

Short-term climate change effects on maize phenological phases in northeast Italy

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Abstract

This study evaluates the response of maize growing cycle length to meteorological variables at regional scale particularly, in the short-term period, considering global climate change. The experiment was carried out in Veneto Region (Northeast Italy) where maize phenological data collected by the regional network from 2005 to 2007 were combined with temperature data to analyse the relationship between BBCH stages and thermal sum. The effects of climatic changes in the near and medium term on maize phenology and on water requirements were also evaluated over a grid of climatic data obtained from different climatic models. The piecewise analysis gave the best fitting between BBCH and Growing Degree Days observed data characterized by two lines with different slopes with BBCH 70 (beginning of fruit development) as changing stage. The angular coefficient of the first line was 2.6 times than the second one (0.028) suggesting that the early stages of the growing cycle are more sensitive to air temperature. The simulation of maize phenology evolution highlights a modest variation at the 2020-time horizon, while an expected reduction of maize growing cycle of about 10 days has been estimated for 2030-time horizon. Long-term phenological observation are desirable to confirm our findings and to improve the strength of dataset.

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Introduction

A rising air temperature trend has been found around the world during the last decades with a general increase in growing season length (Skaggs and Baker, 1985; Robeson, 2002; Cola *et al.*, 2016) and this trend is predicted to accelerate in the future (Tao *et al.*, 2006). In addition, many studies highlight a positive trend for the Mediterranean region and Italy (Brunetti *et al.*, 2000a, 2000b, 2004, 2006; Ciccarelli *et al.*, 2008; Founda *et al.*, 2004; Kumar *et al.*, 2005).

A widely used approach to historic trends of climatic variables is based on linear interpolation, while an important aspect of climate evolution is represented by abrupt changes with different climatic phases separated by breakpoints (Bryson, 1974; Lockwood, 2001), which can be evidenced with techniques of discontinuity analysis (Seidel and Lanzante, 2004). The breakpoints show one of the most characteristic features of the climatic system, which is a turbulent, non-linear system affected by sudden transitions from one state to another (Lorenz, 1963).

Temperature is one of the major environmental factors that determines growth and development of plants and it consequently strongly affects phenology and yield (Menzel, 2000; Milošević *et al.*, 2015). Changes in plant phenology are considered to be the most sensitive and observable indicators of plant responses to climate change (Wang *et al.*, 2017; Piao *et al.*, 2019). Most studies focus on changes in natural vegetation but, due to their potential economic importance, a growing interest for agricultural and horticultural varieties have been also showed (Chmielewsky *et al.*, 2004; Vanaja *et al.*, 2017; Ahmad *et al.*, 2019; Guo *et al.*, 2019; Wu *et al.*, 2019; Zhang and Tao, 2019). However the relationship between air temperature changes and variations in the timing of phenological stages of cultivated plants plays a key role for crop management. In fact, changes in the appearance of phenophases in both fruit trees and field crops could be of great economic importance, because the efficacy of agronomic techniques (nitrogen fertilization, distribution of growth regulators, pest control treatments) differs in relation to the phenological stage at which they are applied.

So, crop phenology monitoring has to be closely connected with appropriate timeliness of the agricultural practices (Evans and Hough, 1984). This could have a direct impact on yield formation processes and so on final crop yield (Hough, 1981; Chmielewsky *et al.*, 2004). Harvest timing is also strongly affected by the speed of phenological development. The ability to forecast the harvest date is important for organizing labour, machinery, and marketing. The monitoring and forecasting of crop phenology can therefore help the farmer to achieve a better economic return.

An improved understanding of crop responses to temperature can lead to more reliable simulations of crop yield, and could aid the design of crops that are better matched to their environment

(Atkinson and Porter, 1996; Tao *et al.*, 2006). Furthermore the importance of understanding the specific environmental cues that drive species' phenological responses as well as the complex interactions between temperature and precipitation when forecasting phenology over the coming decades has been highlighted by Bjorkman *et al.* (2015). The use of phenological observations has a great potential to assess ecological responses to climate change, and assembling data into phenological observation programs provides datasets to evaluate spatial and temporal impacts of climate on vegetation (*e.g.* Chmielewski and Rötzer, 2002; Van Vliet *et al.*, 2003; Rajawatta *et al.*, 2016).

