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Research paper

Quantification the impacts of climate change and crop management on phenology of maize-based cropping system in Punjab, Pakistan

Ghulam Abbas[a], Shakeel Ahmad[a,*], Ashfaq Ahmad[b], Wajid Nasim[c,*], Zartash Fatima[a], Sajjad Hussain[a], Muhammad Habib ur Rehman[d], Muhammad Azam Khan[e], Mirza Hasanuzzaman[f], Shah Fahad[g,*], Kenneth J. Boote[h], Gerrit Hoogenboom[h]

[a] Bahauddin Zakariya University, Multan, 60800, Pakistan
[b] University of Agriculture, Faisalabad, 38000, Pakistan
[c] COMSATS Institute of Information Technology, Vehari, 61100, Pakistan
[d] Muhammad Nawaz Shareef University of Agriculture, Multan, 60800, Pakistan
[e] In-Service Agriculture Training Institute, Sargodha, Sargodha, Pakistan
[f] Sher-e-Bangla Agricultural University, Dhaka, 1207, Bangladesh
[g] College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, Hubei, China Department of Agriculture, Abdul Wali Khan University Mardan, Khyber Pakhtunkhwa, Pakistan
[h] University of Florida, Gainesville, FL 32611, USA

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ABSTRACT

Crop production is greatly impacted by growing season duration, which is driven by prevailing environmental conditions (mainly temperature) and agronomic management practices (particularly changes in cultivars and shifts in sowing dates). It is imperative to evaluate the impact of climate change and crop husbandry practices on phenology to devise future management strategies to prepare for climate change. Historical changes in spring and autumn maize phenology were observed in Punjab, Pakistan during 1980–2014. Sowing (S) of spring maize was earlier by an average of 4.6 days decade^{-1}, while autumn maize 'S' and emergence (E) were delayed on average 3.0and 1.9 days decade^{-1}. Observed anthesis (A) plus maturity (M) dates were earlier by 7.1 and 9.2 days decade^{-1} and 2.8 and 4.4 days decade^{-1}for spring and autumn maize, respectively. Similarly, S-A, S-M and A-Mphases were shortened on average by 2.4, 4.6 and 1.9 days decade^{-1} and 5.5, 7.8 and 2.2 days decade^{-1} for spring and autumn maize, respectively. The variability in phenological phases of spring and autumn maize had significant correlation,with the increase in temperature during 1980–2014. Employing the CSM-CERES-Maize model using standard hybrid for all locations and years illustrated that model-predicted phenology has accelerated with climate change more than infield-observed phenology. These findings suggest that earlier late sowing and shifts of cultivars requiring high total growing degree day during 1980–2014, have partially mitigated the negative impact of climate change on phenology of both spring and autumn grown maize.

1. Introduction

Punjab is the most populated (99.94 million) province, with 57% of total population of Pakistan and it is the second largest province area-wise (205344 square kilometer) after Baluchistan (GOP, 2015). The prevailing climate of central Punjab is semiarid (mean temperature 10.5–24.4 °C and rainfall 300–600 mm) and southern Punjab is arid (mean temperature 18.5–31.4 °C and rainfall 75–200 mm). Mostly precipitation occurs during monsoon season (July-September) in central and southern Punjab (Nasim et al., 2012; Rasul et al., 2012; Ahmad et al., 2016; Mehmood et al., 2016).

Maize is the third largest cereal/grain crop area-wise and produces raw material for an array of multiple products in Pakistan. Its share in value added agriculture (VAA) and gross domestic product (GDP) is 2.1% and 0.4%, respectively in Pakistan. The area used for crop production and annual total production in Punjab province and Pakistan (GOP, 2015) is presented Fig. 1.

Climate change will significantly impact agricultural production in recent and coming decades, based on research studies conducted at local, regional, continental and global levels (Rasul et al., 2012; Estrella et al., 2007; Lobell et al., 2013; He et al., 2015; Ahmad et al., 2016, 2017a; Amin et al., 2017a; Fahad and Bano, 2012; Fahad et al., 2013,

* Corresponding authors.
E-mail addresses: shakeelahmad@bzu.edu.pk (S. Ahmad), wajidnasim@ciitvehari.edu.pk (W. Nasim), shah_fahad80@yahoo.com, shah.fahad@mail.hzau.edu.cn (S. Fahad).

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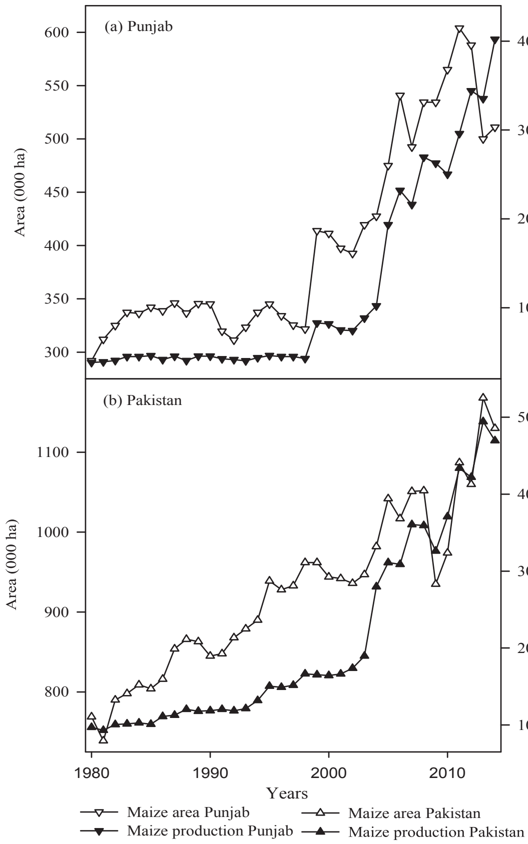

Fig. 1. Maize area and production from 1980 to 2014 forPunjab (a) and Pakistan (b), respectively.

2014a, 2014b, 2015a, 2015b; Noman et al., 2017; Saud et al., 2013, 2014, 2016, 2017). The mean surface air temperature of the earth has increased by 0.8 °C from the industrial revolution to recent years (IPCC, 2014). It has been reported that the warmest decade throughout the past decades was the 2000 s and the most recent warmest year was 2014 (IPCC, 2014). A climate change trend has also been reported for Punjab, Pakistan throughout the previous three decades and predominantly in 2000 s (Wang et al., 2011a; Amin et al., 2015; Nasim et al., 2016a, 2016b). The mean annual surface temperature has increased consistently, which affects the socio-economic sector of Pakistan (Farooqi et al., 2005; Akram and Hamid, 2015; Ahmad et al., 2015; Abbas et al., 2017; Adeel et al., 2017). The observed average warming trend in central and southern Punjab, Pakistan has ranged from 0.80 to 1.4 °C during the past three decades and could increase 2–4 °C in the future, which could be a very serious threat to the agricultural sector (Afzaal et al., 2009; Rasul et al., 2012; Mueller et al., 2014; Anjum et al., 2016; Ali et al., 2016; Ahmad et al., 2017a, 2017b).

Crop phenology (stages and phases) is driven by the prevailing weather conditions and normally expressed in growing degree day's accumulation. It affects crop management practices including cultivar selection and shifts in sowing dates (Tubiello et al., 2002; Menzelet al., 2006; Kucharik and Serbin, 2008; Lashkari et al., 2012; Lin et al., 2015; Ahmad et al., 2016; Ishaq and Memon, 2016; Jan et al., 2017). The negative impact of climate change especially due to an increase in temperature on crop phenology can be mitigated by changes in crop management. For example, developing and introducing new cultivars with a longer duration of the growth period could have a positive impact on crop phenology and ultimately enhance yield under a warming trend (Araya et al., 2015; Amin et al., 2016; Amin et al., 2017b; Fahad et al., 2016a, 2016b, 2016c, 2016d). An increase in temperature during the growing season due to climate warming has a negative impact of maize phenology, including the individual growth stage and phase duration. Variations in phenological stages and phases of a crop are vital indicators of changes in environmental situations and climatic conditions (Streck et al., 2008; Li et al., 2014; Meng et al., 2014; He et al., 2015). Climate thermal trend could accelerate the phenological stages of crop, while longer duration cultivars could cause slower development (Moradi et al., 2013; Javaid et al., 2017). Interactions among cultivar shifts, crop management practices and environmental change, however, cannot be analyzed and interpreted with statistical models. Crop growth models can efficiently simulate the relationships among changes in local weather conditions, cultivar change and crop management practices. However, the impact of multiple and interacting factor on crop phenology can be separated into single factor impact (Liu et al., 2012; Wang et al., 2013; Zhao et al., 2014; Khan et al., 2016; Qasim et al., 2016; Rozina et al., 2017). Xiao et al. (2016) reported that changing cultivar delayed physiological maturity and resulted in longer reproductive phase by 2.4–3.7 days decade^{-1} in North China Plain. Maize anthesis **(A)** and physiological maturity **(M)** were delayed and total growth duration was also prolonged by an average 1.5, 6.5 and 6.3 days decade^{-1}, respectively, in North China region. Therefore, there is a need to conduct research on the potential application of management practices and their adaptation for developing new strategies to mitigate the negative impacts of climate change on crop phenology (Gouache et al., 2012; Zhang and Huang, 2013; Lakho et al., 2017).

