defined as days with a minimum temperature below 10 °C [18]. A clear downward trend in the number of cold days in both cities is expressed by Fig. 3. This decrease of FD10 is of -30days over the period 1961-2007 years in Marrakech, which means -0.64 cold days/year and only -6 days over the period of 47 years in Essaouira. On the other hand, SU30 index corresponds to the total annual number of summer days, defined as days with a maximum temperature above 30°C [19-20]. In Marrakech, although the number of summer days is quite variable from one year to another, a significant rise in SU30 values between 1961 and 2007 is presented by the trend line (Fig. 3). The total gain of hot days is 20 days over the period of 47 years, which means +0.42 summer days/year. Climate change seems to be making hot summer days hotter and stretching their numbers into heat waves. Unlike Marrakech, SU30 values are very low in Essaouira. In fact, SU30 values in this coastal city vary from only 0 to 9 summer days/year. Although the trend line shows a true positive evolution, it’s considered very weak and non-significant.

- *Cold waves (CWDI) and warm spells (WSDI) duration indices*

This index defines a cold wave as at least six consecutive days with a minimum temperature below the 10th percentile, statistical parameter signifying a value for which frequency is 10% in an annual series sorted in ascending order [21]. The value of the 10th percentile is 5.6 °C for Marrakech and 10.6 °C for Essaouira. Analysis of CWDI trends shows a strong downward trend in both meteorological stations (Fig. 3). The drop of cold waves is of -6 days in Marrakech and -5 days in Essaouira over the same period (1961-2007). As for the heat waves index (WSDI), it is defined as the total annual number of days with at least six consecutive days of a maximum temperature above the 90th percentile [22]. In our case, the 90th percentile is equal to 37.3 °C in Marrakech and 23 °C in Essaouira. The occurrence of warm spell evolved with clear increasing trends for the both meteorological stations (Fig. 3). The increase in warm spells frequency corresponds to +0.11 days/year for Marrakech (+5 days over 47 years) and +0.32 days/year for Essaouira (+15 days over 47 year). These heat waves cause the most harm among elderly people and young children. City dwellers are at particular risk because of elevated temperatures in cities, known as the "urban heat island effect" due to the magnifying effect of paved surfaces and the lack of tree cover.

The evolution of all the previous extreme indices gave another indication about the recent warming and drought that affected Marrakech and Essaouira. They also suggest that climate change effects are more pronounced in the continental areas (Marrakech) than in the coastal areas (Essaouira) of Morocco.

