Climatic Change (2009) 96:549–564
DOI 10.1007/s10584-009-9571-9

Potential impact of climate change on durum wheat cropping in Tunisia

J. P. Lhomme · R. Mougou · M. Mansour

Received: 11 December 2007 / Accepted: 22 January 2009 / Published online: 1 April 2009

Abstract The potential effect of climate change on durum wheat in Tunisia is assessed using a simple crop simulation model and a climate projection for the 2071–2100 period, obtained from the Météo-France ARPEGE-Climate atmospheric model run under the IPCC (International Panel on Climate Change) scenario A1B. In the process-oriented crop model, phenology is estimated through thermal time. Water balance is calculated on a daily basis by means of a simple modelling of actual evapotranspiration involving reference evapotranspiration, crop coefficients and some basic soil characteristics. The impact of crop water deficit on yield is accounted for through the linear crop-water production function developed by the FAO (Food and Agriculture Organization of the United Nations). Two stations are chosen to study the climate change effect. They are representative of the main areas where cereals are grown in Tunisia: Jendouba in the northern region and Kairouan in the central region. In the future scenario, temperature systematically increases, whereas precipitation increases or decreases depending on the location and the period of the year. Mean annual precipitation declines in Jendouba and raises in Kairouan. Under climate change, the water conditions needed for sowing occur earlier and cycle lengths are reduced in both locations. Crop water deficit and the corresponding deficit in crop yield happen to be slightly lower in Kairouan; conversely, they become higher in Jendouba.

J. P. Lhomme (✉)
IRD (UR060), CEFE-CNRS, 1919 route de Mende, 34293 Montpellier cedex 5, France
e-mail: jean-paul.lhomme@ird.fr

R. Mougou
INRGREF, BP 10, Ariana 2080, Tunisia

M. Mansour
CRRHAB, Chott Mariem, 4042, Tunisia

1 Introduction

In the Maghreb countries, agriculture plays an important economic and social role and has been identified as the most vulnerable sector to the climatic changes predicted by the General Circulation Models (GCM) simulations (Abou Hadid 2006). Over the Mediterranean region GCM generally predict an increase in mean temperature and a decrease in mean precipitation (Gibelin and Déqué 2003). In Tunisia, agriculture is mainly extensive in spite of efforts undertaken for its intensification. Although 80% of agricultural land is rain-fed, agriculture remains by far the main water-consuming sector and represents over 80% of total water consumption. The lands cultivated under rain-fed conditions are mainly cereals and fruit crops including olive trees (Abou Hadid 2006). Farming systems are largely based upon cereals activity and the sector has a significant influence on the national economy (Abou Hadid 2006). Cereals (the most cultivated one being durum wheat) are sown in autumn and harvested in spring. They constitute a very important part of Tunisians diet with also a symbolic value (Aubry et al. 1991). Water being the major limiting factor in Tunisia, annual variability in yields is mainly explained by rainfall variability (Latiri-Souki and Aubry 1991; Louati et al. 1999). Water deficits affect many plant processes, such as organ development and growth, resulting in a decrease in dry matter production (Latiri-Souki et al. 1998 among others).

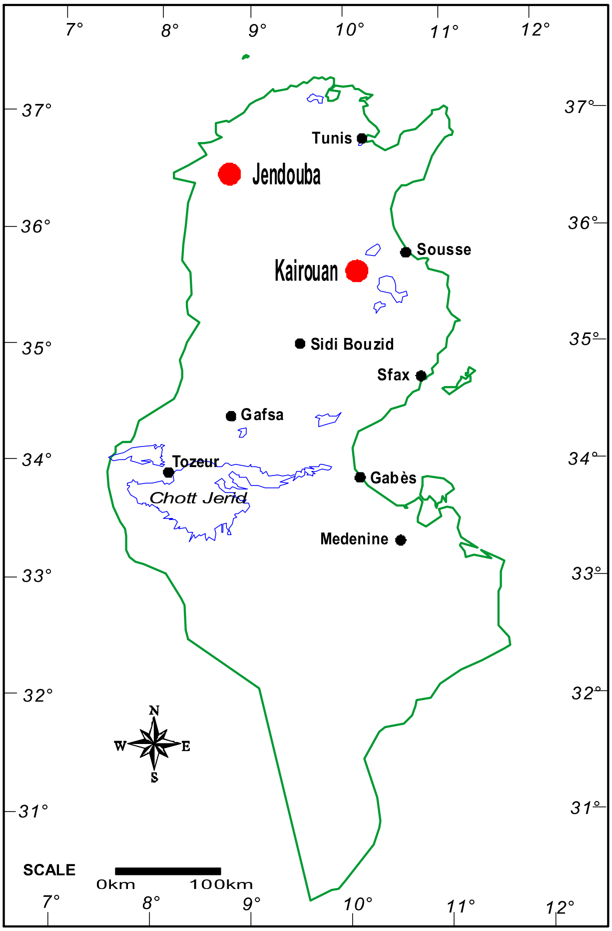
Studies on the potential impacts of climate change on wheat yield have been conducted worldwide for more than a decade (Delécolle et al. 1995; Rosenzweig and Hillel 1998; Reyenga et al. 1999; Luo et al. 2003). These studies generally run process-based crop models with the climatic data projected by GCM. Our study follows similar steps. Its objective is to assess the impact of climate change on the cultivation of durum wheat (mainly crop calendar and yield response to water deficit) by using observed and predicted weather data concurrently with a simple simulation model based on thermal time and water balance. Our approach remains essentially agro-meteorological with a regional scope. CO_2 effects, as well as those of excessive temperatures, are not considered in the modelling. Climate change is represented by the outputs of the ARPEGE-Climate GCM model of MétéoFrance, run under a given scenario of the International Panel on Climate Change (IPCC). Two locations have been chosen, which are representative of the main regions where durum wheat is cultivated in Tunisia.

