Shiraz University

Iran Agricultural Research

Journal homepage: https://iar.shirazu.ac.ir

Research Article

Investigating the impact of climate change on the phenology stages of autumn wheat in Mazandaran province, Iran

Mehdi Nadi * , **Bahareh Shamgani Mashhadi**

Department of Water Engineering, Sari Agricultural Sciences and Natural Resources University, Sari, Mazandaran, Iran.

ARTICLE INFO

Keywords:
Climatic scenarios
Downscaling
Growing degree days

ABSTRACT- Anthropogenic climate change can affect crop phenological stages. This study aims to investigate the impacts of climate change on climatic parameters and wheat phenology stages in Mazandaran province in the north of Iran. For this purpose, the CanESM5 model in three Shared Socioeconomic Pathway scenarios (SSP126, SSP245, and SSP585) was analyzed in three periods (2025-2049, 2050-2074, and 2075-2100). In order to evaluate the downscaling model, some indicators such as root mean square error, mean bias error, correlation coefficient, and Nash-Sutcliffe were employed. Also, to investigate the effect of climate change on wheat phenological stages, the growing degree days of each phenological stage were used. The findings indicated a temperature increase of 1.5 to 5 °C across minimum, maximum, and mean temperatures. Growing degree days variation results showed that the highest annual growing degree days is in the third period (i.e., 2075-2100), with an increase of 68.5% compared to the base period (1986-2020) under scenario SSP585. Based on the findings, it is projected that climate change will lead to a decrease in growth period length of autumn wheat. This reduction could range from 40 to 70 days, affecting all phenological stages of autumn wheat except for the waxy ripe and maturity stages. As a result of the shortened growth period length, the waxy ripe and maturity stages will occur in colder weather conditions, thereby prolonging the final phenological stages of autumn wheat. Considering the uncertainty of climate models, examining several General Circulation Models can help to express more accurate opinion on growth period length of wheat in the future.

INTRODUCTION

The rise in greenhouse gases and associated climate change has disrupted the Earth's climate system equilibrium, with global warming as its primary and most significant repercussion in the twenty-first century (Sheikhi Arjanaki et al., 2021). These changes have led to the changes in the average climate parameters and far-reaching impacts on human life and nature, including an increase in the average temperature of the Earth and the occurrence of weather phenomena such as floods, tropical storms, heat waves, and droughts (Bararkhanpour et al., 2024; Alotaibi, 2023; Eckardt et al., 2023; Barjaktarević, 2022). The Intergovernmental Panel on Climate Change (IPCC)'s 4th, 5th, and 6th Assessment Reports predicted global warming and its impacts, despite some skepticism. These predictions align with actual observations (Carvalho et al., 2022), and Coupled Model Intercomparison Project 6 (CMIP6) models further indicate increased extreme weather events (Zhang et al., 2024), significant climate region changes and a long-term impact of human interventions (Sheikhi Arjanaki et al., 2023). The latest predictions of the CMIP6 models indicate that the global average temperature will rise by more than 5.4 degrees Celsius in the highest emission scenario and by 1.1 degrees Celsius in the highest reduction scenario by the end of the 21st century (Ghazi et al., 2023). General circulation models are crucial for predicting climate change, but downscaling methods like Statistical Down Scaling Model (SDSM) are essential for improving spatial resolution (Dehghan et al., 2020; Baghanam et al., 2020; Munawar et al., 2022; Asgari et al., 2021; Legasa et al., 2023).

Climate change is accelerating wheat phenological stages, reducing growing periods, and decreasing yields (Ruja et al., 2022; Poggi et al., 2022; Ishtiaq et al., 2022; Phukon et al., 2022; Bouras et al., 2019). Warmer temperatures and altered precipitation patterns are key drivers. Understanding these impacts is crucial for predicting and adapting to future wheat production challenges. Liu et al. (2018) evaluated the impacts of climate change and crop management on the spring and winter wheat phenological processes during 1981-2010 in China. They found that an increase in temperature reduced the mean vegetative growth period and whole growth period and increased the reproductive growth period. It was suggested that planting and flowering dates could be controlled by proper management. Li et

*Corresponding author: Associate Professor, Department of Water Engineering, Sari Agricultural Sciences and Natural Resources University, Sari, Iran. I. R. Iran
E-mail address: m.nadi@sanru.ac.ir
https://doi.org/10.22099/iar.2024.49899.1582
Received 08 April 2024; Received in revised form 01 November 2024; Accepted 03 November 2024
Available online 25 January 2025

al. (2016) studied the effects of climate change on the phenology of winter wheat cultivars and performance in northern China. They concluded that a rise in temperature would diminish the Growth Period Length (GPL). However, changes in GPL had no significant trends. They also proposed that the replacement of new cultivars would make the phenology of winter wheat GPL longer by 3.3-8.3 days. Growing Degree Days (GDD) can aid in plant assessment, planting timing, and harvest prediction (Keramitsoglou et al., 2023). Studies highlight the importance of cultivar selection and sowing date adjustments (Lobell and Gourdji, 2012; Rezaei et al., 2018; Mukherjee et al., 2019). Specifically, Zhang et al. (2022) found that climate change will significantly impact winter wheat yields in China, with earlier maturation and yield declines in northern regions. Rezaei et al. (2018) and Mukherjee et al. (2019) also linked increased temperatures to accelerated wheat development and reduced yields. In Austria, Lalic et al. (2016) assessed the effectiveness of short-term Numerical Weather Prediction in predicting the accumulation of GDD and meteorological conditions for apple scab appearance. They found that short-term prediction is potentially effective in predicting apple scab appearance and has a slight advantage in lowland regions. In Iran, evaluation of wheat growth due to the climate change in Khuzestan province showed that under two scenarios of RCP4.5 and RCP8.5, the temperature will increase by 1.6 and 2.3 degrees Celsius, and the length of the growing season will decrease by 7.5% and 9.3%, respectively (Eyni-Nargeseh et al., 2019).

Abshenas et al. (2022) conducted a study in Golestan province using various models to assess how changes in temperature and rainfall impact wheat photosynthesis, respiration, and dry matter production. The study found that rising temperatures result in a shorter growing season for wheat and a decrease in photosynthesis, ultimately leading to the reduced wheat production by 2050. Additionally, the increasing temperatures and changing rainfall patterns in Mazandaran province caused several problems, including increased water requirements for agriculture, worsening drought, soil erosion, decreased fertility, and an increase in pests and plant diseases. To tackle these challenges, farmers in Mazandaran province need to adopt climate change adaptation strategies, such as adjusting cultivation patterns, improving irrigation methods, implementing modern irrigation systems, effectively managing agricultural waste, and raising awareness among farmers about climate change and its consequences (Keikha et al., 2022). An analysis of temperature and rainfall trends in Mazandaran province from 1981 to 2011 shows that air temperature has risen, and rainfall has declined. These climate variations have significantly affected the yields of key agricultural products like rice, wheat, and barley. Using simulation models, researchers predict that even a one-degree increase in temperature and a one-millimeter decrease in rainfall could require a shift in cultivation patterns in Mazandaran province (Darzi-Naftchali et al., 2016). Overall, climate change is widely recognized as a severe threat to agriculture in Mazandaran province. However, with careful planning, appropriate measures, and comprehensive cooperation among relevant authorities and farmers, it is possible to mitigate the adverse effects of this phenomenon and contribute to the long-term sustainability of agricultural production in the province.

Given the significant impact of climate change on the growth stages of crops in the future, particularly in Mazandaran province which is responsible for the majority of rice production in Iran, it is crucial to enhance wheat cultivation in the region through effective planning and management. This study aims to examine how climate change will influence the phenology stages of autumn wheat and the variations in GDD until the year 2100.