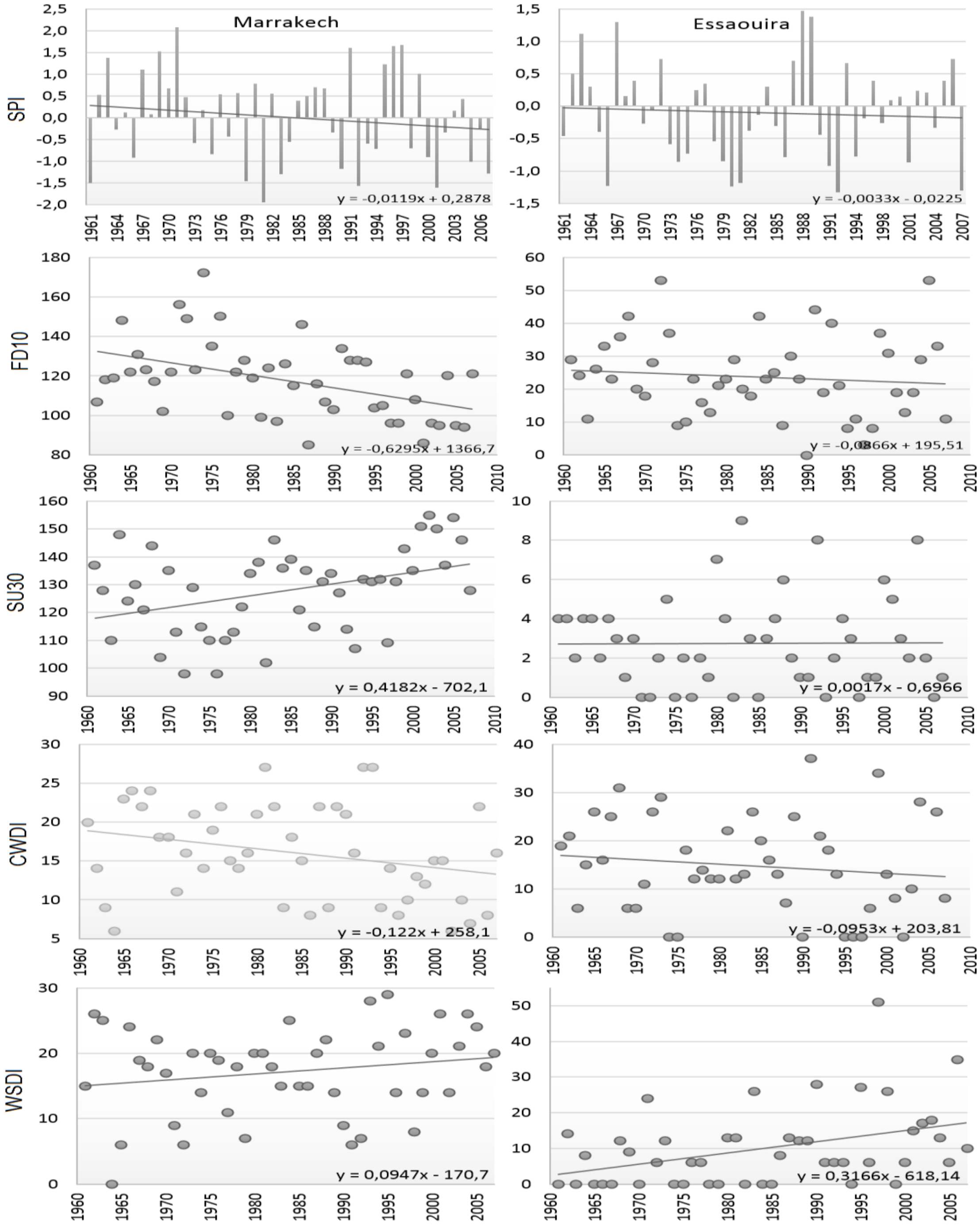

Figure 3: Long-term trends of extreme climate indices in Marrakech (left panel) and Essaouira (right panel)

3.2. Observed change of temperature and precipitation in Morocco

The instrumental data in the Arab region provide evidence for significant warming trends, generally reflected by more and stronger warm extremes and fewer and weaker cold extremes [23]. In Morocco, the analysis of temperature over all the 29 meteorological stations shows a general upward trend over the 47 years of study, especially for minimum temperatures. Comparison of average interannual temperature over two decades 1971-1980 and 1998-2007 reveals an increase in temperatures for all the stations. The spatialization of this climate on the territory of Morocco is illustrated by Fig.4. It exhibits the most affected areas with warming in two large areas in the North and the South of the country. The gain of average temperature in these areas is of 2 to 4 °C over two decades (1971-1980 and 1998-2007), respectively.

Furthermore, Morocco is highly vulnerable to extreme precipitation events [24]. The country suffers from more severe and recurrent droughts combined with an increasingly growing water demand [25-26-27]. During the last three decades, the random fluctuations in precipitation (disorderly succession of dry years and wet years) are superimposed to an overall downward in precipitations. According to [28], this decrease varies, by region, between 3% and 30%. The evolution of annual rainfall averages at certain Moroccan stations show a clear precipitation decline (Fig. S2). It's thus deduced an identical situation for all the stations: a general downward trend of annual rainfall and a very high interannual variability.

