Climatology and Trends in Temperature-Based Agroclimatic Indices Over Western Anatolia, Turkey

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Research Article

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Abstract

Temperature has a control on growth, development and yield of crops. Extreme high and low temperatures can be a limiting factor on crops. Extreme temperatures have accompanied global average temperature increase. Investigating the changes in indices derived using daily minimum and maximum temperatures may provide information about how extreme temperatures related to crop production have changed under global warming. In this sense, it is aimed in this study to investigate the climatology and monotonic temporal trends of a number of temperature-based agroclimatic indices with use daily minimum (TN) and maximum (TX) temperatures recorded over the period from 1966 to 2018 at 36 weather stations across western Anatolia, Turkey. The temperature-based agroclimatic indices were divided into two groups, cold-related and heat-related indices. The cold-related indices included number of frost days (NFD), first fall/winter frost (FFF), last winter/spring frost (LSF), frost period (FP) and accumulated frost (AF), where a frost was defined as when TN is equal to or less than 0°C. The heat-related indices were comprised of plant heat stress day (PHSD), plant heat stress accumulation (PHSA), growing season start (GSS), growing season end (GSE), growing season length (GSL) and growing degree-day (GDD). Significance of trends were assessed using Mann-Kendall test, and the slopes of trends were quantified by Sen's Slope Estimator. The results firstly showed that southern and western coastal stations have the lowest frequency, intensity and duration of frost as a result of rarely occurring frost events. These stations are also characterized by the highest GDD, the earliest GSS, the latest GSE and hence the longest GSL, even with never-ending growing seasons in many years. They are also exposed to the highest heat stress in terms of frequency and intensity. On the other hand, the stations located in the North-eastern part of the study area have completely opposite character for all indices in comparison to southern and western coastal stations. Trend analysis revealed that frequency of frost events had decreasing trends (i.e., decreased NFD), accompanied by later onset of FFF, earlier onset of LSF, and hence shortened FP and decreased AF. As for growing season indices, in general, GSS occurred earlier, GSE occurred later, and GSL extended. Growing degree-day and heat stress indices had substantial increasing trends, implying that, over the course of study period, the study area have had more thermal accumulation, and exposed to more heat stress that may hinder crop development.

1 Introduction

Temperature is one of the main controlling factors on growth, development and yield of crops (Hatfield and Prueger 2015). This control can be simply handled in two ways. One is related with their thermal requirements. Some basic thermal requirements have to be met in order to fulfill not only their particular phenophases but also whole life cycle (Luo 2011). The other one is related with extreme temperatures. Very high or low temperatures can be a limiting factor on crops, particularly during crucial phenophases like anthesis, which may slow down the growth, cause injury or death, and yield loss (Luo 2011; Piticar 2019).

Global average temperature has been increasing for more than one hundred years due to emissions of greenhouse gases (mainly, carbondioxide) into atmosphere. Increased temperature would be beneficial

for high latitude regions, allowing more favourable conditions for crop production, by creating longer and warmer growing season (Hassol and Corell 2006). On the other hand, the most prominent impact of the warming on crops is related with extreme temperatures since observations showed that changes in extreme temperature events have accompanied global average temperature increase, e.g. decreased cold days and nights, increased warm days and nights (IPCC 2013).

The impact of temperature on crop growth and yield are assessed based not only on average temperature but also on temperature-derived proxies/indices (Kukal and Irmak 2018). Various indices/proxies derived with use of daily minimum and/or maximum temperatures provide information about how extreme temperatures related to crop production have changed under global warming, which may not be captured by examining the changes in average temperature (Kukal and Irmak 2018). These indices, also called as temperature-based agroclimatic indices, can be divided into two broad categories as cold-related and heat-related indices. Cold-related indices are associated with detrimental impacts of low temperatures. Number of frost days (NFD), first fall frost (FFF), last spring frost (LSF), frost period (FP) or frost-free period (FFP) are among the most-widely used cold-related indices. On the other hand, heat related indices are related with the adverse effects of high temperatures on crop development or with thermal requirement of crops, such as plant heat stress days (PHSD), growing degree-day (GDD), growing season start (GSS), growing season end (GSE) or growing season length (GSL). The results of previous studies have documented changes, in general, toward warmer conditions, decreases in incidences, duration or strength of cold-related indices (e.g., shorter FP, earlier LSF or decreased NFD), and/or increases in those of heat related indices (e.g., increased PHSD, earlier GSS, later GSE or increased GDD), in USA (Anandhi et al. 2013a; Anandhi et al. 2013b; Kukal and Irmak 2018), in the Balkan Peninsula (Charalampopoulos 2021), in Chile (Piticar 2019), in Poland (Graczyk and Kundzewicz 2016), in Canada (Shen et al. 2005), in the Iberian Peninsula (Garcia-Martin et al. 2021), in Argentina (Brendel et al. 2020; Fernandez-Long et al. 2013), in Russia (Grigorieva et al. 2010; Gudko et al. 2021), in Central Europe (Wypych et al. 2017).

Agriculture is of prime importance for western Anatolia, Turkey, where a very wide range of field and horticultural crops are grown. Given the fact that temperature increase is spatially inhomogeneous around the globe, and impacts of warming on agricultural crops should be evaluated for regional and sub-regional scales (Kukal and Irmak 2018), and that the Mediterranean basin, including western Turkey, has been considered as region susceptible to present and future climate change (Caloiero and Guagliardi 2021; Goubanova and Li 2007), it would be crucial to document how the temperature-based agroclimatic indices have changed under global warming in Western Anatolia. In this study, a number of temperature-based agroclimatic indices were analysed for their climatology and long-term (from 1966 to 2018) temporal changes over western Anatolia, Turkey. The findings are expected to contribute to the implementation of measures for climate change adaptation and mitigation in Western Turkey, and to the current knowledge on their changes in regional/subregional scale from climatological point of view.

2 Materials And Methods

2.1 Study area

Western Anatolia, roughly enclosed by the latitudes 36.3 N and 40.3 N, and longitudes 26.4 E and 30.6 E (Fig. 1). It is neighbored by three water bodies, Marmara Sea on the North, Aegean Sea on the West and Mediterranean sea on the South. The climate is Mediterranean climate in the western and southern parts. Summer season is hot and dry, and winter is mild and rainy. Snow and frost are rare in coastal parts. Winter is cold and snowy in high elevations. January and July are the coldest and hottest months, with average temperatures of 6.4°C and 26.8°C, respectively. Annual average temperature is about 16.3°C. Annual average precipitation is 725.9 mm, and most of it falls in winter. Percentage of summer rainfall is 5.7%. Marmara climate is dominant in northern part of study area. It is a transition between Mediterranean and Black Sea climates. Winter is not as mild as Mediterranean, and summer is not as rainy as Black Sea Climate. It has warmer winter and wetter summer than continental climate. Average temperature is 4.9 and 23.7°C in January and July, which are the coldest and hottest months, respectively. Annual average temperature and total rainfall are 23.7°C and 595.2 mm, respectively (Şensoy et al. 2022).