2 Materials and methods

2.1 Sites description

Tunisia experiences a steep climatic gradient from North to South, annual rainfall ranging from more than 1000 mm in the mountains of Kroumirie to almost 0 in the Saharian region (Hénia 1993). The stations chosen to perform the study are Jendouba in the northern part of the country and Kairouan in the central region (Fig. 1). Both have a typical Mediterranean climate with rain in winter and a hot-dry summer. They are separated by a ridge of mountains (called La Dorsale), which generates a significant rainfall gradient on a relatively short distance (Sakiss et al. 1991). Jendouba (lat. 36° 29’ N, long. 8° 48’ E, alt. 143 m) is located in the Mejerda

Fig. 1 Map of Tunisia showing the two locations considered in the study



valley in the semi-arid zone: its mean annual rainfall is 462 mm with a coefficient of variation of 0.23 (Hénia 1993). Kairouan (lat. 35° 40’ N, long. 10° 06 E, alt. 60 m) is located in the arid zone of Tunisia, a climatic transition between the Mediterranean zone and the Sahara region (Benzarti 1996), where drought represents a permanent risk for rain-fed agriculture. Annual rainfall is highly variable with a coefficient of variation of 0.39 and a mean of 304 mm (Hénia 1993). Very high temperatures can have a negative effect on crops grown in summer, worsened by high solar radiation and high evaporation (Abou Hadid 2006). Sirocco (a very dry wind blowing from the Sahara) represents another important risk for crops at both locations: it occurs between April and September and generates a high evaporative demand (Henia and Mougou 1998). In the Jendouba plains soils are formed by the alluvial deposits of the river Mejerda and its tributaries: they are mainly silt clay loam with a relatively high water storage capacity (Souissi and Ghezal 1971). Soils of the Kairouan region are more sandy: in the south part water storing capacity is relatively low but higher in the north part (Barbery and Mohdi 1983). Around Jendouba, cereal cultivated areas are fairly stable with relatively high yields. In the Kairouan region, these areas exhibit a large variability and comparatively low yields. During the last 50 years, cereals average yield in Tunisia has been multiplied by 3 (from 0.6 to 1.8 t ha^{-1}) owing to the introduction of high yield varieties (Ben-Salem et al. 2006). Nevertheless, in spite of improvement of farming techniques, yields remain far below their potential level, with a high variability from 1 year to another in relation with climatic hazards (Deghais et al. 2007).

2.2 Weather data

Thirty years (1961–1990) of daily records of precipitation and mean air temperature for Jendouba and Kairouan are used to run the crop model for the current situation. Reference crop evapotranspiration (ET_0), which represents the evapotranspiration of a hypothetical reference crop with a fixed surface resistance, is calculated following the FAO methodology based upon the Penman-Monteith model (Allen et al. 1998). Due to a lack of available data, ET_0 values are calculated for both locations over the 1986–2003 period: they are first calculated on a daily basis and then transformed into inter-annual monthly means expressed in mm day^{-1}, a procedure justified by the much lesser variability of reference evapotranspiration compared to precipitation. Figure 2 shows the mean monthly values of temperature, precipitation and reference evapotranspiration for the current situation in both locations. In Jendouba, the mean

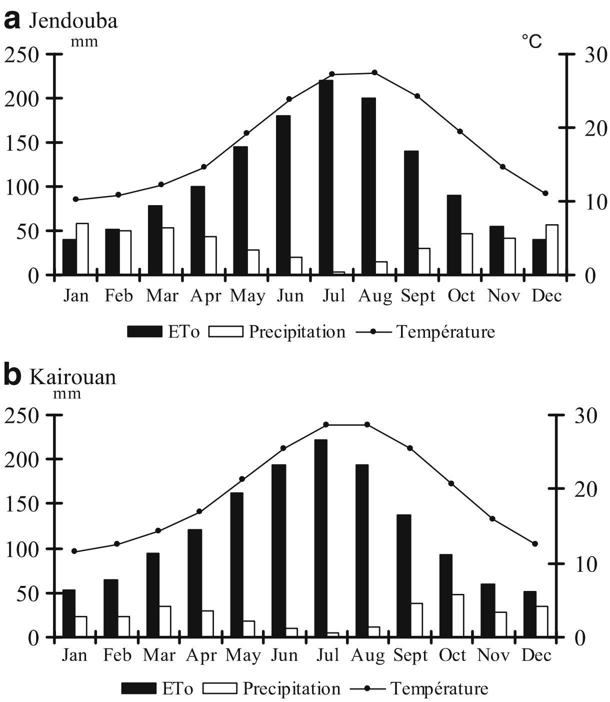


Fig. 2 Mean monthly values of precipitation, reference evapotranspiration and average air temperature for Jendouba and Kairouan (recorded data)

annual temperature is around 16°C, but very high temperatures of 48°C can be registered in summer. Frost does not constitute an important constraint although negative temperatures reaching −7.7°C can be registered (Hénia 1993). In Kairouan, the mean annual temperature is higher (19.5°C) and the maximum temperature can also reach 48°C. Negative temperatures are registered, but with a lower frequency than that of Jendouba. High temperatures registered in summer have no direct effect on wheat since it is generally harvested in May at the latest.

Simulated data of precipitation, temperature, air humidity, wind velocity and solar radiation over 30 years were obtained from Météo-France atmospheric model ARPEGE-Climate Version 4 (Déqué 2007) with a resolution of about 50 km over Tunisia. It is the only model which provides data with such a spatial resolution, compatible with the steep climatic gradient of Northern and Central Tunisia. A first data set represents the present climate and covers the 1961–1990 period. A second data set represents the possible future climate over 2071–2100, where greenhouse gas and aerosol concentrations are prescribed by IPCC scenario A1B (IPCC 2001): carbon dioxide emissions increase until around 2050 and then decreases. This scenario constitutes a good mid-line for carbon dioxide output and economic growth. The daily data set of the future scenario is obtained by matching the recorded climatic data of the two stations (Jendouba and Kairouan) with those simulated for the grid points closest to these stations. First, climate anomalies are calculated on a monthly basis (Caballero et al. 2007; Huard 2007): for temperature, they are defined as the differences (δ) in inter-annual monthly means between the future scenario and the actual one; for the other parameters (precipitation, air humidity, solar radiation, wind speed), they are defined as their ratio (ρ). Then, the monthly anomalies (δ and ρ) calculated in this way are applied to the baseline (observed) daily values to generate the future scenario