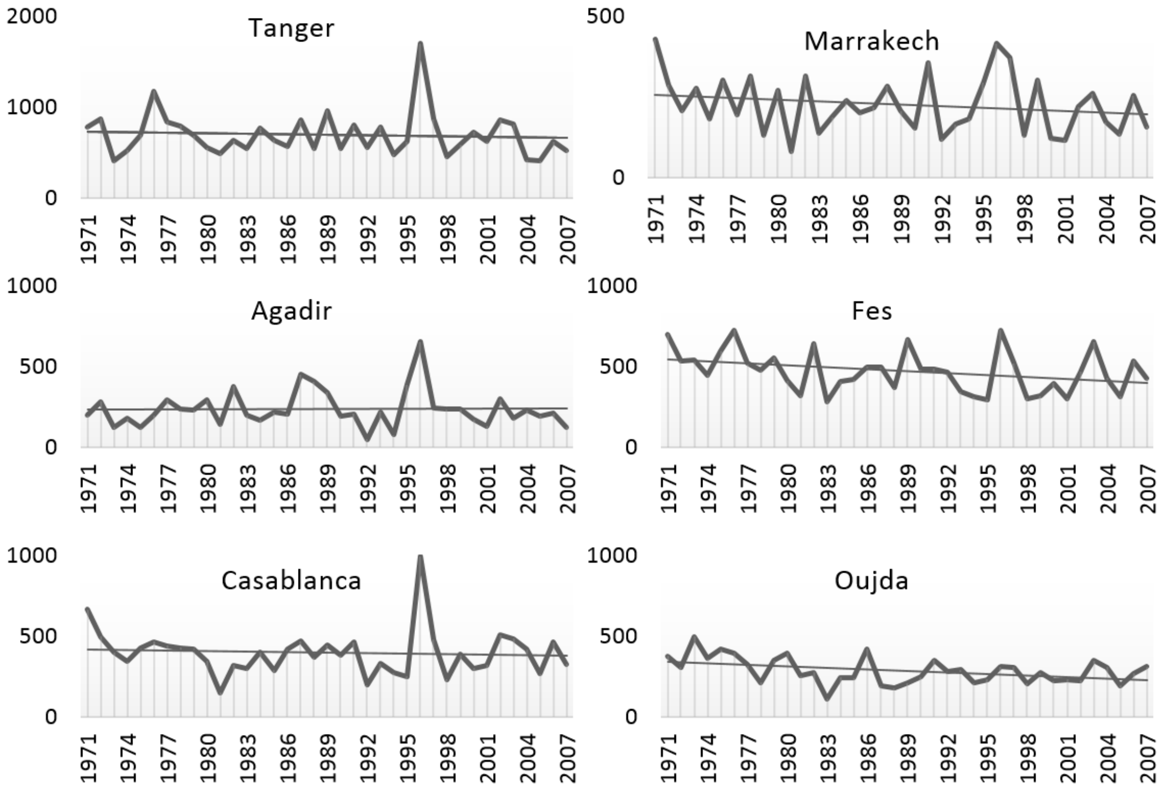

Figure S2: Evolution of precipitation (mm) at some Moroccan stations

According to [29], there is a strong tendency towards a decrease of precipitation totals and wet days together with an increase in the duration of dry periods, mainly for Morocco and western Algeria. In our case, spatialization of rainfall evolution shows some areas with a moderate decrease of precipitation (5 to 20 mm) in Southern Morocco, while Northern areas are the most affected with drought. In fact, the decrease of precipitation reached a maximum of 41.6 mm (Fig. 4). The deficit areas (North and central Morocco) are, paradoxically, the areas of intense agricultural activities [30] and large population concentrations.

3.3. Climate change scenarios for the 21st century in Morocco

Future simulations, developed using computer tools based on A2 and B2 scenarios, predict for the city of Marrakech, a temperature increase of about 2.3 °C by the year 2050 and about 4.7 °C by the year 2099. These simulations, which were generated by SDSM for A2 and B2 scenarios, anticipate more drought and warming above all the territory of Morocco by the late 21st century. They show a situation of increasing temperature and decreasing precipitation. Figure 5 presents positive temperature anomalies for the future horizons: 2011-2040, 2041-2070 and 2071-2099 (with 1961-1990 as a reference period).