2.2 Data

Daily minimum (TN) and maximum (TX) temperatures recorded during the period from 1966 to 2018 at 36 weather stations operated by State Meteorological Agency of Turkey were used to produce agroclimatic indices. The stations are listed in Table 1, and shown in and Table 1. These stations were selected considering the longest common period of record, and minimal missing data. TN and TX data were subjected to a careful quality control procedure to detect missing data and to verify that TX was greater than TN. Missing data were less than 0.15% for any series at any station. Missing data were filled by using data of neighboring stations with simple linear regression (Hu et al. 2012). Annual mean series of TX and TN were examined for homogeneity using the double mass curve method, and no apparent breakpoint were detected (Hu et al. 2012).

2.3 Agroclimatic indices

Table 2 presents the list of the agroclimatic indices and their definitions. Frost indices (NFD, LSF, FFF, FP and AF) are based on the threshold 0°C, i.e. a frost day is a day when TN is equal to or less than 0°C. Number of frost days (NFD) is the number of days when TN is equal to or less than 0°C from July 1 to next year's June 30, which covers entire cold season. First fall frost (FFF) is the date when first frost in fall or winter occurs. Last spring frost (LSF) is the date when last frost in winter or spring occurs. Frost period (FP) is the duration between FFF and LSF. Accumulated frost (AF) is the sum of degree-days when TN is less than 0°C.

Heat stress due to elevated temperature above certain threshold has adverse effects on crops, in which case their resources are utilized to cope with heat stress rather than growth (Harding et al. 2015). The threshold temperature above which crop development is hindered varies among crop species. In this study two heat stress indices were selected, plant heat stress days (PHSD) (Mateyesi et al. 2021), and plant heat stress accumulation (PHSA), with three temperature thresholds 25, 30 and 35°C. PHSD is defined as the number of days when TX is above the threshold. Analogous to FA, PHSA is the sum of deviations between TX and the thresholds 25, 30 and 35°C.

Table 1
The list of stations with their geographical attributes.

Station Name	Latitude (°N)	Longitude (°E)	Elevation (m.a.s.l.)
Afyon	38.7380	30.5604	1034
Akhisar	38.9118	27.8233	92
Aydın	37.8402	27.8379	56
Ayvalık	39.3113	26.6861	4
Bandırma	40.3315	27.9965	63
Bergama	39.1098	27.1710	53
Bodrum	37.0328	27.4398	26
Burdur	37.7220	30.2940	957
Bursa	40.2308	29.0133	100
Çanakkale	40.1410	26.3993	6
Çeşme	38.3036	26.3724	5
Datça	36.7083	27.6919	28
Denizli	37.7620	29.0921	425
Dikili	39.0737	26.8880	3
Dinar	38.0597	30.1531	864
Dursunbey	39.5778	28.6322	637
Edremit	39.5895	27.0192	21
Elmalı	36.7372	29.9121	1095
Fethiye	36.6268	29.1239	3
Finike	36.3024	30.1458	2
Güney	38.1515	29.0587	825
İzmir	38.3949	27.0819	29
Keles	39.9150	29.2313	1063
Kuşadası	37.8597	27.2652	25
Kütahya	39.4171	29.9891	969
Manisa	38.6153	27.4049	71
Marmaris	36.8395	28.2452	16

Station Name	Latitude (°N)	Longitude (°E)	Elevation (m.a.s.l.)
Milas	37.3027	27.7804	57
Muğla	37.2095	28.3668	646
Ödemiş	38.2157	27.9642	111
Salihli	38.4831	28.1234	111
Selçuk	37.9445	27.3673	17
Simav	39.0925	28.9786	809
Tavşanlı	39.5384	29.4941	833
Tefenni	37.3161	29.7792	1142
Uşak	38.6712	29.4040	919

Growing season length (GSL) is the period from growing season start (GSS) to growing season end (GSE), from the last occurrence of at least 6-day interval with daily mean air temperature below the threshold before 1 July to the first occurrence of at least 6-day interval with daily mean air temperature below the threshold after 1 July (Grackzyk and Kundzewicz 2016). Three thresholds (5, 10 and 15°C) were considered in this study.

Table 2
The list of temperature-based agroclimatic indices used in the study

Index	Abbreviation	Definition	Unit
Cold-related indices			
Number of frost days	NFD	Number of days when TN is equal to or less than 0°C	Days
Last winter/spring frost	LSF	Date of last winter/spring frost	Date
First fall/winter frost	FFF	Date of first fall/winter frost	Date
Frost period	FP	Number of days between FFF and LSF	Days
Accumulated frost	AF	Sum of degree-days when TN is less than 0°C	°C
Heat-related indices			
Plant heat stress day	PHSD _{25,30,35}	Number of days when TX is greater than 25, 30 and 35°C	Days
Plant heat stress accumulation	PHSA _{25,30,35}	Sum of degree-days when TX is greater than 25, 30 and 35°C	°C
Growing season start	GSS _{5,10,15}	Last occurrence of at least 6-day spell with daily mean air temperature below 5, 10 and 15°C	Date
Growing season end	GSE _{5,10,15}	First occurrence of at least 6-day spell with daily mean air temperature below 5, 10 and 15°C	Date
Growing season length	GSL _{5,10,15}	Number of days between GSS _{5,10,15} to GSE _{5,10,15}	Days
Growing degree-days	GDD _{5,10,15}	Accumulated temperature above 5, 10 and 15°C	°C

Crops need particular heat accumulation to complete their specific phenologic phases and whole life cycle (Lu 2011). Growing degree-day (GDD) is a useful and widely used tool to quantify the accumulation. The formula given below was used to calculate GDD:

$$GDD = \sum \left[\frac{(TX + TN)}{2} \right] - T_{base}$$

where T_{base} is the lower threshold temperature below which crop growth does not occur. Furthermore, there is an upper temperature threshold (T_{UT}) above which crop growth ceases. These impacts of extreme low and high temperatures on crop growth are incorporated into the calculation of GDD by handling TX and TN independently in such a way that TX and TN are set to lower or upper temperature

thresholds if they are below T_{base} or above T_{UT} respectively (Paparrizos and Matzarakis 2017). Three different base temperatures (5, 10 and 15°C) with one common upper threshold (30°C) were selected (Fernandez-Long et al. 2013; Matzarakis et al. 2007).

2.4 Trend analysis

In this study, monotonic temporal changes in agroclimatic indices were evaluated using non-parametric Mann-Kendall test. Magnitudes of the changes were quantified with use of Sen's Slope estimator. An Excel template MAKESENS was used to test the statistical significances of trends, with significance level of 5%, and to estimate their magnitudes (Salmi et al. 2002). Trend-free prewhitening (TFPW) procedure was applied to agroclimatic series having significant serial correlation at %5 level (Yue et al. 2002). However, TFPW was not accomplished for series with very low coefficient of variation ($Cv = 0.1$) for all sample sizes (Bayazit and Önöz 2007).