$$T_f = T_c + \delta t \tag{1}$$

$$P_f = P_c \times \rho_P \tag{2}$$

where T_f and P_f are the daily values of temperature and precipitation for the future climate (subscript f), T_c and P_c those of the current climate (subscript c). To calculate the modified ET_0 the anomalies on sunshine duration N are needed. They are calculated from those on solar radiation R_s by $\Delta N = (N_0/bR_{s0})\Delta R_s$, obtained from Angstrom formula: $R_s/R_{s0} = a + b\,N/N_0$, with R_{s0} the extraterrestrial radiation and N_0 the daylight hours. Coefficient b is taken to be equal to 0.42 for Jendouba and 0.57 for Kairouan (Louhichi 1979). As the predicted increase of atmospheric CO_2 concentration is expected to enhance crop stomatal resistance, reference crop evapotranspiration (ET_0) should certainly decrease in the future scenario, all other meteorological conditions being equal. This alteration, however, is difficult to predict and like other effects of elevated CO_2 (see below), it has not been taken into account.

2.3 Wheat crop simulation

A simple and generic process-oriented model was devised to account for the development, water balance and yield of wheat crop. This model is designed with an agro-meteorological perspective to be used at regional scale. It works on a daily time step using three main climatic inputs: daily precipitation, mean daily temperature and reference evapotranspiration. It is general enough in its conception to be extended to any annual crop. More complex crop models, such as DSSAT-CERES, CropSyst (Stockle et al. 2003) or STICS (Brisson et al. 2003) were not used because, being site-specific, they compute crop dynamics at small spatial scales (field level) and require too many input parameters.

The crop is sown if a minimum amount of precipitation P_{so} (=20 mm) has occurred during N_{so} (=5) consecutive days (see Table 1). In the current situation, the sowing date is limited to the traditional time of sowing in Tunisia, i.e., between $DOY_1 = 305$ (1 November) and $DOY_2 = 365$ (31 December). For the future scenario, this period of sowing is extended from 1 October to 31 January to take account of the possible effects of climate change (we assume that the criterion used for sowing can be fulfilled before or after the traditional limits). If this condition is not met, sowing fails. An alternative is also examined. It consists in prescribing the sowing date on a given day ($DOY_1 =$ 1 November) and in providing a given amount (P_{so}) of supplemental irrigation on the same day (Teixeira et al. 1995). Defined as the application of a limited amount of water to the crop when rainfall fails to supply enough water, supplemental irrigation is used by roughly 25% of the farmers in Tunisia (Zairi et al. 2003; Mougou et al. 2008).

The lengths of crop development stages are expressed in thermal time (or growing degree day GDD) with a base temperature of 0°C (Latiri, personal communication): GDD_1 for the initial stage (germination and seedling growth), GDD_2 for the

Table 1 Main parameters of the crop model and corresponding values for durum wheat

	Parameter		Symbol	Values
Sowing date	Not prescribed	Initial date of the potential sowing period	DOY_1	305 (C) 274 (F)
		Final date of the potential sowing period	DOY_2	365 (C) 31 (F)
	Prescribed	Required amount of precipitation	P_{so}	20 mm
		Number of consecutive days	N_{so}	5 days
Phenology	Thermal time for the initial stage		GDD_1	400°C days
	Thermal time for the development stage		GDD_2	300°C days
	Thermal time for the mid-season stage		GDD_3	750°C days
	Thermal time for the late-season stage		GDD_4	1,000°C days
Water balance	Minimum value of total available water		TAW_n	20 mm
	Maximum value of total available water		TAW_x	150 mm (J) 100 mm (K)
	Crop coefficient (initial stage)		K_{c1}	1.00
	Crop coefficient (mid-season stage)		K_{c2}	1.15
	Crop coefficient (end of the late-season stage)		K_{c3}	0.25
Crop cycle interruption	Limit date expressed in number of days after flowering		N_f	15 days
	Number of consecutive days without available water		N_{ds}	7 days

J stands for Jendouba, *K* for Kairouan, *C* for current climate, *F* for future climate, *DOY* day of the year development stage (tillering), GDD_3 for the mid-season stage (stem elongation) and GDD_4 for the late-season stage (anthesis and grain filling). A total of 2,450 degree-day is needed to complete the entire cycle (see Table 1). Wheat cultivars grown in Tunisia are neither photoperiodic (no effect of photoperiod on flowering) nor responsive to vernalisation (no effect of cold temperatures).

Dry spells frequently occur during the growing season, mostly in the arid region of Kairouan. If dry spells are long and occur during critical stages, the crop can fail (Blum 1996). Our modelling accounts for this important feature of rain-fed agriculture in a simple and pragmatic way, which was discussed with local agronomists (Latiri, personal communication). If a dry spell of N_{ds} (=7) consecutive days without available water occurs before a given date, determined as a number of days N_f (=15) after flowering, the crop cycle completely fails without producing yield. If it occurs after this date, the crop cycle is stopped, but nevertheless it provides a certain yield modulated by the water stress (see below).

The water balance model for the root zone, developed and validated against experimental data by Lhomme and Katerji (1991) (see the "Appendix" for the details of the model), is based upon the same principles as the CROPWAT model developed by the FAO (Allen et al. 1998). It uses a bucket approach with a single soil layer. Soil reservoir maximum capacity TAW_x (for a rooting depth of 1 m) is taken to be 150 mm and 100 mm respectively in Jendouba and Kairouan (Souissi and Ghezal 1971; Barbery and Mohdi 1983). The single crop coefficient approach developed by the FAO (Allen et al. 1998) is used to calculate crop evapotranspiration. This approach considers two stages in the calculation: a first stage under standard conditions and a second stage under non-optimal conditions (water stress conditions). Crop evapotranspiration ET_c under standard conditions (i.e., under adequate supply of water) is calculated by multiplying reference crop evapotranspiration ET_0 by a crop coefficient K_c varying predominately with crop characteristics ($ET_c = K_c ET_0$). The crop coefficient curve is described from three values of K_c corresponding to three different stages: initial stage ($K_{c1} = 1.00$), mid-season stage ($K_{c2} = 1.15$) and end of the late season stage ($K_{c3} = 0.25$). Between each stage, K_c values are linearly interpolated. The model does not account for the feedback action of crop water deficit on leaf area (LAI) development and hence on crop coefficients. The water balance model allows one to calculate the cumulative crop water deficit (CWD) over a given period, defined as the summation of the daily water deficits (WD)

$$CWD = \sum_i WD(i) = \sum_i (ET_c(i) - ET(i)) \tag{3}$$

where ET represents actual evapotranspiration. A normalized water stress index (WSI), with a value between 0 (no stress) and 1 (total stress), is also defined as

$$WSI = CWD \Big/ \left(\sum_i ET_c(i) \right) = 1 - \sum_i ET(i) \Big/ \sum_i ET_c(i) \tag{4}$$

