Investigation of Climate-Change Impact on Agriculture

Application of the FAO Strategy to Cereals in Morocco

In the Frame of a Cooperation of
Institut National de la Recherche Agronomique (INRA, Morocco),
Istituto di Biometeorologia di Concilio delle Riceche Nationale (IBIMET of CRN, Italia)
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Draft Report of the consultancy
From 26 July 2007 to 11 August 2007

Sassari

August 2007

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1. Introduction

Evidence is growing that the global climate is changing. While the knowledge of a global warming is very wide spread and causes are discussed for years now the question arises, what the impact of a possible global climate change may be. Since climate change is expected to lead to weather change all branches of economics that are directly linked to climate and weather may be prone to the most direct impact. Among these branches is agriculture und thus the base of food security. Therefore it is important to estimate the possible (at least potential) impact of climate change on agriculture.

The question how climate change will affect crop yields can not be solved straight forward. Crop growth on the one hand depends on many meteorological and non-meteorological factors. Among the main meteorological factors are temperature, precipitation and radiation. The course in time of these variables during the growing season determines whether the plants get enough water and radiation to grow. All these can be modeled by plant-specific soil-water balance models. One very simple but also very general model of this kind is the AgrometShell (see e.g. CLIMPAG: Climate Impact on Agriculture, FAO, 2007) of FAO. It is used for decades now under very different climate conditions and for a wide range of crops in order to perform in-season crop-yield forecasts and early warning of yield failure.

Future climate scenarios on the other hand are outputs of global circulation models (GCM) driven by increased heating due to enhanced greenhouse gas concentrations. Although these models run on the fastest computers available and their development was supported with hundreds of millions of US$ they can not calculate the recent local climates to a degree of accuracy necessary for agrometeorological investigations. However, it is generally believed that the changes in the output of GCMs due to enhanced warming are a realistic forecast of what may happen if the further increase in atmospheric greenhouse gases happens to appear.

In the present case study cereal yields (average yields of winter wheat, bread wheat and barley) of Morocco are investigated. It is first shown how Climate-Change knowledge can generally be transformed into estimates of crop-yield changes according to the FAO strategy. Section 3 describes the database of yield, meteorological data and climate change and provides some statistical features and criteria for the selection of part of the data.

In section 4 the estimated weather-yield function is provided. Section 5 describes the setup of the experiments performed and section 6 provides the results on the basis of climate change scenario and with respect to corresponding weather changes, soil-water balance changes and cereal-yield changes. Eventually section 7 gives a short summary of the findings and an outlook on further work.

2. From Climate Change to Crop-Yield Change

In an earlier study (Grieser et al., 2007) the classical FAO strategy for early in-season yield predictions is extended for the investigation of climate change impact on agriculture. Fig. 1 depicts this strategy.

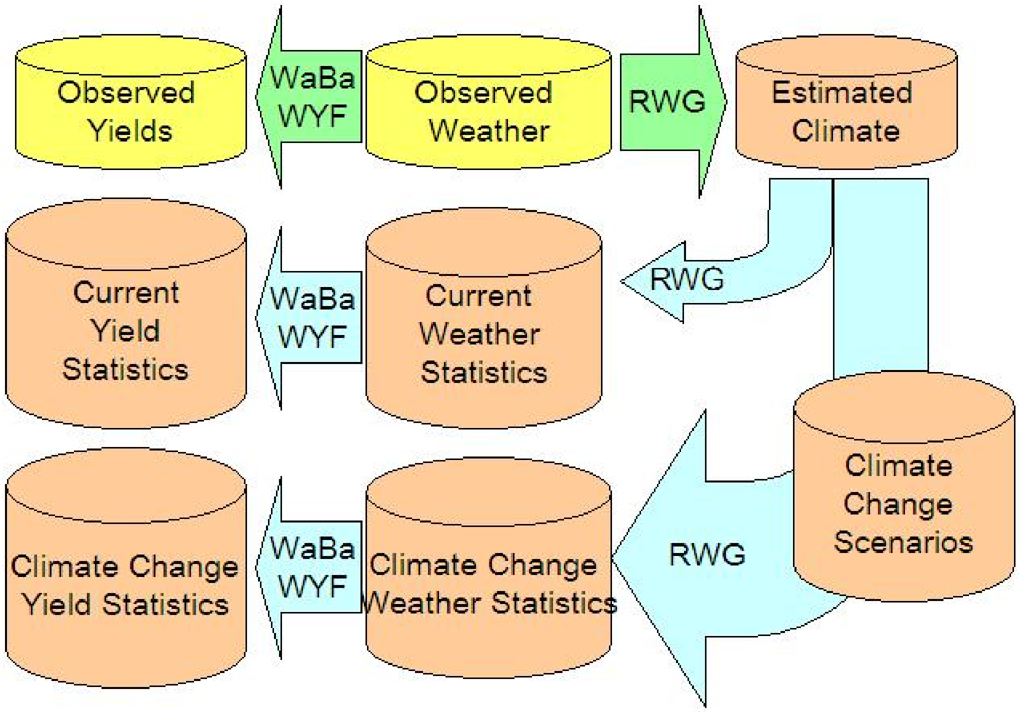

Fig. 1: Strategy for the investigation of climate-change impact on agriculture. Yellow data container are observations. Red data container are modeled data. Green arrows indicate fit to observations. Blue arrows indicate model runs. WaBa means crop-specific soil-water balance. WYF stands for weather-yield function. RWG means stochastic weather generator. Climate change scenarios are taken from GCM output.

The classical FAO strategy links weather observations with observed yields by a) running a crop-specific soil-water balance and b) linking the output (indices like evaporation, soil water content, etc. per stage of the growing cycle) statistically with observed yields. As a first step to go beyond this strategy a stochastic weather generator (RWG) is fit to the observations. Its parameters (averages, variances, co-variances, persistence measures, etc.) reflect the local climate.

With the weather generator long time series of synthetic weather data according to current and changed climate can be produced, fed into the water-balance model and finally transformed into corresponding yields. A statistical analysis of the output shows whether and how climate change may impact crop yields.

The search for the weather-yield function is performed with AgrometShell (AMS, Peter Hoefsloot, http://www.hoefsloot.com/agrometshell.htm). For the automatic runs of long time series the computer program WABAL (Rene Gommes, 2003) is used.

The weather generator used is M&Rfi by Martin Dubrovsky (2007). It models rain by a Markov chain up to order 3. Temperatures and radiation are combined in a three-dimensional autoregressive process of order 1 which is case sensitive and distinguishes between rainy and dry days. Wind speed and humidity can be modeled by a resampling technique.

3. Data Base

3.1 Yield Data

For the investigations of this study yields of winter wheat, spring wheat, barley and maize are available at province level for the period from 1980 to 2006 with one general gap in 1982 and some partial gaps in other years. For this case study only the average of wheat and barley is used (further on summarized as cereals) for which the data are nearly complete.

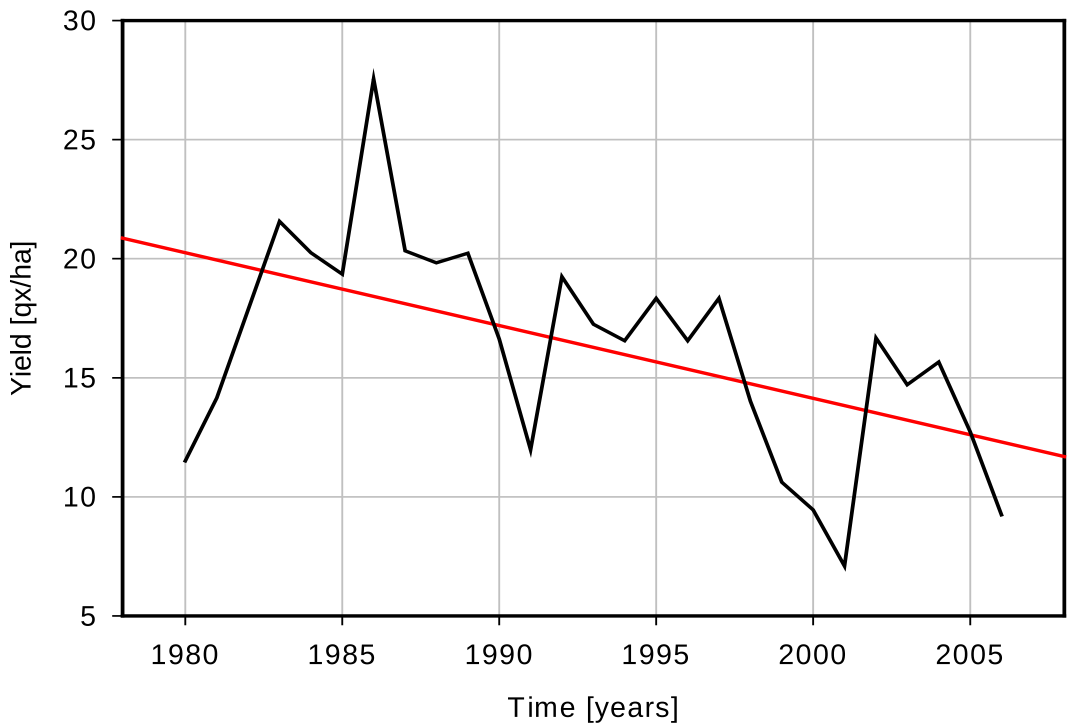

Fig. 2: Cereal-yield observations in Quarzazate. Red line marks the pronounced negative trend.

The average cereal yield (averaged over all years and provinces) is 11.2 qx/ha, (where a qx is 100 kg) with a province to province variability of 4.2 qx/ha and a mean year to year variability of 5 qx/ha. The minimum average yield occurs in Chichaoua with 2.9 qx/ha while the maximum average yield of 19.8 qx/ha is more than 6 times higher and occurs in Gherb. The temporal variability is about 50 % of the average yield. This is a high variability which may reflect a strong dependency on weather.

