Climatology of growing degree days in Greece

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ABSTRACT: Growing degree days (GDD) were calculated for 40 meteorological stations distributed across Greece, on the basis of daily maximum and minimum air temperature (T_{MAX} and T_{MIN} , respectively) for the 10 year period from 1978 to 1987. Duration of growing periods (classified in 10 d intervals) differed among stations. The longest period was from April 1 to November 30, and the shortest from May 1 to September 30. Growing season varies across Greece from about 1600 GDD in the northern mountainous areas to >2900 GDD in the lowlands and the southernmost regions. Most spring-sown crops need no more than 1500 GDD to mature; consequently, there are no temperature limitations in Greece for crops such as corn, cotton and tobacco. Despite the sparse climatic network it was possible to create high resolution maps with statistically significant results ($r = 0.83$ to 0.89 ; $p = 0.95$), providing reliable information for agricultural planning.

KEY WORDS: Growing degree days · Agriculture · Regional maps · Greece

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1. INTRODUCTION

The most widely cultivated crops grow best at specific optimum temperatures; e.g. corn, tomatoes and sweet peppers are best cultivated at 21 to 23°C (Gilmore & Rogers 1958, Wolf et al. 1986, Bakker & Uffelen 1988). Because of the differences in the growing season, especially for corn, farmers in Greece need to accurately assess the maturity of their crops to ensure maximum yield quality with low moisture at harvest time. Since corn and many other plants are hybrids, the estimation of maturity is not possible by the traditional 'days to maturity' method, which is based on the time it takes for a plant to grow from seed to harvest. Instead, estimation is conducted on the basis of growing degree days (GDD) as a specific number of GDD—required by the plant to reach maturity, regardless of the number of days taken to accumulate them. Different methods exist for the calculation of GDD, depending on the crop of interest or the personal preferences of the researcher (Gilmore & Rogers 1958, Perry et al. 1986, McMaster & Wilhelm 1997).

Our approach differs from the real time estimation of GDD for a field. We describe the climatologic importance of GDD to determine locations and time periods most appropriate for cultivation of corn and other summer crops in Greece. Maps presenting the distribution of GDD in the country during a 10 year period were constructed. This timeframe is accepted as an appropriate period for analysis of daily temperature data (Court 1974).

To calculate the accumulated GDD, the daily growing degree units are usually summed for the number of the days of growth beginning at planting (Darby & Lauer 2002). For this climatological study, however, the estimation of GDD was carried out for a specified period from the beginning of April to the end of November. Following this estimation we applied a gradual 10 day decrease of the start and end dates, resulting in different growing periods, with the minimum period from May 1 to September 30.

According to these estimations, GDD for the mean growing season in Greece range from about 1600 in the northern and mountainous areas of the country to >2900 in the lowlands. These limits exceed the crop maturity

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requirements of most crops: maize 1360–1630, dry beans 1100–1300, sugar beet 1400–1500, barley 1290–1540 (http://en.wikipedia.org/wiki/growing_degree_day).

Detailed GDD information for hybrids can be obtained from seed companies and salesmen. The company ratings should be made using the 30/10 system or other equivalent systems. Commonly, this system with daily higher (30°C) and lower (10°C) temperature limits is used in published weather data (Darby & Lauer 2002).

The GDD method is used with real data from the field, where thermometers measuring daily maximum and minimum temperature (T_{MAX} and T_{MIN} , respectively) are installed in a small shelter. This technique has a wide application in many states of the USA. We intend to use this method in collaboration with interested farmers in Greece. This type of research is still in its infancy and lack of real GDD values prohibits the comparison with plant production.

2. DATA AND STUDY AREA

Calculation of daily heat accumulation depends on the availability of datasets on daily T_{MAX} and T_{MIN} . In Greece temperature data are collected by the Hellenic National Meteorological Service (HNMS), the Ministry of Agriculture, and the Ministry for the Environment, Physical Planning and Public Works. Access to these data, however, is very limited. The latter 2 authorities do not publish their data and the HNMS discontinued their publication in 1989. Recent data records of HNMS are in electronic form and available for a high fee, which increases with the volume of data. Therefore, we have analyzed the issue using earlier data published by HNMS (1978–1987) for 40 first class meteorological stations (Table 1, Fig. 1). The majority of these stations have complete data series for the period analyzed (1978–1987).

The following stations had gaps in their data series (missing years in parenthesis): Chalkis (1978, 1979), Chania (1983), Korinthos (1984), Orestias (1982–1984, 1986), Volos (1983–1985, 1987). The stations used provide an almost complete data coverage of the country.

3. METHODS

3.1. Calculation of growing degree days

The canonical form for calculating GDD is:

$$\text{GDD} = [(T_{\text{MAX}} + T_{\text{MIN}})/2] - T_{\text{BASE}} \quad (1)$$

Where T_{MAX} is the daily maximum air temperature in °C (in our study), T_{MIN} is the daily minimum temperature in °C, and T_{BASE} is the temperature below which growth ceases.