The purpose of this research was to evaluate the phenological trends of spring and autumn maize crop through 1980–2014 based on observed data collected from 10 locations for central and southern Punjab, Pakistan. One of the objectives was to correlate farmer field-observed phenological stages and phases with trends of increasing temperature to determine the extent to whichthe warming trends have had an impact on phenology of spring and autumn maize crops. The second objective was to use a dynamic crop simulation model to study the individual impacts of the warming trend, crop husbandry practices and hybrid shifts on spring and autumn maize phenology in central and southern Punjab, Pakistan.

Table 1
Spring and autumn maize hybrids grown at different location in Punjab*, Pakistan.

Sr. No.	Site Name	Hybrids
1	Sialkot	FH-810, Soan, Sargodha-2002, Pioneer-30R50, NK-6621, Pioneer-32F10, NK-8441
2	Gujranwala	MMRI yellow, Changeez, Pioneer-3025, Pahari, NK-6385, Pioneer-34N43, NK-8711
3	Hafizabad	Pearl, Shaheen, Pioneer-30Y87, NK-6617, Pioneer-33H25, NK-7002, P-31R88
4	Sheikhupura	Agaiti-2002, Neelum, Pioneer-31R88, NK-6651, Pioneer-32B33, NK6413, Ghouri
5	Nankana Sahib	Sadaf, Synthetic-51, Monsanto-919, Pioneer-31P41, Azam, Kisaan, SH-139
6	Multan	Yousafwala hybrid, Pachaitisufaid, Monsanto-Opener, Pioneer-32T78, Sawan-3
7	Lodhran	Sahiwal-2002, Synthetic-66, Monsanto-974-AW, Monsanto-6525, Babar, Raka-Poshi
8	Bahawalpur	Agaiti-72, Zia, Monsanto-5219, ICI-8288, Agaiti-85, Jalaal-2003, SWL-2002
9	Bahawalnagar	Akbar, Golden-85, ICI-984, Monsanto-6142, YHD-444, PAK-Afghoee, B-202
10	Rahim Yar khan	Synthetic-551, Sultan-6, ICI-993, ICI-11, NK-8001, YHD-555, BS-2, M-919

*Source = Government of Punjab, Pakistan.

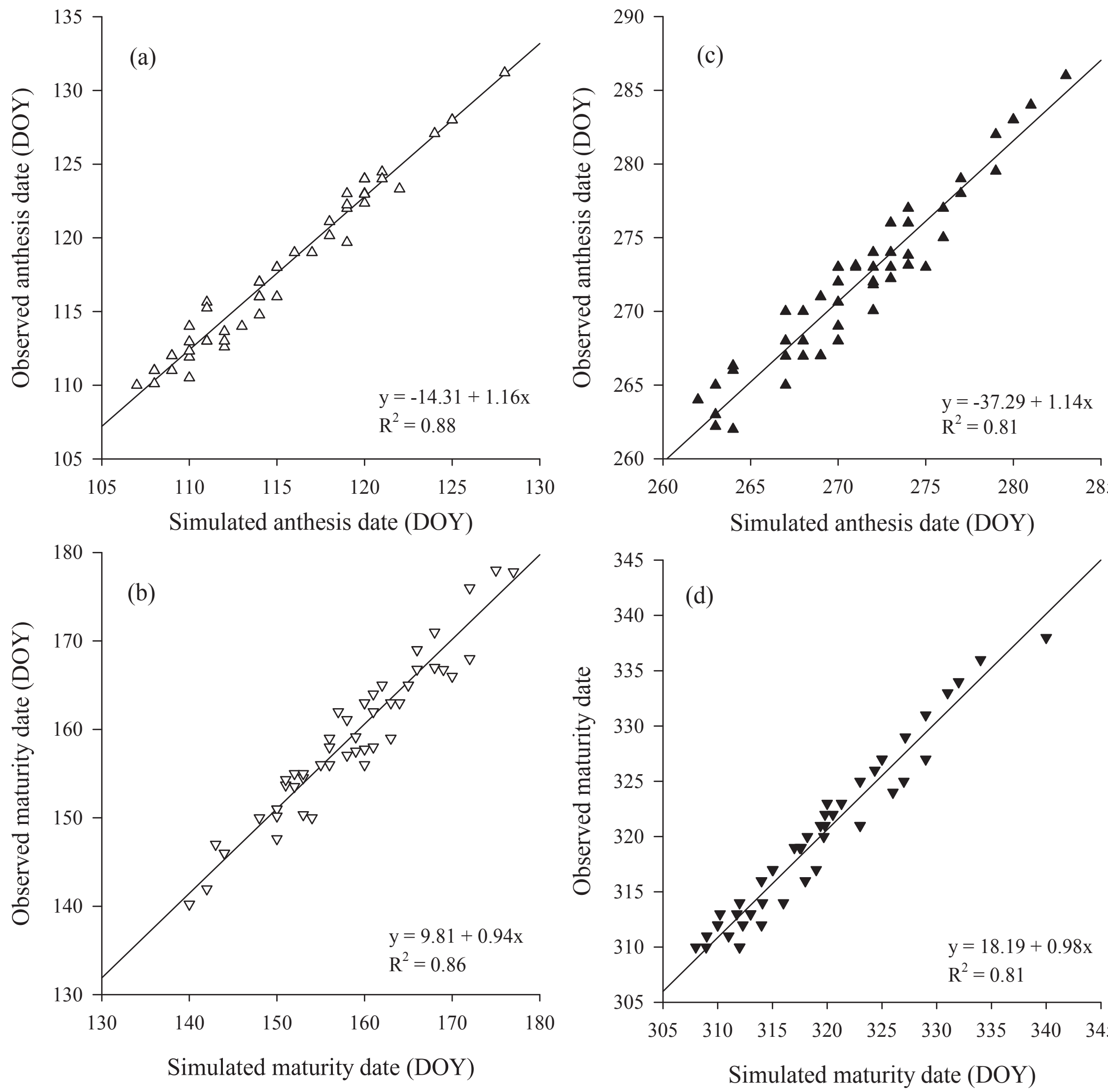

Fig. 2. Comparison of simulated and observed anthesis dates and maturity dates for spring (a, b; unfilled symbols) and autumn seasons (c, d; filled symbols) maize crop, respectively during 1980–1985 for 10 locations in Punjab, Pakistan.

2. Materials and methods

2.1. Description of area, weather and maize phenological data

Maize sown in spring and autumn is the third major cereal crop grown in central and lower Punjab, Pakistan. Ten locations (each with a local weather station) were chosen for this study along with 35 years of observations from 1980 to 2014 (Table 1). Data regarding phenological stages of spring and autumn maize during 1980 to 2014were collected from 10 selected locations from Department of Agriculture (Extension Wing), Government of the Punjab, Pakistan. Sowing, emergence, anthesis (50%) and physiological maturity dates were the observed phenological stages for spring and autumn maize. With the help of these observed phenological stages, three phenological phases: **S-A**, **S-M** and **A-M**, were determined. All management practices were decided by the local farming community for both spring and autumn maize crops. Old spring and autumn maize cultivars were replaced with improved cultivars by the local farming community after every6-8 years (on an average, 7 cultivars over the weather record period per local weather station) (Table 1). This successive adoption of cultivars was associated with a higher total growing degree days requirement. Meteorological data (maximum and minimum temperature; rainfall and solar radiation) during 1980 to 2014for the ten chosen locations were obtained from Pakistan Meteorological Department (PMD), Islamabad, Pakistan.