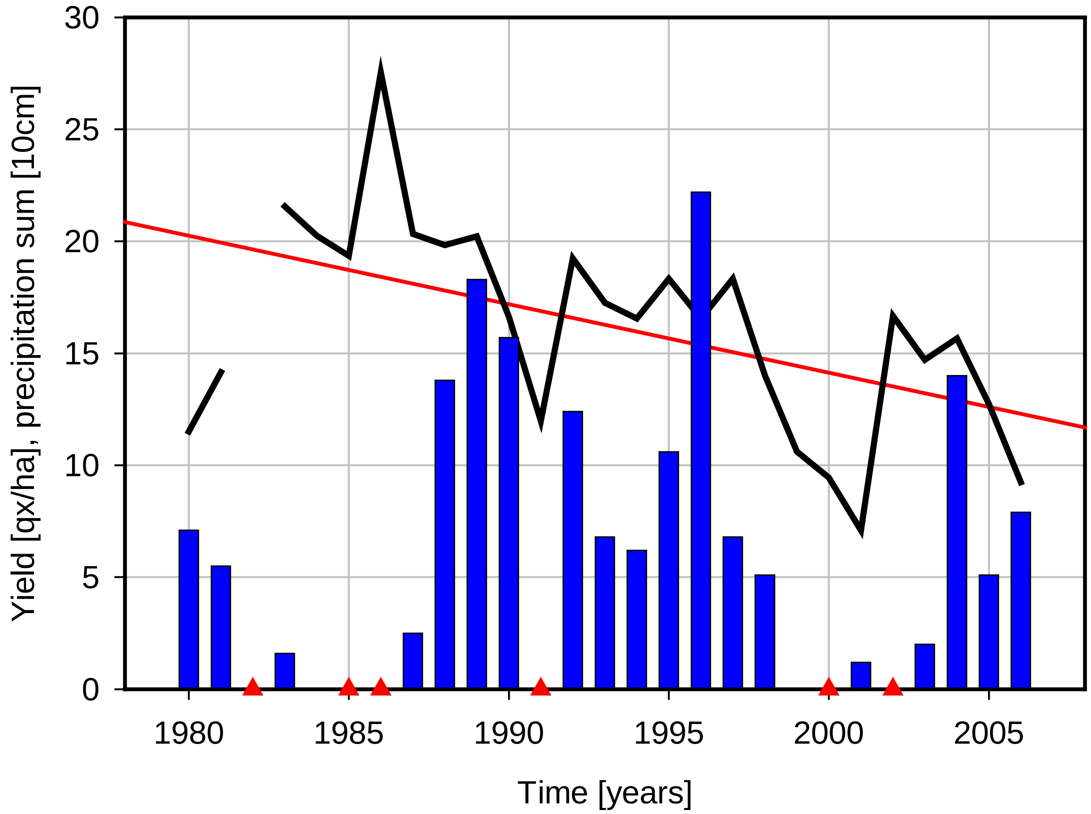

Fig. 3: Time series of in-season rain sum and cereal yields in Ourzazate. Black line depicts the yield observations. Blue bars are the precipitation sum from November to May of the respective season and red triangles mark incomplete precipitation records. Red line is the yield trend.

Trends are generally small with an average slope of .019 qx/ha and a nearly 8 times higher province to province variability of .149 qx/ha. The mean of the ratio of slope to average (the relative trend) is .2 % per year. This means that no cross-country trend is visible. Given 28 observations a trend is significant on the 95 % level (i.e. by chance only 5 % of estimated trends in random time series of this length would exhibit a larger trend) if the coefficient of determination r^2 is higher than 6.65 %. This is the case for 5 provinces (Rabat 22 %, Doukkala 11 %, Chichaoua has only a short time series of 8 years and is not further investigated, Ouarzazate 27 %, and Tafilalet 14 %). Except Doukkala and Tafilalet the trends are negative and may thus not be attributed to agricultural development or improved farming practices. The trends may rather reflect trends in meteorological variables. If the trends were of non-meteorological origin they should be removed from the data before a link to weather variables is searched. If the trends can be neglected or may be linked to meteorological variability they should not be extracted.

In order to investigate the question whether the trend in cereal observations in Ourzazate may be correlated with meteorological changes, the rain sum during growing season (November to May) is plotted together with the time series of yields in Fig. 3. Since it can not be excluded that the trend in the observed yields is linked to meteorological variability the yield records are not detrended.

3.2 Meteorological Data

For 30 meteorological stations within Morocco daily observations of mean, minimum and maximum temperature, mean sea level pressure, humidity, precipitation, visibility, mean and maximum wind speed and evapotranspiration estimated by Hargreaves formula are available for a period ending in December 2006. For the different stations the records start between 1945 (Agadir) and 1994 (Chefchaouen). Some of the station records have long and recent gaps like Agadir (from 1992 to 2004).

Penman-Monteith PET (PET_{PM}) can not be calculated from these observations since no observations of solar radiation are available. However, the database of the FAO Agromet Group (New LocClim, 2005) contains long term averages of monthly observations of all necessary variables to calculate PET by Penman-Monteith method and by Hargreaves method (PET_H) for 17 stations within the bounding box of Morocco[1]. This allows a comparison of PET_H and PET_{PM}. Fig. 4 shows the scatter diagram of the 204 values (17 stations times 12 months) and the regression line as well as the 1:1-line. The equation

$$PET_H = 2.2 + 1.048\ PET_{PM} \qquad (1)$$

Explains over 83 % of the variability. Therefore PET_H can be regarded as a good approximation of PET_{PM}. No further transformations are performed.

[1] latitude between 27° and 36°, longitude between –14° and –1°.

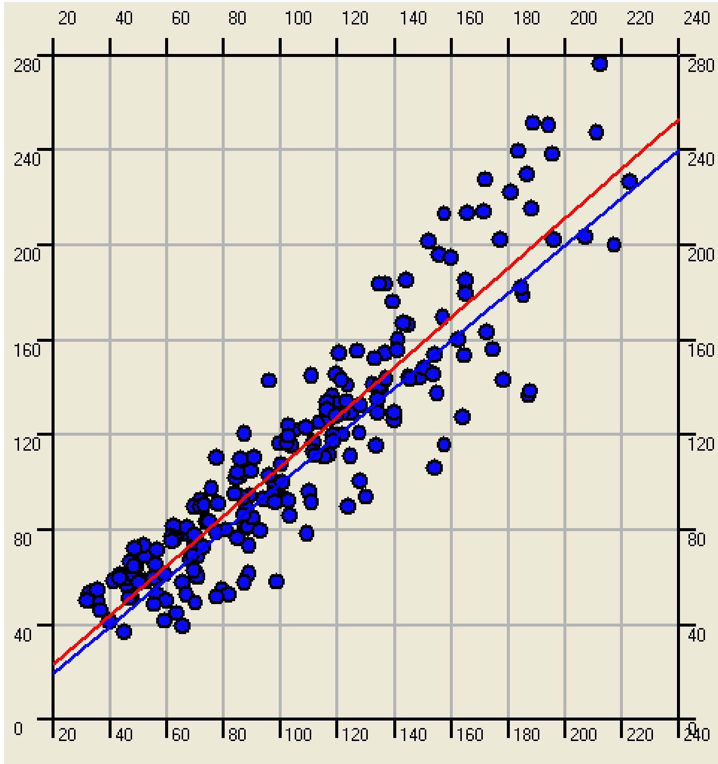

Fig. 4: Scatterplot of longterm monthly averages of Penman-Monteith PET (x axis) vs Hargreaves PET (y axis) for the bounding box of Morocco. The 1:1 line is blue. The regression line is shown in red.

For the fit of the stochastic weather generator long time series are favoured in order to obtain stable results. For the run of the crop-specific soil-water balance model as much as possible cases are desired, where a case means a station and a year for which cereal yields are available. Therefore one task is to attribute wheat yields (province averages) to meteorological data (point observations). Since the provinces are reasonable small and homogeneous it is assumed that the water balance parameters estimated at station locations are representative for the whole surrounding province. Table 1 shows the stations and their attributed provinces.

Table 1: Stations, surrounding provinces and reason why they are not used (if so).

Station-ID	Station Name	Province Name	Reason if not used.
1	Agadir-Almassira	AGADIR	Short met. record
2	Agadir	AGADIR	Short met. record
3	Arwi	NADOR	Short met. record
4	Benimellal	BENI MELLAL	
5	Casablanca	CASABLANCA	
6	Chefchouane	CHEFCHAOUEN	Short met. record
7	Elhouceima	AL HOCEIMA	
8	Errachidia	ERRACHIDIA	No yield data
9	Essaouira	ESSAOUIRA	
10	Fes	FES	

11	Ifrane	IFRANE	Short met. record
12	Kasbat	BENI MELLAL	
13	kenitra	KENITRA	Short met. record No yield data
14	Laayoune	LAAYOUNE	Short met. record No yield data
15	Larache	LARACHE	No yield data
16	Marrakech	MARRAKECH	
17	Meknes	MEKNES	
18	Mudelt	KHENIFRA	
19	Nador	NADOR	
20	Nouasser	SETTAT	
21	Ouarzazate	OUARZAZATE	
22	Oujda	OUJDA	
23	Rabat	RABAT-SALE	
24	Safi	SAFI	
25	Sidi-Ifni	TIZNIT	
26	Sidi-slimane	KENITRA	Short met. record No Yield data
27	Tanger	TANGER	
28	Tan-Tan	TAN-TAN	Short met. record No Yield data
29	Taza	TAZA	
30	Tetuan	TETOUAN	

The water balance can be run with the knowledge of only two meteorological variables: precipitation and potential evapotranspiration (PET). Therefore the station data are loaded into AgrometShell and the water balances are run for the years 1980 to 2006. The output is used to find the weather-yield function (s. section 4).

Evapotranspiration, however, is no basic meteorological variable and should not be used as a basic variable in the stochastic weather generator. Therefore instead of running the generator with only 2 variables (precipitation and PET) three generic and one derived variables are used for the fit of the weather generator. The variables are minimum temperature, maximum temperature, precipitation and estimated solar radiation.