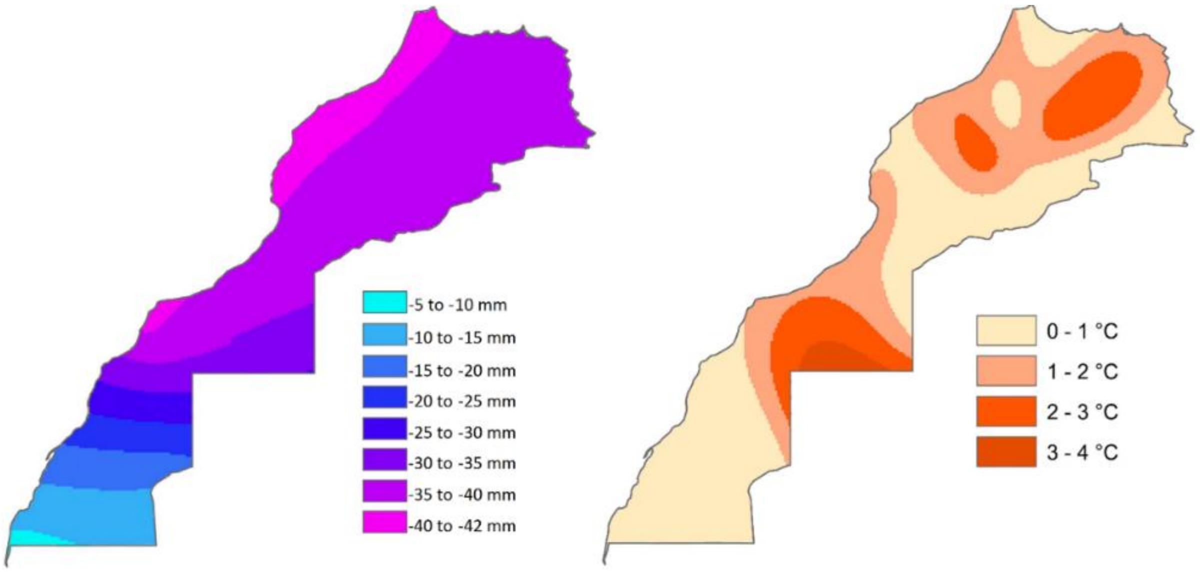

Figure 4: Precipitation and temperature anomalies between 1971-1980 and 1998-2007 in Morocco

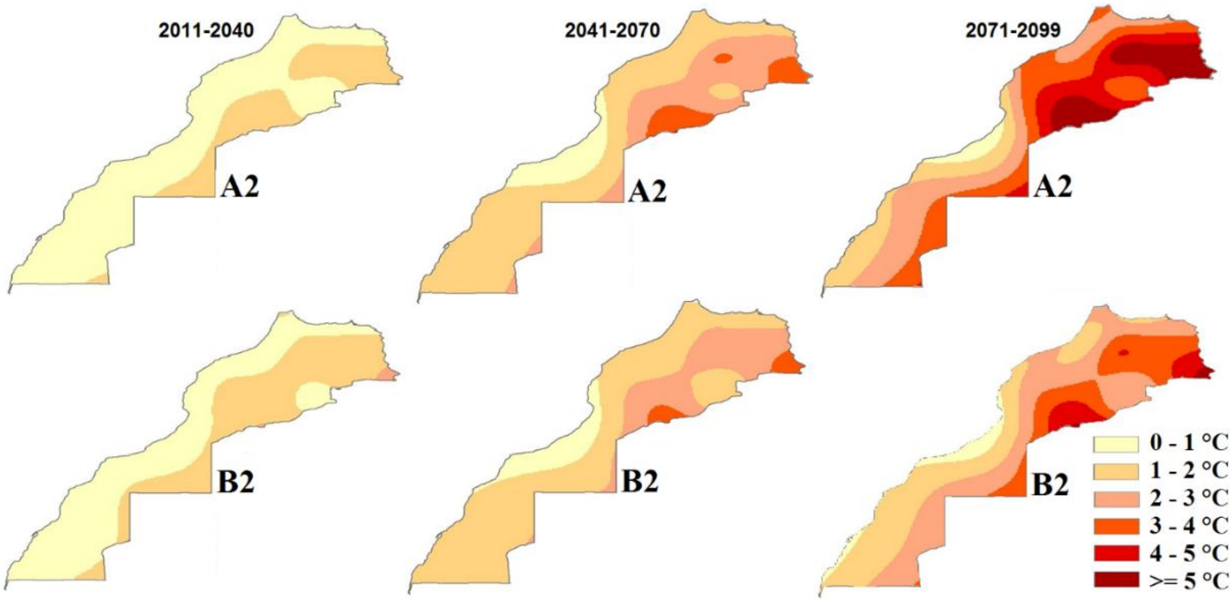

Figure 5: Future projections of temperature according to A2 and B2 scenarios

The gain of temperature in Morocco varies between 0.9 to 1 °C by the year 2040, 1.8 to 1.9 °C by the year 2070 and 2.5 to 3.6 °C by the year 2099. Both climate scenarios, for different periods, show that North-East and Central Morocco are the most affected areas with warming.

Moreover, Figure 6 shows the percentage of change in precipitation for the future horizons: 2011-2040, 2041-2070 and 2071-2099 (with 1961-1990 as a reference period). It is noted that extreme drought is anticipated in the north of Morocco by the end of the 21st century. The average decrease of rainfall amount over the period 1961-1990 is comprised between -15.2mm (-2.5%) to -20.5mm (-4.4%) by the year 2040, -51.9mm (-10.7%) to -61.3mm (-11.9%) by the year 2070 and -70.2mm (-14.8%) to -109,6mm (-22.3 %) by the year 2099. The highest rainfall reduction is recorded in the North of the country according to A2 and B2 scenarios.