MATERIALS AND METHODS

Study area

Mazandaran province is located in the north of Iran and on the southern shore of the Caspian Sea. The province occupies an area of about 23,756 km², between (35.47° N, 36.35° N) and (50.34° E, 54.10° E). Meteorological data of maximum, minimum, and mean temperature were obtained from the synoptic stations, which recorded data for at least 30 years. Fig. 1 shows the study area and the location of meteorological stations (Nadi and Yousefi Kebriya, 2024).

This study used four meteorological stations with a temperate climate to downscale temperature data. The geography and climate of the meteorological stations are shown in Table 1, and the data covers the period 1986-2020 (Yousefi Kebriya et al., 2022). Moving from west to east in the province, the amount of rainfall reduces (Yousefi Kebriya et al., 2021), and the climate changes from per-humid A to sub-humid (Nadi and Dastigerdi, 2022).

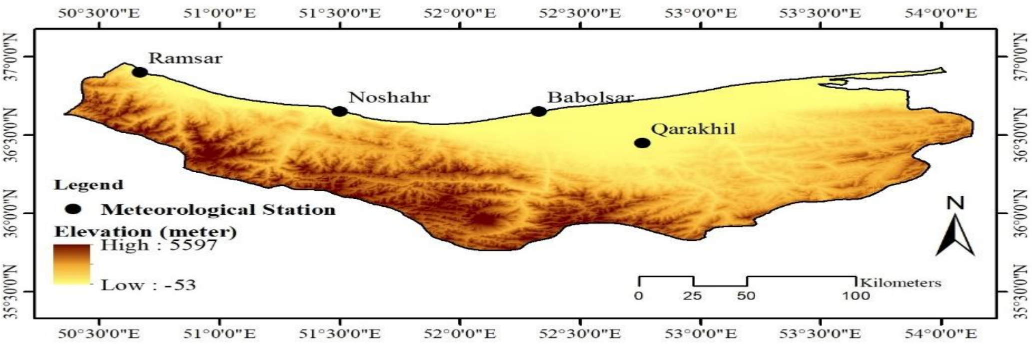

Fig. 1. Location of study area and studied meteorological stations.

Table 1. Geographical and climatic characteristics of the studied meteorological stations

Station	Lon	Lat	Elevation	T_{min}	T_{max}	T_{mean}	Rainfall	Climate
Babolsar	52.65	36.72	-21	14.7	21.5	17.8	939.2	Temperate humid
Ramsar	50.67	36.90	-20	14.1	20.2	16.9	1213.02	Temperate per-humid A
Noshahr	51.50	36.65	-20.9	13.5	20.3	16.7	1273.9	Temperate per-humid A
Qarakhil	52.77	36.45	14.7	12.9	22.1	17	695.5	Temperate sub humid

Downscaling of climate data

In this research, the outputs of the Canadian Earth System Model version 5 (CanESM5) were used, which is a global climate model developed by the Canadian Centre for Climate Modelling and Analysis of Environment and Climate Change Canada. CanESM5 simulations contribute to the CMIP6 and will be employed for climate science and service applications in Canada (Swart et al., 2019). The temperature data were downscaled using the SDSM 6.1 software package. SDSM was selected due to its proven effectiveness in handling complex terrain and its ability to incorporate a variety of predictors, making it suitable for our study area. In SDSM, suitable predictors were utilized for each meteorological variable based on the correlation matrix between variables (i.e., minimum, maximum, and mean temperatures) and 26 National Center for Environmental Prediction (NCEP) meteorological variables. These predictors were chosen as they represent key climatic factors influencing temperature variations in the region. Climatic data were produced by calibrating the parameters of the multiple regression equation between predicted selected variables and the intended meteorological variable (Wilby et al., 2002). The multiple regression approach was employed to capture the complex relationships between predictors and temperature. The climatic variable was downscaled until 2100 in three scenarios: SSP 126, SSP 245, and SSP 585, and the data were analyzed in four periods, i.e., base period (1986-2020), near future (2025-2049), middle future (2050-2074), and far future (2075-2100). These time periods and scenarios were selected to represent a range of potential future climate conditions, allowing for a comprehensive assessment of temperature changes.

GDD calculation

The GDD required for autumn wheat phenology was determined based on the plant’s response to the temperature, which varies for different day lengths and temperatures (Ritchie and Nesmith, 1991). Hence, GDD was initially calculated via Eq. (1), based on the determined planting date (i.e., October 23). The required GDD for the 7 phenology stages of autumn wheat in the base period of selected meteorological stations was calculated and compared with three future periods under different SSP scenarios.

$$GDD = \sum_0^n \frac{T_{max} + T_{min}}{2} - T_{base} \qquad \text{Eq. (1)}$$

where GDD is the total growing degree days for n days, T_{max} and T_{min} are the maximum and minimum daily temperatures, respectively, and T_{base} is the base temperature which is considered 4 °C (Hou et al., 2014).

Evaluation criteria

The root mean square error (RMSE), mean bias error (MBE), Pearson correlation coefficient (R), and Nash-Sutcliffe (NS) efficiency were employed to evaluate the performance of the temperature downscaling model. RMSE quantifies the average magnitude of the error between predicted and observed temperatures. MBE represents the average difference between predicted and observed values, indicating model bias. The Pearson correlation coefficient (R) measures the linear relationship between predicted and observed temperatures, with values ranging from -1 to 1, where 1 indicates perfect positive correlation. The NS efficiency assesses the overall model performance relative to the observed variance, with values closer to 1 indicating better agreement between predicted and observed data. These metrics were calculated according to Eq. (2), Eq. (3), and Eq. (4).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \qquad \text{Eq. (2)}$$

$$MBE = \frac{1}{n}\sum_{i=1}^n (p_i - o_i) \qquad \text{Eq. (3)}$$

$$NS = 1 - \left(\frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \overline{O}_i)^2}\right) \qquad \text{Eq. (4)}$$

where P_i is the estimated value, O_i is the observed value, and n is the number of data points. The lower values of the MAE and RMSE indicate the higher efficiency of the temperature downscale model, and the closer the R and NS values to 1 show the better the agreement between the model output and the actual data.

RESULTS

Data downscaling

The results of selecting suitable predictors from 26 atmospheric components for downscaling minimum, maximum, and average temperatures in the studied stations are shown in Table 2. Geopotential height at 500 hPa, relative humidity at 500 hPa, relative humidity at 850 hPa, surface specific humidity, and mean temperature at 2 m are the best predictors of temperature variables in the studied stations. These atmospheric components play crucial roles in temperature dynamics. Geopotential height at 500 hPa is associated with large-scale atmospheric circulation patterns, which significantly influence temperature advection. Relative humidity at both levels provides information about moisture content in the atmosphere, a key factor in radiative processes and latent heat fluxes affecting temperature. Surface specific humidity directly relates to near-surface moisture conditions, impacting evaporation and energy balance. Mean temperature at 2 meters represents the baseline temperature from which deviations due to other predictors can be assessed. The analysis of error evaluation indices in Table 2 indicates the appropriate downscaling of temperature data so that, in most cases, the R is more than 0.85, and the NS in most variables is greater than 0.75. Also, the MBE partial positive and negative values represent the absence of bias in the model downscaling. However, the data simulation was more acceptable for the Babolsar station, but in the Qarakhil station, the model showed weaker performance.