When crop water requirements are not met, stomatal closure occurs to reduce further water loss, resulting in a reduction in the uptake of CO_2 and photosynthesis. This leads to a reduction in biomass production and crop growth, with a direct impact on crop development and yield. To evaluate the effect of crop water deficit on yield, the linear crop-water production functions developed by Doorenbos and Kassam (1979) are used. Yield deficit YD is determined as

$$YD = (Y_m - Y_a)\big/Y_m = K_y\left[1 - \sum_i ET(i)\Big/\sum_i ET_c(i)\right] = K_y WSI \qquad (5)$$

where K_y is the yield response factor, Y_a is the actual crop yield and Y_m is the maximum crop yield obtained with unrestricted water supply. When the water stress index WSI is calculated over the entire growing period, K_y is equal to 1.0 for winter wheat according to Doorenbos and Kassam (1979, Table 24). This means that the relative yield deficit YD is equal to the WSI. This general approach, developed and applied by the FAO to all sorts of crops, has been validated in many field studies, in particular with durum wheat in Tunisia (Raes et al. 2006).

The main outputs of the model are: crop sowing date (when not prescribed as input), the date corresponding to crop physiological maturity (harvesting generally occurs several days after this date), crop cycle length, cumulative evapotranspiration, cumulative water deficit, water stress index (WSI) and yield deficit (YD). In this simple approach, any potential effect of elevated CO_2 is neglected. Accurately simulating the fertilisation effect of rising CO_2 concentration is a rather challenging task. Tubiello and Ewert (2002) pointed out that most of crop models used in climate change assessments have not been sufficiently tested with data from elevated CO_2 experiments. Recently, using free-air carbon dioxide enrichment (FACE) data, Long et al. (2006) showed that the effects of elevated CO_2 would be lower than thought previously. This result, however, was contradicted by Tubiello et al. (2007), who concluded that "the jury is still out concerning the real strength of the effects of elevated CO_2 on crop yields in farmers' fields, due to several key uncertainties". According to the study by Luo et al. (2005) on wheat yield in South Australia, this effect would be insignificant compared to the influence of changes in rainfall and temperature.

Table 2 Monthly mean anomalies between the future and reference scenarios: P is precipitation; T is mean temperature; H is air relative humidity; U is wind speed at 10 m; R_s is solar radiation; ET_0 is reference evapotranspiration (monthly means)

	J	F	M	A	M	J	J	A	S	O	N	D
Jendouba												
P (%)	−41	−38	−33	−44	−7	−30	+2	+5	+10	+12	−2	−28
T (°C)	+2.5	+3.0	+3.1	+3.5	+4.1	+4.1	+4.6	+4.9	+3.9	+3.5	+2.8	+2.2
H (%)	−4	−7	−8	−10	−9	−7	−7	−6	−1	+2	0	−2
U (%)	−11	−9	−8	+1	+7	+4	0	+2	+3	−7	−5	−7
R_s (%)	+7	+2	+7	+5	0	+3	+2	+1	+3	−5	−1	+2
ET_0 (%)	+16	+20	+22	+25	+18	+16	+14	+14	+13	+4	+3	+11
Kairouan												
P (%)	+8	+33	−27	−29	−3	−10	−26	−20	+21	+94	+17	+37
T (°C)	+2.7	+3.0	+3.0	+3.0	+3.0	+3.7	+4.4	+4.8	+3.9	+3.6	+2.9	+2.6
H (%)	−1	−2	−3	−5	−1	−5	−6	−9	−2	+3	+1	0
U (%)	−6	−3	0	+1	+2	+4	0	+6	+5	+6	−2	0
R_s (%)	+2	−1	+2	+1	−1	0	+2	+1	+3	−6	−3	0
ET_0 (%)	+10	+11	+12	+13	+8	+11	+10	+15	+13	+8	+8	+10

3 Results and discussion

3.1 Impact of climate change on climate characteristics

The weather data (precipitation and temperature) simulated by ARPEGE-Climate over the 1961–1990 period for Jendouba and Kairouan cells have been compared to the data recorded over the same period (see Fig. 3). The comparison of means was made using the Student-Fisher t test (at $P < 0.05$). For most of months, the differences between mean monthly temperatures are not significant, except for the maximum temperatures in Kairouan from February to June. Annual temperatures do not differ significantly either. On the other hand, monthly amounts of precipitation are significantly different between simulated and observed data for almost all months in the two stations. Annual amounts are also significantly different. ARPEGE-Climate model underestimates annual precipitations almost 1 year out of two in Jendouba and more than 6 years out of ten in Kairouan: the maximum differences between observed and simulated data are 368 mm for Kairouan and 258 mm for Jendouba. In fact, most climate models do not simulate correctly local precipitation distribution. At grid cell scale, rainfall is much more variable than other variables like temperature or solar radiation (Baron et al. 2005; Ines and Hansen 2006). Consequently, the comparison between grid cell estimates and point measurements is necessarily tricky and subject to caution. Additionally, in North Africa, precipitations often have convective features; which means they are greatly variable from one place to another and difficult to predict through climate models.