2.2. Analysis of observed data

Linear regression employed to determine the tendencies in observed phenological stages and phases of spring and autumn maize crop in relation to mean seasonal temperature. With the help of maximum occurrence of phenological stages at each location, time frames for measuring thermal trends were obtained. The time frame of growth period **(S-M)** was counted since the earliest date of sowing to the latest maturity date through the past decades at every location. In this procedure, the measured warming tendency was not dependent on the corresponding phenological stages and phases variations. Correlation of dates of sowings with averagely temperature (monthly) for the period of month of sowing was determined to assess whether average monthly temperature affected the sowing dates. Subsequent linear regression was applied to determine the influence of changing temperature on the phenology of spring and autumn maize.

$$OP_{nt} = a_{nt}T_{nt} + b_{nt} + \varepsilon_{nt} \tag{1}$$

In Eq. (1), farmer field observed phases (‘DOY’, day of year) or its duration in days is symbolized by ‘OP_{nt}’ for the corresponding nth local

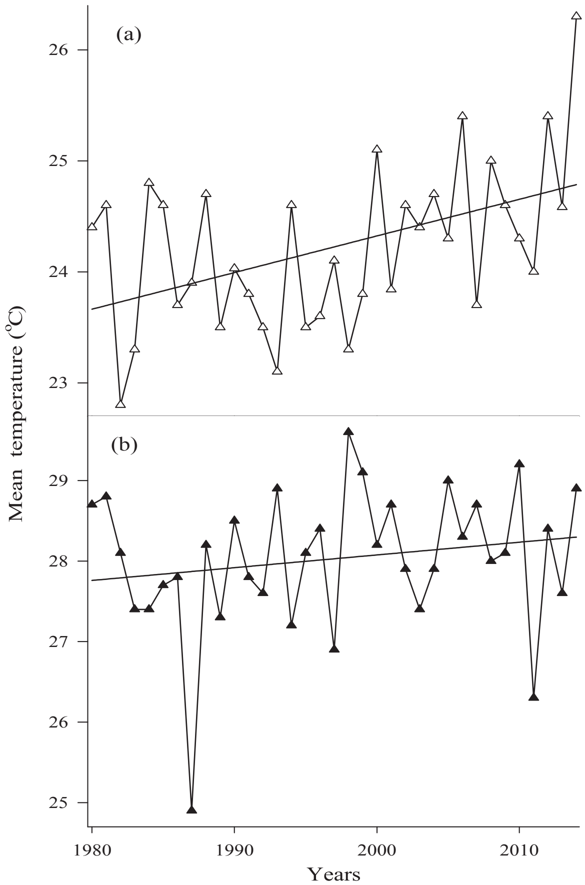

Fig. 3. Mean temperature trends in spring (a) and autumn (b) season from 1980 to 2014 in Punjab, Pakistan.

weather station or location in the respective t year.'T_{nt}' represents average daily temperature in °C during the relevant phenological stage or phase for the specific locations in year*t*. The regression coefficient (days °C^{-1}) of phenological stage or phase responding to temperature are symbolized by the variable 'a_{nt}'. Variables'b_{nt}' and 'ϵ_{nt}' represent the intercept and error term for each particular location, respectively. The phenological stages and phases for spring and autumn maize responding to increasing temperature and crop agronomic management changes were analyzed by variable regression coefficient (a_{nt}).

2.3. Calculating growing degree days and simulating phenological development with CSM-CERES-Maize

The Decision Support System for Agro-technology Transfer (DSSAT) is a modular framework of crop growth modeling software, which was originally developed under the auspices of 'IBSNAT' (International Benchmark Sites Network for Agro-technology Transfer) (Jones et al., 2003; Hoogenboom et al., 2015). In DSSAT, CSM-CERES-Maize model, the phenological stages and phases for spring and autumn maize are predicted based onan accumulation of growing degree days (total thermal time requirement) and hybrid-specific total growing degree days required for each developmental phase. The total accumulation of growing degree days (total thermal time demand) for phenological phases **'S-A'** and **'A-M'** is calculated with the following given formula:

$$ATT = \sum_{i=1}^{n} DTT \tag{2}$$

In this equation, DTT is defined as thermal time day^{-1} and n is the number of days for a given crop phenological phase. The crop modules of DSSAT use day-to-day weather data as input, maximum and minimum temperature, rainfall along with solar radiation for calculating the daily growth and development rates, including the total growing degree days or thermal time per day (Jones et al., 2003).This study used the CSM-CERES-Maize model DSSAT version 4.6 (Jones et al., 2003; Hoogenboom et al., 2015).A detailed description of the processes of the CSM-CERES-Maize model can be found in Tsuji et al. (1994).

Only one hybrid and the same crop management practices were used throughout the study period. The phenological stages and phases for spring and autumn maize were predicted with CSM-CERES-Maize to determine the effect of temperature on maize phenology separate from changes in technology related to crop management and maize hybrid adaptation. The **'A'** and **'M'** dates and the numbers of days from planting to maturity were simulated from 1980 to 2014 for all 10local weather stations. A single, most dominant hybrid from 1980 to 1982 for each location was used for the calibration of the CSM-CERES-Maize model, resulting in 10 different hybrids. Following model calibration, the observed data for spring and autumn maize phenology from 1983 to1985 were used for model evaluation. Then, CSM-CERES-Maize was used to simulate spring and autumn maize phenological stages and phases from 1980 to 2014 based on the same hybrid and crop management practices. The effect of temperature on the simulated spring and autumn maize phenological phases, including **S-A**, **A-M**, and **S-M** was assessed with linear regression analysis by using the following equation:

$$SP_{nt} = C_{nt}T_{nt} + d_{nt} + \varepsilon_{nt} \tag{3}$$

In this linear regression analysis equation, the model predicted phenological stages ('DOY', day of year) or the duration of the phenological phases (days) is symbolized by "SP_{nt}"for the corresponding n^{th} local weather station or location and for the relevant year't'.'T_{nt}' represents mean daily phenological phase temperature in °C during the related phenological phase for specific location in 't' year. The regression coefficient (days °C^{-1}) of phenological phase responding to the warming trend is symbolized by 'c_{nt}' variable. The variables 'd_{nt}' and 'ϵ_{nt}'are the intercept and error term for every particular location, respectively. The response of the spring and autumn maize predicted phenological phases to temperature are represented by the regression coefficient ('c_{nt}').

2.4. Calculation of total growing degree days for spring and autumn maize phenology

Total growing degree days (GDD) for spring and autumn maize phenological phases, **S-A**,**A-M** were computed according to Gallagher and Biscoe (1978) by using the following equation that calculates growing degree days as function of mean temperature above a base temperature.

$$GDD = \frac{\sum (Tmax + Tmin)}{2} - Tb \tag{4}$$

where, Tb is the base temperature taken as 8 °C for maize (Jones et al., 2003).

Comparison of the model simulated and farmer's field observed crop phenological stages i.e.**'A'** and **'M'** dates for 1983 to 1985for model evaluation for the 10 study locations is shown in Fig. 2.The CSM-CERES-Maize model performed well for all locations, as shown by the agreement between the model predicted anthesis and physiological maturity dates and observed phenological data for**'A'**and **'M'** for spring maize (slope = 1.16, R^2 = 0.88, $p < 0.01$ having slope = 0.94, R^2 = 0.86, $p < 0.01$, respectively) and for autumn maize (slope = 1.14, R^2 = 0.81, $p < 0.01$ having slope = 0.98, R^2 = 0.81, $p < 0.01$, respectively).