To predict crop responses to climate change, it is necessary to know how crops have responded to changes in the past. Unfortunately, only a few phenological records are of sufficient length to show any response to natural climate variability, not only in Italy but also across Europe.

For this purpose a regional phenological network was created in Veneto Region, Northeast Italy, from 2005 to 2007, in order to support farm management at local scale and obtain data for agro-environmental studies. This network concentrated on the most important crops of the Region: maize, winter wheat and grapes.

Veneto is characterized by a Mediterranean climate, but with some peculiar characteristics due to geographical factors, such as the mitigation action of the Mediterranean Sea, the orographic effect of the Alps and the influence of the continental climate of central Europe. Average maximum and minimum temperature in the period 1956-2007 were 16.8 and 6.8°C, respectively. Both values had positive significant linear trends ($P < 0.01$) of 0.046 and 0.026°C per year for maximum and minimum, respectively (Chiaudani *et al.*, 2008). The most marked change in air temperature occurred at the end of the 1980s, which corresponds well to similar trends in many parts of the world (Houghton *et al.*, 2001).

The aim of this study is to evaluate the effects of global climate change in the short-term period on maize growing cycle length and on its water requirements at regional scale.

Materials and methods

Rationale of the work

Maize phenological data collected by the regional network from 2005 to 2007 were combined with temperature data to analyse the relationship between Biologische Bundesanstalt, Bundessortenamt and Chemische Industrie (BBCH) stages describing phenology and thermal sum. This relationship has been used to identify the Growing Degree Days (GDD) corresponding to the most significant growth stages.

Phenological and climatic networks

Veneto Region, Northeast Italy, is an area spanning from 44° 45' N to 46° 45' N and from 10°45' E to 13°15' E. The phenological network, formed on a voluntary basis, consisted of seven sites well scattered over the plain in the region (Figure 1).

Meteorological data were collected from agrometeorological stations belonging to the ARPAV network (www.arpav.it) (Table 1). The weather stations were selected so that data were as representative as possible for the whole region; the phenological crop sites were selected in a radius of max. 10 km from each weather station. A total of six meteorological stations were selected, one of them (Bovolone) serving as reference for two sites (Belfiore d'Adige and Buttapietra).

An observation field was selected in each site to monitor the phenological phases on 25 plants in a marked area of 20 m² in the central part of the field. Plants were observed every 10-15 days during the entire growing season each year and the date of appearance of a phenological stage was recorded when 50% of the plants in the observation area had reached the same development stage. Each maize growth stage was recorded based on the BBCH scale (Lancashire *et al.*, 1991; Stauss, 1994).

During the monitoring period, maize FAO classes remained the same but hybrids were changed. However, the hybrids shared a similar genetic background and the days to flowering and maturity were essentially the same.



Figure 1. Phenological network.

Table 1. Geographical information on the weather stations.

Weather station	Phenological site	Province	Areal	Latitude (North)	Longitude (East)	Elevation (m)
Bovolone	Belfiore d'Adige	Verona	Low plain	45°23'0"	11°12'0"	26
Bovolone	Buttapietra	Verona	Low plain	45°21'0"	10°56'0"	38
Castelfranco Veneto	Castelfranco Veneto	Treviso	High plain	45°40'51"	11°56'18"	43
Badia Polesine	Fiesso Umbertiano	Rovigo	Low plain	44°58'0"	11°36'0"	9
Legnaro	Legnaro	Padova	Low plain	45°21'0"	11°58'0"	12
Vicenza	Noventa Vicentina	Vicenza	Low plain	45°17'0"	11°32'0"	16
Portogruaro	San Stino di Livenza	Venezia	Coastal plain	45°17'0"	12°42'54"	6

Table 2 lists the maize hybrids and sowing dates used during the 3-year experimental period.

In order to describe the relationship between temperature and maize crop development, records of daily mean air temperature in the period April-October 2005-2007 were used.

Phenological data analysis

In each location and year the thermal sum as Growing Degree Days (Σ GDD) was calculated for the whole growing season, where:

GDD = Daily Average Temperature – Base Temperature

GDD describe the heat energy received by the crop over a given time period, thus integrating the area under the diurnal temperature curve, summing the daily heat energy over an interval of time and then relating the accumulation of heat energy to progress in development or growth processes (McMaster and Wihelm, 1997).