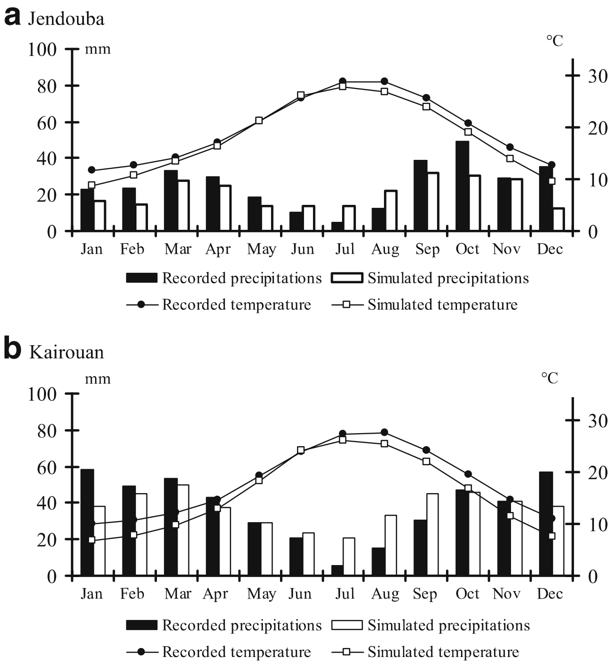


Fig. 3 Mean monthly values of precipitation and average air temperature: comparison of the control scenario (ARPEGE-Climate) with the reference (recorded data) over the 1961–1990 period

The impact of climate change on the annual pattern of precipitation differs significantly between the two stations (Table 2 and Fig. 4). In Jendouba, precipitation tends to increase in summer from July to October (up to +12%), but decreases the rest of the year (down to −44% in April), the annual mean precipitation decreasing by 20%. On the other hand in Kairouan annual precipitation is up by 11%: precipitation increases from September to February (with a maximum of +94% in October) and then decreases the rest of the year (down to −29% in April). The huge increase of 94% in October seems anomalous in comparison with the values of the other months in Kairouan (always less than 40%). An explanation could be the fact that October is the rainiest month of the year with mainly convective events which are difficult to predict accurately. The marked difference in rainfall change between Jendouba and Kairouan due to the ridge (La Dorsale), which separates the two locations and generates an important climatic disparity, will translate into contrasted impacts on crop cycles (see below). In the future climate, maximum and minimum temperatures systematically increase, in Jendouba as well as in Kairouan (Table 2 and Fig. 4): the maximum anomalies occur in July and August and are around +5°C for minimum temperature and a little more than +4°C for maximum temperature. Air relative humidity generally decreases, except in October and November. Wind speed anomaly is either positive or negative with no clear trend. Reference evapotranspiration ET_0 systematically increases in the future scenario (Table 2). The largest increase for Jendouba is registered in April (+25% from 101 mm in the current situation) and the minimum in October and November with

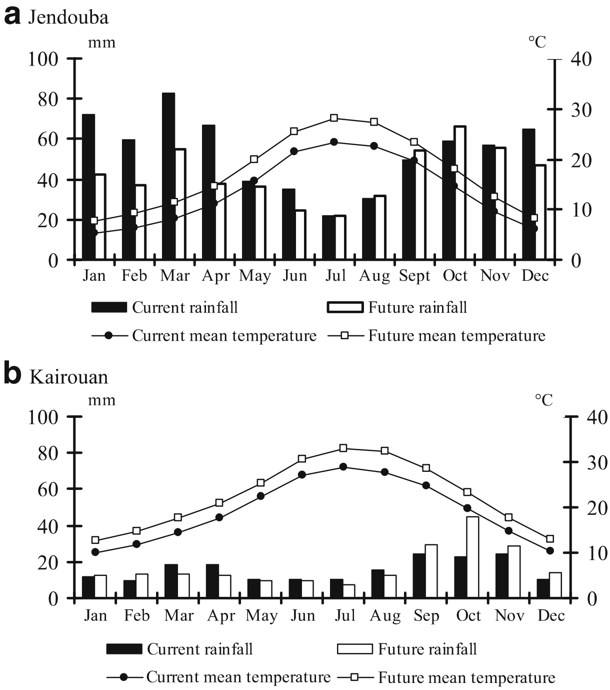


Fig. 4 Mean monthly values of precipitation and average air temperature in the current and future scenarios for Jendouba and Kairouan

+4% and +3% respectively. The increase of ET_0 in Kairouan is less than +15% all the year round, the lowest increase (+8%) being also registered in October (from 92 mm) and in November (from 60 mm).

3.2 Impact of climate change on crop cycle characteristics

There are two rules of decision to determine the sowing date: a dynamical sowing (20 mm during 5 consecutive days in autumn) and a prescribed date (the 1 November) with supplemental irrigation (see Section 2.3 and Table 1). In the case of dynamical sowing, Table 3 shows that the percentage of sowing failure is lower in the future scenario. The difference is particularly clear for Kairouan, where the percentage of sowing failure decreases from 34% to 7%. Regarding the percentage of crop cycle failure due to the occurrence of a dry spell of 7 consecutive days (see Section 2.3), it slightly increases in the future scenario in both stations (Table 3), but the difference is not very significant. The shortening of the crop cycle due to the occurrence of dry spells does not change notably between the reference and the future scenario. When the sowing date is prescribed (the 1 November) with a supplemental irrigation (20 mm) the percentage of crop cycle failure decreases in Kairouan, but it remains 0% in Jendouba (Table 3); the percentage of crop cycle shortening does not change significantly.

When the sowing date is not prescribed, it is moved forward in the future scenario at both locations (see Table 4). In Jendouba, it moves from 22 November to 30 October (mean values). In Kairouan, the sowing date also gains about 1 month in the future scenario: the mean date moves from 20 November to 21 October. Crop cycle mean duration is reduced of approximately 25 days at both locations. This means that crop maturity occurs much earlier. In Jendouba, it occurs around 12 April instead of the end of May, and in Kairouan around 21 March instead of mid-May. If the sowing date is prescribed on 1 November (Table 4), the crop maturity in the future scenario occurs a little less than 1 month earlier at both locations. As dry spells often occur at the end of the rainy season (April and May), this advanced maturity could be a great advantage for the crop, its grain filling period fitting better the favourable period.