Projected temperature change

Comparison of observed and downscaled data for three future periods (i.e., 2025-2049, 2050-2074, and 2075-2100) under different SSP scenarios for mean, minimum, and maximum data is indicated in Table 3, Table 4, and Table 5, respectively. Overall, the mean temperature under scenario SSP126 in the period 2025-2049 would rise by 1.5 °C for all stations, and Qarakhil and Ramsar stations would increase by 1.9 and 1.5 °C, respectively, which are the highest values. The results also show that for the period 2075-2100, an increase of about 3 °C is predicted. Under scenario SSP245, the highest rise in the temperature of Ramsar station is 3 °C in the periods 2050-2074 and 2075-2100. For most of the stations under the pessimistic emission scenario (i.e., scenario SSP585), the rising temperature would reach 5 °C compared to the base period, as shown in Table 3. These projected temperature changes are expected to have profound implications for local ecosystems, agriculture, and human activities. Rising temperatures can lead to shifts in vegetation patterns, altered hydrological cycles, and increased heat stress for both humans and livestock. Agricultural yields may be impacted due to the changes in growing seasons, water availability, and the prevalence of pests and diseases. Furthermore, extreme heat events can pose significant health risks and infrastructure challenges. The observed trends in minimum and maximum temperatures are consistent with the overall warming pattern. The highest rise in the minimum temperature under scenario SSP126 is predicted to be 1.9 and 2.8 °C for Qarakhil and Ramsar stations in the periods 2050-2074 and 2075-2100, respectively. However, a slight temperature rise is observed for 2075-2100 compared to the period 2050-2074. The increase in the minimum temperature of Qarakhil station under scenarios SSP245 and SSP585 in the periods 2050-2074 and 2075-2100 has increased. Also, the rise in the minimum temperature in the periods 2050-2074 and 2075-2100 follows an incremental trend, as shown in Table 4. For the Qarakhil station, the maximum temperature in 2050-2074 under scenario SSP585 would increase to 5.36 °C. Overall, in all subsequent periods, the maximum temperature rises between 2.5-5.36 °C, as shown in Table 5. These results are in agreement with the study conducted via CMIP6 models. Tang et al. (2022) found that all extreme temperature indices show significant increasing trends under SSP245 and SSP585 scenarios in the Earth's three poles, including the Arctic, Antarctic, and Tibetan Plateau. Meinshausen et al. (2019) provided greenhouse gas concentration projections for the SSP scenarios, including SSP1-1.9 and SSP5-8.5, which influence temperature changes. Aadrita and Jahan (2021) assessed the impact of climate change on temperature extremes in Bangladesh under SSP126, SSP245, SSP370, and SSP585 scenarios, finding an increase in the frequency of hot days.

Table 2. Coefficients of selected predictors in Statistical Down Scaling Model (SDSM) and evaluation indices of downscaling the temperature variables

Station	Climate variable	Selected predictor					Evaluation indices			
		P500[1]	R500[2]	R850[3]	Shum[4]	Temp[5]	MBE	RMSE	R	NS
Babolsar	T_{max}	0.89	0.47	0.57	0.73	0.93	-0.34	2.47	0.94	0.89
	T_{mean}	0.90	0.52	0.62	0.78	0.95	0.35	1.88	0.96	0.93
	T_{min}	0.87	0.55	0.66	0.79	0.92	1.09	2.40	0.93	0.98
Ramsar	T_{max}	0.62	---	0.69	0.76	0.79	0	4.47	0.76	0.62
	T_{mean}	0.65	---	---	0.72	0.80	0.32	4.01	0.82	0.66
	T_{min}	0.64	---	---	0.72	0.79	0.78	4.15	0.78	0.65
Noshahr	T_{max}	0.81	---	0.57	0.70	0.83	-0.37	3.58	0.85	0.74
	T_{mean}	0.84	---	0.60	0.73	0.86	0.07	3.08	0.90	0.80
	T_{min}	0.83	---	0.60	0.73	0.86	0.12	3.07	0.90	0.78
Qarakhil	T_{max}	0.84	0.52	0.58	0.73	0.86	-0.12	3.42	0.88	0.78
	T_{mean}	0.79	0.47	0.54	0.80	0.68	-0.22	4.41	0.84	0.67
	T_{min}	0.82	---	0.58	0.73	0.85	-0.14	3.61	0.89	0.76

1. 500 hPa Geopotential height; 2. Relative humidity of 500 hPa; 3. Relative humidity of 850 hPa; 4. Surface specific humidity; 5. Mean temperature at 2 m. MBE: Mean Bias Error, RMSE: Root Mean Square Error, R: pearson correlation coefficient, NS: Nash-Sutcliffe

Table 3. Mean comparison of daily mean temperature in the future with base period data under different emission scenarios (°C)

Stations	Scenarios	Base period	2025-2049	2050-2074	2075-2100
Qarakhil	SSP126	16.92	18.41*	18.97*	18.93*
	SSP245	16.92	18.30*	19.28*	19.73*
	SSP585	16.92	18.54*	20.17*	22.01*
Babolsar	SSP126	17.11	18.19*	18.67*	18.63*
	SSP245	17.11	18.08*	18.97*	19.45*
	SSP585	17.11	18.28*	19.82*	21.46*
Noshahr	SSP126	16.16	17.34*	17.84*	17.82*
	SSP245	16.16	17.24*	18.16*	18.60*
	SSP585	16.16	17.43*	18.99*	20.69*
Ramsar	SSP126	16.04	17.57*	18.22*	18.11*
	SSP245	16.04	17.62*	18.48*	19.04*
	SSP585	16.04	17.73*	19.18*	21.09*

* $P < 0.05$

Table 4. Mean comparison of daily minimum temperature in the future with base period data under different scenarios (°C)

Stations	Scenarios	Base period	2025-2049	2050-2074	2075-2100
Qarakhil	SSP126	12.46	14.36*	14.86*	14.77*
	SSP245	12.46	14.20*	15.09*	15.53*
	SSP585	12.46	14.45*	15.96*	17.71*
Babolsar	SSP126	13.30	13.98*	14.47*	14.40*
	SSP245	13.30	13.83*	14.70*	15.07*
	SSP585	13.30	14.02*	15.54*	17.19*
Noshahr	SSP126	12.77	13.93*	14.44*	14.38*
	SSP245	12.77	18.83*	14.72*	15.15*
	SSP585	12.77	14.02*	15.54*	17.18*
Ramsar	SSP126	12.69	14.09*	14.76*	14.63*
	SSP245	12.69	14.15*	15.01*	15.53*
	SSP585	12.69	14.23*	14.70*	17.62*

* $P < 0.05$

Table 5. Mean comparison of daily maximum temperature in the future with base period data under different scenarios (°C)

Stations	Scenarios	Base period	2025-2049	2050-2074	2075-2100
Qarakhil	SSP126	21.40	22.93*	23.52*	23.49*
	SSP245	21.40	22.81*	23.83*	24.34*
	SSP585	21.40	23.06*	24.78*	26.76*
Babolsar	SSP126	20.94	22.14*	22.60*	22.58*
	SSP245	20.94	22.07*	22.90*	23.39*
	SSP585	20.94	22.21*	23.74*	25.27*
Noshahr	SSP126	19.57	20.76*	21.30*	21.26*
	SSP245	19.57	20.68*	21.61*	21.11*
	SSP585	19.57	20.78*	22.48*	24.24*
Ramsar	SSP126	19.39	21.07*	21.74*	21.65
	SSP245	19.39	21.11*	21.98*	22.55*
	SSP585	19.39	21.25*	22.71*	22.78*

* $P < 0.05$

Projected changes in GDD

The annual GDD trend under different scenarios is shown in Fig. 2, Fig. 3, and Fig. 4. According to these results, GDD follows an incremental trend in the current century. However, for scenario SSP126, GDD increases on a significant slope until 2050, and then the slope declines, with GDD remaining almost unchanged in the third decade. Based on scenario SSP245, the GDD variation trend is incremental. The incremental trend showed a more significant slope in the SSP585 outputs. The SSP126 outputs indicated a GDD rise of 31-53% for the next century. However, the SSP245 and SSP585 results suggested GDD rises of 43-98% and 74-121% until the end of 2100, respectively. Moreover, among the meteorological stations, Qarakhil and Babolsar stations have the highest and the lowest GDD estimations, respectively. The discrepancy in GDD estimates between Qarakhil and Babolsar stations is likely influenced by a combination of geographical, climatic, and possibly microclimatic factors. Potential factors contributing to this disparity include latitude and altitude, with Qarakhil's potentially higher location leading to increased solar radiation and, consequently, higher temperatures, boosting GDD. Additionally, coastal influences like cloudiness might moderate Babolsar's temperatures, resulting in reduced GDD. Furthermore, microclimatic conditions, such as local vegetation, can impact temperature and humidity, affecting GDD calculations for both stations. The increase in GDD value at all coastal stations in Mazandaran indicates that these areas have the potential to cultivate crops that thrive in higher temperatures in the future.