Base temperature, *i.e.* the temperature below which the process of interest does not progress, was set at 8°C (Cicchino *et al.*, 2000).

The phenological dataset was used to identify the best equation, among linear, hyperbole and piecewise models, to describe the relationship between BBCH values and Σ GDD. The three equations were then compared using the Akaike Information Criterion (AIC) (Burnham and Anderson, 2002) and the Akaike weight derived from AIC.

For least squares regression statistics, the AIC can be computed as:

$$AIC = n \cdot \ln(\hat{\sigma}^2) + 2 \cdot K$$

where

$$\hat{\sigma}^2 = \frac{\sum \hat{\epsilon}_i^2}{n}$$

with $\hat{\epsilon}_i^2$ being the estimated residuals for each equation, n the number of data points and K the number of parameters of the model, including $\hat{\sigma}^2$.

The ratio n/K being smaller than 40, as suggested by Burnham and Anderson (2002), AIC was corrected for bias adjustment as follows:

$$AICc = AIC + \frac{2K(K+1)}{n-K-1}$$

The different models were then compared through the AIC dif-

ferences (Δ_i) and Akaike weights (W_i), calculated as follows:

$$\Delta_i = AIC_i - AIC_{\min}$$

where AIC_i is the specific value of each model and AIC_{\min} is the lowest value over all the candidate models and:

$$W_i = \frac{\exp\left(-\frac{1}{2} \Delta_i\right)}{\sum_{r=1}^R \exp\left(-\frac{1}{2} \Delta_r\right)}$$

where R is the number of models compared.

W_i ranges from zero to one, indicating the probability that the i^{th} model should be the best among those compared.

The best equation was then used for a further analysis to identify the GDD at which the most important phenological stages were reached. The stages described in Table 3 were selected because they are considered the most closely related to agronomic practices and harvest management.

Phenological trends future evolution

In order to evaluate the effects of climatic changes in the near and medium term on maize phenology and on water requirements, the simulation dataset of Duveiller *et al.* (2017) has been used. This dataset is based on simulations generated by different Global Circulation Models (GCM) that have been dynamically down-scaled using Regional Climate Models (RCM). Duveiller *et al.* (2017) chose these models because they are based on widely used global circulation models and show maximum diversity in output weather variables. In general, DMI and METO are the coldest and warmest regarding surface air temperature, respectively, ETHZ falls in between but shows different precipitation (Van der Fels-Klerx *et al.*, 2019). The A1B scenario has been considered, with three different coupled GCM-RCM models (ECHAM5 GCM coupled with the HIRHAM5 RCM, denoted as DMI-HIRHAM5-ECHAM5; HadCM3 GCM coupled with CLM RCM, denoted as ETHZ-CLM-HadCM3Q0 and HadCM3 GCM coupled with the HadRM3Q0 RCM, denoted as METO_HC-HadCM3Q0-HadCM3Q0).

The dataset consists of consolidated and coherent future daily weather data for Europe on a 25×25 km grid, based on three-time horizons (2000, 2020 and 2030), each represented by 30 synthetic years.

The grid cells falling on the Veneto region plain area have been considered. For each combination 'grid cell × time horizon × reconstructed year', a theoretical sowing date has been calculated

Table 2. Sites, varieties, and sowing dates of the maize phenological network from 2005 to 2007.

Phenological site	2005		2006		2007	
	Hybrid	Planting date	Hybrid	Planting date	Hybrid	Planting date
Belfiore d'Adige	DKC738	05 April	DKC6040	03 April	DKC6040	13 April
Buttapietra	Costanza	29 April	Costanza	10 May	Costanza	07 April
Castelfranco Veneto	Costanza	27 April	Costanza	18 April	Costanza	07 April
Fiesso Umbertiano	PR33A46	30 March	MITIC	30 March	DK6530	13 April
Legnaro	Costanza	01 May	Costanza	05 May	Costanza	24 April
Noventa Vicentina	MITIC	05 April	PR34N43	13 April	PR34N43	12 April
San Stino di Livenza	DKC6040	29 March	DK6530	05 April	-	-

using the model developed by Maton *et al.* (2007). Afterwards, the Σ GDD corresponding to the selected phenophases (Table 3) was used to identify the day of the year (DOY) of the appearance of the main development stages.