Solar radiation R_S is estimated by Hargreaves formula

$$R_S = R_A \sqrt{T_X - T_N}\, k_{RS} \qquad (2)$$

from top-of-atmosphere incoming solar radiation R_A (calculated with the programme ExtraRad, 2007, see e.g. http://www.hoefsloot.com/agrometshell.htm) for every day and every station, maximum and minimum temperatures T_X and T_N, respectively and the Hargreaves coefficient k_{RS} which is between .16 (inland stations far from the sea) and .19 for stations at the coast line (see Allen et al., 1999).

3.3 Crop Calendar

The major cereal in Morocco is winter wheat. The correlation between winter wheat yields and the overall cereal yields is about .65. Therefore here winter wheat is modeled as a representative for the overall cereal production. Winter is planted in November and harvested in May. The planting dates, however, depend on weather and thus differ from year to year and province to province. Planting occurs shortly after the first considerable rain. IBIMET estimated planting dates from rain occurrences and amounts. For the soil water balance calculations the planting dekads are used. The range of planting dekads is fixed between dekad 30 and 34 in order to avoid too early or too late planting. The dekads used are provided in appendix A2.

3.4 Crop Coefficients

Crop coefficients for winter wheat during the growing cycle are provided by INRA and depicted in Figure 5. The pre-season crop coefficient is set to .15.

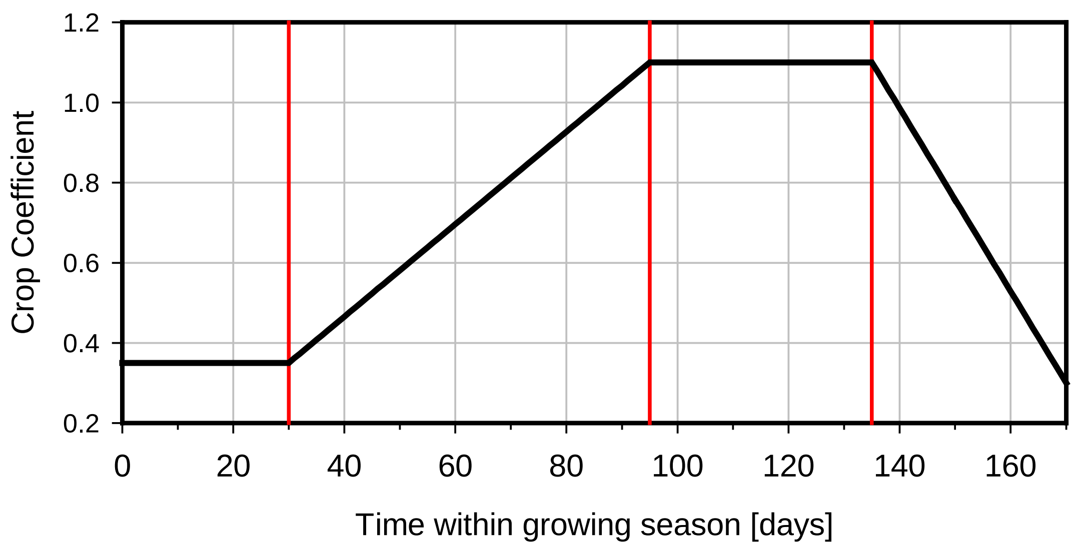

Fig. 5: Crop coefficients of winter wheat in Morocco. The red lines separate the 4 growing stages (initial, vegetative, flowering, ripening).

3.5 Water holding capacities

From the FAO world map of soils water holding capacities (WHC) are extracted on a .5° grid by IBIMET. The values scatter between 16mm and 145mm. Since this scatter reveals no order and no reason for it is found, IBIMET and the author agreed to try and use 60mm and 80mm for all locations as an “effective” WHC. The value that leads to better modeling results is finally used.

3.6 Climate Change data

Possible future climate change is provided by many global circulation models (GCMs) on the basis of different scenarios of human influence (expressed as greenhouse gas emissions) and different climate sensitivities.

Here results are used that are based on

- the so-called IPCC SRES A2 scenario,
- the Hadley Center Model version 3 (HadCM3),
- a climate sensitivity of 2.09°C/CO_2 doubling,
- a pattern scaling method by Dubrovský et al. (2005),
- the projection to the year 2100.

The monthly climate change data for the locations of each station in Morocco are provided by M. Dubrovský. For the months of the growing season of winter wheat in Morocco they are provided in the tables of appendix A3.

For simplicity only changes in mean values are considered. No changes in variances, co-variances, persistence or fraction of days with rain are considered. Though this is a restriction it allows to isolate the effect of changes in the average of a meteorological variable. Changes in averages are assumed to be the most reliably estimates provided by the global circulation models. Furthermore they may face the strongest changes and thus may have the pronounced impact on agriculture.

For the growing season (November to April) the average temperature over all stations is expected to rise by3.3 °C with the least increase in Laayoune (.8 °C) and the highest increase of 3.9 °C in Oujda. Only in one month at one station a negative change is forecast (-.7 °C in November in Laayoune). No strong in-season variability is seen.

Precipitation changes are more widespread, ranging from –54.7 % in Tetuan to 52.2 % in Tanger. The average over all stations is –24.5 %. The range of variability (both, station to station and month to month) is very high.

Modeled changes in solar radiation range from –11.5 % to 3.8 % with an average of 1.5 %.

Summarizing this, it can be said that in the year 2100 Morocco may be expected to become warmer, dryer and more prone to solar radiation.

Since in this work radiation and potential evapotranspiration are parameterized by Hargreaves method, explicit changes in radiation are not considered. This avoids inconsistencies.

4. The Weather-Yield Function

The output of the crop-specific soil-water balance model are actual evapotranspiration ETA, excess water WEX, and water deficit WDEF for the initial phase i, the vegetative phase v, the flowering phase f, the ripening phase r and the total growing season t. Furthermore the water satisfaction index Idx (which is the fraction to which the water requirements of the plants are met) is provided for 3 cases: IdxLatest for the latest dekad for which data were available and IdxHarvest for the end of the season. They are the same in case of full data availability. The third water satisfaction index, IdxNorm, is the water satisfaction index in case that not the rain and PET of the actual season is used but the long term average (normal) values. This index thus is linked to the local productivity potential. The soil water content at the beginning of the growing season WSi, the total water requirement TWR and the starting dekad of the growing season are also stored. Together with the year all these variables are cross-correlated and correlated with the yield observations in order to find possible relations.

All output parameters which explain more than 4% of the yield observations are then used in multiple stepwise regression (leaving out the most unsignificant regressor in each step) in order to empirically find the best appropriate relation between a preferable low number of parameters and cereal yields. Chosen are only those parameters which are significant on a 95% level.

494 cases are available if all 19 stations and 26 years are used. Because of gaps in the data the calculation of the water balance failed in 5 cases and 489 cases are left.

However, the stations and attributed yields are spread all over the country and it may be not adequate to mix the situation in the Atlas mountains with the situation at the coast line. In order to investigate this effect 3 groups of stations are used which are

a) all 19 stations
b) only the 10 stations close to Settat (Benimellal, Casablanca, Essaouira, Fes, Kasbat, Marrakech, Meknes, Nouasser, Rabat, Safi)
c) only the 7 closest stations (Benimellal, Casablanca, Essaouira, Kasbat, Marrakech, Nouasser, Safi).

Furthermore the relation between meteorological data and yield data may depend on time for several reasons. Inhomogeneities due to changed farming practices, observation rules and other reasons may contribute.

Therefore the relation is investigated not only for the whole period from 1980 to 2006 but also for the last 15 years from 1992 to 2006. Table 2 contains the multiple correlation coefficients and the selected variables for all these cases.

Table 2: Results of 7 experiments to find a weather-yield function.

Period	Stations	Number of cases	WHC	Coefficient of determination	Selected parameters
1980-2006	19	489	60	7.6%	WEXv, ETAt
1992-2006	19	285	60	12%	WEXv, WEXt, ETAf
1980-2006	10	255	60	18.6%	IdxNorm,WDEFf, WDEFt, ETAt
1980-2006	7	180	60	14.6%	IdxNorm, WDEFf, ETAf
1992-2006	10	150	60	29.5%	TWR, IdxNorm, WEXv, WDEFf
1992-2006	19	285	80	15%	WEXv, ETAf
1992-2006	10	150	80	27.4%	TWR, IdxNorm, WEXv, WDEFf

Several things can be learned from Table 2. Firstly, it was not possible to find a single weather-yield equation valid for the whole region. It seems that the data reflect too different situations[2]. The coefficient of determination is best if 10 stations in and close to Settat are selected. The use of less stations (7 in this case) did decrease the coefficient of determination. This may be due to the effect that not enough different situations are within the sample in this case in order to statistically "learn" the relation. Furthermore it can clearly be seen that shorter time series of 15 years show much better correlation than longer time series. This may be mainly due to inhomogeneities in the meteorological data and changes in farming and observing practices.

Compared to these effects the dependency on WHC is low. While for the use of all stations the correlation is increased by 2% it is decreased in case of the use of the subset of 10 stations if WHC = 80 mm is used instead of 60 mm.

Furthermore it can be seen that in none of the cases the initial conditions (planting dekad, initial soil water content or WEX, WDEF, and ETA during the initial stage) are selected. Yields of cereals seem to be rather independent from these conditions. Also not found is a relation to weather conditions during the ripening stage.

It is concluded here that the best relation is the one based on 15 years, 10 stations and a WHC of 60mm. The resulting equation is

$$Y = a_0 + a_1\,\mathrm{TWR} + a_2\,\mathrm{IdxNorm} + a_3\,\mathrm{WEXv} + a_4\,\mathrm{WDEFf} \qquad (3)$$

with
a_0 = -16.633 Qt/ha,
a_1 = dY/dTWR = 0.0686 Qx/ha/mm,

[2] In fact Riad Balaghi (2007) from INRA suggested to search for specific weather-yield relations for each province. Those locally explain up to 61% of the local wheat yield variance.

a_2 = dY/dIdxNorm = 0.1327 Qx/ha/%,
a_3 = dY/dWEXv = 0.0258 Qx/ha/mm,
a_4 = dY/dWDEFf = 0.0955 Qx/ha/mm,

where dY/dX means the first deviative of Y with X. The coefficients a_1 to a_4 can be interpreted as sensitivities. As an example a_4 means that each mm increase of water deficit during the flowering state reduces the yield by 9.55 kg/ha in case that all other influences stay constant[3].