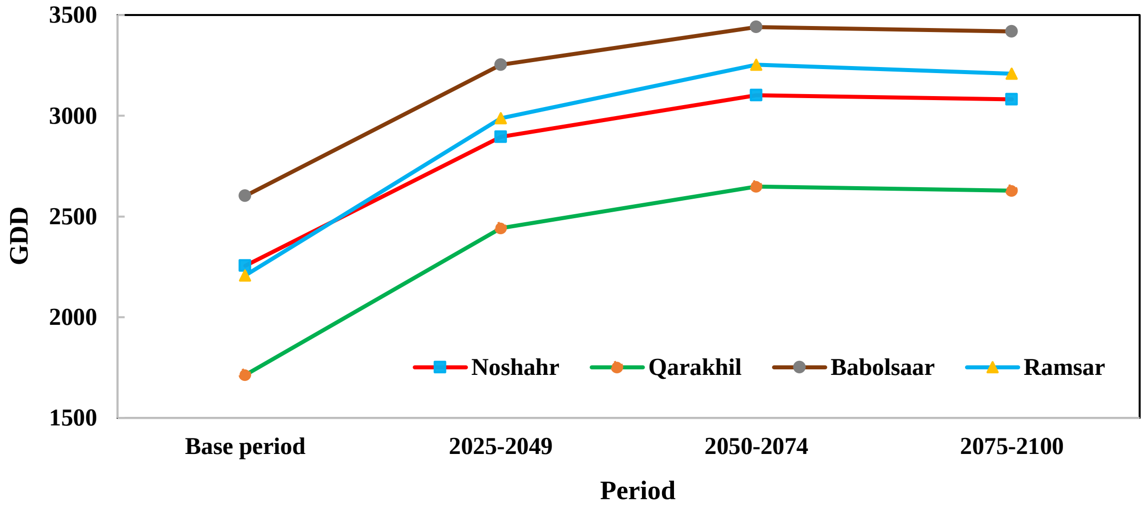

Fig. 2. Growing Degree Days (GDD) annual variations for autumn wheat in the future under the SSP126 scenario in studied stations.

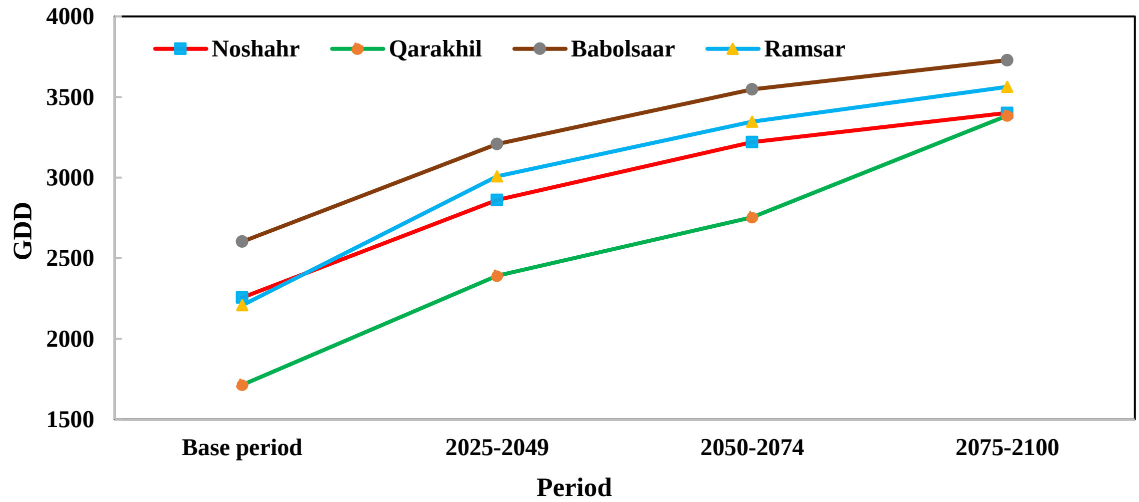

Fig. 3. Variation of annual Growing Degree Days (GDD) of autumn wheat in the future under SSP245 scenario in studied stations.

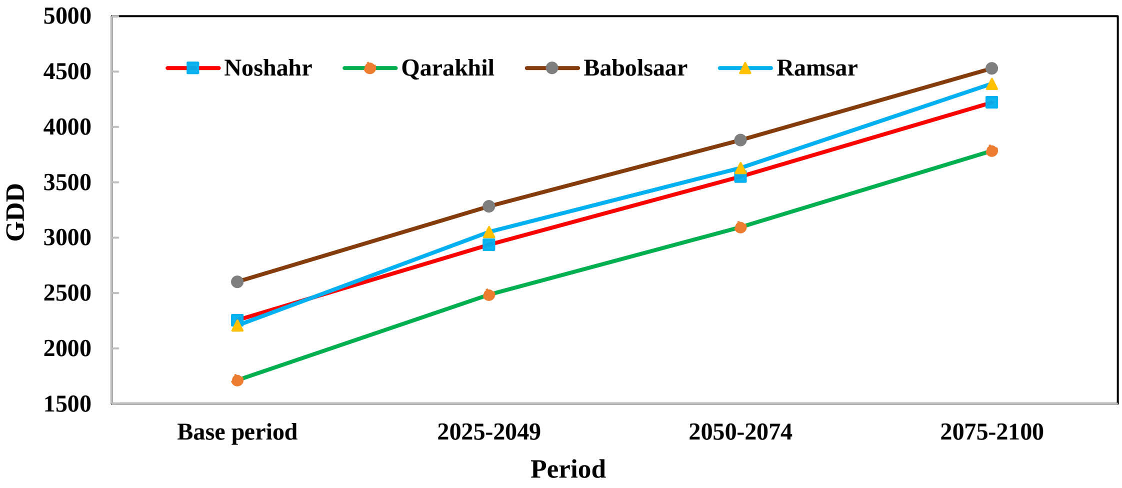

Fig. 4. Variation of annual Growing Degree Days (GDD) of autumn wheat under SS585 scenarios in studied stations.