3 Results And Discussion

3.1 Climatologies of agroclimatic indices

3.1.1 Climatologies of cold-related indices

Table 3 presents the long-term averages of cold-related agroclimatic indices. It should be firstly noted that the indices FFF, LSF and FP were not assessed for the stations Bodrum, Datça and Finike since frost event occurs very rarely at these stations. As evidenced from NFD, frost occurs, on average, once a year at Bodrum, once and twice a decade at Datça and Finike, respectively. Therefore, rarely occurred frost events at these stations did not allow an analysis for FFF, LSF and FP. When considered the rest of stations, earliest FFF occurs late October or early November. The earliest one belongs to Tavşanlı (October 23), followed by Kütahya (October 25), Simav (October 26), Keles (October 30) and Afyon (October 31), all of which are located on northeastern part, characterized by relatively higher latitude and elevation. Some of southern stations have also relatively earlier FFF due to the higher elevation (ranging from 957 to 1142 m) despite they have lower latitude. These are Tefenni (November 2), Elmalı (November 10) and Burdur (November 12). Coastal stations in the South and West have relatively later FFF. The latest FFF occurs at Marmaris (January 17), which is a coastal station and has the second lowest latitude after Fethiye, when Bodrum, Datça and Finike are not considered. Other coastal stations in the north of Marmaris have earlier FFF than Marmaris. For example, it is January 3 at İzmir, January 6 at Çeşme, December 24 at Milas and December 12 at Edremit.

The pattern of LSF over the study area is just a mirror image of that of FFF. LSF occurs earlier at southern and western coastal stations than those at northern, inland and high-elevation stations. The earliest one occurs, on average, in February 6 at Çeşme, Fethiye and Marmaris, all of which are coastal stations. The latest LSF occurs at inland, southern and high-elevation stations such as Burdur (March 31), Elmalı (April 2) and Tefenni (April 13), or at high-elevation stations in northeastern part such as Afyon (April 13), Keles (April 27), Kütahya (April 18), Simav (April 18) and Tavşanlı (April 26).

Table 3
Long-term averages of cold-related indices

Station	FFF	LSF	FP	NFD	AF
Afyon	Oct 31	Apr 13	165.7	87.0	-367.6
Akhisar	Nov 22	Mar 22	121.0	36.6	-79.0
Aydın	Dec 16	Feb 27	74.5	13.7	-19.8
Ayvalık	Dec 30	Feb 23	55.0	10.1	-15.6
Bandırma	Dec 1	Mar 24	114.7	30.3	-61.1
Bergama	Dec 9	Mar 7	88.3	19.3	-33.8
Bodrum	NA	NA	NA	1.0	-1.0
Burdur	Nov 12	Mar 31	140.5	60.0	-199.1
Bursa	Nov 21	Mar 29	129.8	39.5	-88.1
Çanakkale	Dec 8	Mar 5	87.5	20.5	-41.8
Çeşme	Jan 6	Feb 6	28.3	4.0	-3.7
Datça	NA	NA	NA	0.1	-0.1
Denizli	Dec 2	Mar 7	95.9	26.5	-59.1
Dikili	Dec 21	Feb 24	64.8	11.7	-17.8
Dinar	Nov 6	Apr 10	155.7	69.1	-226.9
Dursunbey	Nov 8	Apr 6	149.5	63.9	-196.5
Edremit	Dec 12	Mar 4	81.3	15.8	-27.6
Elmalı	Nov 10	Apr 2	143.7	71.4	-228.0
Fethiye	Dec 28	Feb 6	33.7	4.3	-4.7
Finike	NA	NA	NA	0.2	-0.2
Güney	Nov 21	Mar 31	131.5	46.8	-149.2
İzmir	Jan 3	Feb 13	33.8	4.9	-5.7
Keles	Oct 30	Apr 27	180.9	92.8	-375.7
Kuşadası	Dec 22	Feb 23	60.4	10.0	-14.4
Kütahya	Oct 25	Apr 18	176.2	90.2	-370.5

NA stands for not applicable, indicating that rarely occurred frost events did not allow the calculation of average. Units are days for NFD and FP, and °C for AF.

Station	FFF	LSF	FP	NFD	AF
Manisa	Dec 4	Mar 9	96.1	23.1	-41.0
Marmaris	Jan 17	Feb 6	13.1	1.7	-1.5
Milas	Dec 24	Feb 18	57.2	9.8	-12.3
Muğla	Nov 26	Mar 20	115.2	36.0	-77.8
Ödemiş	Nov 22	Mar 20	119.1	33.7	-66.4
Salihli	Nov 26	Mar 14	108.8	31.7	-63.3
Selçuk	Nov 29	Mar 14	106.0	25.7	-43.6
Simav	Oct 26	Apr 18	174.7	75.3	-254.0
Tavşanlı	Oct 23	Apr 26	186.4	96.2	-387.7
Tefenni	Nov 2	Apr 13	162.7	88.8	-334.6
Uşak	Nov 8	Apr 7	151.2	63.8	-205.1
NA stands for not applicable, indicating that rarely occurred frost events did not allow the calculation of average. Units are days for NFD and FP, and °C for AF.					

As shown in Table 3, NFD is the lowest at Bodrum, Datça and Finike, which is less than or equal to 1.0 day. These are southern or southwestern coastal stations. Therefore, it can be easily estimated that FP is also the lowest at Bodrum, Datça and Finike. NFD and FP increases gradually along coastline toward North, reaching 114.7 days of FP and 30.3 days of NFD at Bandırma, the northernmost coastal station. They take maximum values at high-elevation stations in northeastern part, such as Tavşanlı (NFD=96.2 days, FP=186.4 days), Keles (NFD=92.8 days, FP=180.9 days) and Kütahya (NFD=90.2 days, FP=176.2 days). Burdur, Tefenni and Elmalı, located in southern part, have higher values, compared to surrounding coastal and/or low-elevation stations, ranging 140.5 to 162.7 days of FP and 60.0 to 88.8 days of NFD. The pattern is almost the same for AF. It ranges from -0.1°C at Datça to -334.6°C at Tefenni, and to -387.7°C at Tavşanlı.

Frequency and intensity of frost, together with the duration of frost period are important factors that determine whether crops can be grown in a specific area (Kalma et al. 1992). In this sense, the climatic conditions in southern and western coastal parts of the study area are better by far for growing crops, with the lowest frequency and intensity of frost and with the shortest duration of frost period. On the other hand, the conditions in the northeastern part are in opposite character, with the highest frequency and intensity of frost and with the longest duration of frost period.

3.1.2 Climatologies of heat-related indices

Table 4 presents long-term averages of growing season indices (growing season start, growing season end and growing season length). The averages of growing season indices couldn't be calculated at 14

and 2 sites for the base temperatures of 5 and 10 C, respectively, as these sites experienced never-ending growing seasons in many years (ranging from 31 to 50 years) or over the whole study period (53 years). These sites are generally located in southern or western coastal areas. For the base temperature of 5 C, when 14 sites with dominating never-ending growing seasons aren't accounted for, the earliest and latest GSS (GSE) occur in January 29 at Manisa (November 25 at Keles) and in March 19 at Keles (January 15 at Ödemiş), respectively. For the base temperature of 10 C, GSS (GSE) takes place, on average, as early as in February 3 at Bodrum (October 27 at Keles), and as late as in April 26 at Keles (January 18 at Marmaris). The earliest and latest occurrences of GSS (GSE) shifted to March 22 at Datça (September 28 at Keles) and to May 30 at Keles (December 6 at Datça), respectively, for 15 C. Higher values of GSL occur at western near-coastal stations for 5 C when the stations having never-ending growing seasons are excluded, and at southern and southwestern coastal stations for 10 and 15 C, with maximum values of GS_5 , GSL_{10} and GSL_{15} being at Manisa (346.2 days), Bergama (344.8 days) and Datça (260.2 days), respectively. The lowest values take place on north-eastern part, occurring at Keles with values of 251.9, 184.5 and 122.2 days, respectively. The results indicate that southern or western coastal/near-coastal stations have the best climatic conditions in terms of growing season indices.