Table 3 Statistics on crop failure for Jendouba (J) and Kairouan (K) under 2 types of sowing rule

	Sowing failure[a]		Crop cycle failure[b]		Crop cycle shortening[c]	
	J (%)	K (%)	J (%)	K (%)	J (%)	K (%)
Sowing date is not prescribed						
Current situation	10	34	0	21	0	3
Future scenario	7	7	3	24	3	0
Sowing date is prescribed on the 1 November with a 20 mm supplemental irrigation						
Current situation	0	0	0	34	0	5
Future scenario	0	0	0	24	3	7

Percentages are calculated on the whole sample of years (29)
[a]Percentages of years when sowing fails (the condition required is not fulfilled)
[b]Percentages of years when crop cycle fails (interrupted by a dry spell)
[c]Percentages of years when crop cycle is shortened by a dry spell

Table 4 Statistics on crop cycle characteristics (mean value and standard deviation calculated on the number of successful cycles) for Jendouba (J) and Kairouan (K): sowing date, crop cycle end (physiological maturity) and cycle length

	Sowing date (DOY)		Crop cycle end (DOY) (physiological maturity)		Crop cycle length (day)	
	Jendouba	Kairouan	Jendouba	Kairouan	Jendouba	Kairouan
Sowing date is not prescribed						
Current situation	326 ± 18 (22 Nov.)	324 ± 18 (20 Nov.)	150 ± 10 (30 May)	134 ± 12 (14 May)	190 ± 10	175 ± 9
Future scenario	303 ± 27 (30 Oct.)	294 ± 20 (21 Oct.)	102 ± 25 (12 Apr.)	80 ± 23 (21 Mar.)	164 ± 9	150 ± 7
Sowing date is prescribed on the 1 November with a 20 mm supplemental irrigation						
Current situation	305 (1 Nov.)	305 (1 Nov.)	136 ± 6 (16 May)	116 ± 14 (26 Apr.)	196 ± 6	176 ± 14
Future scenario	305 (1 Nov.)	305 (1 Nov.)	109 ± 5 (19 Apr.)	91 ± 12 (1 Apr.)	169 ± 5	151 ± 12

3.3 Impact of climate change on water deficit and yield

Table 5 shows the impact of the future scenario on yield deficit index $YD = (Y_m - Y_a)/Y_m$, which is equivalent to the Water Stress Index *WSI*, since $K_y = 1$ in Eq. 5. Yield deficit index simply expresses the relative yield reduction with respect to a potential yield as a consequence of deficit water conditions. It is not an absolute index of crop yield and should be handled with care. The potential effects on crop yield of other climatic factors, such as elevated CO_2, are not accounted for. The sowing rules previously considered are examined in Table 5: (1) not-prescribed sowing date; (2) prescribed sowing date with supplemental irrigation. The conditions in the current situation being much drier in Kairouan than in Jendouba, the *WSI* and thus the yield deficit index are obviously higher in Kairouan (58% against 32% in Jendouba, when the sowing date is not prescribed; 56% against 25% when it is prescribed). In the future scenario the *YD* index increases in Jendouba, whereas it decreases in Kairouan. This means that the water conditions for wheat cultivation in the future scenario tend to improve in Kairouan whereas they get worse in Jendouba. With not-prescribed sowing date, yield deficit is approximately equal (around 45%) for Jendouba and Kairouan in the future scenario. With prescribed sowing date, Jendouba remains more favourable than Kairouan for wheat cultivation in the future scenario, but the difference between the two stations is smaller (44% against 53%).

It is important to underline that a shorter crop cycle in the future scenario (due to higher temperatures) means that the future maximum yield Y_m will be certainly

Table 5 Statistics on yield deficit *YD* (mean value and standard deviation) under two types of sowing rule: (1) sowing date is not prescribed; (2) sowing date is prescribed on the 1 November with a 20 mm supplemental irrigation

	(1) YD = WSI (1)		(2) YD = WSI (2)	
	Jendouba (%)	Kairouan (%)	Jendouba (%)	Kairouan (%)
Current situation	32 ± 13	58 ± 10	25 ± 12	56 ± 13
Future scenario	44 ± 14	47 ± 16	44 ± 10	53 ± 16

reduced with respect to the Y_m under the current climate. Indeed, a lesser amount of solar radiation will be captured through photosynthesis leading to a reduced biomass. As this aspect is not accounted for by the model, our values of yield deficit are certainly underestimated when compared to the current maximum yield. On this point, the model could be improved by making Y_m a function of cumulative solar radiation through a simple procedure such as the one developed by Monteith (1977), where the daily dry matter production is expressed as the product of incoming solar radiation by three efficiencies (climate, absorption, conversion). Future modelling developments will be made in that direction.

3.4 Concluding remarks

The effects on durum wheat cropping of a climate projection simulated for 2071–2100 have been assessed through an agro-meteorological analysis carried out in two representative stations of Tunisia (Jendouba and Kairouan). In the future scenario, temperature systematically increases for both stations, whereas precipitation increases or decreases depending on the period of the year. These periods do not necessarily coincide between the two stations. The climatic conditions required for sowing occur earlier and crop cycle length is reduced. Water balance and consequently crop yield deficit slightly improve in Kairouan, but get worse in Jendouba. It is worthwhile noting that these results are obtained from a single GCM model (ARPEGE-Climate) run under a given scenario (A1B of IPCC) and are obviously conditioned by their likelihood. The choice of the GCM was essentially dictated by the resolution of its spatial scale (50 km), the chosen scenario representing a real medium state and a good compromise between pessimistic and optimistic projections. It is worthwhile stressing also that this study provides a picture of the impact of climate change on wheat cycle and yield when no adaptive and specific strategies are put into practice. In reality, farmers would certainly react to climate change by implementing innovative agronomic practices and by gradually adopting new wheat varieties more suited to the evolving climatic conditions. We have seen that it would be pertinent to sow earlier in the future scenario (approximately 1 month before the current dates) because of more favourable water conditions at the start of the autumn in both locations. Besides, wheat varieties with shorter cycle could certainly be beneficial. In Jendouba, since winter and spring precipitations will decrease substantially, a shorter cycle will allow the crop to take better advantage of the rainiest period of the year (from December to March). In Kairouan, as precipitations increase in January and February but diminish after, a shorter cycle would also be beneficial. This type of management planning should obviously minimize the impacts above mentioned. Durum wheat varieties such as Oum Rabia and Khiar have confirmed their quality of drought tolerance and their good adaptation to the difficult conditions occurring at crop cycle end (INRAT 1998). The newly released durum variety Maali, which is up to 4 days earlier and more drought tolerant than the widely grown variety Karim and the bread wheat variety Utique (Deghais et al. 2007), will certainly result in a substantial increase in grain yields under the simulated climate projection.