Changing of phenology stage

The investigated wheat cultivar (Morvarid) has seven phenological stages, including germination, emergence, tillering, booting, flowering, waxy ripe, and maturity. The GDD requirements of each stage are 70, 400, 685, 875, 1075, 1575, and 1825 degree-days, respectively (Ritchie and Nesmith, 1991). The change of wheat phenological stages in meteorological stations under different scenarios is demonstrated in Fig. 5, Fig. 6, and Fig. 7. The results showed that the Qarakhil and Babolsar stations have the longest and the shortest GPL, respectively. Also, the GPL will be shortened in all meteorological stations and scenarios. In scenario SSP126, the shortening trend of GPL in the first period (2025-2049) is greater than in the other two periods, and the trend is constant in the last period (2075-2100). For Ramsar station, the GPL from germination to flowering reduced from 158 days to 113 days in 2025-2049 and 103 days for the periods 2050-2074 and 2075-2100. At the same time, since the waxy ripe and maturity stages happen in colder months, the total number of days with proper temperatures increased. Overall, GPL will reduce from the germination to waxy ripe stages. Also, for the period 2075-2100, approximately 25 days are reduced from the length of the period of germination to flowering in some stations. Still, for the Qarakhil station, this number reached 51 days, as shown in Fig. 5. The rise in temperature shortened the dormancy period and accelerated the flowering stage (late February). Nakatsuka et al. (2018) and Tun et al. (2021) found that the climate change causes early flowering and shortens GPL. The GPL variation in scenario SSP245 as shown in Fig. 6, demonstrate a descending trend on a moderate slope until 2100. These results are almost the same as those of scenario SSP126. The descending trend of GPL variation in scenario SSP585, as shown in Fig. 7, exhibited a steeper slope. In some stations, the cumulative number of days with suitable growth temperatures from germination to maturity increased by 63 days compared to the base period by the year 2100. For some stations, a slight difference from the base period was observed since the waxy ripe and maturity periods happen in colder months.

Other researchers in Iran have also reported a decrease in the length of wheat growth due to the climate change. For example, Rahmani et al. (2014) predicted a 30% decrease in the GPL and yield of wheat in the near future in the Birjand region. In the Zabol area, Mohammadi et al. (2018) discovered a reduction of 14 to 32 days in the GPL of wheat. Additionally, Ababaei et al. (2010) found in Isfahan that, along with shortening GPL, the relative and absolute yield of wheat would decline by 18%. In the Sararud region of Kermanshah, Mohammadi et al. (2014) revealed that climate change would not only reduce the GPL of wheat by 25 days but also decrease the suitable period for wheat cultivation by 9 to 20 days in the future.

Therefore, climate change can have a significant effect on wheat phenology in the investigated stations. The shortening of GPL in global warming conditions can create both opportunities and challenges for farmers. Among these opportunities, we can mention the possibility of growing several crops per year and reducing the need for irrigation. Farmers can respond to these changes by selecting suitable cultivars, adjusting planting dates, improving irrigation, nutrition management, crop diversification, and pest control, as observed in South Asia, where a significant temperature increase in 2022 resulted in earlier crop development compared to 2021 (Mehmood et al., 2023).

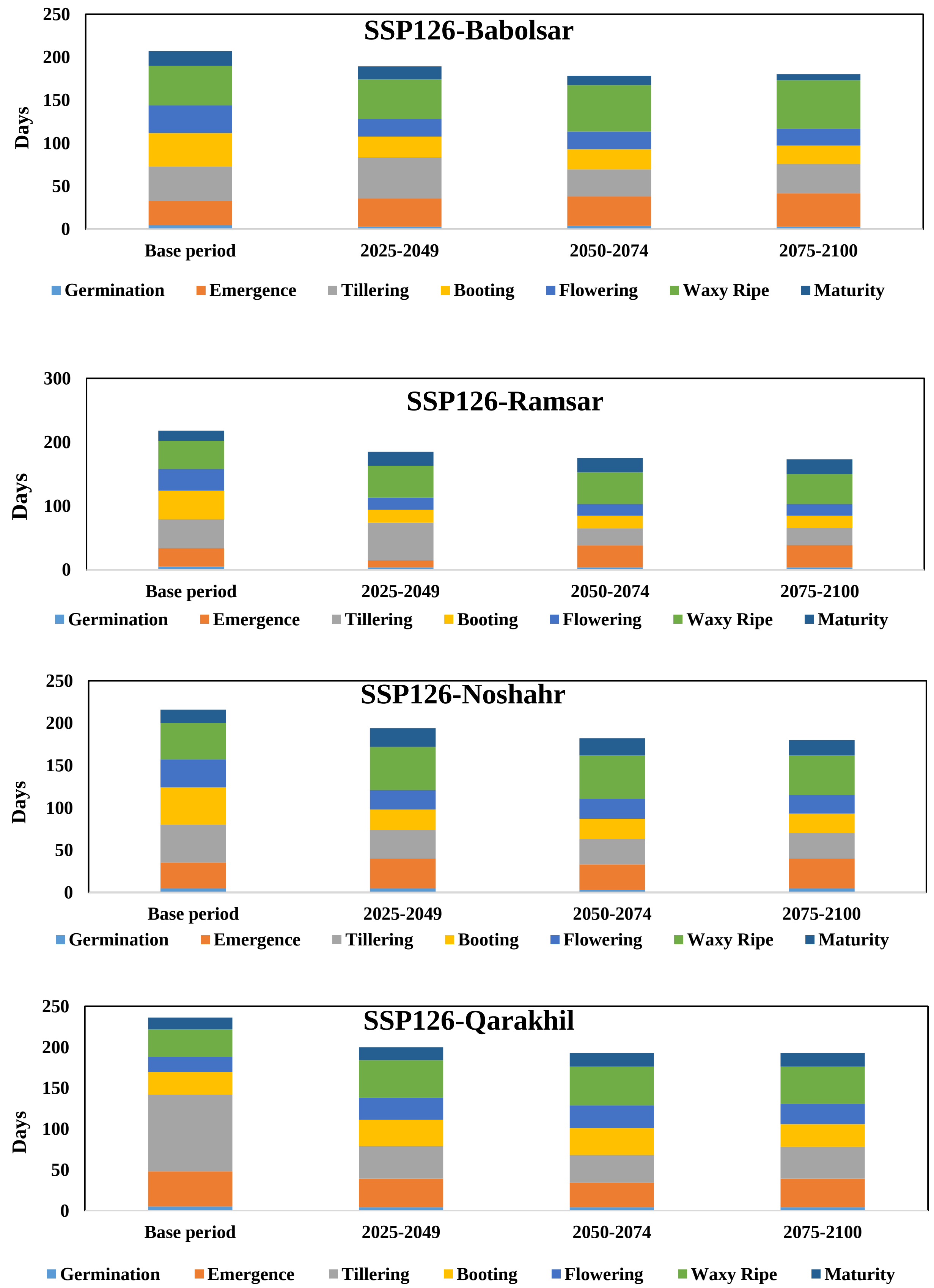

Fig. 5. Variation of phenology stages length under SSP126 scenario.