Climatologies of GDD indices for all base temperatures behave in the same pattern as other heat related indices (Table 5). Southern and western coastal stations (e.g., Datça, Bodrum, Marmaris, Finike, Fethiye, İzmir, Milas, Aydın) had the highest heat accumulation, in the order of 4500-5000, 3000-3500 and 1800-2000°C for the base temperatures 5, 10 and 15 C, respectively. On the other hand, the stations located in northeastern part, with the highest elevations between 809 and 1063 m, have the lowest GDD values, in the order of 2500-3000, 1500-1850 and 800-1100°C, respectively.

Table 4
Long-term averages of growing season indices

Station	GSS ₅	GSE ₅	GSL ₅	GSS ₁₀	GSE ₁₀	GSL ₁₀	GSS ₁₅	GSE ₁₅	GSL ₁₅
Afyon	Mar 6	Dec 1	270.7	Apr 15	Oct 31	200.6	May 19	Oct 6	141.2
Akhisar	Feb 3	Jan 5	338.3	Mar 15	Nov 29	260.1	Apr 17	Oct 31	198.7
Aydın	NA	NA	NA	Feb 24	Dec 16	296.7	Apr 5	Nov 13	223.8
Ayvalık	NA	NA	NA	Mar 7	Dec 10	278.4	Apr 14	Nov 7	207.9
Bandırma	Feb 15	Jan 3	324.3	Mar 31	Nov 25	239.7	May 4	Oct 24	174.5
Bergama	Feb 6	Jan 14	344.8	Mar 13	Dec 1	262.7	Apr 16	Nov 2	200.9
Bodrum	NA	NA	NA	Feb 3	Jan 16	344.9	Mar 26	Dec 1	250.6
Burdur	Feb 24	Dec 14	294.2	Apr 2	Nov 13	226.0	May 6	Oct 18	166.5
Bursa	Feb 12	Dec 27	319.3	Mar 24	Nov 23	244.2	Apr 28	Oct 24	180.0
Çanakkale	Feb 14	Jan 9	332.1	Mar 24	Nov 28	250.7	Apr 26	Oct 26	184.2
Çeşme	NA	NA	NA	Feb 20	Dec 29	313.1	Apr 10	Nov 14	219.1
Datça	NA	NA	NA	NA	NA	NA	Mar 22	Dec 6	260.2
Denizli	Feb 5	Dec 30	327.9	Mar 12	Dec 1	265.6	Apr 18	Oct 31	197.8
Dikili	NA	NA	NA	Mar 7	Dec 11	280.5	Apr 15	Nov 6	206.3
Dinar	Feb 26	Dec 16	295.0	Apr 6	Nov 13	222.5	May 11	Oct 17	160.2
Dursunbey	Mar 3	Dec 9	282.5	Apr 9	Nov 10	216.3	May 10	Oct 12	155.5
Edremit	NA	NA	NA	Mar 10	Dec 9	274.2	Apr 15	Nov 6	205.8
Elmalı	Feb 22	Dec 17	299.3	Apr 5	Nov 15	225.0	May 10	Oct 19	163.7
Fethiye	NA	NA	NA	Feb 8	Jan 8	331.9	Apr 3	Nov 24	236.5

Station	GSS ₅	GSE ₅	GSL ₅	GSS ₁₀	GSE ₁₀	GSL ₁₀	GSS ₁₅	GSE ₁₅	GSL ₁₅
Finike	NA	NA	NA	NA	NA	NA	Mar 31	Dec 2	247.3
Güney	Feb 24	Dec 19	299.3	Apr 1	Nov 19	233.0	May 2	Oct 21	173.2
İzmir	NA	NA	NA	Feb 25	Dec 22	301.3	Apr 4	Nov 13	223.9
Keles	Mar 19	Nov 25	251.9	Apr 26	Oct 27	184.5	May 30	Sep 28	122.2
Kuşadası	NA	NA	NA	Feb 23	Dec 21	302.5	Apr 9	Nov 12	218.1
Kütahya	Mar 12	Nov 29	263.3	Apr 16	Nov 1	199.7	May 18	Oct 3	138.8
Manisa	Jan 29	Jan 9	346.2	Mar 8	Dec 1	268.9	Apr 13	Nov 2	203.5
Marmaris	NA	NA	NA	Feb 11	Jan 18	339.2	Mar 30	Nov 27	243.0
Milas	NA	NA	NA	Feb 18	Dec 24	311.2	Apr 7	Nov 17	225.0
Muğla	Feb 9	Jan 5	332.1	Mar 23	Nov 25	247.6	May 1	Oct 27	180.2
Ödemiş	Feb 2	Jan 15	342.6	Mar 8	Dec 5	273.8	Apr 17	Nov 1	198.6
Salihli	Feb 7	Jan 2	329.2	Mar 13	Nov 30	262.7	Apr 13	Oct 30	201.2
Selçuk	NA	NA	NA	Mar 1	Dec 9	284.2	Apr 12	Nov 6	209.0
Simav	Mar 4	Dec 8	280.3	Apr 14	Nov 6	207.4	May 15	Oct 8	146.7
Tavşanlı	Mar 6	Dec 3	272.7	Apr 14	Nov 4	204.4	May 16	Oct 5	142.9
Tefenni	Mar 7	Dec 7	276.3	Apr 10	Nov 5	209.3	May 16	Oct 10	147.5
Uşak	Feb 28	Dec 14	289.9	Apr 10	Nov 11	216.0	May 12	Oct 14	155.4

NA stands for not applicable, indicating that never-ending growing season did not allow the calculation of average. Unit is days for GSL indices.

Table 5
Long-term averages of growing degree-day
indices

Station	GDD ₅	GDD ₁₀	GDD ₁₅
Afyon	2925.3	1786.4	998.0
Akhisar	4201.2	2769.6	1644.2
Aydın	4659.8	3098.7	1833.2
Ayvalık	4415.7	2861.1	1622.8
Bandırma	3661.5	2280.9	1237.8
Bergama	4261.8	2781.4	1616.2
Bodrum	5216.9	3500.0	2039.7
Burdur	3419.4	2153.7	1234.5
Bursa	3750.8	2380.1	1342.9
Çanakkale	3912.4	2451.5	1333.9
Çeşme	4581.8	2976.0	1665.8
Datça	5286.1	3521.2	2012.1
Denizli	4229.5	2773.4	1627.9
Dikili	4378.6	2821.2	1569.7
Dinar	3338.4	2091.9	1204.2
Dursunbey	3229.4	1978.9	1089.7
Edremit	4347.0	2838.5	1644.1
Elmalı	3398.1	2148.1	1230.4
Fethiye	4839.0	3233.8	1901.3
Finike	5017.0	3334.7	1947.4
Güney	3577.5	2248.2	1261.0
İzmir	4771.5	3153.4	1841.2
Keles	2543.7	1470.7	789.4
Kuşadası	4546.9	2943.8	1637.6
Kütahya	2859.6	1737.7	973.3

Unit is °C for all.