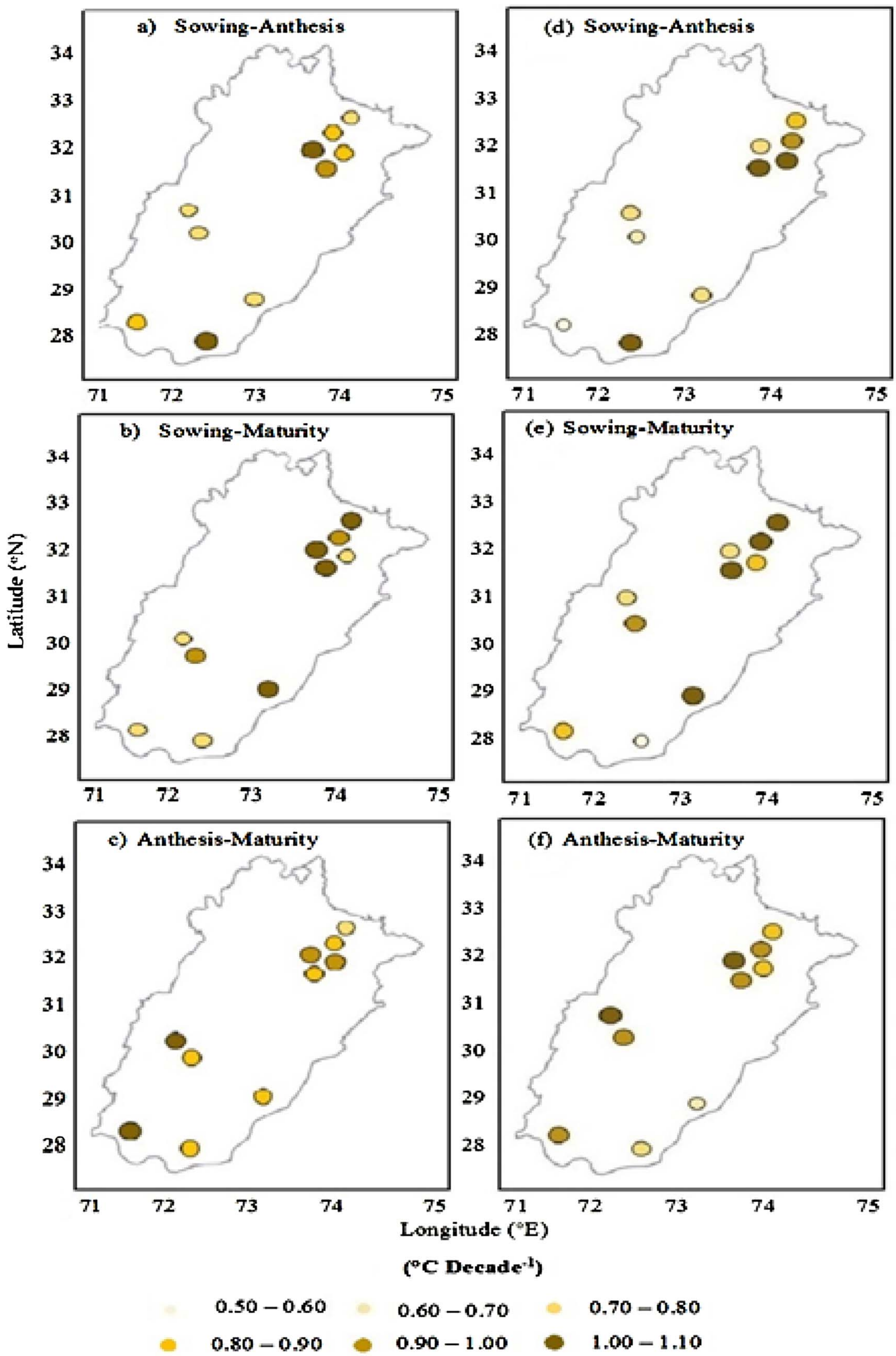

Fig. 4. Observed trends in mean temperature during the phenological phases {sowing-anthesis (a, d); sowing-maturity (b, e); and anthesis-maturity (c, f)} for spring (a, b and c; left) and autumn (d, e and f; right) seasons maize crop from 1980 to 2014 in Punjab, Pakistan.

Table 2
Average observed phenology (day of year; DOY) of spring and autumn maize in Punjab, Pakistan during the period of 1980–2014.

Location	Sowing	Emergence	Anthesis[a]	Maturity[b]
Spring				
Sialkot	37 ± 6.0	41 ± 5.8	103 ± 6.3	142 ± 5.3
Gujranwala	31 ± 7.1	35 ± 6.6	108 ± 5.3	139 ± 4.7
Hafizabad	39 ± 4.2	44 ± 3.9	102 ± 4.4	147 ± 6.3
Sheikhupura	30 ± 5.1	34 ± 4.8	106 ± 6.6	149 ± 4.2
Nankana Sahib	36 ± 6.4	40 ± 6.1	113 ± 3.2	153 ± 5.4
Multan	32 ± 5.9	36 ± 5.4	107 ± 3.9	149 ± 5.2
Lodhran	40 ± 4.6	44 ± 4.2	113 ± 4.4	144 ± 6.0
Bahawalpur	38 ± 5.2	42 ± 4.9	105 ± 5.8	150 ± 7.4
Bahawalnagar	41 ± 3.4	45 ± 3.2	116 ± 4.9	154 ± 5.9
Rahim Yar Khan	45 ± 6.2	49 ± 5.8	110 ± 6.8	148 ± 6.3
Autumn				
Sialkot	202 ± 5.6	206 ± 5.2	256 ± 5.3	316 ± 6.4
Gujranwala	209 ± 4.9	213 ± 4.5	249 ± 6.1	312 ± 5.8
Hafizabad	213 ± 3.7	217 ± 3.4	258 ± 5.3	310 ± 4.1
Sheikhupura	205 ± 5.9	109 ± 5.3	250 ± 6.8	318 ± 5.9
Nankana Sahib	201 ± 6.2	205 ± 5.9	260 ± 7.4	315 ± 4.7
Multan	204 ± 5.1	208 ± 4.5	264 ± 4.9	317 ± 6.7
Lodhran	207 ± 6.4	211 ± 6.1	257 ± 6.2	324 ± 4.0
Bahawalpur	215 ± 4.8	219 ± 4.5	266 ± 4.4	320 ± 5.6
Bahawalnagar	209 ± 5.7	213 ± 5.2	255 ± 5.8	315 ± 5.2
Rahim Yar Khan	213 ± 5.3	217 ± 4.8	259 ± 6.4	326 ± 6.1

[a] 50% Anthesis.
[b] 50% Physiological maturity; ± Standard deviation.

2.5. Difference among observed and simulated crop phenological response to temperature

In Eq. (1), variable 'a_{nt}'is regression coefficient which represents the response of spring and autumn maize phenology to the change in cultivar, planting date and temperature. However, in Eq. (3), only the influence of temperature on model-predicted crop phenology is considered by 'c_{nt}' regression coefficient. If the difference between the regression coefficient ($a_{nt} - c_{nt}$) is represented by negative values, it means that local farmers grew short duration cultivars in the early or "cooler"years. If the difference between regression coefficient is given by positive values, it means that local farmers grew longer duration cultivars in the later or "hotter" years. 'Paired *t*-test' was exploited to determine the significant difference ($p < 0.01$) between the regression **coefficient**.

3. Results

3.1. Temperature trend in spring and autumn season of maize

A warming trend of 0.95 and 0.89 °C decade^{-1}was observed for the spring and autumn seasons, respectively for maize grown in Punjab, Pakistan from 1980 to 2014 (Fig. 3). A larger warming trend was observed during the spring season as compared to the autumn season. The trend of the mean temperature increase from **S-A** ranged from 0.7 to 1.1 and 0.5–1.1 °C decade^{-1}for the spring and autumn season and by an average 0.90 and 0.82 °C decade^{-1}for the spring and autumn season (Fig. 4). The warming trend was also observed during the A-M phase, ranging from 0.8 to 1.1 °C decade^{-1} for spring season maize (with average 0.95 °C decade^{-1}) and 0.6–1.1 °C decade^{-1}for autumn season maize (with average 0.85 °C decade^{-1}). Similarly, the warming trend during S-M phase ranged from 0.7 to 1.1 for the spring season and from 0.5 to 1.1 °C decade^{-1}for the autumn season.

3.2. Spatial and temporal variability of spring and autumn maize phenology stages

The spring maize crop is generally sown from mid-January to mid-February and the autumn maize crop is generally sown from early July to mid-August, respectively in Punjab, Pakistan(Table 2). Sowing dates for spring maize were advanced by 3.5–5.5 days decade^{-1} (statistically significant at 9 locations), with an average4.6 days decade^{-1}(Fig. 5a). However, sowing dates for autumn maize were delayed from 1.5 to 4.2 days decade^{-1} (statistically significant at 9 locations), with an average of 3.0 days decade^{-1}(Fig. 5b). Similar patterns were observed for emergence dates for both spring and autumn maize crops, because emergence dates were straightly linked to sowing dates. The advancement for emergence dates ranged from 0.9 to 1.5 days decade^{-1} (statistically significant at 8 locations), with an average of 1.2 days decade^{-1} for spring maize. Emergence dates for autumn maize were delayed ranged from 1.4 to 2.4 days decade^{-1} (statistically significant at 9 locations), with an average of1.9 days decade^{-1}. Anthesis of spring sown maize occurred from mid-March to early April and autumn sown maize occurred from early September to early October, generally (Fig. 6). Anthesis dates for spring maize were advanced by 5.6–8.6 days decade^{-1} (with average 7.1 days decade^{-1}; statistically significant at 9 locations) and for autumn maize by 1.3–3.9 days decade^{-1} (on average 2.8 days decade^{-1}; statistically significant at 8 locations). Generally, physiological maturity of spring maize occurred from end-April to early-May and autumn season maize occurred from mid-October to early-November. Physiological maturity of spring maize was advanced by 5.4–12.9 days decade^{-1} (averagely 9.2 days decade^{-1}; statistically significant at 8 locations) and for autumn maize it was advanced by 2.1–6.7 days decade^{-1} (on an average 4.4 days decade^{-1}; statistically significant at 8 locations) (Fig. 7).

3.3. Spatial and temporal variability of spring and autumn season maize phenological phases

The **S-A** phase of spring maize was reduced by 1.3–3.4 days decade^{-1} (on an average 2.4 days decade^{-1}; statistically significant at 7 locations), while, for autumn maize it was reduced by 3.5–7.5 days decade^{-1} (with an average of 5.5 days decade^{-1}; also statistically significant at 7 locations). The **A-M** phase for spring maize was reduced by an average of 1.9 days decade^{-1} and it ranged from 1.0 to 2.8 (statistically significant at 9 locations) and for autumn maize it was reduced by 2.2 days decade^{-1} and it ranged from 1.2 to 3.1 days decade^{-1} (statistically significant at 9 locations). As a result of reduction of growth period, S-A, A-M and S-M phases were reduced. The S-M phase for spring maize was reduced by 2.2–6.9 days decade^{-1} (with average 4.6 days decade^{-1}; statistically significant at 8 locations) and for autumn maize it was reduced by 6.5–9.0 days decade^{-1} (averagely 7.8 days decade^{-1}; statistically significant at 9 locations) (Fig. 8).