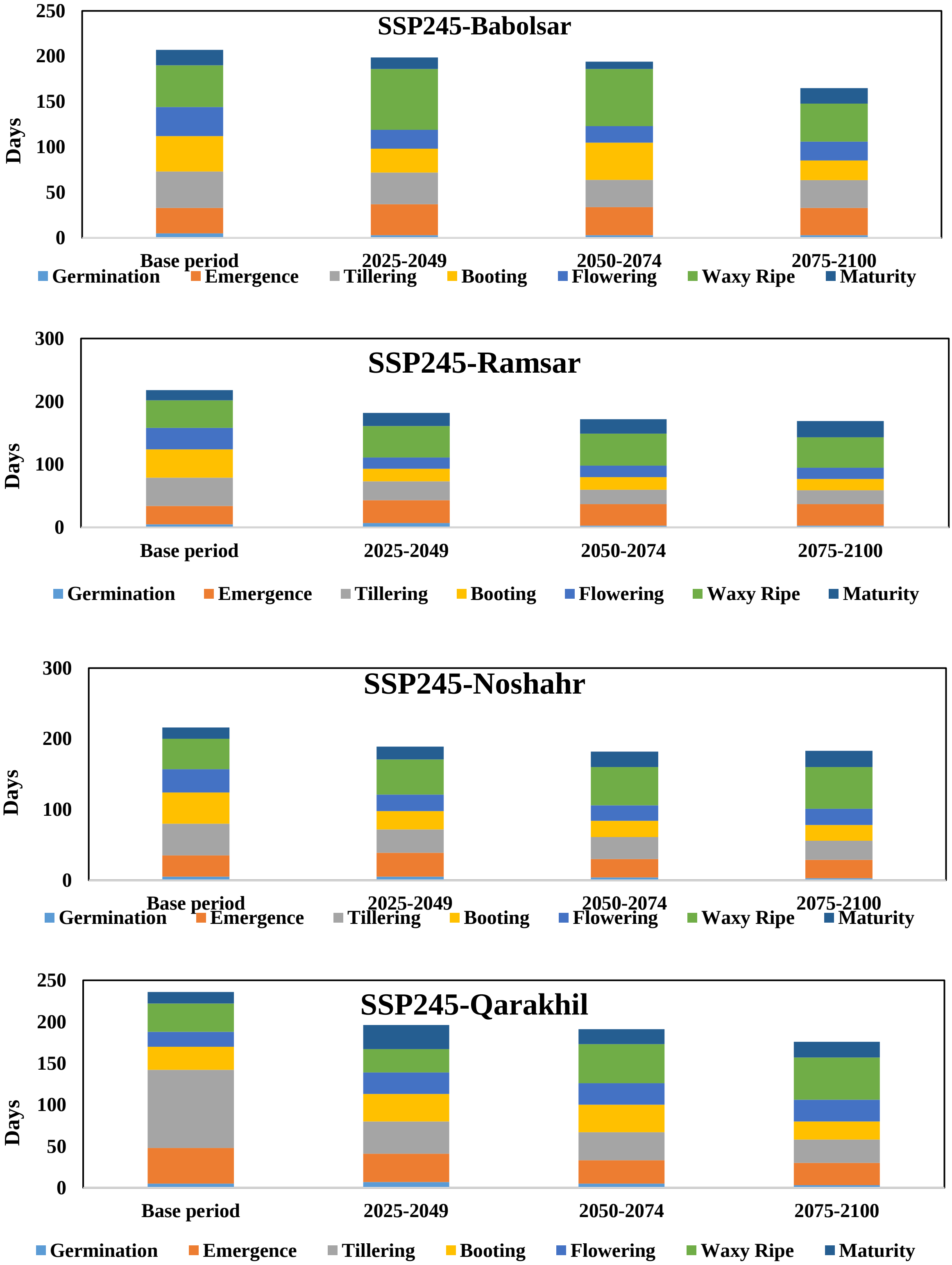

Fig. 6. Variation of phenology stages length under SSP245 scenario.

Fig. 7. Variation of phenology stages length under SSP585 scenario.

DISCUSSION

According to the results, the days that provide heating requirements for each plant stage, from germination to maturity, will reduce under different SSP scenarios until 2100. The results were consistent with Ren et al. (2019), suggesting that the temperature rise due to the climate change and a reduction in the number of freezing days make the start of the growing season earlier and reduce the GPL of spring and autumn wheat. Rising temperatures due to the climate change in Mazandaran will reduce the autumn wheat GPL by 40-70 days, resulting in early crop flowering. Reduced GPL under different SSP scenarios means less time for wheat growth to complete its life cycle, potentially hindering optimal yields. This phenomenon has also been mentioned in similar studies by Rahmani et al. (2014) and Ababaei et al. (2010). Muleke et al. (2022), Abendroth et al. (2021), and Ahmed (2015) have previously found that increasing GDD due to the climate change causes maturity to occur early, shortening the crop lifespan and decreasing crop production. Furthermore, Aslam et al. (2017) anticipated a decrease in flowering days for GDD in wheat phenological stages under high temperatures. According to Fatima et al. (2021), Ahmad et al. (2017), Hatfield and Prueger (2015), and Jagadish et al. (2016), high temperatures accelerate phenological stages, resulting in early maturity and crop aging, as well as changes in planting management and crop usage. It seems that there is a shortening trend in phenological stages, from germination to flowering until 2100 under different SSP scenarios; also, the flowering stage will change from March to late January. For most of the studied stations, the maturing stage under high radiation was predicted for late March, while maturing happens in May under scenario SSP126. This can be fixed by proper cultivar management or breeding. It is worth noting that although GPL reduces due to the climate change, the waxy ripe and maturity length increase in most scenarios, despite the changes in the other phenological stages due to the shifting of these last two stages from June to the colder months of May and April.

CONCLUSION

According to the results, climate change and increased temperature seem to make it possible to cultivate wheat in the highlands of Mazandaran province with enough spring precipitation. However, the crop yield may be improved by cultivation management and using climate-compatible species. The combined effects of reduced GPL, early phenology, and potential water scarcity can impact crop yield. While some areas may benefit from milder winters, others may suffer from heat stress and water limitations, and its implications for agricultural productivity and food security are significant. Changes in phenological stages may disrupt traditional agricultural practices and increase the risk of crop loss. However, these challenges also present opportunities. Farmers can mitigate negative effects and ensure sustainable wheat production by adopting weather-resistant cultivars, changing planting dates, and implementing efficient irrigation methods. Climate change not only impacts the phenological stages and growth period of wheat but also affects its overall yield and grain yield. Furthermore, it has the potential to contribute to the spread of plant diseases, either by altering phenological stages or by reducing the prevalence of common diseases through high temperatures and the elimination of pest insects. These scenarios warrant further research and discussion regarding the effects of climate change on the growth and development of wheat.

FUNDING

No funding was received for this research.

CrediT AUTHORSHIP CONTRIBUTION STATEMENT

All authors contributed to the study's conception and design. In this research: Conceptualization, Methodology, Validation, Review and editing the final format was performed by the first author: Mehdi Nadi. Also, Software, Data curation, Visualization and original draft preparation was done by the second author: Bahareh Shamgani Mashhadi.

DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY

Data will be made available upon request to the corresponding author.

ETHICAL STATEMENT

This research was conducted in according to the ethical standards, ensuring that all data collection, analysis, and reporting processes are conducted with integrity, transparency, and respect for participant confidentiality.

ACKOWLEDGEMENTS

The Authors would like to thanks the Iranian Meteorological Organization for providing us with the meteorological data.

REFERENCES

Aadrita, M. M., & Jahan, N. (2021). *Projection of precipitation and temperature extremes over Bangladesh from CMIP6 SSP-RCP scenarios.* New Orleans, USA: AGU Fall Meeting.

Ababaei, B., Sohrabi, T., Mirzaei, F., Rezaverdinejad, V., & Karimi, B. (2010). Climate change impact on wheat yield and analysis of the related risks:(Case study: Esfahan Ruddasht Region). *Water and Soil Science (Agricultural Science)*, *20.1*(3),135-150. (In Persian).

Abendroth, L. J., Miguez, F. E., Castellano, M. J., Carter, P. R., Messina, C. D., Dixon, P. M., & Hatfield, J. L. (2021). Lengthening of maize maturity time is not a widespread climate change adaptation strategy in the US Midwest. *Global Change Biology*, *27*(11), 2426-2440. https://doi.org/10.1111/gcb.15565.

Abshenas, A., Kamkar, B., Soltani, A., & Kazemi, H. (2022). Predicting the effects of climate change on physiological parameters determining wheat yield in 2050 (case study: Golestan province, Iran). *Environ Monit Assess*, *194*(10), 734. https://doi.org/10.1007/s10661-022-10428-7.

Ahmad, S., Abbas, Q., Abbas, G., Fatima, Z., Rehman, A., Naz, S., Younis, Jahanzeb Khan, R., Wajid, N., Rehman, M. H, Ahmad, A., Rasul, Gh., Khan, M. A., & Hasanuzzaman, M. (2017). Quantification of climate warming and crop management impacts on cotton phenology. *Plants*, *6*(1),7. https://doi.org/10.3390/plants6010007.