Station	GDD ₅	GDD ₁₀	GDD ₁₅
Manisa	4372.0	2888.3	1718.1
Marmaris	5051.2	3382.0	1979.2
Milas	4697.8	3138.1	1862.1
Muğla	3914.6	2519.2	1469.1
Ödemiş	4203.8	2746.9	1609.0
Salihli	4243.0	2784.7	1644.1
Selçuk	4353.0	2842.9	1642.7
Simav	3035.7	1850.1	1059.2
Tavşanlı	2960.4	1836.2	1078.4
Tefenni	3091.2	1919.6	1098.4
Uşak	3198.0	1967.3	1100.9
Unit is °C for all.			

Table 6 presents long-term mean values of heat-stress indices. These indices, as expected, are generally higher at southern or western coastal and near-coastal stations such as Aydın, Milas, Ödemiş and Finike, than those with higher latitude and/or altitude such as Keles, Kütahya and Bandırma. Maximum values occur at Aydın, Milas and Ödemiş, western coastal or near-coastal stations, with TX exceeding 25, 30 and 35 C up to 178, 127 and 56 days a year, respectively. PHSA is also maximum at these stations for all thresholds. For example, maximum PHSA₂₅ is 1367.3°C at Aydın. The lowest values are recorded at northern coastal stations such as Bandırma or at northeastern high-elevation stations such as Keles and Kütahya. Keles is the station in which minimum frequency and accumulation occurs, with PHSD₃₅ and PHSA₃₅ being 0.6 days and 0.8°C, respectively. It follows that while crops grown in southern or western coastal areas are exposed to higher heat stress, in terms of both frequency and accumulation, in comparison to northern or northeastern stations.

Table 6
Long-term averages of heat-stress indices

Station	PHSD ₂₅	PHSA ₂₅	PHSD ₃₀	PHSA ₃₀	PHSD ₃₅	PHSA ₃₅
Afyon	100.8	425.8	35.6	82.0	2.8	3.2
Akhisar	166.0	1173.9	110.2	474.7	40.9	91.6
Aydın	178.0	1367.3	127.0	596.4	55.9	127.1
Ayvalık	142.1	758.2	74.2	205.6	9.5	12.6
Bandırma	102.7	352.2	22.3	49.7	2.1	4.2
Bergama	155.1	968.8	94.8	334.1	23.7	44.8
Bodrum	163.6	1057.4	98.1	391.6	31.5	67.5
Burdur	129.3	709.0	67.4	208.1	12.0	18.1
Bursa	131.0	647.7	60.5	158.4	7.0	11.2
Çanakkale	117.0	530.0	48.0	103.6	2.8	3.3
Çeşme	141.9	605.1	53.3	90.8	1.9	2.2
Datça	150.5	795.9	76.1	210.4	10.5	16.5
Denizli	158.5	1085.6	101.5	425.5	36.2	74.7
Dikili	133.1	630.2	54.3	154.4	9.0	15.0
Dinar	126.6	653.4	62.2	175.7	8.9	12.7
Dursunbey	110.6	487.0	41.2	101.2	4.0	5.6
Edremit	149.2	865.0	84.2	268.1	15.9	24.9
Elmalı	131.3	674.4	65.2	172.4	7.1	7.8
Fethiye	173.5	1129.7	109.7	413.4	32.0	58.8
Finike	171.2	1070.2	103.2	371.5	27.5	56.3
Güney	123.3	636.0	59.7	167.5	8.6	12.7
İzmir	157.0	919.1	89.9	288.8	17.4	28.5
Keles	68.8	214.7	13.0	23.9	0.6	0.8
Kuşadası	141.2	647.9	55.1	142.3	6.8	11.1
Kütahya	97.4	388.8	30.9	70.4	2.7	3.2

Units are days and °C for PHSD and PHSA indices, respectively.

Station	PHSD ₂₅	PHSA ₂₅	PHSD ₃₀	PHSA ₃₀	PHSD ₃₅	PHSA ₃₅
Manisa	162.9	1171.7	110.4	481.2	42.5	90.9
Marmaris	163.4	1079.1	103.6	402.4	30.6	55.9
Milas	177.0	1317.8	120.7	562.5	50.2	128.9
Muğla	145.0	909.5	87.2	320.6	23.7	41.0
Ödemiş	170.7	1246.1	116.7	520.1	47.2	100.9
Salihli	166.9	1191.6	113.0	484.1	42.8	87.1
Selçuk	164.6	1028.5	98.2	352.5	24.7	44.2
Simav	110.8	479.1	40.8	93.1	2.9	3.6
Tavşanlı	114.5	559.1	50.5	145.5	8.6	13.4
Tefenni	116.1	552.9	51.1	127.2	4.5	5.5
Uşak	111.6	526.1	47.6	117.6	4.6	5.2
Units are days and °C for PHSD and PHSA indices, respectively.						

3.2 Trend analysis

3.2.1 Trends in cold-related indices

Table 7 presents trends of cold-related indices. It should be noted that trends of LSF, FFF, FP, NFD and AF were not determined for Bodrum, Datça and Finike, as these sites had rarely occurred frost events through study period. The results revealed that LSF decreased at 31 sites (significant at 15 sites), and increased non-significantly at only 2 sites. Trend magnitudes ranged from 0.9 days/decade at Keles to -7.4 days/decade at Fethiye. Weaker and nonsignificant trends are dominant at the stations located in northeastern part. Trends at coastal or near-coastal stations are generally stronger and significant, e.g., at Fethiye, Kuşadası, Bergama, İzmir and Milas with rates -7.4, -6.5, -5.1, -4.8 and -4.7 days/decade. On the other hand, FFF had a different pattern in terms significances and magnitudes of trends. Only 6 stations experienced significant trend for FFF, all of which were in increasing direction. These 6 stations are neighboring sites in western-central part of the study area, namely Denizli, Akhisar, Selçuk, Kuşadası, Aydın and Milas. Trend magnitudes varied from -3.4 days/decade at Marmaris to 5.3 days/decade at Milas. Regional average rates of change of LSF and FFF were -3.0 and 1.5 days/decade, respectively, suggesting earlier occurrences of last frost and later occurrences of first frost. This, firstly, implies a decreased FP (or, increased frost-free period). Secondly, decrease in FP is mostly due to earlier occurrences of LSF rather than later occurrences of FFF, as a result of stronger LSF trend. The implied decrease in FP is confirmed by the results given in Table FP decreased at 30 sites, and increased 3

sites. Decreasing trends were statistically significant at 14 stations. None of increasing trends were significant. FP decreased, on average, 4.8 days per decade over the study area from 1966 to 2018. Accordingly, any frost event has become less likely accross study area, quantified by the index NFD. Number of days with frost (NFD) has declined, on average, by 1.9 days per decade. The results of the index AF documented increasing trends at 31 sites of which 11 were significant. This increase implies a decrease in cold accumulation of temperature below 0 C. The trend magnitude ranged from 29.1°C/decade, observed at Afyon, to -0.2°C/decade, observed at Burdur. Averaged trend magnitude was 8.2°C/decade. All these results indicate that the study area has been experiencing less and weaker frost events from 1966 to 2018. It follows that the frequency and intensity of frost damage on crops grown in the study area has diminished, and that the climate has become more favourable in terms of frost damage.