Comparison of observed and simulated climates

The simulated climates for the 2000 and 2020 horizons were compared with the observed data in the period 1998-2002 for the 2000 horizon and 2011-2016 for the 2020 horizon, considering the data from the ARPAV network. For each cell, the station closer to the barycentre of the cell has been considered. The comparison has been carried out on monthly averages of rainfall, T_{max} and T_{min}, calculating linear regressions between observed and simulated data for each of the three coupled models and the two-time horizons, thus obtaining a set of 18 regressions (3 parameters \times 3 models \times 2-time horizons).

To evaluate the overall performance of the models, the slope, intercept and R² of each regression have been considered, calculating the squared deviation from the expected values (slope = 1, intercept = 0, R² = 1 for an estimation with perfect accuracy and precision). The model having the lowest sum of the squared deviations has been considered as the best.

Results and discussion

Phenology and GDD, 2005-2007

The three models (linear, hyperbolic and piecewise regressions) were compared separately for FAO 500 and 600 classes; for both classes, the lowest value of AIC was obtained for the piecewise regression, thus this model was retained for further analyses (Table 4), confirming that the single-line approach to the thermal sum is not completely realistic for maize (Cutforth and Shaykevich, 1990; Streck *et al.*, 2008). According to Kumudin *et al.* (2014) the precision of nonlinear empirical functions is superior to that of linear empirical functions in predicting maize phenology.

The piecewise regressions for FAO 500 and FAO 600 were then compared with a merged model common for the two classes. The comparison with a partial F-test gave a not significant result (F=0.80 with 4 and 8 d.f., P=0.52), thus the common regression for

the two classes was retained (Figure 2).

In maize Nielsen *et al.* (2002) observed significant increases in the thermal time requirement comparing early May vs. June sowings of the same cultivars. In our network, FAO 500 hybrids were sown 13 days earlier than FAO 600 hybrids on average. This could have slowed down thermal accumulation in early sown crops, thus reducing differences between FAO 500 and 600 hybrids. Furthermore, PR34N43 and PR33A46 (belonging to the FAO class 500) have a theoretical growing cycle duration very close to that of FAO 600 hybrids MITIC NK and COSTANZA used in most sites and years.

According to the piecewise function the crop phenology response to thermal sum is characterized by two lines with different slopes (Figure 2). The angular coefficient of the first line is 0.073 whilst in the second it becomes 0.028. The change of slope takes place around BBCH 70 (beginning of fruit development), suggesting that the early stages of the growing cycle are more sensitive to air temperature (Wang *et al.*, 2008). As reviewed in Sánchez *et al.* (2014) an important period in maize development is from emergence to the end of tassel initiation when maize goes

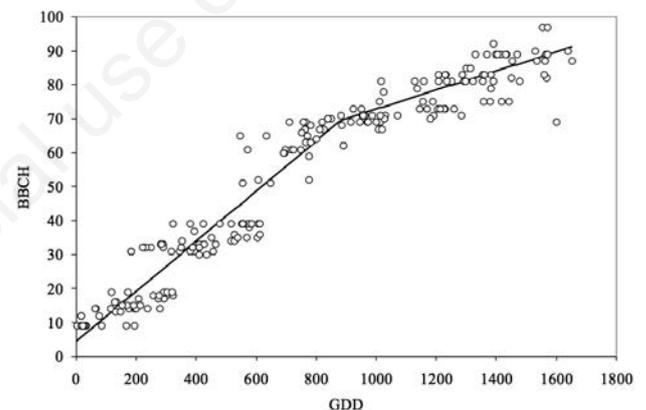


Figure 2. Piecewise regression between BBCH stage and GDD for all the phenological data. Piecewise regression equation: $y = 4.449 + 0.074x$ for $x < 883.5$; $y = 69.637 + 0.028x$ for $x > 883.5$; $R^2 = 0.934$.

Table 3. Selected maize phenological cycle key stages.

BBCH code	Main stage	Secondary stage and description
09	Emergence	Germination
39	Stem elongation	9 or more nodes detectable
60	Flowering, anthesis	Beginning of male and female flowering
73	Development of the fruit	Early milk
83	Ripening	Early dough: kernel content soft, about 45% dry matter
89	Ripening	Fully ripe: kernels hard and shiny, about 65% dry matter

Table 4. Statistics on the comparison of the three models for the BBCH/GDD relationship.