Since the coefficient of determination is 29.5% this means that 70.5% of the variance of the yield data set leaves unexplained. In other words this means that the ratio of standard deviation of the meteorological signal in the yield dataset to the residual standard deviation is the square root of .295/.705, which is .647. To put it again in other words, this means that the standard deviation of the unexplained variability is about 50% higher than the standard deviation of the found meteorological signal in the yield data.

However, in this work it is not the aim to find best forecast relationships but to find a link between meteorological data and yield data which is valid for more than one province within Morocco. Such a link can than be used in order to investigate the possible impacts of climate change to yields.

The 4 variables in eq. (3) are not only highly significantly linked to the yields, they reflect also very reasonable relations.

The total water requirements, TWR, provide information on the actual evaporation potential of the plants. High TWR indicate good radiative and temperature conditions for the plants. However, since cereal growth in Morocco is water limited high TWR values are usually linked to situations with less than normal rain. Therefore TWR is negatively correlated to ETA in this case. Furthermore significant links between TWR and the index at harvest and water deficits are found, which expresses the same relation that high values of TWR mean good radiative and thermal conditions but are usually linked to water shortage.

The normal index, IdxNorm, depends on average local weather conditions and the planting dekad that varies between 30 and 34 in this case (see table A2). It is therefore an important input variable in order to distinguish different locations in the dataset.

The excess water during the vegetative stage, WEXv, indicates water satisfaction during this stage plus enough water to be stored and used later during the flowering stage. Therefore excess water during the vegetative stage is positively linked to yields.

The water deficit during the flowering stage, WDEFf, is obviously an important influence on crop yields since water shortage during the flowering phase cannot be compensated by water surplus during other stages.

[3] Note that water deficit is measured as a negative number. A larger water deficit means a negative number of larger absolute value.

When interpreting the influence of the 4 water-balance parameters on crop yields one should keep in mind that they are not independent. Table 3 shows the correlations between them.

Table 3: Correlations between the water balance parameters that drive cereal yields.

	TWR	IdxNorm	WEXv	WDEFf
TWR	1	-.6	-.14	-.76
IdxNorm		1	.18	.39
WEXv			1	.09
WDEFf				1

5. Numerical Experiments

According to the strategy depicted in the flow chart of Fig. 1 several experiments are performed in order to investigate the potential impact of climate change to cereal yields in Morocco.

In order to apply eq. (3) the calculation of IdxNorm is necessary. This parameter depends strongly on the planting dekad. The later the planting the higher the risk of having a warm and dry phase at the end of the season. On the other hand it is not possible to plant earlier than the first significant rain (about 10mm) happened to occur, unless irrigation is applied.

Before the experiments with synthetic weather series can be performed one has to decide on when to start the growing season within these experiments. The rule that the growing season starts after the first significant rain should not be applied to all cases of the future scenarios since a dryer climate (see section 5) means that planting would always be late and thus the growing season would reach into the hot summer of the following year.

In order to deal with this problem and since here only potential sensitivity of yields to climate change are of interest the planting dekads are fixed to 33. This value is slightly higher than the average actual value of 32.8 estimated for the observation phase from 1980 to 2006 (see Table A2).

Table 4 depicts the average value of idxNorm as it results from calculations with actual planting dekads and observed meteorological data, with fixed planting dekads of 33 and observed meteorological data, with fixed planting dekads of 33 and 1000 years of modeled meteorological data and with 1000 year of modeled climate change data and 3 different values of the planting dekad.

Table 4: Normal water satisfaction index, IdxNorm, in case of case sensitive planting dekads, fixed planting dekads of 33 and observed meteorological data, synthetic meteorological data of current and future climate.

Planting Dekad	Variable	33	33	33	34	32
Met Data	Observations	Observations	Synthetic Current Climate		Synthetic Climate Change	
Benimellal	71.7	67	77	42.0	39	45.0
Casa	82.6	77	84	61.0	55	68.0
Essaouira	73.5	73	73	48.0	45	50.0
Fes	79.5	79	92	57.0	52	60.0
Kasbat	70.1	67	72	43.0	41	46.0
Marrakech	34.7	34	36	22.0	20	24.0
Meknes	87.3	81	87	59.0	53	64.0
Nouasser	72.1	68	84	53.0	48	57.0
Rabat	88.9	86	100	61.0	55	69.0
Safi	65.3	63	70	49.0	43	52.0
Average	73	70	78	50	45	54

Table 4 shows that a fixed planting dekad reduces the calculated cereal yield by 3/73 compared to a planting dekad in response to the occurring rain. Using synthetic meteorological data from the weather generator, however, IdxNorm and thus yields are increased. Table 3 also shows that for future scenarios IdxNorm decreases considerably for different planting dekads. The later the planting, the higher the decrease in IdxNorm. It is obvious from eq. (3) that this has a negative effect on yields. However, detailed experiments with synthetic weather series reveal how the other 3 parameters (TWR, WEXv, and WDEFf) react on climate change and how the final effect on yields will be.

All yields are calculated with the planting dekad 33.

6. Results

6.1 Simulations under current climate conditions

6.1.1 Comparison of observed and modeled weather characteristics

The weather generator M&Rfi is fit to the station observations in order to produce time series of artificial meteorological data which should have the same statistical features as the observed weather records.

The fit failed only for the station Ouarzazate. The reason for that seems to be the very low precipitation while there is very high PET during the growing season. The ratio of average decadal PET to average decadal precipitation during the growing season is a good measure to compare different stations. Table 5 shows that for all stations except Ouarzazate this ratio is below 5.18 with an average of 2.04 and a standard deviation below 1.2. For Ouazazate however it is above 11 and thus about 7 standard deviations above the average of the other stations. Therefore it can be concluded that the meteorological conditions at Ouazazate are very specific and may not be suitable for un-irrigated cereal growth. The data of this station are excluded from further analysis.

Table 5: Ratio of PET to Precipitation during the growing season from dekad 31 to 11.

Station	PET [mm/dekad]	Precipitation [mm/dekad]	Ratio
Benimellal	27.29	14.22	1.92
Casa	22.18	15.84	1.40
Elhouceima	20.52	10.15	2.02
Essaouira	19.15	11.29	1.70
Fes	23.71	15.56	1.52
Kasbat	27.04	14.38	1.88
Marrakech	28.52	7.64	3.73
Meknes	23.55	16.07	1.47
Midelt	21.67	4.18	5.18
Nador	21.88	11.42	1.92
Nouasser	25.11	14.31	1.75
Oujda	23.94	8.89	2.69
Rabat	23.02	20.52	1.12
Safi	24.57	13.85	1.77
Sidi-Ifni	20.15	5.17	3.90
Tanger	20.13	25.43	0.79
Taza	21.84	20.37	1.07
Tetuan	19.38	22.75	0.85
Minimum	19.15	4.18	0.79
Average	22.98	14.00	2.04
Maximum	28.52	25.43	5.18
Standard Deviation	2.76	5.79	1.16

For the sake of simplification only PET, precipitation sum and number of precipitation days during growing season (dekad 31 to 11) are used for comparison between observed and modeled weather under current climate conditions. As a first simple measure Table 6 (a to c) shows the averages during the observation period and for 1000 years of modeled data.

Table 6a: Observed and modeled mean PET during growing season, as well as absolute and relative differences for all stations.

Station	Observation [mm/dekad]	Modeled [mm/dekad]	Absolute Difference	Relative Difference [%]
Benimellal	27.29	27.41	0.12	0.44
Casablanca	22.18	21.29	-0.89	-4.01
Elhouceima	20.52	20.24	-0.28	-1.36

Essaouira	19.15	19.02	-0.13	-0.68
Fes	23.71	23.6	-0.11	-0.46
Kasbat	27.04	27.07	0.03	0.11
Marrakech	28.52	27.81	-0.71	-2.49
Meknes	23.55	22.85	-0.7	-2.97
Midelt	21.67	21.65	-0.02	-0.09
Nador	21.88	20.91	-0.97	-4.43
Nouasser	25.11	24.37	-0.74	-2.95
Oujda	23.94	23.44	-0.5	-2.09
Rabat	23.02	22.51	-0.51	-2.22
Safi	24.57	24.22	-0.35	-1.42
Sidi-Ifni	20.15	19.79	-0.36	-1.79
Tanger	20.13	19.64	-0.49	-2.43
Taza	21.84	21.46	-0.38	-1.74
Tetuan	19.38	18.6	-0.78	-4.02
Minimum	19.15	18.60	-0.97	-4.43
Average	22.98	22.55	-0.43	-1.92
Maximum	28.52	27.81	0.12	0.44
Standard Deviation	2.76	2.82	0.33	1.44

Table 6b: Observed and modeled mean precipitation during growing season, as well as absolute and relative differences for all stations.

Station	Observation [mm/dekad]	Modeled [mm/dekad]	Absolute Difference	Relative Difference [%]
Benimellal	14.22	13.9	-0.32	-2.25
Casablanca	15.84	15.33	-0.51	-3.22
Elhouceima	10.15	10.37	0.22	2.17
Essaouira	11.29	11.22	-0.07	-0.62
Fes	15.56	15.38	-0.18	-1.16
Kasbat	14.38	14.14	-0.24	-1.67
Marrakech	7.64	7.35	-0.29	-3.80
Meknes	16.07	15.69	-0.38	-2.36
Midelt	4.18	4.24	0.06	1.44
Nador	11.42	11.19	-0.23	-2.01
Nouasser	14.31	14.15	-0.16	-1.12
Oujda	8.89	8.72	-0.17	-1.91
Rabat	20.52	20.41	-0.11	-0.54
Safi	13.85	13.73	-0.12	-0.87
Sidi-Ifni	5.17	5.08	-0.09	-1.74
Tanger	25.43	25.32	-0.11	-0.43
Taza	20.37	19.94	-0.43	-2.11
Tetuan	22.75	22.76	0.01	0.04
Minimum	4.18	4.24	-0.51	-3.80
Average	14.00	13.83	-0.17	-1.23
Maximum	25.43	25.32	0.22	2.17
Standard Deviation	5.79	5.76	0.18	1.48

Table 6c: Observed and modeled fraction of days with precipitation during growing season, as well as absolute and relative differences for all stations.