Studies conducted for other geographies around the World have found similar results, in which NFD and FP decreased, FFF occurred later, LSF occurred earlier, and decrease in FP was mostly due to the earlier onset of LSF rather than later onset of FFF. Some of these geographies are Poland (Graczyk and Kundzewicz 2016), Central Europe (Wypych et al. 2017), Kansas, USA (Anandhi et al. 2013a), Catskill mountain region of New York, USA (Anandhi et al. 2013b), the continental USA (Kukal and Irmak 2018) and the Iberian Peninsula (Garcia-Martin et al. 2021). On the other hand, decrease of FP resulted from later onset of FFP in the Southern Federal District of Russia (Gudko et al. 2021).

Table 7
Trend rates of cold-related indices.

Station	LSF	FFF	FP	NFD	AF
Afyon	-2.9	0.4	-4.3	-4.0	29.1
Akhisar	-2.1	4.3	-7.3	-2.7	7.6
Aydın	-6.1	5.1	-11.6	-1.5	2.8
Ayvalık	-3.0	-1.2	-1.2	-0.8	1.6
Bandırma	-2.4	1.0	-4.0	-1.6	5.0
Bergama	-5.1	3.2	-8.6	-2.5	4.2
Bodrum	NA	NA	NA	NA	NA
Burdur	0.7	-2.9	4.0	0.5	-0.2
Bursa	-1.2	2.2	-2.6	-1.1	5.1
Çanakkale	-5.0	2.5	-7.1	-2.1	4.7
Çeşme	-1.2	-2.6	0.0	0.0	0.1
Datça	NA	NA	NA	NA	NA
Denizli	-6.6	4.3	-9.1	-3.8	10.6
Dikili	-2.9	0.7	-4.2	-1.0	2.0
Dinar	-1.3	-0.5	-0.9	-1.7	10.6
Dursunbey	-0.5	-1.0	0.0	-1.0	6.5
Edremit	-4.7	4.1	-8.6	-1.9	4.2
Elmalı	-2.0	0.4	-3.3	-2.9	23.5
Fethiye	-7.4	2.6	-10.6	-1.2	1.3
Finike	NA	NA	NA	NA	NA
Güney	-2.1	3.3	-5.0	-3.0	9.7
İzmir	-4.8	-0.5	-3.5	-0.5	0.5
Keles	0.9	0.0	0.2	-0.3	14.9
Kuşadası	-6.5	5.0	-14.4	-2.7	4.5
Kütahya	-1.0	2.7	-3.0	-3.6	27.2

NA stands for not applicable, indicating that rarely occurred frost events did not allow a trend analysis. Statistically significant trends at 95% are shown in bold. Trend rates are days per decade for LSF, FFF, FP and NFD, and °C per decade for AF.

Station	LSF	FFF	FP	NFD	AF
Manisa	-3.3	1.2	-4.4	-1.3	3.7
Marmaris	-2.3	-3.4	0.0	0.0	0.0
Milas	-4.7	5.3	-12.0	-2.4	3.2
Muğla	-1.4	0.7	-2.8	-1.4	3.2
Ödemiş	-1.8	2.1	-4.3	-2.0	6.6
Salihli	-2.7	3.1	-5.8	-1.3	3.3
Selçuk	-6.9	4.9	-12.5	-3.9	8.2
Simav	-1.7	1.3	-4.1	-3.7	15.6
Tavşanlı	-1.0	1.6	-4.4	0.0	11.2
Tefenni	-4.2	-1.9	-1.5	-4.0	28.0
Uşak	-0.9	0.4	-1.5	-2.5	12.6
NA stands for not applicable, indicating that rarely occurred frost events did not allow a trend analysis. Statistically significant trends at 95% are shown in bold. Trend rates are days per decade for LSF, FFF, FP and NFD, and °C per decade for AF.					

3.2.2 Trends in heat-related indices

The trend rates of the indices GSS, GSE and GSL for all threshold temperatures are given in Table 8. It should be noted that trends weren't calculated for 12 and 2 stations for thresholds 5 and 10 C, respectively, due to many never-ending growing seasons at these stations over the study period.

Table 8
Trend rates of growing season indices

Station	GSS ₅	GSE ₅	GSL ₅	GSS ₁₀	GSE ₁₀	GSL ₁₀	GSS ₁₅	GSE ₁₅	GSL ₁₅
Afyon	-0.3	2.2	3.2	-3.3	0.6	3.8	-4.0	0.7	4.4
Akhisar	-3.0	-3.9	0.4	-1.4	1.8	3.9	-2.9	1.3	5.0
Aydın	NA	NA	NA	-1.1	2.7	4.4	-5.4	1.6	6.9
Ayvalık	NA	NA	NA	-1.4	2.1	4.1	-1.4	2.0	3.3
Bandırma	-2.8	-1.5	2.3	-2.2	1.1	2.9	-0.4	1.4	1.3
Bergama	-4.0	-3.9	0.0	-2.9	1.7	4.6	-1.9	1.8	4.0
Bodrum	NA	NA	NA	-1.7	0.0	-0.2	-5.5	2.2	8.1
Burdur	-1.3	2.6	4.7	-2.9	0.5	2.9	-2.6	1.0	3.3
Bursa	-0.8	0.8	2.3	-2.1	0.9	3.2	-1.0	1.4	2.1
Çanakkale	0.6	-2.3	-5.0	-1.7	2.5	5.0	-0.9	1.1	1.3
Çeşme	NA	NA	NA	-1.7	0.3	1.9	-2.6	1.5	4.0
Datça	NA	NA	NA	NA	NA	NA	-3.2	2.1	5.8
Denizli	-3.0	0.0	3.9	-3.5	1.6	5.9	-3.2	1.6	5.4
Dikili	NA	NA	NA	-4.0	2.2	6.4	-1.3	1.0	2.2
Dinar	-1.9	4.0	7.0	-3.9	1.5	5.4	-0.6	1.7	2.4
Dursunbey	0.0	2.8	3.1	-1.1	1.5	3.1	-1.6	-0.4	0.0
Edremit	-2.3	-3.9	-3.9	-3.4	3.8	7.5	-3.8	2.6	6.0
Elmalı	-1.5	3.5	5.6	-4.1	-0.3	3.2	-3.2	1.3	4.5
Fethiye	NA	NA	NA	-2.6	-1.8	3.6	-5.8	3.6	10.0
Finike	NA	NA	NA	NA	NA	NA	-3.8	4.0	7.7
Güney	-0.8	3.0	4.4	-3.9	0.4	4.2	-1.4	1.7	3.7
İzmir	NA	NA	NA	-2.0	1.1	2.7	-3.6	0.8	4.5
Keles	0.0	0.7	0.5	0.6	0.2	-0.2	-1.2	-0.9	0.0
Kuşadası	NA	NA	NA	-5.7	3.3	10.0	-6.3	4.6	11.2
Kütahya	-0.9	2.3	3.3	-1.2	1.1	2.9	-2.5	1.1	3.3
NA stands for not applicable, indicating that never-ending growing seasons do not allow a trend analysis. Statistically significant trends at 95% are shown in bold. Trend rates are days per decade for all.									