Model	K	RMS	FAO 500			FAO 600				
			AIC _c	Δ_i	w _i	K	RMS	AIC _c	Δ_i	w _i
Linear regression	2	593.29	295.98	122.21	0.00	2	62.06	670.83	78.78	0.00
Piecewise	3	39.39	173.77	0.00	1.00	3	37.66	592.04	0.00	1.00
Hyperbole	2	47.32	179.65	5.89	0.05	2	45.16	619.31	27.26	0.00

through its juvenile stage and temperature is important for potential crop yields, because during tassel initiation the potential number of kernels is defined. Moreover maize is particularly sensitive to high and extreme temperatures before and during anthesis, with negative effect of high temperatures on pollination (Sánchez *et al.*, 2014; Hatfield and Prueger, 2015). On the basis of the piecewise equation, the following Σ GDD were identified for the corresponding BBCH selected stages on the hybrids used: 61 for BBCH 09, 469 for BBCH 39, 753 for BBCH 60, 1050 for BBCH 73, 1401 for BBCH 83 and 1612 for BBCH 89.

Simulation of the evolution of phenology

For all the models, the reference evapotranspiration (ET_0) resulted more or less constant for the 3-time horizons (Figure 3); this reflect a progressive increase of daily crop ET coupled with a proportional shortening of the growing cycle of the maize. The rainfall pattern is, on the other hand, markedly different for the 3 models. With DMI-HIRHAM5-ECHAM5, the rainfall pattern at 2030 is similar to that of 2000, as a consequence, the water deficit ($Rain-ET_0$) remains constant, with a progressive increase during the crop cycle, leading to a deficit of about -300 mm at crop ripening. With ETHZ-CLM-HadCM3Q0, the period from spring to the begin of summer becomes progressively dryer going from year 2000 to 2030, leading to an increase of water deficit in the first part of the crop cycle, while the situation after anthesis is less affected. With METO_HC-HadCM3Q0-HadCM3Q0, the limitation of rainfall in the near future is mostly concentrated in summer, while the situation in pre-anthesis is far less variable.

Thus, the three models depict very different situations for maize in the next future. To identify the model giving the more reliable forecast at 2030 for the specific area considered, we have then compared the simulated rainfalls and temperature at year 2000 and 2020 to those observed in a 5-year time window as closest as possible to the time horizon considered. It is worth noting that a 5-year window can be considered too short for the comparison of observed and simulated data, in particular for rainfalls. On the other hand, considering the progressive evolution of climate conditions, enlarging the time windows should have increased the variability without improving the reliability of the estimates, being the simulations centred on specific years (2000 and 2020).

Looking at the regressions between observed and simulated data, the model better representing the average climate of the plain area of Veneto region is ETHZ-CLM-HadCM3Q0 (Table 5).

Considering this model, the situation of maize crops is practically unaffected at 2020 horizon, while relevant differences are forecasted for 2030 (Figure 4). Particularly, the average amount of rainfall is reduced by 62 mm (-22.7% in respect to year 2000), with a consistent deficit accumulated in pre-anthesis (-48 mm). The shortening of the duration of the growing cycle reduces also ET_0 , nevertheless the water deficit increases by 42 mm, again with a stronger effect in the first part of the crop cycle, while the maturation is less affected.

Rainfall is one of the key parameters impacting the crop growth (Arriaga and Lowery, 2003; Mumtaz *et al.*, 2017). The above reported forecasts give information of great importance for maize agronomic management to maximize the yields and to reduce the negative aspects, such as mycotoxins contamination in grain (Blandino *et al.*, 2017). The reduction of maize cycle due to higher temperature together with the rainfall concentration in the spring season suggest for the next years, in the areas where water is available for irrigation, the cultivation of longer FAO class genotype. In addition, delivering water at night-time through subsurface drip irrigation may help reduce root-zone soil temperature, which may translate into improved plant growth and yield in regions where high-temperature stress is a factor limiting plant growth and development (Dong *et al.*, 2016).

Instead, where water is not available for summer crops irrigation, considering that drought reduced cereal yield and completely damaged crops (Lesk *et al.*, 2016), the cultivation of shorter maize FAO class genotype is necessary.