Station	Observation [%]	Modeled [%]	Absolute Difference	Relative Difference [%]
Benimellal	18.37	17.86	-0.51	-2.78
Casablanca	21.09	20.6	-0.49	-2.32
Elhouceima	16.56	16.24	-0.32	-1.93
Essaouira	15.63	15.31	-0.32	-2.05
Fes	23.14	22.78	-0.36	-1.56
Kasbat	18.4	18.05	-0.35	-1.90
Marrakech	11.93	11.46	-0.47	-3.94
Meknes	21.02	20.74	-0.28	-1.33
Midelt	11.61	11.5	-0.11	-0.95
Nador	18.86	18.4	-0.46	-2.44
Nouasser	20.85	20.76	-0.09	-0.43
Oujda	16.38	16.28	-0.1	-0.61
Rabat	22.93	22.59	-0.34	-1.48
Safi	18.65	18.32	-0.33	-1.77
Sidi-Ifni	9.83	9.66	-0.17	-1.73
Tanger	25.63	25.69	0.06	0.23
Taza	24.02	23.56	-0.46	-1.92
Tetuan	24.53	24.53	0	0.00
Minimum	9.83	9.66	-0.51	-3.94
Average	18.86	18.57	-0.28	-1.61
Maximum	25.63	25.69	0.06	0.23
Standard Deviation	4.59	4.61	0.18	1.01

Table 6 clearly shows that the total PET and precipitation during the growing season can be very well reproduced by M&Rfi. Relative errors do locally not exceed 5 % and are about 1 % on average for precipitation and 2 % for PET. M&Rfi also reproduces very well the number of days with rain though the fraction of rainy days is slightly underestimated in all cases. On average it produces 1.6% less days with rain than the observations do.

With respect to the 3 meteorological variables which are regarded as most important for plant growth modeling (precipitation sum, evapotranspiration sum and number of rainy days) the weather generator M&Rfi provides very realistic time series of arbitrary length.

6.1.2 Comparison of observed and modeled soil-water characteristics

The crop-specific soil-water balance model is fit to 15 years of meteorological data of 10 stations (see section 4). For these stations the soil-water parameters calculated with meteorological observations and with 1000 years of synthetic meteorological data are shown in Table 8 a to d. In all cases the planting dekad was set to 33.

Table 7a: Differences in total water requirements, TWR, (in mm) between the soil water model driven by 15 years of meteorological observations and alternatively driven by 1000 years of synthetically generated meteorological data.

Station	Observed meteorological data	Modeled meteorological data	Absolute Difference	Relative Difference [%]
BENI MELLAL	377.53	386.0	8.5	2.2
CASABLANCA	283.47	295.1	11.7	4.1
ESSAOUIRA	253.00	259.6	6.6	2.6
FES	335.73	338.2	2.4	0.7
KASBAT	365.67	386.6	20.9	5.7
MARRAKECH	381.13	394.0	12.8	3.4
MEKNES	323.93	326.7	2.7	0.8
NOUASSER	351.80	343.1	-8.7	-2.5
RABAT-SALE	317.93	316.3	-1.6	-0.5
SAFI	323.87	339.0	15.2	4.7
Average	331.4	338.5	7.0	2.1

Table 7b: Differences in normal water satisfaction index, IdxNorm, (in %) between the soil water model driven by 15 years of meteorological observations and alternatively driven by 1000 years of synthetically generated meteorological data.

Station	Observed meteorological data	Modeled meteorological data	Absolute Difference	Relative Difference [%]
BENI MELLAL	67.00	77	10	14.9
CASABLANCA	77.00	84	7	9.1
ESSAOUIRA	73.00	73	0	0.0
FES	79.00	92	13	16.5
KASBAT	67.00	72	5	7.5
MARRAKECH	34.00	36	2	5.9
MEKNES	81.00	87	6	7.4
NOUASSER	68.00	84	16	23.5
RABAT-SALE	86.00	100	14	16.3
SAFI	63.00	70	7	11.1
Average	69.5	77.5	8.0	11.5

Table 7c: Differences in water excess during the vegetative state, WEXv, (in mm) between the soil water model driven by 15 years of meteorological observations and alternatively driven by 1000 years of synthetically generated meteorological data.

Station	Observed meteorological data	Modeled meteorological data	Absolute Difference	Relative Difference [%]
BENI MELLAL	35.40	20.8	-14.6	-41.2
CASABLANCA	70.20	49.9	-20.3	-29.0
ESSAOUIRA	29.20	30.8	1.6	5.6
FES	52.20	37.2	-15.0	-28.7
KASBAT	44.07	27.7	-16.3	-37.1
MARRAKECH	20.07	2.3	-17.8	-88.5
MEKNES	71.67	43.4	-28.2	-39.4
NOUASSER	52.13	35.1	-17.0	-32.6
RABAT-SALE	86.13	81.7	-4.4	-5.2
SAFI	73.67	44.0	-29.7	-40.3
Average	53.5	37.3	-16.2	-30.2

Table 7d: Differences in water deficit during the flowering state, WDEFf, (in mm) between the soil water model driven by 15 years of meteorological observations and alternatively driven by 1000 years of synthetically generated meteorological data.

Station	Observed meteorological data	Modeled meteorological data	Absolute Difference	Relative Difference [%]
BENI MELLAL	-75.27	-89.2	-13.9	18.4
CASABLANCA	-44.53	-53.4	-8.9	19.9
ESSAOUIRA	-0.73	-53.7	-52.9	7218.6
FES	-51.93	-59.5	-7.5	14.5
KASBAT	-64.80	-84.2	-19.4	29.9
MARRAKECH	-95.73	-121.5	-25.7	26.9
MEKNES	-47.73	-55.8	-8.1	17.0
NOUASSER	-77.07	-72.5	4.5	-5.9
RABAT-SALE	-47.27	-46.7	0.6	-1.3
SAFI	-60.80	-82.2	-21.4	35.3
Average	-56.6	-71.9	-15.3	27.0

Table 7a reveals that the total water requirements, TWR, are very good reproduced by the run of the water balance model with synthetic weather data from M&Rfi. Differences are mainly below 5 % with an average of 2 %. Since TWR is mainly driven by PET (which is reproduced very well by M&Rfi) this result is expected.

The normal water satisfaction index, IdxNorm, however, is overestimated by up to 23 % with an average of about 11 %. Also this result is expected (at least qualitatively) since the normal precipitation of the artificial dataset is averaged over 1000 years while the normal rain of the observations is only an average over less than 30 years. Rain happens to occur only on a small number of days. Therefore the average over 1000 years yields to a much smoother mean annual cycle than averaging over only 30 years. This means that the long-term average (normal) annual cycle of the artificial data should better suit the demands of plants. The discrepancy of IdxNorm between 30 year of observed weather and 1000 years of modeled weather demonstrates that 30 years of data is not enough to reliably estimate a mean annual cycle of rain per day in an arid region.

For the same reason the excess water during the vegetative stage, WEXv, is considerably decreased (by 30 % on average). A smoother annual cycle (where the effect of few heavy rains are over-weighted by many days with no or little rain) that water input is more evenly distributed during the growing season and less water excess situations occur.

The water deficit during the flowering phase is increased by 27 % on average. This is a more difficult to interpret. One reason may be that the distribution of length of dry spells between rainy days may not be modeled adequately by M&Rfi. However, no further investigation of the reproduction of length of wet spells or dry spells is done during this consultancy.

6.1.3 Comparison of observed and modeled yield characteristics

As seen in the previous section, the averages of soil-water balance variables react different on the synthetic weather compared to the observed weather records. This should also affect modeled yields. Table 8 therefore provides a comparison of different modeled and observed yields by province. A comparison of column 3 and 4 shows that the influence of the knowledge of the planting dekad on the overall average yield is not high (11.3 Qt/ha instead of 11.89 Qt/ha).

Modeled yields based on synthetic data are on average about 3 % below the observed averages. Though this means no large difference in case of the whole area of all regarded provinces, the difference is very sensitive with respect to the different provinces. While in the provinces with low yields (Essaouira and Marrakech) the yields are heavily underestimated by 30 to 40 %, the yields of most of the other provinces is slightly overestimated. The highest average yield, however, occurring in Meknes, is slightly underestimated.

Table 8: Observed average yield during the period for which the model is fit (1992 – 2006), estimated average yield during this period as it results from the observed weather records during the fit and resulting from observed weather with planting dekad fixed to 33 instead of a flexible planting dekad. Modeled yield averages resulting from synthetic weather data are also provided and their differences to the results form the runs with observed meteorological data.

Meteorological data source		Observations	Observations	Synthetic		
Planting Dekad		Variable	33	33		
Yields	Observed	Modeled during fit	Modeled	Modeled	Absolute Difference	Relative Difference [%]
Benimellal	14.2	12.8	11.9	12.1	0.2	1.8

Casa	15.5	11.2	10.6	11	0.4	3.9
Essaouira	7.1	11.2	11.1	6.5	-4.6	-41.4
Fes	13.1	13.7	13.3	14.1	0.8	6.3
Kasbat	14.2	12.1	12.3	12.1	-0.2	-1.6
Marrakech	6.3	6.5	5.4	3.6	-1.8	-33.3
Meknes	16.1	14.2	13.6	13.1	-0.5	-3.9
Nouasser	12.4	11.5	10.5	12	1.5	14.2
Rabat	11.3	15	14.3	16	1.7	11.9
Safi	8.5	10.7	10.0	9.2	-0.8	-8.4
Average	11.87	11.89	11.3	10.97	-0.3	-2.9

Since the weather generator M&Rfi reproduces the weather characteristics very well, also the overall yields are estimated with a difference to the observations of less than 3 %.