3.4. Spatial and temporal variability of maize cultivars growing degree day's requirement

Requirement of total growing degree days for spring maize cultivars during **S-A** phase was increased on an average by 85 °C days decade^{-1} and it ranged from 66 to 104 °C days decade^{-1} (statistically significant at 4 locations) and for autumn maize it ranged from 68 to 116 °C days decade^{-1} (averagely by 92 °C days decade^{-1}; statistically significant at 5 locations) (Fig. 9). Similarly, requirement of total growing degree days during **A-M** (reproductive phase) was also increased and for spring maize it ranged from 68 to 83 °C days decade^{-1} (averagely 76 °C days decade^{-1}; statistically significant at 4 locations) and for autumn maize it ranged from 70 to 108 °C days decade^{-1} (averagely 89 °C days decade^{-1}; statistically significant at 5 locations).

3.5. Effect of temperature on observed phenology

There was a negative correlation between temperature and the sowing dates for spring maize, ranging from −1.2 to −1.3 days °C^{-1} (averagely −2.1 days °C^{-1}), while there was a positive correlation

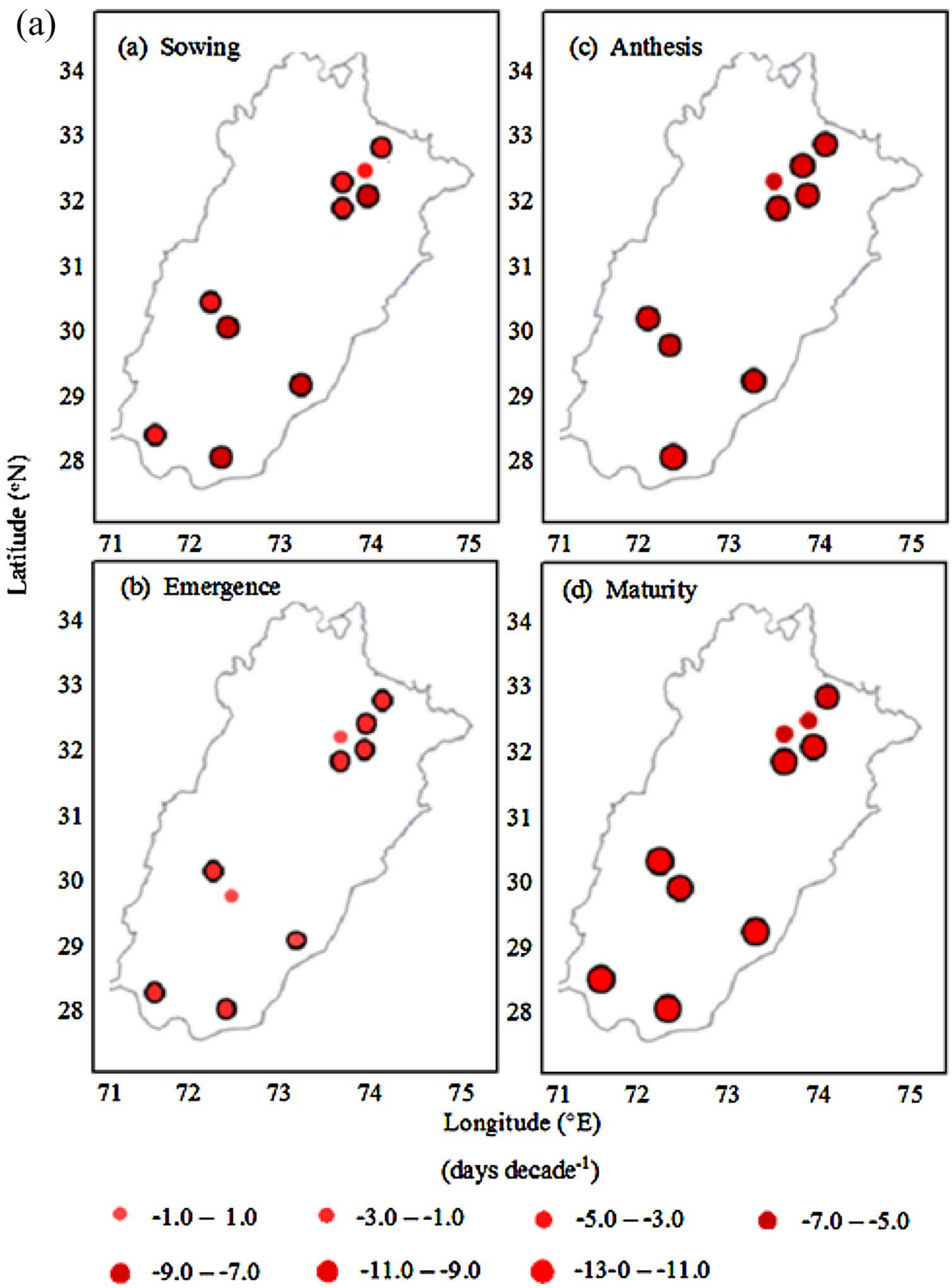

Fig. 5. (a) Observed trends in phenology of spring season maize {sowing (a); emergence (b); anthesis (c); and maturity (d); circles with black borderline indicate statistical significant trends at $p = 0.05$ levels} from 1980 to 2014 in Punjab, Pakistan. (b) Observed trends in phenology of autumn season maize {sowing (a); emergence (b); anthesis (c); and maturity (d); circles with black borderline indicate statistical significant trends at $p = 0.05$ levels} from 1980 to 2014 in Punjab, Pakistan.

between temperature and sowing dates for autumn maize ranging from 2.6 to 4.3 days °C^{-1}with average value of 3.5 days °C^{-1}. However, it was statistically significant at 9 locations for both spring and autumn seasons (Table 3 and Fig. 10). Spring maize emergence dates were negatively correlated with temperature by an average −0.38 days °C^{-1} and ranged from −0.1 to −0.6 days °C^{-1} (statistically significant at 8 locations) and for autumn maize were also negatively correlated and ranged from −0.1 to −0.9 days °C^{-1} (averagely −0.46 days °C^{-1}; statistically significant at 9 locations). Anthesis of spring maize was advanced by ranging from 1.9 to 4.8 days °C^{-1} (on an average 3.7 days °C^{-1}; statistically significant at 9 locations) and for autumn maize advancement of anthesis ranged from 0.9 to 4.4 days °C^{-1} (averagely 2.1 days °C^{-1}; statistically significant at 8 locations). Physiological maturity of spring maize was negatively correlated with temperature by an average of −3.7 days °C^{-1} and it ranged from −1.8 to −5.9 days °C^{-1} and for autumn maize it ranged from −3.1 to −5.6 days °C^{-1} (averagely −3.9 days °C^{-1}). However, it was statistically significant at 8 locations for both spring and autumn season crops.

All phenological phases for both spring and autumn maize were negatively correlated with temperature. Spring maize **S-A** phase was shortened by ranging from 2.0 to 2.9 days °C^{-1} (averagely 2.3 days °C^{-1}) and for autumn maize it ranged from 0.9 to 3.7 days °C^{-1} (with average 2.1 days °C^{-1}). However, it was statistically significant at 7 locations for both seasons. Spring maize **S-M** phase was reduced by an average 4.1 days °C^{-1}, while, it ranged from 1.9 to 6.6 days °C^{-1} (statistically significant at 8 locations) and for autumn maize it was reduced by an average 3.7 days °C^{-1}, while, it ranged from 1.8 to 5.5 days °C^{-1} (statistically significant at 9 locations). Anthesis to maturity phase of spring maize was shortened by ranging from 0.7 to 2.4 (on an average 1.5 days °C^{-1}) and for autumn maize it ranged from 1.7 to 4.9 days °C^{-1} (on an average 3.1 days °C^{-1}). However, it was statistically significant at 9 locations for both spring and autumn season crops.