Conclusions

The maize phenology response to thermal sum is characterized by two lines with different slopes confirming that the linear approach to the thermal sum is not completely realistic for maize. Comparing three climatic models, they depict very different situations for maize in the next future with the more reliable results

Table 5. Regressions between observed and simulated data for each of three evaluated models.

Model	Variable	Year	Slope	Intercept	R ²	Squared deviation
DMI-HIRHAM5-ECHAM5	Rain	2000	0.071	58.952	0.017	6314.5
		2020	0.135	53.225	0.051	
	Tmax	2000	0.940	-0.206	0.983	
		2020	0.993	-1.059	0.985	
	Tmin	2000	0.959	0.653	0.951	
		2020	1.054	-1.079	0.968	
ETHZ-CLM-HadCM3Q0	Rain	2000	0.244	37.009	0.121	1999.6
		2020	0.393	25.031	0.251	
	Tmax	2000	0.966	-0.804	0.985	
		2020	0.980	-0.341	0.990	
	Tmin	2000	0.972	0.535	0.949	
		2020	0.991	0.316	0.965	
METO_HC-HadCM3Q0-HadCM3Q0	Rain	2000	-0.015	65.904	0.015	4862.8
		2020	0.533	22.707	0.198	
	Tmax	2000	0.978	-0.329	0.986	
		2020	0.931	0.736	0.988	
	Tmin	2000	1.019	0.515	0.954	
		2020	0.996	0.280	0.969	