Station	GSS ₅	GSE ₅	GSL ₅	GSS ₁₀	GSE ₁₀	GSL ₁₀	GSS ₁₅	GSE ₁₅	GSL ₁₅
Manisa	-1.4	-3.2	0.8	-0.7	0.5	1.7	-2.1	1.7	4.0
Marmaris	NA	NA	NA	0.5	0.0	0.7	-2.8	2.0	5.3
Milas	NA	NA	NA	-4.0	2.2	8.0	-7.8	2.9	11.4
Muğla	-3.3	-0.9	2.3	-3.3	0.8	3.9	-1.4	0.2	1.4
Ödemiş	-4.6	-4.2	3.3	-0.7	2.5	3.8	-2.3	0.4	2.7
Salihli	-2.7	-3.9	-0.8	-0.6	1.9	3.0	-2.8	1.9	5.0
Selçuk	NA	NA	NA	-4.9	2.5	6.7	-4.3	1.3	5.9
Simav	-0.5	2.8	3.2	-3.3	1.6	5.7	-4.2	0.9	5.0
Tavşanlı	-1.6	2.3	4.5	-3.3	1.5	4.3	-4.2	0.5	4.6
Tefenni	-4.6	3.5	8.4	-4.7	0.6	5.2	-3.5	1.6	5.0
Uşak	0.0	3.0	3.5	-3.3	1.7	4.4	-1.5	1.0	2.0
NA stands for not applicable, indicating that never-ending growing seasons do not allow a trend analysis. Statistically significant trends at 95% are shown in bold. Trend rates are days per decade for all.									

A number of features are observable. First one is that number of stations with significant trend increased as the threshold increased, except the end indices. While GSS₅ was significant at only one station, GSS₁₀ and GSS₁₅ were significant at 14 and 21 stations, respectively. The corresponding number of stations for GSL₅, GSL₁₀ and GSL₁₅ were 3, 18 and 25, respectively. No such a pattern existed for the end indices. While GSE₅ was significant at 4 stations, GSE₁₀ and GSE₁₅ were significant at 2 and 5 stations, respectively. Second feature is associated with direction of the trends. There were overall decreases for the start indices, and increases for the end indices, implying increases in the length indices, for all thresholds. The third one is related with strength of trend magnitudes. Start indices had stronger trend magnitudes than those of end indices. In terms of mean values, while GSS₅, GSS₁₀ and GSS₁₅ had magnitudes of -1.8, -2.5 and -3.0 day/decade, GSE₅, GSE₁₀ and GSE₁₅ had 0.3, 1.3 and 1.5 day/decade, respectively. These resulted in increases in the length indices, 2.5, 4.1 and 4.5 day/decade for GSL₅, GSL₁₀ and GSL₁₅, respectively. It follows that increasing trends observed in length indices were mostly due to the changes in start indices. Over the period from 1966 to 2018, the study area has become more favourable for crop production in terms of earlier start, later end and lengthening of growing season.

There is no universal definition for climatic growing season, and various approaches are available (Menzel et al. 2003; Walther and Linderholm 2006; Linderholm et al. 2008). Previous studies have found similar results, in which GSL extended, mostly due to earlier onset of GSS rather than later onset of GSE, for example, in Poland (Graczyk and Kundzewicz 2016; Tomczyk and Szyga-Pluta 2019), in the Greater

Baltic Area by Walther and Linderholm (2006), in Germany (Menzel et al. 2003), in the Tibetan Plateau (Dong et al. 2012), and in Northeast China (Dong et al. 2013). On the other hand, Jiang et al. (2011) found that the increase in GSL in Xinjiang province of China was mainly due to the delay of GSE rather than earlier onset of GSS.

The trend rates for growing degree-day indices are presented in Table 9. All stations, with no exception, had statistically significant increasing trends for all indices. The average of trend magnitudes declined as the threshold increases, from 10.2°C/decade for GDD₅ to 8.8°C/decade for GDD₁₀, and to 6.3°C/decade for GDD₁₅. Keles, located North-eastern part, had the lowest rates of increase for all indices, 5.9, 4.7 and 2.8°C/decade, respectively. Fethiye and Kuşadası, located on western and south-western parts, respectively, had the highest rates for GDD₅ and GDD₁₀, 18.0 and 15.4°C/decade, respectively. The maximum rate of increase for GDD₁₅ belonged to Fethiye, with a rate of 12.1°C/decade. With increased GDD, more heat has become available for crops currently grown across the study area. This can be considered beneficial for a particular phenophase to be achieved earlier than before, or for allowing crops with more thermal requirement to be grown. Other studies around the World have also found increasing trends in GDD indices, e.g., in the Balkan Peninsula (Charalampopoulos 2021), in Chile (Piticar 2019), in Poland (Graczyk and Kundzewicz 2016), in the Southern Federal District of Russia (Gudko et al. 2021), in continental USA (Kukal and Irmak 2018). On the contrary to the results of this study, Kadioğlu and Şaylan (2001) found significant decreasing trends in GDD for Turkey from 1930 to 1990. This is due to the differences in start and end of the period for which a possible trend is searched. Data period used by Kadioğlu and Şaylan (2001) included completely the slight cooling period from 1940s to mid-1970s (Meehl 2015; Gonzalez-Hidalgo et al. 2016). However, this study covered the period from 1966 to 2018, including rapid warming after 1970s (Gonzalez-Hidalgo et al. 2016).

Table 9
Trend rates of growing degree day indices

Station	GDD ₅	GDD ₁₀	GDD ₁₅
Afyon	10.0	7.7	4.2
Akhisar	10.7	9.4	6.7
Aydın	10.2	9.4	7.2
Ayvalık	7.9	7.0	5.2
Bandırma	9.4	7.7	5.5
Bergama	9.7	8.3	6.2
Bodrum	11.2	10.6	8.9
Burdur	7.7	7.0	5.1
Bursa	9.8	8.4	5.9
Çanakkale	9.6	7.6	5.3
Çeşme	7.1	6.7	5.0
Datça	7.0	7.2	7.2
Denizli	13.4	11.3	8.5
Dikili	8.9	7.8	6.0
Dinar	8.4	7.0	4.4
Dursunbey	6.2	5.5	3.7
Edremit	12.4	10.6	7.8
Elmalı	6.8	5.8	3.9
Fethiye	18.0	15.4	12.1
Finike	16.9	14.4	11.1
Güney	8.2	6.9	5.1
İzmir	7.9	7.4	5.7
Keles	5.9	4.7	2.8
Kuşadası	18.0	15.4	11.0
Kütahya	10.0	7.9	3.9

Statistically significant trends at 95% are shown in bold. Trend rates are °C per decade for all.