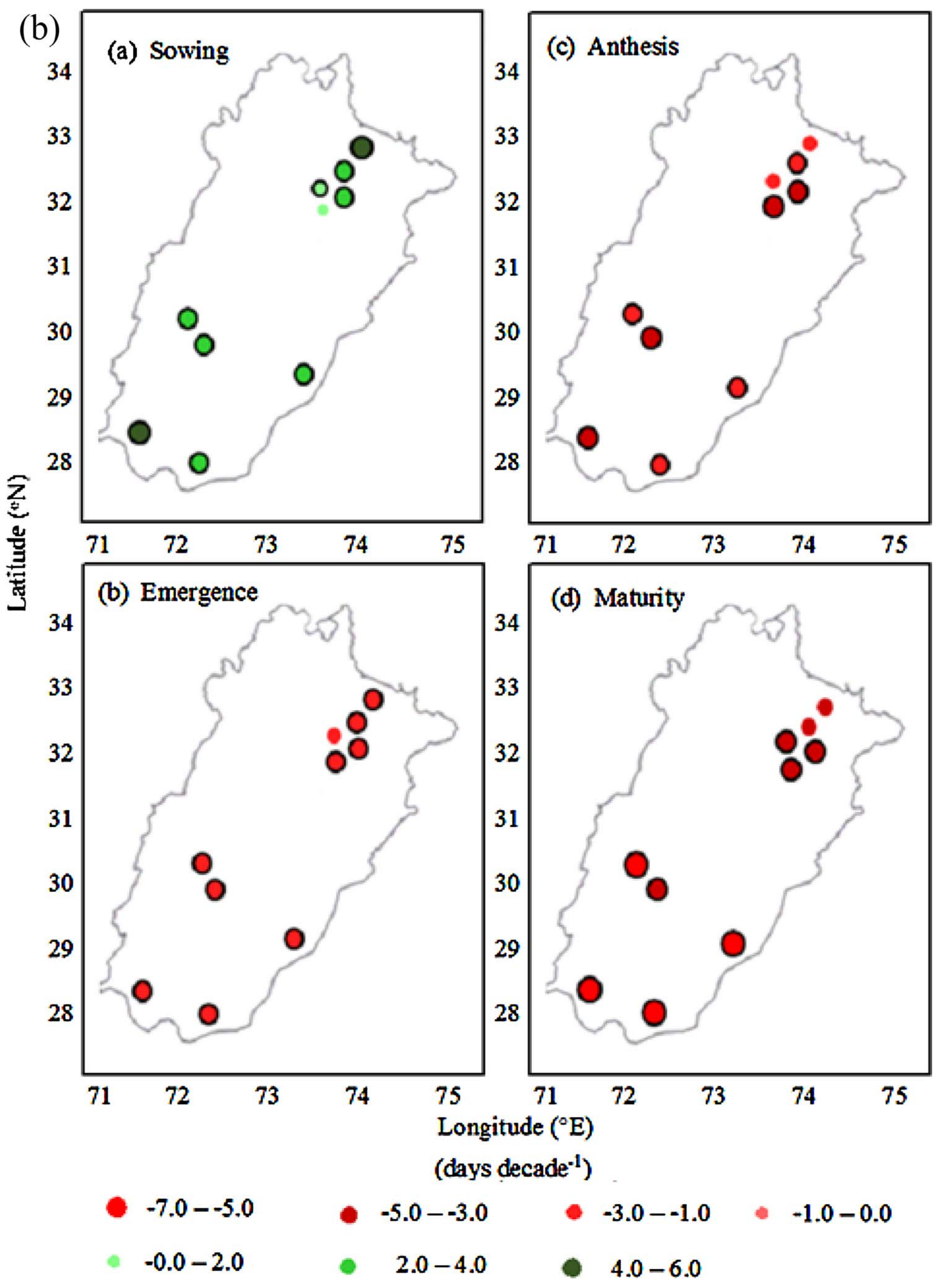

Fig. 5. (*continued*)

3.6. Effect of temperature on simulated phenology

Simulated phenology was negatively correlated with temperature (Table 3 and Fig. 10). The **S-A** phase was reduced by an average 2.8 days °C^{-1} and ranged from 2.1 to 3.5 days °C^{-1} for spring maize (statistically significant at 9 locations). However, for autumn maize **S-A** phase was also reduced and it ranged from 1.4 to 4.0 days °C^{-1} (averagely 2.4 days °C^{-1}; statistically significant at 9 locations). The S-M phase was shortened ranging from 2.0 to 6.7 for spring maize with averagely 4.4 days °C^{-1} (statistically significant at 9 locations), while for it ranged from 1.5 to 5.6 days °C^{-1} (on an average 3.9 days °C^{-1}; statistically significant at 10 locations). Reproductive phase (A-M) of spring maize was also shortened by an average of 1.9 days °C^{-1} and it ranged from 0.9 to 2.7 days °C^{-1}, while for autumn maize it ranged from 2.0 to 5.0 days °C^{-1} (an average of 3.4 days °C^{-1}). However, it was statistically significant at 10 locations for both spring and autumn season crops.

3.7. Observed and simulated phases of spring and autumn season's maize crop

The response of phenological phases to temperature for the observed datawas lesser as compared to model-simulated phenological data (Table 4). Difference between observed and simulated values of regression coefficient means were statistically significant for spring maize which were 0.5, 0.2 and 0.3 days °C^{-1} and for autumn maize were 0.3, 0.2 and 0.2 days °C^{-1} for S-A, S-M and A-M phases, respectively.

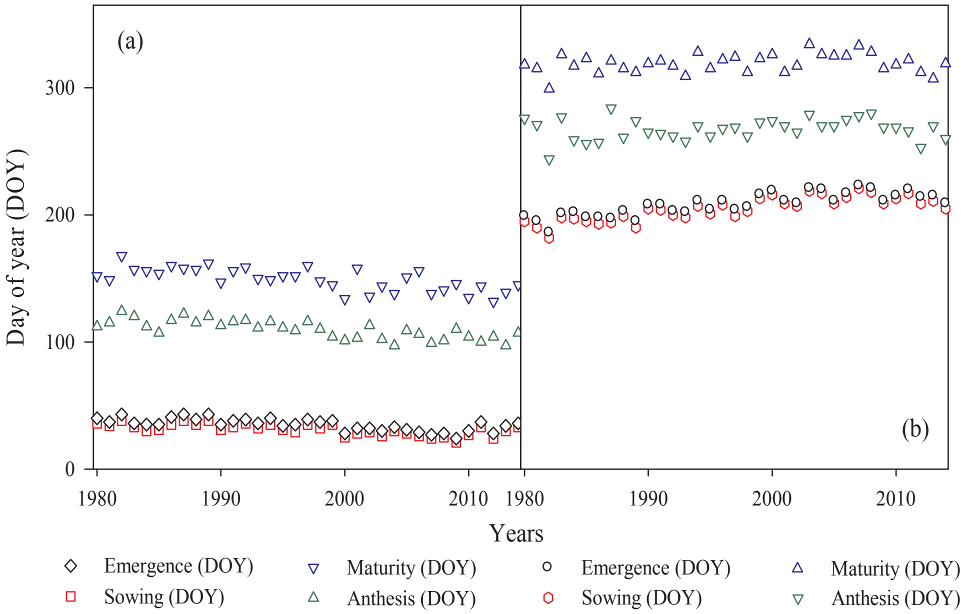

Fig. 6. Time series plots of farmer field observed dates of sowing, emergence, anthesis and maturity of spring (a) and autumn (b) maize in Punjab, Pakistan.