Acknowledgements We are very grateful to Michel Déqué of Météo-France (Toulouse) for providing us with the climatic data over Tunisia simulated by the ARPEGE-Climate atmospheric model. We also wish to thank Kawther Latiri and Abdelaziz Zairi (INRGREF, Tunis) for their expertise and help to build up the durum wheat model. The assistance of Florent Mouillot (IRD, Montpellier) to collect the simulated weather data is acknowledged too.

Appendix: Crop water balance simulation

The capacity of the soil reservoir TAW (total available water) is defined as the difference between the amount of water stored in the root zone (depth Z_r) at field capacity (θ_{FC}) and at wilting point (θ_{WP})

$$TAW = (\theta_{FC} - \theta_{WP})\, Z_r \tag{6}$$

where TAW and Z_r are expressed in mm and θ in m^3m^{-3}. Similarly, available water (AW) is defined as the difference between the actual soil water content (θ) of the reservoir and its water content at wilting point (θ_{WP}). It is expressed by the same equation as (6) in which θ replaces θ_{FC}. TAW varies as a function of the rooting depth between a minimum value TAW_n, when the crop is sown, and a maximum value TAW_x when roots have reached their maximum development. A simple linear variation is used to represent this evolution between the sowing date and the flowering initiation

$$TAW\,(i) = TAW_n + (i/L)\,(TAW_x - TAW_n) \tag{7}$$

where i is the day number counted from the sowing date and L is the total duration of the phase. Then, between flowering and harvesting, TAW remains constant (TAW_x).

The daily water balance of the root zone is computed as a recurrent process

$$AW\,(i) = AW\,(i-1) + P\,(i) + I\,(i) - ET\,(i) - D\,(i) \tag{8}$$

where $AW(i)$ is the available water of the reservoir at the end of day i; $AW(i-1)$ is the available water at the end on the previous day; $P(i)$ is the precipitación on day i; $I(i)$ is net irrigation; $ET(i)$ is crop evapotranspiration and $D(i)$ is deep percolation. To initiate the water balance an initial value of AW is arbitrary fixed. Runoff from the soil surface and capillary rise from the groundwater table are deliberately disregarded in our agrometeorological approach. They are very dependent on the specific characteristics of the terrain where the crop is grown. Consequently, they are very variable and difficult to predict on a regional basis. Deep percolation (D) is calculated as the amount of water in excess with respect to the capacity of each reservoir (TAW). It is expressed as the positive difference between the total water inputs ($P + I$) and the water holding capacity of the reservoir (difference between TAW and AW)

$$D = (P + I) - (TAW - AW) \qquad if \quad (P + I) > (TAW - AW) \tag{9}$$

$$D = 0 \qquad if \quad (P + I) \leq (TAW - AW) \tag{10}$$

Under limiting conditions of soil water, crop evapotranspiration is written as

$$ET = K_{ws} K_c ET_0 \tag{11}$$

where K_{ws} is a coefficient describing the effect of water stress on crop transpiration. The FAO method (Allen et al. 1998, chapter 8) is used to determine K_{ws}. It is based upon the concept of readily available water (RAW), defined as the fraction p [0–1] of TAW that the crop can extract without reducing its transpiration: $RAW = pTAW$; p was taken to be equal to 2/3. When available water is greater than $TAW - RAW$, K_{ws} is equal to 1; when it is lower, crop evapotranspiration is assumed to decrease in proportion to the amount of remaining water

$$K_{ws} = \frac{AW}{TAW - RAW} \tag{12}$$

References

Abou Hadid AF (2006) Final report to assessment of impacts, adaptation, and vulnerability to climate change in North Africa: food production and water resources. AIACC project no. AF90, published by the international START secretariat. http://www.aiaccproject.org/Final%20Reports/Final%20Reports/FinalRept_AIACC_AF90.pdf

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56

Aubry C, Besse T, Chehida-Ghana A, Elloumi M, Gara M, Lamarche K, Latiri-Souki K, Sebillotte M, Soler LG (1991) Céréalicultures et dynamiques des systèmes agraires en Tunisie. Ann Inst Natl Rech Agron Tunis (numéro spécial) 64:189–236

Barbery J, Mohdi M (1983) Carte des Ressources en Sols de la Tunisie. Feuille de Kairouan. Direction des Sols, ES-202, 49 pages+cartes

Baron C, Sultan B, Balme M, Sarr B, Traore S, Lebel T, Janicot S, Dingkuhn M (2005) From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact. Philos Trans R Soc B. 360:2095–2108. doi:10.1098/rstb.2005.1741

Ben-Salem H, Zaibet L, Ben-Hammouda M (2006) Perspectives de l'adoption du semis direct en Tunisie. Une approche économique. Options Méditerr Sér A 69:69–75

Benzarti Z (1996) La maîtrise des eaux de surface: l'expérience des lacs collinaires en Tunisie. La Revue des Géographes Tunisiens, vol 4. Faculté des Sciences Humaines et Sociales de Tunis. Groupe de Recherche sur la Variabilité du Climat et l'Homme en Tunisie (GREVACHOT), pp 15

Blum A (1996) Crop responses to drought and the interpretation of adaptation. Plant Growth Regul 20:135–148

Brisson N, Gary C, Justes E, Roche R, Mary B, Ripoche D, Zimmer D, Sierra D, Bertuzzi P, Burger P, Bussière F, Cabidoche YM, Cellier P, Debaeke P, Gaudillère JP, Hénault C, Maraux F, Seguin B, Sinoquet H (2003) An overview of the crop model STICS. Eur J Agron 18:309–332

Caballero Y, Voirin-Morel S, Habets F, Noilhan J, LeMoigne P, Lehenaff A, Boone A (2007) Hydrological sensitivity of the Adour-Garonne river basin to climate change. Water Resour Res 43:W07448