Ahmed, M. (2015). Response of spring wheat (*Triticum aestivum* L.) quality traits and yield to sowing date. *PloS one*, *10*(4), p.e0126097. https://doi.org/10.1371/journal.pone.0126097

Alotaibi, M. (2023). Climate change, its impact on crop production, challenges, and possible solutions. *Notulae Botanicae Horti AgrobotaniciCluj-Napoca*, *51*(1), 13020-13020. https://doi.org/10.15835/nbha51113020.

Asgari, A., Darzi-Naftchali, A., Nadi, M., & Saber Ali, S. F. (2021). Predicting temperature and solar radiation by SDSM model based on RCP scenarios (Case Study: Gharakheil synoptic station). *Irrigation and Water Engineering*, *12*(1), 348-363. (In Persian) https://doi.org/10.22125/iwe.2021.138350.

Aslam, M. A., Ahmed, M., Stöckle, C. O., Higgins, S. S. & Hayat, R. (2017). Can growing degree days and photoperiod predict spring wheat phenology? *Frontiers in Environmental Science*, *5*, 57. https://doi.org/10.3389/fenvs.2017.00057.

Baghanam, A. H., Eslahi, M., Sheikhbabaei, A., & Seifi, A. J. (2020). Assessing the impact of climate change over the northwest of Iran: An overview of statistical downscaling methods. *Theoretical and Applied Climatology*, *141*(3), 1135-1150. https://ui.adsabs.harvard.edu/link_gateway/2020ThApC.141.1135B/doi:10.1007/s00704-020-03271-8.

Bararkhanpour Ahmadi, S., Nadi, M., Mazloum Babanari, S., & Jedariforoughi, A. (2024). Analyzing the effect of climate change on the trend of extreme temperatures along the coast of Mazandaran province based on CMIP6 models. *Journal of Water and Soil Protection Research*, *30*(4), 1-27. (In Persian) https://doi.org/10.22069/jwsc.2023.21185.3635.

Barjaktarević, D. A. (2022). Climate changes-challenges and possible solutions. *Baština*, *32*(57), 165-175. https://doi.org/10.5937/bastina32-33831.

Bouras, E., Jarlan, L., Khabba, S., Er-Raki, S., Dezetter, A., Sghir, F., & Tramblay, Y. (2019). Assessing the impact of global climate changes on irrigated wheat yields and water requirements in a semi-arid environment of Morocco. *Scientific Reports*, *9*(1), 19142. https://doi.org/10.1038/s41598-019-55251-2.

Carvalho, D., Rafael, S., Monteiro, A., Rodrigues, V., Lopes, M., & Rocha, A. (2022). How well have CMIP3, CMIP5 and CMIP6 future climate projections portrayed the recently observed warming. *Scientific Reports*, *12*(1), 11983. https://doi.org/10.1038/s41598-022-16264-6

Darzi-Naftchali, A., Maldar-Badeli, M., Ziatabar-Ahmadi, M., & Karandish, F. (2016). Analyzing climate change effects on agriculture sustainability in Mazandaran province. *Iranian Journal of Irrigation and Drainage*, *9*(6), 994-1004. (In Persian).

Dehghan, S., Salehnia, N., Sayari, N., & Bakhtiari, B. (2020). Prediction of meteorological drought in arid and semi-arid regions using PDSI and SDSM: A case study in Fars province, Iran. *Journal of Arid Land*, *12*, 318-330. http://dx.doi.org/10.1007/s40333-020-0095-5.

Eckardt, N. A., Ainsworth, E. A., Bahuguna, R. N., Broadley, M. R., Busch, W., Carpita, N. C., & Zhang, X. (2023). Climate change challenges, plant science solutions. *The Plant Cell*, *35*(1), 24-66. https://doi.org/10.1093/plcell/koac303.

Eyni-Nargeseh, H., Deihimfard, R., Rahimi-Moghaddam, S., & Mokhtassi-Bidgoli, A. (2019). Analysis of growth functions that can increase irrigated wheat yield under climate change. *Meteorological Applications*, *27*(1), 1-10. https://doi.org/10.1002/met.1804.

Fatima, Z., Abbas, G., Iqbal, P., Zakir, I., Khan, M. A., Kamal, G. M., & Ahmad, S. (2021). Quantification of climate warming and crop management impacts on phenology of pulses-based cropping systems. *International Journal of Plant Production*, *15*, 107-123. https://doi.org/10.1007/s42106-020-00112-6.

Ghazi, B., Przybylak, R., & Pospieszyńska, A. (2023). Projection of climate change impacts on extreme temperature and precipitation in Central Poland. *Scientific Reports*, *13*(1), 18772. https://doi.org/10.1038/s41598-023-46199-5.

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4-10. https://doi.org/10.1016/j.wace.2015.08.001.

Hou, P., Liu, Y., Xie, R., Ming, B., Ma, D., Li, S. & Mei, X. (2014). Temporal and spatial variation in accumulated temperature requirements of maize. *Field Crops Research*, *158*, 55-64. https://doi.org/10.1016/j.fcr.2013.12.021.

Ishtiaq, M., Maqbool, M., Muzamil, M., Casini, R., Alataway, A., Dewidar, A. Z., & Elansary, H. O. (2022). Impact of climate change on phenology of two heat-resistant wheat varieties and future adaptations. *Plants*, *11*(9), 1180. https://doi.org/10.3390/plants11091180.

Jagadish, S. V., Bahuguna, R. N., Djanaguiraman, M., Gamuyao, R., & Prasad, P. V. (2016). Implications of high temperature and elevated CO2 on flowering time in plants. *Frontiers in Plant Science*, *7*, 166037. https://doi.org/10.3389/fpls.2016.00913.

Keikha, A., Khanlary, A., Ali Keikha, A., & Sabouhi, M. (2021). The effect of climate change on land usage and agricultural sector performance in Mazandaran province. *Environmental Science and Technology*, *22*(10), 93-104. (In Persian). https://doi.org/10.22034/jest.2019.7770.1642.

Keramitsoglou, I., Sismanidis, P., Sykioti, O., Pisinaras, V., Tsakmakis, I., Panagopoulos, A., & Kiranoudis, C. T. (2023). SENSE-GDD: A satellite-derived temperature monitoring service to provide growing degree days. *Agriculture, 13*(5), 1108. https://doi.org/10.3390/agriculture13051108.

Lalic, B., Francia, M., Eitzinger, J., Podraščanin, Z., & Arsenić, I. (2016). Effectiveness of short-term numerical weather prediction in predicting growing degree days and meteorological conditions for apple scab appearance. *Meteorological Applications*, *23*(1), 50-56. http://dx.doi.org/10.1002/met.1521.

Legasa, M. N., Thao, S., Vrac, M., & Manzanas, R. (2023). Assessing three perfect prognosis methods for statistical downscaling of climate change precipitation scenarios. *Geophysical Research Letters*, *50*(9). e2022GL102525.https://doi.org/10.1029/2022GL102525.

Li, K., Yang, X., Tian, H., Pan, S., Liu, Z. & Lu, S. (2016). Effects of changing climate and cultivar on the phenology and yield of winter wheat in the North China Plain. *International Journal of Biometeorology*, *60*(1), 21-32. https://doi.org/10.1007/s00484-015-1002-1.

Liu, Y., Chen, Q., Ge, Q., Dai, J., Qin, Y., Dai, L., Zou, X., & Chen, J. (2018). Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. *Agricultural and Forest Meteorology*, 248, 518-526. http://dx.doi.org/10.1016%2Fj.agrformet.2017.09.008.

Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. *Plant Physiology*, 160(4), 1686-1697. https://doi.org/10.1104/pp.112.208298.

Mehmood, V., Malik, A. I., Zafar, Z., Shahzad, M., Berns, K., & Fraz, M. M. (2023). Multi-year monitoring of wheat phenology and effect of climate change in the south Asian region using Sentinel-2 NDVI time series analysis, In *Image and Signal Processing for Remote Sensing XXIX*, Amsterdam, Netherlands. SPIE-International Society for Optics and Photonics. http://dx.doi.org/10.1117/12.2683148.