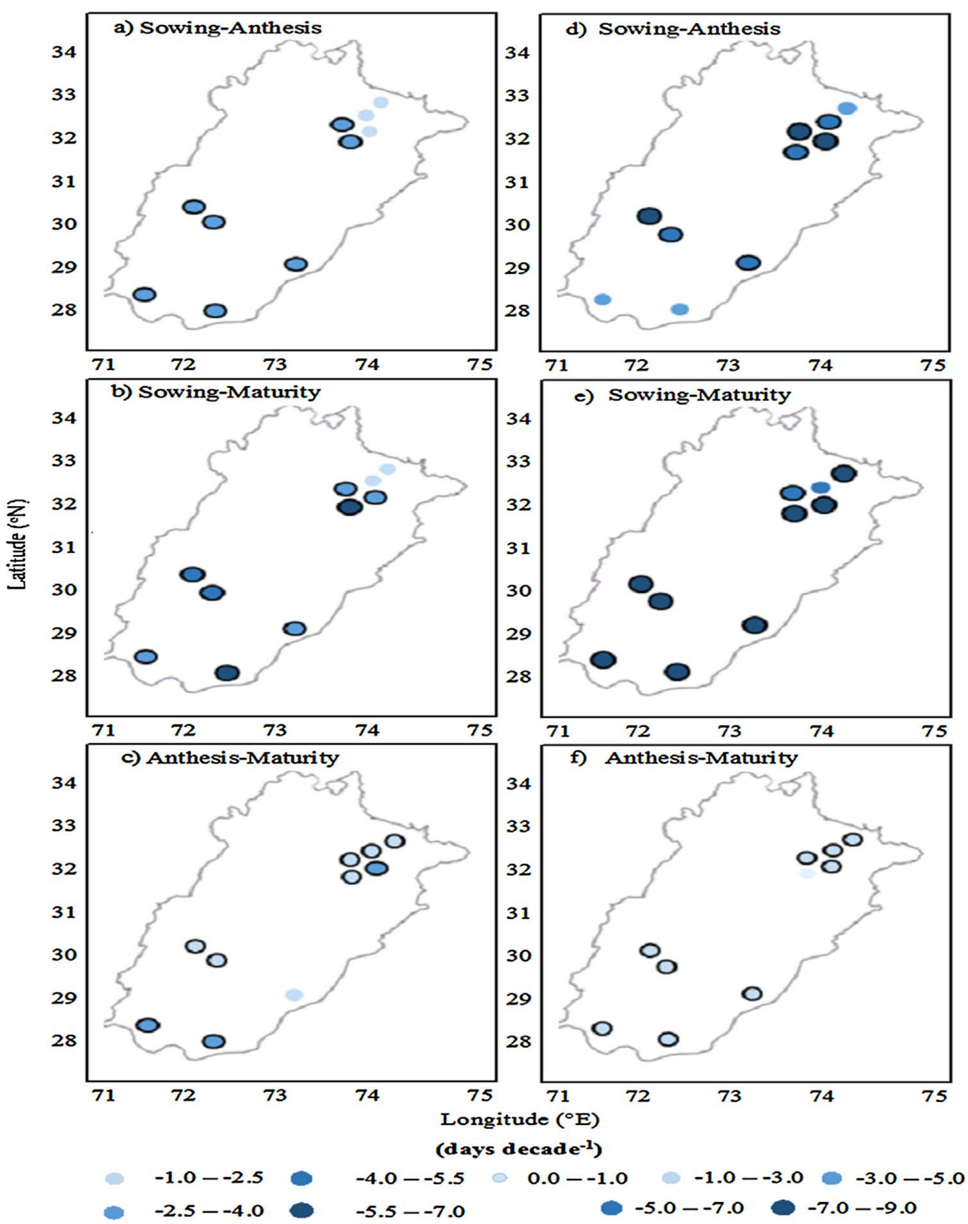

Fig. 7. Observed trends in phenology {(a, d) sowing-anthesis; (b, e) sowing-maturity and (c, f) anthesis to maturity; circles with black borderline indicate statistical significant trends at $p = 0.05$ levels} of spring (a, b and c; left) and autumn (d, e and f; right) season's maize from 1980 to 2014in Punjab, Pakistan.

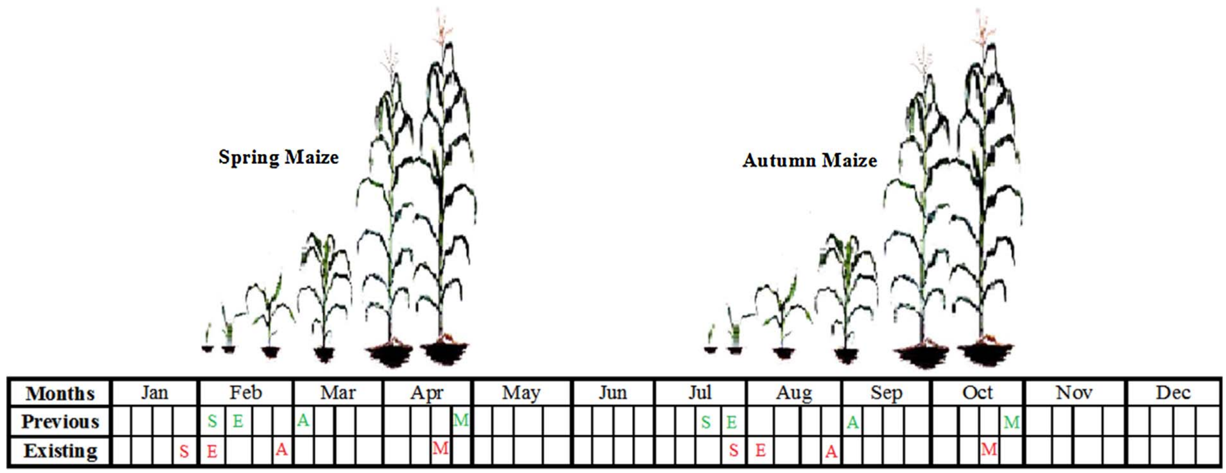

Fig. 8. Spatial and temporal variability of spring (left) and autumn (right), respectively maize phonological phases as effected by an increase in temperature in Punjab, Pakistan. S = Sowing; E = Emergence; A = Anthesis; M = Maturity. Alphabets with green and red colors represent previous and prevailing trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

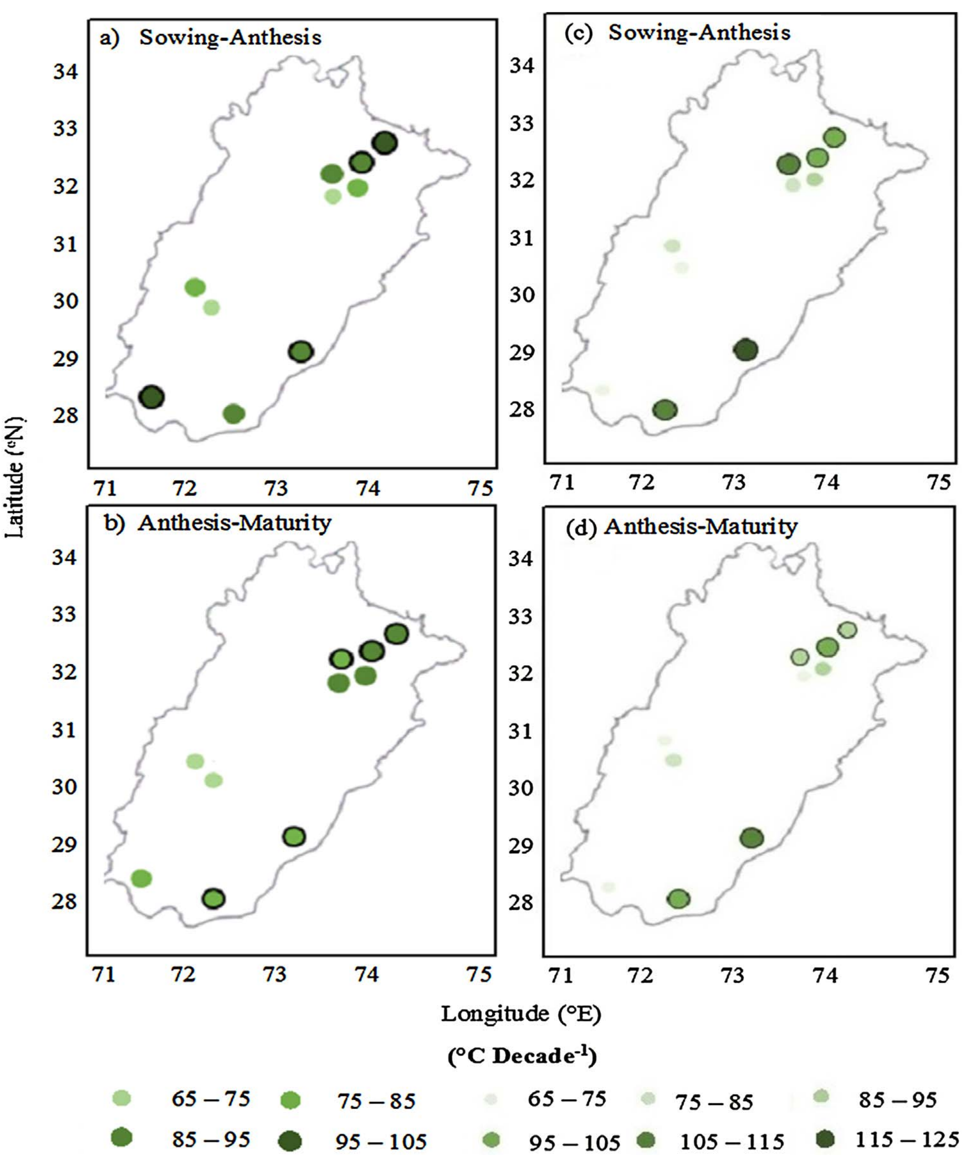

Fig. 9. Observed trends in thermal time required for spring (a, b; left) and autumn (c, d; right) season's maize from sowing-anthesis(a) and anthesis to maturity (b);circles with black borderline indicate statistical significant trends at $p = 0.05$ levels in Punjab, Pakistan.

Table 3
Summary of observed and simulated phenology response to temperature for spring and autumn maize in Punjab, Pakistanfrom 1980 to 2014.

Phenology	No. neg.[a]	No. pos.[b]	No. sig. neg.[c]	No. sig. pos.[d]	Reg. mean[e] (days °C^{-1})
Spring Stages (Observed)					
Sowing	10	0	9	0	−2.08
Emergence	10	0	8	0	−0.38
Anthesis	10	0	9	0	−3.74
Maturity	10	0	8	0	−3.66
Spring Phases (Observed)					
Sowing-Anthesis	10	0	7	0	−2.34
Sowing-Maturity	10	0	8	0	−4.19
Anthesis-Maturity	10	0	9	0	−1.52
Spring Phases (Simulated)					
Sowing-Anthesis	10	0	9	0	−2.79
Sowing-Maturity	10	0	9	0	−4.49
Anthesis-Maturity	10	0	10	0	−1.89
Autumn Stages (Observed)					
Sowing	0	10	0	9	3.52
Emergence	10	0	9	0	−0.46
Anthesis	10	0	8	0	−2.09
Maturity	10	0	8	0	−3.99
Autumn Phases (Observed)					
Sowing-Anthesis	10	0	7	0	−2.19
Sowing-Maturity	10	0	9	0	−3.73
Anthesis-Maturity	10	0	9	0	−3.10
Autumn Phases (Simulated)					
Sowing-Anthesis	10	0	9	0	−2.41
Sowing-Maturity	10	0	10	0	−3.97
Anthesis-Maturity	10	0	10	0	−3.42

[a] Number of locations with negative regression **coefficient**.
[b] Number of locations with positive regression **coefficient**.
[c] Number of locations with significant negative regression **coefficient**.
[d] Number of locations with significant positive regression **coefficient**.
[e] Mean of regression **coefficient**.