The next section provides the results of the climate change experiment and compares them with the modeled results of the current climate.

6.2 Simulations under climate-change conditions

According to section 3.6 and appendix A3 temperatures are expected to rise by about 3 °C and precipitation is expected to decrease by about 24 % on average in Morocco until the end of this century. It is expected that these changes lead to more often and more pronounced water shortage and thus worse yields. Section 6.2.1 discusses in more detail the expected changes in weather characteristics. Section 6.2.2 shows the effects on water balance parameters and finally section 6.2.3 provides estimates of yield changes due to climate change.

6.2.1 Comparison of weather characteristics under current and climate-change situation

Climate change as it is expressed here affects the averages of maximum and minimum daily temperatures (without changes in the diurnal temperature range) as well as precipitation sums. Changes in temperatures affect PET due to the use of Hargreaves approximation. Not changed is the number (or fraction) of rainy days. This means that the average amount of rain per rainy day decreases. The mean precipitation and PET during the growing season modeled for the current and the changed climate is provided in Table 9 for each station.

Table 9: Mean decadal PET and precipitation during growing season for different stations within Morocco under the current climatic situation and climate change conditions as estimated for 2100.

	PET [mm/dekad]	Precipitation [mm/dekad]

Station	Current Climate	Projected for 2100	Difference	Current Climate	Projected for 2100	Difference
Benimellal	27.4	30.4	3.0	13.9	10.1	-3.8
Casa	21.3	22.9	1.6	15.3	12.2	-3.1
Elhouceima	20.2	22.1	1.9	10.4	8.0	-2.4
Essaouira	19.0	20.8	1.7	11.2	7.8	-3.5
Fes	23.6	26.1	2.5	15.4	11.6	-3.8
Kasbat	27.1	30.0	2.9	14.1	10.4	-3.7
Marrakech	27.8	30.4	2.6	7.4	5.3	-2.0
Meknes	22.9	25.2	2.4	15.7	11.8	-3.9
Midelt	21.7	24.3	2.6	4.2	3.1	-1.2
Nador	20.9	22.9	2.0	11.2	8.4	-2.8
Nouasser	24.4	26.4	2.0	14.2	11.2	-3.0
Oujda	23.4	25.8	2.4	8.7	6.7	-2.1
Rabat	22.5	24.7	2.2	20.4	15.7	-4.8
Safi	24.2	26.4	2.2	13.7	10.2	-3.5
Sidi-Ifni	19.8	21.6	1.9	5.1	3.0	-2.1
Tanger	19.6	21.5	1.8	25.3	20.3	-5.0
Taza	21.5	23.6	2.2	19.9	15.4	-4.5
Tetuan	18.6	20.3	1.7	22.8	18.3	-4.5
Average	22.5	24.7	2.2	13.8	10.5	-3.3

As Table 9 reveals, PET is expected to increase by 2.2 mm/dekad from 22.5 mm/dekad to 24.7 mm/dekad until the end of this century. At the same time average precipitation is expected to decrease by 3.3 mm/dekad from 13.8 mm/dekad to 10.5mm/dekad. To put it in other words, on each hectar 33,000 liters of rain will be missed on average per dekad. The climatological water deficit (PET-Precip) will be even higher since at the same time PET is expected to be increased. It rises from now 8.7 mm/dekad to 14.2 mm/dekad. This is an increase of 63 %. The effect to agriculture should be tremendous.

6.2.2 Comparison of soil-water characteristics under current and climate-change situation

Table 10 (a to d) provides the estimated changes in the 4 water balance parameters that mainly drive cereal yields between today's situation and climate change conditions as projected for 2100.

Table 10a: Estimated changes in average total water requirement, TWR, (in mm) from today's climate to 2100 for cereals.

	Total water requirements			
	Today's Climate	In 2100	Absolute Difference	Relative Difference [%]
Benimellal	386.0	430.8	44.7	11.6
Casa	295.1	318.6	23.5	8.0
Elhouceima	284.7	312.8	28.1	9.9
Essaouira	259.6	284.4	24.8	9.6
Fes	338.2	376.0	37.8	11.2

Kasbat	386.6	430.7	44.2	11.4
Marrakech	394.0	431.8	37.9	9.6
Meknes	326.7	362.7	36.0	11.0
Midelt	311.3	350.9	39.6	12.7
Nador	293.3	323.2	30.0	10.2
Nouasser	343.1	372.5	29.4	8.6
Oujda	336.0	372.4	36.4	10.8
Rabat	316.3	350.0	33.7	10.6
Safi	339.0	370.9	31.9	9.4
Sidi-Ifni	270.8	297.1	26.3	9.7
Tanger	280.1	308.2	28.1	10.0
Taza	310.4	343.4	33.0	10.6
Tetuan	264.4	290.0	25.6	9.7
Average	318.6	351.5	32.8	10.3

Table 10b: Estimated changes in average normal water satisfaction index, IdxNorm, (in %) from today's climate to 2100 for cereals.

	Normal Watersatisfaction Index			
	Today's Climate	In 2100	Absolute Difference	Relative Difference [%]
Benimellal	77	42	-35	-45.5
Casa	84	61	-23	-27.4
Elhouceima	72	45	-27	-37.5
Essaouira	73	48	-25	-34.2
Fes	92	57	-35	-38.0
Kasbat	72	43	-29	-40.3
Marrakech	36	22	-14	-38.9
Meknes	87	59	-28	-32.2
Midelt	26	16	-10	-38.5
Nador	76	45	-31	-40.8
Nouasser	84	53	-31	-36.9
Oujda	53	31	-22	-41.5
Rabat	100	61	-39	-39.0
Safi	70	49	-21	-30.0
Sidi-Ifni	33	16	-17	-51.5
Tanger	100	71	-29	-29.0
Taza	92	67	-25	-27.2
Tetuan	100	74	-26	-26.0
Average	73.7	47.8	-25.9	-35.2

Table 10c: Estimated changes in average excess water during the vegetative stage, WEXv, (in mm) from today's climate to 2100 for cereals.

	Excess Water during the vegetative Stage			
	Today's Climate	In 2100	Absolute Difference	Relative Difference [%]

Benimellal	20.8	8.1	-12.7	-61.0
Casa	49.9	29.8	-20.1	-40.2
Elhouceima	16.8	7.0	-9.8	-58.6
Essaouira	30.8	8.9	-21.9	-71.1
Fes	37.2	19.3	-17.9	-48.1
Kasbat	27.7	12.2	-15.6	-56.1
Marrakech	2.3	0.1	-2.2	-96.1
Meknes	43.4	24.4	-19.0	-43.8
Midelt	0.4	0.0	-0.3	-97.1
Nador	15.7	5.1	-10.7	-67.7
Nouasser	35.1	17.3	-17.8	-50.8
Oujda	4.5	1.1	-3.4	-74.8
Rabat	81.7	56.3	-25.4	-31.1
Safi	44.0	19.2	-24.8	-56.4
Sidi-Ifni	1.9	0.1	-1.8	-95.3
Tanger	116.6	96.8	-19.8	-17.0
Taza	79.6	54.7	-24.9	-31.3
Tetuan	100.4	82.2	-18.3	-18.2
Average	39.4	24.6	-14.8	-37.6

Table 10d: Estimated changes in average water deficit during the flowering stage, WDEFf, (in mm) from today's climate to 2100 for cereals.

	Water Deficit during the flowering Stage			
	Today's Climate	In 2100	Absolute Difference	Relative Difference [%]
Benimellal	-89.2	-128.7	-39.6	44.4
Casa	-53.4	-76.3	-22.9	42.9
Elhouceima	-57.3	-82.2	-24.9	43.5
Essaouira	-53.7	-80.4	-26.7	49.7
Fes	-59.5	-94.9	-35.5	59.7
Kasbat	-84.2	-124.8	-40.6	48.2
Marrakech	-121.5	-146.3	-24.8	20.4
Meknes	-55.8	-90.4	-34.5	61.8
Midelt	-105.2	-125.9	-20.7	19.7
Nador	-53.0	-79.9	-26.8	50.6
Nouasser	-72.5	-100.4	-27.9	38.4
Oujda	-85.1	-112.3	-27.3	32.0
Rabat	-46.7	-76.8	-30.2	64.7
Safi	-82.2	-110.0	-27.8	33.7
Sidi-Ifni	-90.5	-109.4	-18.9	20.8
Tanger	-27.1	-47.2	-20.1	74.4
Taza	-41.5	-69.1	-27.6	66.6
Tetuan	-20.8	-38.2	-17.4	83.6
Average	-66.6	-94.1	-27.5	41.2

From Table 10 it can clearly be seen that all parameters change at all stations in the same direction. This indicates the nationwide systematic climate change.

TWR is expected to increase by 10.3 % on average, spanning a range from 8 % to 13 %. Increased TWR means better plant growth if enough water is available. If water is limited it means that water stress is more likely to occur and is expected to be more severe.

The normal index decreases by 35.2 %, spanning from 2 % to 51.5 % decrease. This definitely expresses a negative influence on yields.

Excess water during the vegetative season decreases by 18 % to 97 % with an average decrease of 37.6 %. This indicates that the soils become dryer at the beginning of the flowering phase. It makes the plant more sensitive to shortage of rain during the flowering phase.

Finally the water deficit during the flowering phase decreases by 41 % on average, ranging from 19.7 % to 83.6 %. This definitely has a negative effect on crop grows.

6.2.3 Comparison of yield characteristics under current and climate-change situation

Table 11 shows the tremendous decrease in cereal yields as modeled on the basis of the climate change scenario for 2100.

Table 11: Estimated yield changes due to climate change for cereals in Morocco.