Station	GDD ₅	GDD ₁₀	GDD ₁₅
Manisa	9.1	8.3	6.2
Marmaris	10.2	9.3	8.0
Milas	15.8	13.4	10.3
Muğla	7.8	7.0	5.4
Ödemiş	7.3	6.6	4.4
Salihli	12.1	10.9	8.0
Selçuk	13.0	11.2	7.3
Simav	11.7	8.6	5.0
Tavşanlı	11.5	9.5	5.9
Tefenni	9.3	7.4	4.4
Uşak	8.8	7.1	4.5
Statistically significant trends at 95% are shown in bold. Trend rates are °C per decade for all.			

Table 10
Trend rates of heat-stress indices

Station	PHSD ₂₅	PHSA ₂₅	PHSD ₃₀	PHSA ₃₀	PHSD ₃₅	PHSA ₃₅
Afyon	4.7	47.5	6.3	16.9	0.4	0.3
Akhisar	3.6	86.5	5.6	65.6	8.3	20.4
Aydın	4.1	85.9	4.1	62.7	8.6	26.8
Ayvalık	2.5	60.9	7.0	40.3	3.1	3.0
Bandırma	3.8	28.2	2.8	4.1	0.0	0.0
Bergama	3.1	60.6	6.0	43.9	5.0	9.1
Bodrum	5.0	91.0	6.5	63.8	8.6	19.5
Burdur	4.8	81.7	8.9	51.9	4.2	5.3
Bursa	3.1	47.0	6.4	24.0	1.3	0.8
Çanakkale	1.3	39.4	7.1	19.8	0.4	0.2
Çeşme	1.0	16.9	4.3	8.3	0.0	0.0
Datça	5.9	76.2	9.6	45.5	3.3	5.1
Denizli	4.0	91.7	6.6	67.8	10.0	22.9
Dikili	1.6	46.0	5.3	25.2	2.5	3.9
Dinar	3.2	56.8	7.1	32.4	2.5	2.8
Dursunbey	4.4	52.3	6.9	20.3	0.6	0.8
Edremit	3.6	68.8	7.5	46.8	5.0	6.9
Elmalı	3.3	59.9	7.1	35.5	2.0	1.7
Fethiye	4.3	69.6	3.8	47.5	6.7	15.6
Finike	3.7	55.9	4.5	37.6	4.3	11.1
Güney	3.8	64.3	7.8	37.4	2.6	3.2
İzmir	1.9	42.7	3.5	28.8	2.9	4.4
Keles	5.5	29.1	2.5	3.7	NA	NA
Kuşadası	2.6	33.7	5.3	17.2	1.0	1.6
Kütahya	5.6	40.3	4.6	12.1	0.4	0.3
NA stands for not applicable, indicating that very few occurrences of TX exceeding the threshold did not allow a trend analysis. Statistically significant trends at 95% are shown in bold. Trend rates are days per decade for PHSD indices, and °C per decade for PHSA indices.						

Station	PHSD ₂₅	PHSA ₂₅	PHSD ₃₀	PHSA ₃₀	PHSD ₃₅	PHSA ₃₅
Manisa	2.9	62.2	3.6	44.9	6.7	15.3
Marmaris	3.9	51.5	3.3	32.2	4.4	8.5
Milas	5.3	84.9	4.8	60.0	7.3	27.6
Muğla	3.8	72.0	5.6	50.0	6.3	12.1
Ödemiş	2.0	64.8	2.5	50.7	8.5	21.8
Salihli	3.8	74.9	5.1	60.1	9.4	20.3
Selçuk	3.6	49.2	4.6	37.4	5.0	9.2
Simav	6.4	67.2	9.1	27.1	0.9	1.0
Tavşanlı	8.2	88.0	10.3	40.4	3.1	3.7
Tefenni	5.0	61.9	8.0	29.7	1.2	1.2
Uşak	3.8	57.0	7.0	24.4	1.1	0.8
NA stands for not applicable, indicating that very few occurrences of TX exceeding the threshold did not allow a trend analysis. Statistically significant trends at 95% are shown in bold. Trend rates are days per decade for PHSD indices, and °C per decade for PHSA indices.						

In Table 10, trend rates of heat-stress indices are presented. Trend rates of PHSD₃₅ and PHSA₃₅ for Keles were not calculated as few data were available, not sufficient for trend calculation, due to very rarely occurred TX exceeding 35°C. The results documented that all plant heat stress indices experienced significantly increasing trends at almost all stations. Number of stations with non significant increase is not more than 3 for any index, even none for PHSA₂₅ and PHSD₃₀. When averages of trend rates compared, those of the PHSD₂₅ and PHSD₃₅ were found to be the same, being 3.9 days/decade. But, that of PHSD₃₀ were much higher (5.9 days/decade). Average trends for the indices PHSA decreased as the threshold increased, from 60.2 to 36.6, and to 8.2°C/decade, for the thresholds 25, 30 and 35°C, respectively. Substantial increases in heat stress indices suggest that crops grown in the study area have exposed to more heat stress over the course of study period from 1966 to 2018.

4 Conclusions

In this study, temperature-based agroclimatic indices were assessed for their climatology and trends during the period from 1966 to 2018 in western Anatolia, Turkey. Southern and western coastal stations of the study area have the most suitable climatic conditions for growing crops, except heat stress. Frost events are rare, with the frequency being as low as once in ten years. This leads to, on average, very short frost period and very little frost accumulation. Then, climatic growing season even cover full year, with no apparent start and end, particularly for low threshold temperature of 5 C. However, this section of the study area suffers from more heat stress compared to the rest, in terms of both frequency and

accumulation. This is an important factor that may adversely affect crop development and yield in that section. On the other hand, the most unsuitable agroclimatic conditions prevail in northeastern part in terms of cold-related indices. This section is characterized by minimal growing season length and minimal heat stress, maximal frost period, frequency and accumulation etc., in comparison to the rest of the study area. On average, frost period lasts up to 6 months; frost events occur up to 100 times in a year.

Trend analysis showed that, during the period from 1966 to 2018, agroclimatic indices have had tendencies toward warmer conditions. Frequency and intensity of frosts have become less likely, evidenced with decreased NFD and AF, respectively. It follows that frost has become less damaging for crops grown in the study area, in terms of frequency, intensity and duration. Accordingly, results also showed that there have been general earlier occurrences of LSF and later occurrences of FFF. These trends resulted in shorter FP (or, longer frost-free period), which is mostly due to earlier occurrences of LSF. Growing season indices also showed similar patterns. Growing season has started earlier and ended later, extending growing season. The extension of GSL and the shortening FP has provided longer time favourable for crop production. On the other hand, increasing trends in heat stress and growing degree-day indices were more substantial. It follows that the crops grown in the study area have been exposed to more heat stress during the study period. Presently grown crops have been experiencing more damage due to extreme high temperatures. On the other hand, this can be beneficial to grow crops with higher heat requirement, which are not presently grown.

Declarations

Author contribution

All works presented in this paper were done solely by EY

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Data availability

Data used in this study was supplied from State Meteorological Service of Turkey.

Code availability

Codes used to produce the indices are available upon request.

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Not applicable

Conflict of interest

The author declares no competing interests.

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Figures

Figure 1
Study area and locations of the weather stations