Meinshausen, M., Nicholls, Z., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., & Wang, H. J. (2019). The SSP greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development Discussions*, *13*(8) 3571–3605. https://doi.org/10.5194/gmd-2019-222.

Mohammadi, E., Yazdanpnah, H., & Mohammadi, F. (2014). Event of climate change, its impact on durum wheat planting and during the growing season case study: station of Sararood, Kermanshah. *Physical Geography Research*, *46*(2), 231-246. (In Persian) https://doi.org/10.22059/jphgr.2014.51427.

Mohammadi, H. R., Ramroudi, M., Bannayan, M., Asgharipour, M. R., & Fanaee, H. R. (2018). Effect of climate change on phenological stages and growth stages of wheat in Zabol region. *Journal of Plant Ecophysiology*, *10*(34), 181-191. (In Persian) https://www.magiran.com/p1947678.

Mukherjee, A., Wang, S. Y. S., & Promchote, P. (2019). Examination of the climate factors that reduced wheat yield in Northwest India during the 2000s. *Water, 11*(2), 343. https://doi.org/10.3390/w11020343

Muleke, A., Harrison, M. T., De Voil, P., Hunt, I., Liu, K., Yanotti, M., & Eisner, R. (2022). Earlier crop flowering caused by global warming alleviated by irrigation. *Environmental Research Letters, 17*(4),044032. https://doi.org/10.1088/1748-9326/ac5a66.

Munawar, S., Tahir, M. N., & Baig, M. H. A. (2022). Twenty-first century hydrologic and climatic changes over the scarcely gauged Jhelumriver basin of Himalayan region using SDSM and RCPs. *Environmental Science and Pollution Research*, 29, 11196-11208. https://doi.org/10.1007/s11356-021-16437-2.

Nadi, M., & Dastigerdi, M. (2022). Preparation of Mazandaran province climate map with extended de-martonne method. Second National Conference on Environmental Changes Using Remote Sensing Technology and GIS, Poster presentation, complete article, Sari, Iran. Civilica. (In Persian).

Nadi, M., & Yousefi Kebriya, A. (2024). A method for correction of tropical rainfall measuring mission satellite temperature network in Mazandaran province. *Iranica Journal of Energy and Environment*, *15*(1), 100-110. https://doi.org/10.5829/ijee.2024.15.01.10.

Nakatsuka, T., Ide, M., Omiya, R., & Ohno, H. (2018). Effect of storage temperature and its period on bud emergence and flowering of Leucocoryne bulbs. *Horticultural Research (Japan)*, *17*(2), 211-217. http://dx.doi.org/10.2503/hrj.17.211

Phukon, S. N., Kumar, M., Singh, H., & Nandy, S. (2022). Climate change and plant phenological variability. In *Climate change alleviation for sustainable progression*, (pp256-279). CRC Press.

Poggi, G. M., Aloisi, I., Corneti, S., Esposito, E., Naldi, M., Fiori, J., & Ventura, F. (2022). Climate change effects on bread wheat phenology and grain quality: A case study in the north of Italy. *Frontiers in Plant Science*, 13, 936991. https://doi.org/10.3389/fpls.2022.936991

Rahmani, M., Jami Al-Ahmadi, M., Shahidi, A., & Hadizadeh Azghandi, M. (2014). Effects of climate change on the length of growth stages and water requirement of wheat and barley (Case Study: Birjand Plain). *Journal of Agroecology*, *7*(4), 443-460. In (Persian) https://doi.org/10.22067/jag.v7i4.26666

Ren, S., Qin, Q., & Ren, H. (2019). Contrasting wheat phonological responses to climate change in global scale. *Science of the Total Environment*, 665,620-631. https://doi.org/10.1016/j.scitotenv.2019.01.394

Rezaei, E. E., Siebert, S., Hüging, H., & Ewert, F. (2018). Climate change effect on wheat phenology depends on cultivar change. *Scientific Reports*, *8*(1),48-91. https://doi.org/10.1038/s41598-018-23101-2

Ritchie, J. T., & Nesmith, D., S. (1991). Temperature and crop development. *Modeling Plant and Soil Systems, 31*, 5-29. http://dx.doi.org/10.2134/agronmonogr31.c2

Ruja, A., Gorinoiu, G., Suhai, K. R., Agapie, A. L., Sala, F., & Maria Istrate-Schiller, C. (2022). The effect of climate conditions on the phenological features of the autumn oat crop. *Life Science and Sustainable Development, 3*(1), 91-97. https://doi.org/10.58509/lssd.v3i1.172.

Sheikhi Arjanaki, Sh., Nadi, M., Rahmaninia, J., & Mohammad Nazari, B. (2023). Quantifying the impact of climate change on milk production in one of industrial livestock farms in Babolsar. *Research on Animal Production*, *14*(39), 112-120. (In Persian) http://dx.doi.org/10.61186/rap.14.39.112

Sheikhi Arjanaki, Sh., Nadi, M., Rahmaninia, J., & Mohammad Nazari, B. (2021). Climate change impacts on temperature humidity index, (Case study: Ramsar and Babolsar stations). *Journal of Agricultural Meteorology*, *9*(2), 39-47. (In Persian) https://doi.org/10.22125/agmj.2021.284851.1114

Swart, N. C., Cole, J. N., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W.G., Majaess, F., Saenko, O.A., Seiler, Ch., Seinen, C., Shao, A., Sigmond, M., Solheim, L., Salzen, K. V., Yang, D., & Winter, B. (2019). The Canadian earth system model version 5 (CanESM5. 0.3). *Geoscientific Model Development*, *12*(11),4823-4873. https://doi.org/10.5194/gmd-12-4823-2019.

Tang, B., Hu, W., Duan, A., Gao, K., & Peng, Y. (2022). Reduced risks of temperature extremes from 0.5 C less global warming in the Earth's three poles. *Earth's Future*, *10*(2), 1-22. https://doi.org/10.1029/2021EF002525

Tun, W., Yoon, J., Jeon, J. S., & An, G. (2021). Influence of climate change on flowering time. *Journal of Plant Biology*, 64(3), 193-203. https://doi.org/10.1007/s12374-021-09300-x

Wilby, R.L., Dawson, C.W., & Barrow, E.M. (2002). SDSM-a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software*, 17(2), 145-157. https://doi.org/10.1016/S1364-8152%2801%2900060-3

Yousefi Kebriya, A., Nadi, M., & Jamei, M. (2022). Combining interpolation methods and precipitation products of TRMM satellite to increase the accuracy of rainfall maps in Mazandaran province. *Journal of Water and Soil Conservation*, *28* (3), 49-70. (In Persian). https://doi.org/10.22069/jwsc.2022.19286.3477

Yousefi kebriya, A., Nadi, M., & Jamei, M. (2021). Investigation of statistical and geostatistical methods in preparing the rainfall map of Mazandaran province, *Journal of Watershed Management Research*, *12*(23), 212-223 (In Persian). https://doi.org/10.52547/jwmr.12.23.212.

Zhang, B., Song, S., Wang, H., Guo, T., & Ding, Y. (2024). Evaluation of the performance of CMIP6 models in simulating extreme precipitation and its projected changes in global climate regions. *Natural Hazards*. https://doi.org/10.1007/s11069-024-06850-4

Zhang, L., Wang, F., Song, H., Zhang, T., Wang, D., Xia, H., & Min, R. (2022). Effects of projected climate change on winter wheat yield in Henan, China. *Journal of Cleaner Production*, *379*, 134734. https://doi.org/10.1016/j.jclepro.2022.134734.