	Yields			
	Today's Climate	In 2100	Absolute Difference	Relative Difference [%]
Benimellal	12.09	6.41	-5.7	-47.0
Casa	10.95	6.8	-4.2	-37.9
Elhouceima	7.42	3.14	-4.3	-57.7
Essaouira	6.53	1.9	-4.6	-70.9
Fes	14.06	8.16	-5.9	-42.0
Kasbat	12.11	7.02	-5.1	-42.0
Marrakech	3.63	1.99	-1.6	-45.2
Meknes	13.11	8.08	-5.0	-38.4
Midelt	0.05	0	-0.1	-100.0
Nador	8.91	4.02	-4.9	-54.9
Nouasser	12.03	6.81	-5.2	-43.4
Oujda	5.44	2.37	-3.1	-56.4
Rabat	15.99	9.58	-6.4	-40.1
Safi	9.19	5.3	-3.9	-42.3
Sidi-Ifni	0.08	0	-0.1	-100.0
Tanger	16.28	11.92	-4.4	-26.8
Taza	14.96	10.63	-4.3	-28.9

Tetuan	15.38	11.55	-3.8	-24.9
Average	9.9	5.9	-4.0	-40.7

7. Summary and Outlook

Human climate change is expected to alter the weather conditions within the coming decades. This may have a direct influence on weather-related economies like agriculture. In this work the FAO strategy for the investigation of climate change impacts on agriculture is applied to Moroccan data.

In a first step the FAO crop-specific water-balance model is driven by observed meteorological data from 19 stations and for 26 years. The resulting water-balance parameters are statistically and meaningfully linked to observed crop yields. They explain about 30% of the variability. The revealed important variables are total water requirements of the plants, water satisfaction index under normal conditions, water excess during the vegetative phase and water deficit during the flowering phase.

In the second step a stochastic weather generator is fit to the meteorological observations and used to produce long time series of artificial weather with the same statistical features as the observed meteorological data. Tests revealed that the weather generator reproduces well the amount of rain, the fraction of rainy days during the growing season and potential evapotranspiration.

Driving the water balance model with the artificial weather series shows that the important water balance parameters are only roughly reproduced. While total water requirements differ on average only by 2 % from the case where meteorological observations are used, the normal water satisfaction index is increased by about 11% on average. Excess water during the vegetative stage and water deficit during the flowering phase differ by –30 % and 27 %, respectively, from the case of meteorological observations. This may be a result of the fact that the rain is distributed among too many days in the artificial data. However, the deviations in estimated average yield is only 2.9 %, with large spatial variability though.

In a last step the parameters of the weather generator are altered according to a reasonable state-of-the-art climate change scenario (HadCM3 model, SRES A2 scenario). This reveals an increase in average temperature by about 3 °C until the end of this century accompanied by a decrease in precipitation of about 24 % for Morocco. Both changes enhance the risk of droughts. Potential evapotranspiration is increased by about 2.2 mm/dekad while precipitation is decreased by about 3.3 mm/dekad. **Therefore the water-balance parameters face severe changes.** The total water requirements increase by 10 %, the normal index decreases by 35.2 % on average. Water excess during the vegetative stage increases by 37.6 % and water deficit during the flowering stage increases by 41.2 %.

As a result the mean yield is reduced by 40.7 % with 2 provinces where cereal cultivation is no longer possible.

Although these results are very uncertain due to many reasons they indicate the high risk of negative impact of climate change to cereal yields in Morocco.

Among the uncertainties are the simplicity of the water balance model and the crop-yield function, the statistical differences between modeled and observed weather, and the reliability of the climate-change scenario. Major improvements can be expected especially with respect to the crop-yield function and the use of different climate-change scenarios. However, given the fact that higher temperatures and less rain is expected in the future scenarios, further investigations may solidify the main result that cereal production in Morocco may be affected negatively by future climate change.

However, given the high sensitivity of Moroccan yields to weather conditions as it is found in this work, a more comprehensive study of the situation and the threats is highly recommended by this consultant.

Acknowledgements

The author whishes to thank Michele Bernardi who invited him to travel to Sassari and do this very interesting work. Special thanks also to René Gommes for his support and to Martin Dubrovský for his help with the weather generator M&Rfi. Without his help I could not have run the generator successfully. He also provided the necessary climate change data in a read-to-use format. Many thanks to him for his great help.

I am also very grateful to the staff at IBIMET that hosted me so perfectly; providing a cool environment (thanks to AC), several coffees every day (thanks to Pierpaolo Zara) a perfect transport system (thanks to Carla Cesaraccio), a cosy room to spend the nights (thanks to Costantino Sirca), neatly formatted Moroccan meteorological and yield data (thanks to Ileana Iocola), estimates of planting dates of winter wheat (thanks to Carla Cesaraccio), water holding capacities (thanks to Ileana Iocola), all the technical support needed (thanks to the whole IBIMET staff) and nice company (thanks again to the whole IBIMET staff). Furthers thanks to Ileana Iocola who provided the opportunity to see more of Sardegna than Sassari and the IBIMET offices and thanks to the excellent Sardegnian cuisine which let me gain 2 kg extra weight in 2 weeks.

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Appendix

A1 List of Hargreave coefficients for the meteorological stations

Station-ID	Station Name	Hargreaves coefficient
1	Agadir-almassira	1.9
2	Agadir	1.9
3	Arwi	1.9
4	Benimellal	1.7
5	Casa	1.9
6	Chefchouane	1.7
7	Elhouceima	1.8
8	Errachidia	1.6
9	Essaouira	1.9
10	Fes	1.7
11	Ifrane	1.7
12	Kasbat	1.7
13	kenitra	1.9
14	Laayoune	1.9
15	Larache	1.9
16	Marrakech	1.7
17	Meknes	1.7
18	Mudelt	1.6
19	Nador	1.9
20	Nouasser	1.8
21	Ouarzazate	1.6
22	Oujda	1.9
23	Rabat	1.9
24	Safi	1.9
25	Sidi-Ifni	1.9
26	Sidi-slimane	1.7
27	Tanger	1.9
28	Tan-Tan	1.9
29	Taza	1.7
30	Tetuan	1.9

A2 Planting dates of winter wheat

	4	5	7	9	10	12	16	17	18	19	20	21	22	23	24	25	27	29	30
1979	31	31	31	34	31	34	34	31	34	34	31	34	33	31	31	34	31	33	34
1980	33	32	32	33	33	34	32	33	32	34	33	34	32	33	32	32	33	33	32
1981	32	34	34	31	31	34	34	34	34	34	31	34	34	34	34	34	34	34	31
1982	32	32	32	32	32	34	32	32	31	34	32	34	31	32	32	34	32	32	32
1983	33	33	33	33	33	32	33	32	32	34	33	31	34	33	33	32	34	33	32
1984	33	33	34	32	33	32	33	34	34	32	33	32	32	33	32	32	33	33	32
1985	34	34	34	34	32	32	33	34	34	33	34	32	33	34	33	33	34	34	33
1986	33	33	33	33	33	33	33	34	34	33	33	30	33	33	33	32	33	33	33
1987	32	32	33	32	32	34	31	34	32	34	32	31	34	32	31	34	32	32	32
1988	34	32	34	32	34	34	32	32	34	34	34	33	34	34	32	32	32	34	34
1989	31	32	34	34	33	33	34	31	33	34	33	33	34	34	34	33	34	33	34
1990	33	33	34	34	33	34	34	32	34	34	34	34	32	34	34	34	34	34	34
1991	31	30	34	34	33	34	34	33	34	33	31	34	34	34	34	34	32	33	34
1992	33	33	33	33	33	33	32	33	32	34	33	34	32	31	34	34	33	33	32
1993	32	32	31	33	33	32	32	32	34	33	32	32	32	32	32	33	32	33	34
1994	32	32	34	32	32	32	31	32	34	34	32	31	32	32	31	31	32	32	32
1995	33	33	32	34	34	32	34	32	34	32	33	34	34	33	34	34	33	32	34
1996	33	33	34	33	33	33	33	33	34	33	33	34	34	34	32	33	33	33	33
1997	32	34	32	32	34	34	32	32	33	32	32	34	33	34	32	34	34	32	32
1998	31	34	34	34	34	34	34	34	34	34	31	34	33	34	34	34	32	34	34
1999	32	33	33	32	33	33	33	31	32	33	31	31	33	31	33	32	33	33	33
2000	31	31	33	32	32	33	32	32	31	33	33	34	33	32	30	34	33	32	32
2001	32	33	32	34	34	32	34	33	32	32	34	34	33	33	34	34	32	33	32
2002	34	33	33	34	34	33	33	30	34	34	34	34	34	34	34	33	33	34	34
2003	31	31	32	31	31	31	33	32	33	31	31	34	33	31	34	33	31	33	31
2004	32	31	31	31	33	32	32	31	34	31	31	32	32	32	32	31	31	32	31
2005	30	30	34	34	31	34	31	30	34	30	34	34	34	31	31	34	34	34	31

A3 Climate Change Data

Table A3.1: Modeled changes in monthly mean temperatures due to climate change in 2100 based on SRES A2 scenarios, the Hadley Center model and high climate sensitivity (2.09°C global mean warming due to CO_2 doubling).