Deghais M, Kouki M, Salah El Gharb M, El Felah M (2007) Les variétés de céréales en Tunisie. République Tunisienne, Ministère de l'Agriculture et des Ressources Hydrauliques, 445 p

Delécolle R, Ruget F, Ripoche D (1995) Possible effects of climate change on wheat and maize crops in France. In: Rosenzweig C, Ritchie JT, Jones JW (eds) Climate change and agriculture: analysis of potential international impact. ASA special publication 59, Madison

Déqué M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Glob Planet Change 57:16–26

Doorenbos J, Kassam A (1979) Yield response to water. FAO irrigation and drainage paper 33

Gibelin AL, Déqué M (2003) Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim Dyn 20:327–339

Hénia L (1993) Climat et bilan de l'eau en Tunisie. In: Essai de régionalisation climatique par les bilans hydriques, vol XXVI. Faculté des Sciences Humaines et Sociales de Tunis, Publications de l'Université de Tunis I, Deuxième série Géographie, 266 p

Henia L, Mougou R (1998) Contribution à l'étude des phénomènes à risques en Tunisie. Cas de la gelée au sol. Les Publications de l'Association Internationale de Climatologie 8:207–215

Huard F (2007) Aspects méthodologiques de l'utilisation des scénarios de changement climatique. Note technique no. 2, INRA-Agroclim. Avignon, France
Ines AVM, Hansen JW (2006) Bias correction of daily GCM rainfall for crop simulation studies. Agric For Meteorol 138:44–53
INRAT (Institut National de la Recherche Agronomique de Tunisie) (1998) Rapport d'Activités 1998. Ministère de l'Agriculture et des Ressources Hydrauliques, Tunisie, 180 pp
IPCC (2001) Climate change 2001. The scientific basis. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, Van der Linder PJ, Xiaosu D (eds) Contribution of working group I to the third assessment report of the IPCC. Cambridge University Press, UK
Latiri-Souki K, Aubry C (1991) Les céréales dans le semi-aride: potentialités, variation et contraintes. Ann Inst Natl Rech Agron Tunis (numéro spécial) 64:189–236
Latiri-Souki K, Nortcliff S, Lawlor DW (1998) Nitrogen fertilizer can increase dry matter, grain production and radiation and water use efficiencies for durum wheat under semi-arid conditions. Eur J Agron 9:21–34
Lhomme JP, Katerji N (1991) A simple modelling of crop water balance for agrometeorological applications. Ecol Model 57:11–25
Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR (2006) Food and thought: lower-than-expected crop yield simulation with rising CO_2 concentrations. Science 312:1918–1921
Louati MH, Khanfir R, Alouini A, El Echi ML, Frigui L, Marzouk A (1999) Guide pratique de la gestion de la sécheresse en Tunisie. In: Approche méthodologique. Publication du Ministère de l'Agriculture, Tunis
Louhichi B (1979) Etude de la durée d'insolation et du rayonnement global. Recherche de relations entre les deux paramètres. Mémoire de fin d'étude de l'Ecole de l'Aviation et de la Météorologie, Borg El Amri, Tunisie, 75 p
Luo Q, Williams MAJ, Bellotti W, Bryan B (2003) Quantitative and visual assessment of climate change impacts on South Australian wheat production. Agric Syst 77:173–186
Luo Q, Bellotti W, Williams M, Bryan B (2005) Potential impact of climate change on wheat yield in South Australia. Agric For Meteorol 132:273–285
Monteith JL (1977) Climate and the efficiency of crop production in Britain. Philos Trans R Soc Lond Ser B 281:277–294
Mougou R, Abou-Hadid A, Iglesias A, Medany M, Nafti A, Chetali R, Mansour M, Eid H (2008) Adapting dryland and irrigated cereal farming to climate change in Tunisia and Egypt. In: Leary N, Adejuwon J, Barros V, Burton I, Kulkarni J, Lasco R (eds) Climate change and adaptation book, Earthscan, UK. http://www.nhbs.com/title.php?bkfno=170111&ad_id=185
Raes D, Geerts S, Kipkorir E, Wellens J, Sahli A (2006) Simulation of yield decline as a result of water stress with a robust soil water balance model. Agric Water Manag 81:335–357
Reyenga PJ, Howden SM, Meinke H, McKeon GM (1999) Modelling global change impacts on wheat cropping in southeast Queensland, Australia. Environ Model Softw 14:297–306
Rosenzweig C, Hillel D (1998) Climate change and the global harvest: potential impacts of the greenhouse effects on agriculture. Oxford University Press, USA
Sakiss N, Ennabli N, Slimani MS (1991) La pluviométrie en Tunisie. Institut National Agronomique de Tunisie et Institut National de la Météorologie, Tunis, 123 p
Souissi A, Ghezal F (1971) Etude pédologique des plaines des oueds Bou Herthma, Tessa et Mellègue. Division des sols, Ministère de l'Agriculture et des Ressources Hydrauliques, Tunis 150 pages+cartes
Stockle C, Donatelli M, Nelson R (2003) CropSyst, a cropping systems simulation model. Eur J Agron 18:289–307
Teixeira JL, Fernado RM, Pereira LS (1995) Irrigation scheduling alternative for limited water supply and drought. ICID J 44:73–87
Tubiello FN, Ewert F (2002) Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. Eur J Agron 18:57–74
Tubiello FN, Amthor JS, Boote KJ, Donatelli M, Easterling W, Fischer G, Gifford RM, Howden M, Reilly J, Rosenzweig C (2007) Crop response to elevated CO_2 and world food supply. A comment on "Food and thought…" by Long et al., Science 312: 1918–1921, 2006. Eur J Agron 26:215–223
Zairi A, El Amami H, Slatni A, Pereira LS, Rodriguez PN, Machado T (2003) Coping with drought: deficit irrigation strategies for cereals and field horticultural crops in central Tunisia. In: Rossi G, Cancelliere A, Pereira LS, Oweis T, Shatanawi M, Zairi A (eds) Tools for drought mitigation in Mediterranean regions. Water Science and Technology Library. Kluwer Academic Pub