Future projections of SU30 index showed an upward trend over the three projected periods: 2011-2040, 2041-2070 and 2071-2099, compared with the reference period 1961-1990 (Fig. 7). According to this result, the annual increase in the number of summer days will reach extreme values in South and North-East of Morocco by the late 21st century. According to A2 and B2 scenarios, the maximum gain of summer days will be respectively over 80 and 60 days/year. The significant increase of summer days frequency is causing more than just discomfort, as temperatures rise. Extreme heat events are big threat to Morocco. Such extreme events are actually responsible for more deaths annually than hurricanes, lightning, tornadoes, floods, and earthquakes combined [31].

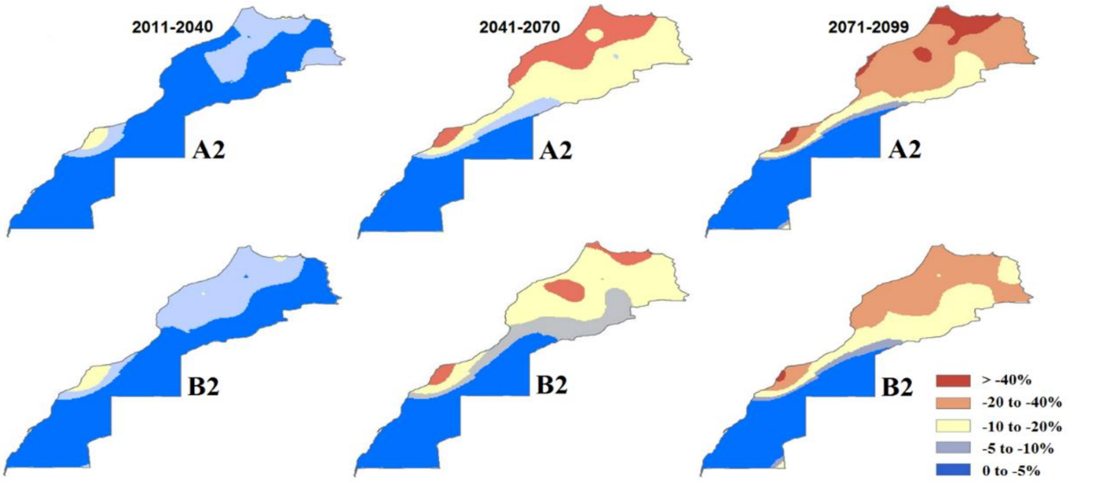

Figure 6: Future projections of precipitation according to A2 and B2 scenarios

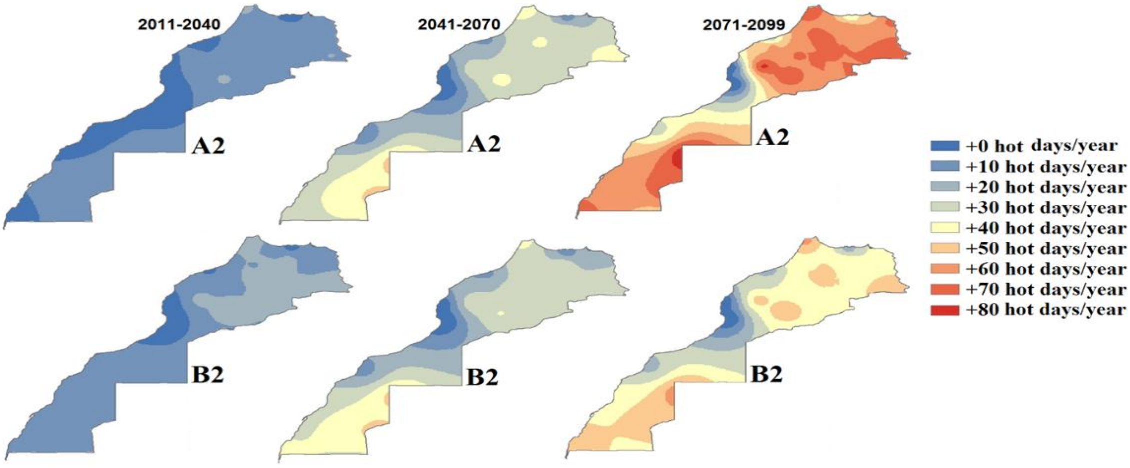

Figure 7: Future projections of the number of summer days according to A2 and B2 scenarios

On the other hand, the arid climate didn't stop gaining ground in various regions of Morocco [32] during the recent decades. Calculation of De Martonne index [33] for the period 1961-1990 showed the existence of five bioclimatic zones in Morocco : 1) Hyper-Arid climate in South, 2) Arid climate in central Morocco and 3) Semi-Arid to 4) Semi-Humid and 5) Humid climate at the North of the country. We calculated De Martonne Index for the future horizons: 2011-2040, 2041-2070 and 2071-2099 (with 1961-1990 as a reference period), using temperature and precipitation produced from SDSM for the 21st century. The comparison of climate situation at different periods (Fig. 8) highlights a remarkable gradual disappearance of humid climate and a migration of aridity towards the North of the country by the late 21st century according to both A2 and B2 scenarios (Fig. 8).