4. Discussion

The observed variability in phenological stages and phases of spring and autumn maize over past decades in central and southern Punjab, Pakistan was probably caused by increase in temperature along with variations in sowing dates and newly introduced hybrids with changed temperature requirements. Changes in sowing dates are decided by local farming community (Ahmad et al., 2016, 2017b; Wang et al., 2011b). The changes in sowing dates for the studied locations were adaptation strategy to counter negative effects of temperature. One degree increase in temperature caused the advancement of sowing dates by an average 2.08 days for spring maize and delaying in sowing dates by an average 3.52 days for autumn maize.

The temperature caused the advancement of the **A-M** dates for both spring and autumn maize, which ultimately caused a reduction in the duration of the phenological phases. Climate warming trend has caused the advancement of anthesis date in various cropping systems (Sparks et al., 2000; Abu-Asab et al., 2001; Fitter and Fitter, 2002; Li et al., 2014; Williams and Abberton, 2004; Sparks et al., 2005; Hu et al., 2005; Wang et al., 2008; Xiao et al., 2016). Reduction in **S-M** phase (total crop duration) has already been reported in observed field data in other crops (Tao et al., 2012, 2014; Zhang et al., 2013) and simulated results of various crop growth models (Tubiello et al., 2002; Yang et al., 2004; Sadras and Monzon, 2006; Streck et al., 2008; Grassini et al., 2009; Lashkari et al., 2012; Lin et al., 2015).

New hybrids are continuously being developed using a range of breeding methods and introduced to the local farming community. These new hybrids are suitable for the current environmental growing situations (Liu et al., 2013; Moradi et al., 2013; Xiao et al., 2016). Many of the new hybrids also might have new phenological characteristics with adjustments to anthesis and maturity dates. In this research, we separated the influence of the newly adopted hybrids in Punjab, Pakistan on maize phenology through simulating the spring and autumn maize phenology by CSM-CERES-Maize model by means of same hybrid during the entire study period. Temperature sensitivity of phenology towards model simulations remained greater when compared to the observed data. As an adaptation strategy, this indicates that approximately14%forspring and 24%for autumn maize (Table 4) of the direct negative impact of the increase in temperature on phenology was mitigated with the introduction of new hybrids that require a higher number of growing degree days for **'A'** and **'M'**. This means that growing hybrids cultivars that took longer to reach **'A'** and **'M'** compared to the original ones grown in partially mitigated the negative effect of the increase in temperature This adaptation strategy was also reported for the maize belt of USA (Sacks and Kucharik, 2011), winter wheat and rice in China (Liu et al., 2010; Tao et al., 2013). If life cycle duration of cultivars is shortened due to an increase in temperature, then the grain yield is reduced and thus less time is available for total dry matter accumulation throughout the vegetative reproductive periods (Araya et al., 2015). Therefore, local farming community adapted new introduced cultivars of spring and autumn maize either with longer duration.

It is expected that the temperature might be more extreme in the future (IPCC, 2014). It has been estimated that average temperature could increase by 2–4 °C by the end of this century (Ahmad et al., 2015). Especially for semi-arid regions such as Punjab, Pakistan, this could be detrimental to agricultural production (Rasul et al., 2012; Ahmad et al., 2016). In future, crop phenology would be more affected due to an increase in temperature (Ahmad et al., 2017a,b). Therefore, the development and adaptation of new hybrids that are heat tolerant

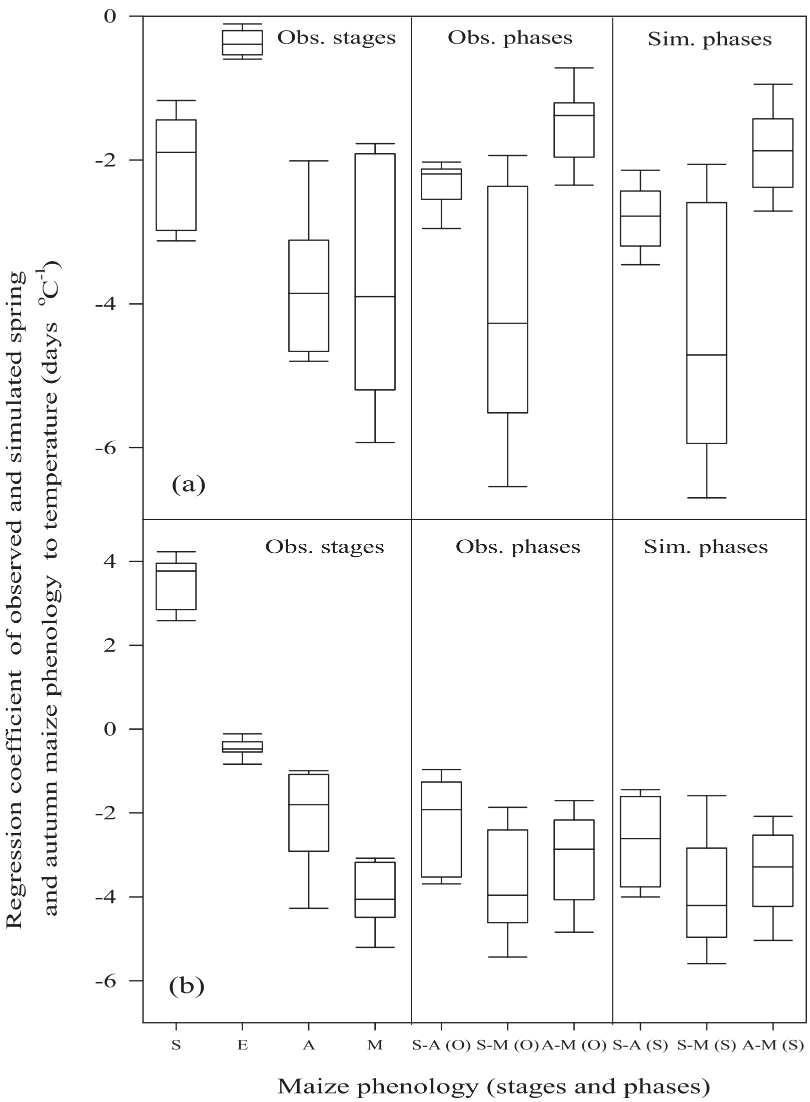

Fig. 10. Observed phenology (stages and phases) and simulated phenology (phases) versus temperature trends of spring (a) and autumn (b) maize cultivar at each location in Punjab, Pakistan from 1980 to 2014. (S: sowing; E: emergence; A: anthesis; M: maturity; S-A: sowing-anthesis; S-M: sowing-maturity; A-M: anthesis-maturity; O: observed; S: simulated). The central line represents median, box limits are 25th and 75th percentiles and whiskers represent the minimum and maximum values.

Table 4
Comparison of the responses of spring and autumn maize phenology with average temperature using the observed and simulated data in Punjab, Pakistan during 1980–2014.

Phenology	Regression coefficient (days°C^{-1}) [a]							
	Obs. data		Sim. data		Difference between obs. and sim. data (days°C^{-1})		t-Test (p-value)	
Phases	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn
Sowing- Anthesis	−2.34	−2.19	−2.79	−2.41	0.45	0.22	0.0011**	0.0025**
Sowing- Maturity	−4.19	−3.73	−4.49	−3.97	0.30	0.24	0.0095**	0.0180*
Anthesis-Maturity	−1.52	−3.10	−1.89	−3.42	0.37	0.24	0.0013**	0.0042**

[a]Mean of regression coefficient; [b]Duration of sowing to maturity; **Significant at $p = 0.01$.

with a higher growing degree day requirement for **'A'** and **'M'** are vital to compensate for the negative impact of the increase in temperature in Punjab, Pakistan.

5. Conclusions

The maize growing region of Punjab, Pakistan has seen an average increase in temperature of 0.90 °C decade^{-1} was observed from 1980 to 2014. Due to the increase in temperature the key phenological stages 'A' and 'M' of spring and autumn maize occurred earlier by 7.1 and 9.2 days decade^{-1} and 2.8 and 4.4 days decade^{-1}, respectively and the duration of the phenological phases **S-A, S-M** and **A-M** was reduced by 2.4, 4.6 and 1.9 days decade^{-1} and 5.5, 7.8 and 2.2 days decade^{-1}, respectively causing a potential decrease in grain yield. The negative impact of the increase in temperature was partially mitigated by adaptation of new hybrids that had a higher growing degree day requirements. An estimated14% and 24% of enhanced temperature effect on phenology of spring and autumn maize, respectively, was compensated with the adoption of new hybrids that had a larger number of growing degree day requirements for the key phenological stages and phases.

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