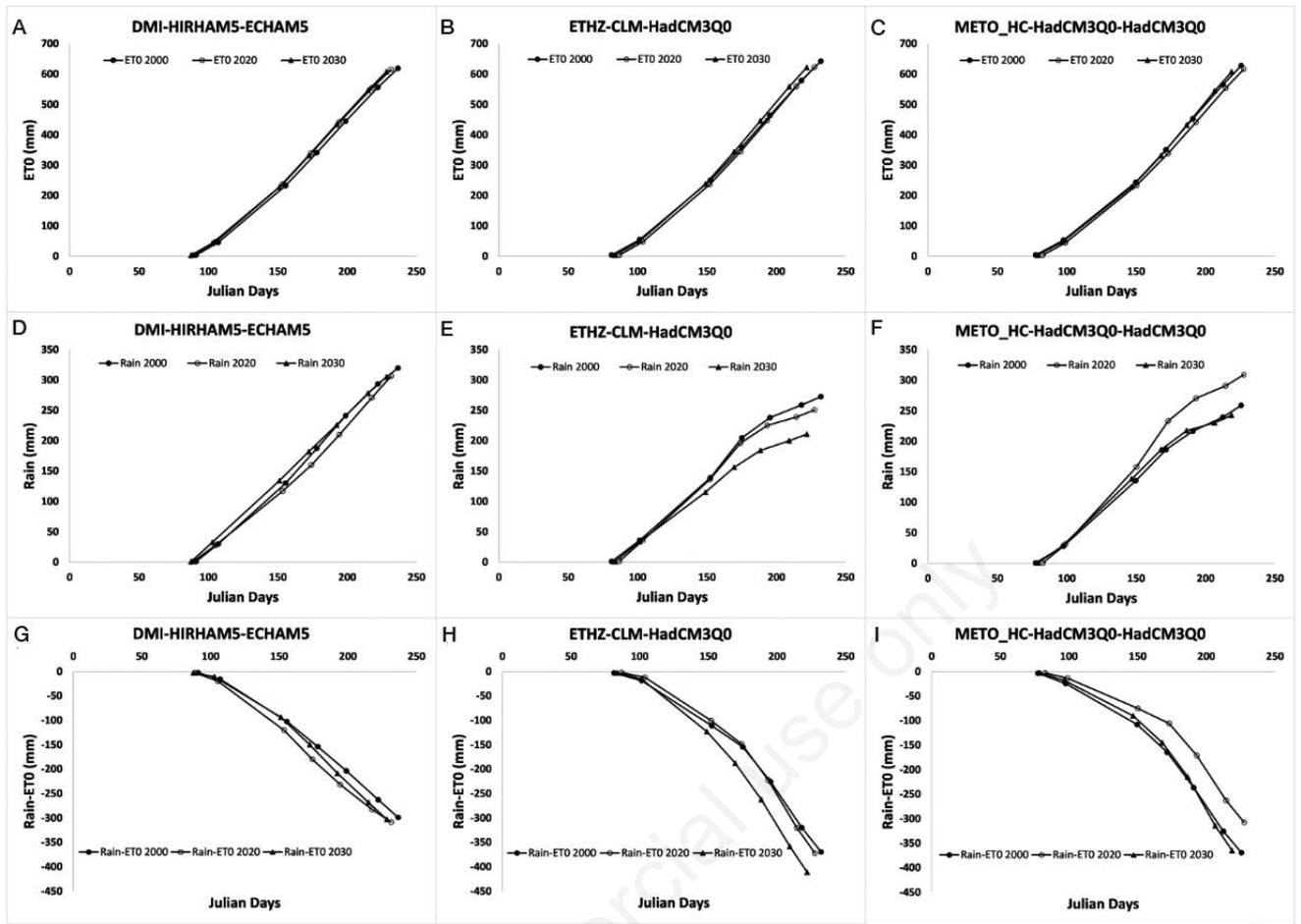


Figure 3. Short term rainfall and ET0 evolution given by the three climatic models.

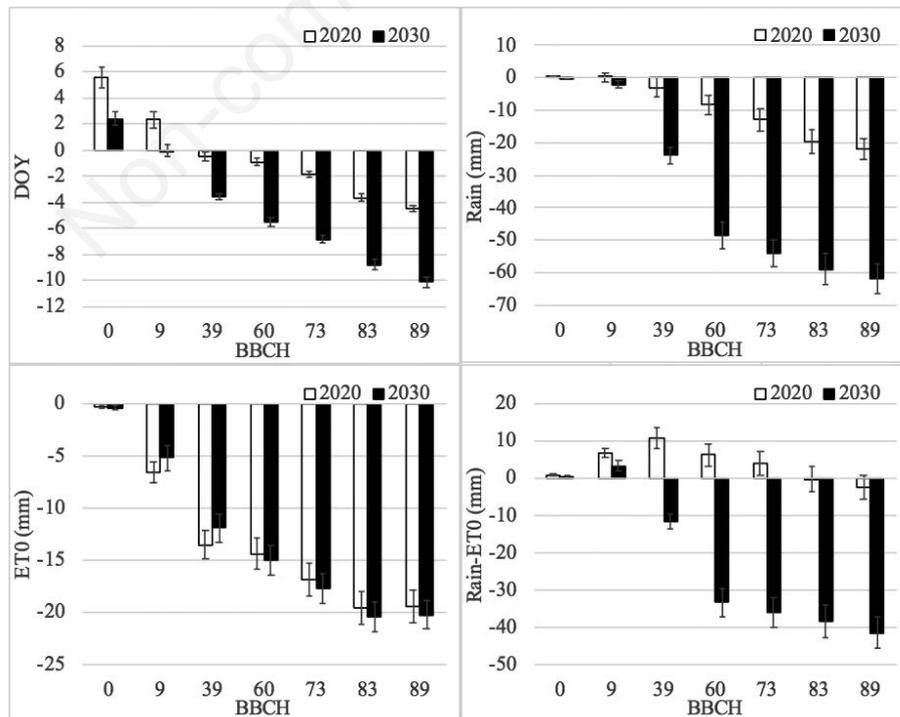


Figure 4. Short term meteorological variables and maize phenological phases evolution given by ETHZ-CLM-HadCM3Q0 model.

observed using ETHZ-CLM-HadCM3Q0 model. Considering this model, the situation of maize crops is practically unaffected at 2020 horizon, while relevant differences are forecasted for 2030 when the growing cycle will be shorter of 10 days with the average amount of rainfall reduced by 62 mm (–22.7% in respect to year 2000), with a consistent deficit accumulated in pre-anthesis (–48 mm). Although phenological data are referred at only three cropping season and so longer observation as desirable to improve the strength of dataset, our forecasts give information of great importance for maize agronomic management to maximize the yields and to reduce the negative aspects suggesting, for the next years, the cultivation of longer FAO class genotypes in the areas where water is available for irrigation, instead of shorter ones where water is not available for full irrigation.

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