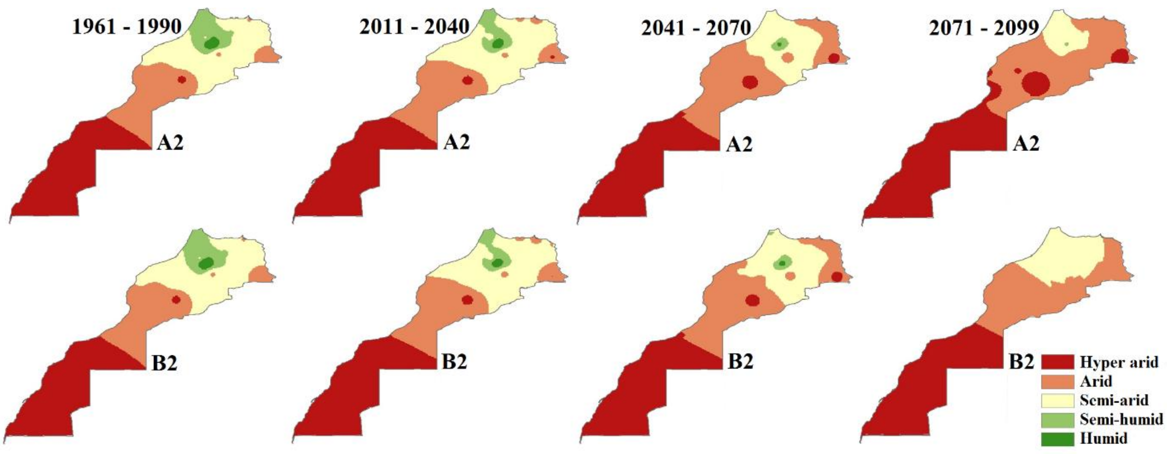

Figure 8: Climate evolution in Morocco by the 21st century according to A2 and B2 scenarios

Conclusions

The study of climate change could firstly highlight the variable and erratic nature of temperature and precipitation in Morocco. However, temperature data analysis reported significant trends towards increasing temperature. Contrariwise, annual amount of precipitation tend to decrease. These respective downward and upward trends of precipitation and temperature are basically reporting an overall decrease of humidity and a regular installation of drought between 1961 and 2007, especially in continental areas. Furthermore, calculation of climate and extreme indices gave another confirmation of warming and drought trends. This is brought out in particular by the significant increase of heat waves and summer days frequencies.

In addition, future climate projections, according to A2 and B2 scenarios also indicated a clear trend towards increasing temperatures. According to A2 scenario, the increase in average annual temperatures will reach 5 °C by the year 2099. The same observation of drought is signaled by the annual rainfall modeling where the model projects a downward trend of tens of millimeters per year all over the country. These projections of climate change in Morocco are likely to manifest by severe climatic, hydrological and agricultural droughts. Therefore, dangerous environmental effects are expected from this rapid change in climate regime that will probably be accompanied by other extreme events such as desertification and biodiversity loss. The impacts will have adverse effects on water resources and agricultural development, which significantly contribute to the national economy.

The global warming trends in Morocco are widening the gap between water demand and supply, hence the need for ways and solutions for filling these gaps. Urgent steps are needed to be undertaken on both national and global levels. It is recommended for the Moroccan policy to include the reduction of greenhouse gas emissions, the use of clean and renewable energy and educating people to adopt adapted behaviors towards a warmer and drier climate. Some of the solutions would be the practice of agricultural crops that require small quantities of water, sea water desalination, sewage treatment and the use of more solar energy in various economic sectors.

Table S1: SPI Classification

SPI ≥ 2	Extreme humidity
1,5 ≤ SPI < 2	High humidity
1 ≤ SPI < 1,5	Moderate humidity
-1 < SPI < 1	Normal
-1,5 < SPI ≤ -1	Moderate drought
-2 < SPI ≤ -1,5	High drought
SPI ≤ -2	Extreme drought

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