Station	November	December	January	February	March	April	May	Growing Season (Nov-Apr)
Agadir-almassira	3.1	3.5	2.9	4.0	3.5	3.5	2.7	3.4
Agadir	3.1	3.5	2.9	4.0	3.5	3.5	2.7	3.4
Arwi	3.8	3.7	2.7	4.1	4.1	3.6	2.6	3.7
Benimellal	3.8	3.8	2.7	4.5	4.0	3.9	2.4	3.8
Casa	2.5	1.9	2.3	3.0	2.7	2.5	2.2	2.5
Chefchouane	3.2	2.7	2.6	4.0	3.5	3.4	2.5	3.2
Elhouceima	3.7	3.5	2.6	4.0	4.0	3.5	2.5	3.6
Errachidia	3.8	4.0	2.7	4.2	4.1	3.8	2.5	3.8
Essaouira	3.0	2.7	2.8	3.7	3.4	3.2	2.7	3.2
Fes	3.5	3.3	2.6	4.2	3.7	3.6	2.5	3.5
Ifrane	3.6	3.4	2.7	4.3	3.8	3.7	2.5	3.6
Kasbat	3.8	3.8	2.7	4.5	4.0	3.9	2.4	3.8
kenitra	3.0	2.4	2.6	4.2	3.3	3.5	2.4	3.2
Laayoune	-0.7	0.0	2.4	2.3	0.0	0.6	2.2	0.8
Larache	3.2	2.6	2.6	4.0	3.5	3.4	2.4	3.2
Marrakech	3.2	3.1	2.8	3.8	3.6	3.4	2.7	3.3
Meknes	3.4	3.1	2.6	4.2	3.7	3.6	2.4	3.4
Midelt	3.8	3.9	2.7	4.3	4.0	3.9	2.5	3.8
Nador	3.8	3.8	2.7	4.1	4.1	3.6	2.6	3.7
Nouasser	2.7	2.1	2.4	3.1	2.9	2.7	2.3	2.7
Ouarzazate	3.7	3.9	2.6	4.0	3.9	3.8	2.5	3.6
Oujda	4.1	4.3	2.7	4.1	4.4	3.7	2.6	3.9
Rabat	3.1	2.6	2.6	4.2	3.4	3.5	2.4	3.2
Safi	3.1	2.4	2.8	3.6	3.4	3.1	2.7	3.1
Sidi-Ifni	2.9	3.7	2.9	4.0	3.4	3.6	2.7	3.4
Sidi-slimane	3.2	2.7	2.6	4.2	3.4	3.5	2.4	3.3
Tanger	4.4	4.2	2.6	4.1	4.6	3.6	2.5	3.9
Tan-Tan	2.6	3.6	2.9	3.8	3.1	3.4	2.7	3.2
Taza	3.6	3.5	2.7	4.1	3.9	3.6	2.5	3.6
Tetuan	4.1	3.8	2.6	4.0	4.3	3.5	2.5	3.7
Minimum	-0.7	0.0	2.3	2.3	0.0	0.6	2.2	0.8
Average	3.3	3.2	2.7	4.0	3.6	3.4	2.5	3.3
Maximum	4.4	4.3	2.9	4.5	4.6	3.9	2.7	3.9
Standard Deviation	0.9	0.9	0.1	0.5	0.8	0.6	0.1	0.6

Table A3.2: Modeled changes in monthly precipitation (in %) due to climate change in 2100 based on SRES A2 scenarios, the Hadley Center model and high climate sensitivity (2.09°C global mean warming due to CO_2 doubling).

Station	November	December	January	February	March	April	May	Growing Season (Nov-Apr)
Agadir-almassira	-19.7	-35.5	-33.8	-31.6	-10.6	-41.9	-44.5	-28.9
Agadir	-19.2	-35.1	-33.6	-31.5	-10.3	-42.0	-44.2	-28.6
Arwi	-27.3	-59.3	-10.2	-34.8	-35.6	-42.0	-14.8	-34.9
Benimellal	-37.5	-37.9	-18.8	-26.8	-23.3	-30.0	-32.4	-29.0
Casa	9.2	-7.4	-15.8	-26.6	-9.3	-31.3	-24.8	-13.5
Chefchouane	-66.1	-26.3	-9.7	-40.0	-32.1	-51.3	-13.3	-37.6
Elhouceima	-18.9	-61.0	-9.7	-35.7	-36.3	-42.3	-13.9	-34.0
Errachidia	-35.9	-41.6	-18.9	-25.0	-25.3	-30.4	-32.4	-29.5
Essaouira	-4.7	-32.4	-27.5	-26.2	-17.2	-41.7	-36.9	-24.9
Fes	-31.7	-40.0	-13.5	-32.8	-24.0	-37.6	-22.1	-29.9
Ifrane	-34.2	-39.0	-15.1	-30.7	-23.8	-34.6	-25.4	-29.6
Kasbat	-37.3	-37.6	-18.7	-26.9	-23.4	-30.1	-32.1	-29.0
kenitra	-4.8	-13.9	-12.6	-37.6	9.0	-43.7	-19.6	-17.3
Laayoune	19.2	10.4	-23.0	29.9	16.1	16.1	-26.0	11.4
Larache	-44.7	-32.5	-9.3	-41.9	-25.8	-53.9	-13.0	-34.7
Marrakech	-24.3	-37.8	-25.2	-25.2	-22.6	-37.8	-35.6	-28.8
Meknes	-32.1	-37.1	-13.9	-33.0	-21.8	-37.3	-22.7	-29.2
Midelt	-35.8	-39.7	-18.0	-26.5	-24.6	-30.9	-30.9	-29.2
Nador	-27.9	-59.3	-10.2	-34.6	-35.7	-41.8	-14.8	-34.9
Nouasser	0.6	-14.6	-16.6	-26.2	-13.7	-31.9	-25.8	-17.1
Ouarzazate	-39.7	-43.7	-20.2	-25.6	-22.2	-29.6	-33.7	-30.2
Oujda	-31.4	-57.4	-10.7	-32.8	-35.0	-39.4	-16.2	-34.4
Rabat	-28.1	-25.4	-13.6	-35.5	-10.0	-39.6	-21.9	-25.4
Safi	178.0	-32.4	-23.2	-23.4	-28.8	-39.2	-32.1	5.2
Sidi-Ifni	-18.4	-37.4	-36.4	-35.1	-7.6	-42.5	-46.6	-29.6
Sidi-slimane	-23.6	-29.3	-12.7	-36.0	-13.4	-41.5	-20.1	-26.1
Tanger	-26.0	281.1	-8.5	-37.8	146.0	-41.4	-13.5	52.2
Tan-Tan	-13.9	-43.4	-37.9	-38.8	-6.6	-43.3	-46.0	-30.6
Taza	-30.2	-46.3	-12.3	-33.3	-28.1	-39.1	-19.5	-31.6
Tetuan	-40.5	-100.0	-8.8	-37.2	-100.0	-41.6	-13.4	-54.7
Minimum	-66.1	-100.0	-37.9	-41.9	-100.0	-53.9	-46.6	-54.7
Average	-18.2	-27.1	-17.9	-30.0	-16.5	-37.1	-26.3	-24.5
Maximum	178.0	281.1	-8.5	29.9	146.0	16.1	-13.0	52.2
Standard Deviation	40.7	61.3	8.6	12.4	36.2	11.7	10.6	18.8

Table A3.3: Modeled changes in monthly solar radiation (in %) due to climate change in 2100 based on SRES A2 scenarios, the Hadley Center model and high climate sensitivity (2.09°C global mean warming due to CO_2 doubling).

Station	November	December	January	February	March	April	May	Growing Season (Nov-Apr)
Agadir-almassira	0.7	1.4	4.2	2.0	1.1	5.2	6.3	2.4
Agadir	0.7	1.4	4.3	2.0	1.2	5.3	6.4	2.5
Arwi	-0.4	1.4	2.8	5.5	0.5	4.7	2.3	2.4
Benimellal	1.8	2.5	2.2	5.6	1.2	8.5	4.4	3.6
Casa	-2.3	-2.4	1.1	2.3	0.1	1.8	1.4	0.1
Chefchouane	-1.8	-1.4	0.2	4.1	-1.0	2.2	-1.7	0.4
Elhouceima	-0.5	1.1	1.9	4.9	0.4	4.0	0.8	2.0
Errachidia	1.4	1.8	1.1	3.1	0.8	5.2	2.6	2.2
Essaouira	1.2	1.5	2.9	2.0	3.4	4.3	4.1	2.6
Fes	-0.3	0.2	1.2	4.5	-0.2	4.5	1.0	1.7
Ifrane	0.2	0.8	1.4	4.7	0.2	5.4	1.8	2.1
Kasbat	1.8	2.6	2.4	6.0	1.2	8.9	4.6	3.8
kenitra	-1.6	-1.8	-0.1	4.1	-1.4	2.8	-1.5	0.3
Laayoune	-25.5	-5.9	-0.4	-6.4	-18.3	-11.3	0.6	-11.3
Larache	-1.7	-1.2	-0.5	3.9	-0.9	1.9	-2.9	0.3
Marrakech	1.2	1.5	2.1	2.1	2.7	4.1	3.3	2.3
Meknes	-0.4	-0.1	1.0	4.6	-0.3	4.5	0.8	1.5
Midelt	1.5	2.2	1.8	4.7	1.0	6.9	3.4	3.0
Nador	-0.4	1.5	3.0	5.5	0.6	4.9	2.5	2.5
Nouasser	-1.5	-1.5	1.2	2.4	0.8	2.3	1.6	0.6
Ouarzazate	1.1	0.7	0.4	1.6	0.2	3.2	1.7	1.2
Oujda	0.4	2.9	3.9	5.9	1.4	6.1	4.1	3.4
Rabat	-1.2	-1.4	0.2	4.4	-1.1	3.6	-0.7	0.7
Safi	1.5	1.6	1.7	2.1	4.7	3.6	2.3	2.5
Sidi-Ifni	0.4	1.1	3.9	1.5	0.4	4.8	5.8	2.0
Sidi-slimane	-1.2	-1.2	0.3	4.3	-1.0	3.3	-0.7	0.7
Tanger	0.9	4.0	0.4	5.2	2.6	5.0	-1.7	3.0
Tan-Tan	0.0	0.7	2.5	0.4	0.0	3.4	3.6	1.2
Taza	-0.3	0.7	1.7	4.6	0.1	4.4	1.4	1.9
Tetuan	0.4	2.8	0.7	4.8	1.7	4.4	-1.1	2.5
Minimum	-25.5	-5.9	-0.5	-6.4	-18.3	-11.3	-2.9	-11.3
Average	-0.8	0.6	1.6	3.4	0.1	3.9	1.9	1.5
Maximum	1.8	4.0	4.3	6.0	4.7	8.9	6.4	3.8
Standard Deviation	4.8	2.0	1.4	2.4	3.7	3.3	2.5	2.6