Table 1. Stations of the Greek Meteorological Network used in this study

Stn	Lat. (°N)	Long. (°E)	Alt. (m)
1 Agrinio	38.97	21.38	46
2 Alex/polis	40.85	25.95	3
3 Andravida	37.92	21.30	10
4 Argostoli	38.18	20.48	2
5 Arta	39.17	21.00	39
6 Athens	37.97	23.70	10
7 Chalkis	38.47	23.60	4
8 Chania	35.50	24.02	62
9 Chios	38.33	26.13	3
10 Filadelfia	38.05	23.67	136
11 Florina	40.78	21.40	650
12 Heraklion	35.33	25.18	38
13 Ierapetra	35.00	45.75	16
14 Ioannina	39.67	26.85	483
15 Kalamata	37.07	22.10	6
16 Kavala	40.93	24.38	60
17 Kerkyra	39.62	19.92	2
18 Korinthos	37.93	22.95	4
19 Kozani	40.30	21.45	625
20 Kythira	36.15	23.00	167
21 Lamia	38.90	22.40	144
22 Larissa	39.63	22.42	73
23 Lesvos	39.10	26.55	2
24 Limnos	39.80	25.07	13
25 Methoni	36.83	21.70	33
26 Mikra	40.52	22.97	4
27 Milos	36.75	24.45	182
28 Naxos	37.10	25.38	9
29 Orestias	41.82	26.52	43
30 Patra	38.25	21.73	1
31 Rhodos	36.38	28.12	35
32 Samos	37.03	26.92	48
33 Serres	41.07	23.57	32
34 Siteia	35.20	26.10	25
35 Skyros	38.90	24.55	4
36 Thira	36.42	25.43	213
37 Trikala	39.55	21.77	112
38 Tripoli	37.52	22.40	512
39 Volos	39.37	22.95	3
40 Zakynthos	37.78	20.88	3

T_{BASE} varies among species and cultivars (Wang 1960). The quantity $(T_{\text{MAX}} + T_{\text{MIN}})/2$ is the mean daily temperature (T_{AVG}), but it is not permissible to replace this quantity with the daily mean temperature, as e.g. $(12 + 18)/2 = 15$, but also $(8 + 22)/2 = 15$. These 2 quantities give the same result, but as we will explain later, they do not have the same biological influence on the plant growing cycle.

Modifications to enhance the biological meaning of Eq. (1) have been suggested by Cross & Zuber (1972), McMaster & Smika (1988), Masle et al. (1989) and Wilhelm & McMaster (1995), who incorporated an upper temperature threshold, added a photoperiodic variable, used maximum or minimum temperature of the day, T_{MAX} or T_{MIN} , or incorporated functions of other environmental factors that affect phenology.

Cross & Zuber (1972) and Perry et al. (1986) found that Eq. (1) was used in different ways in the literature and that users of the results were unaware of the significant

Fig. 1. Stations and topography in Greece. Map derived by digitalization of analogical maps of the Army Geographical Service; grid points: $1' \times 1'$ (1.8×2.3 km for Athens)

errors that may be introduced by these differences. This problem will create confusion among farmers using differently calculated GDD. To avoid this, we first describe the 2 most common implementations of calculating GDD from Eq. (1). These differ with regard to the way in which T_{BASE} is related to the quantity $(T_{\text{MAX}} + T_{\text{MIN}})/2$.

In the first approach $(T_{\text{MAX}} + T_{\text{MIN}})/2 < T_{\text{BASE}}$, the first term of this inequality takes the form of the equality: $(T_{\text{MAX}} + T_{\text{MIN}})/2 = T_{\text{BASE}}$. This method is mostly used by researchers and practitioners involved in small grain production, and also for the calculation of GDD in simulation models.

In the second approach, the separate values of T_{MAX} and T_{MIN} are compared independently with T_{BASE} . If $T_{\text{MAX}} < T_{\text{BASE}}$ then we adopt the value $T_{\text{MAX}} = T_{\text{BASE}}$ and if $T_{\text{MIN}} < T_{\text{BASE}}$ then we adopt $T_{\text{MIN}} = T_{\text{BASE}}$. This is the most commonly used method in calculating GDD for corn and other crops (e.g. Baker et al. 1986, Wilhelm et al. 1987, 1989, Masoni et al. 1990). The ability to calculate daily GDD accumulation depends on the availability of daily temperature records of T_{MAX} and T_{MIN} , recorded at a height of 1.5 m above the ground in meteorological shelters.

GDD can be calculated for the winter wheat growing season (September – July) and for corn (April through October). T_{BASE} for winter wheat is 0°C (McMaster et al. 1994), for corn and other warm season plants it is 10°C (Cross & Zuber 1972).

As our aim was to estimate GDD in Greece during the warm period, we used 10°C as T_{BASE} .

Because in corn and other plants air temperatures greater than a defined upper limit do not improve physiological function, GDDs were calculated on the basis of an upper temperature threshold (T_{UT}). We set this threshold at 30°C for corn (Cross & Zuber 1972) and 25°C for wheat (Austin 1990, Curtis et al. 2002).

In conclusion, to estimate the GDD in this study, if $T_{\text{MAX}} < T_{\text{BASE}}$ or $T_{\text{MIN}} < T_{\text{BASE}}$ their values were replaced by the value of T_{BASE} .

The original data files for the 40 stations were transformed as described above by a FORTRAN program (source code in Appendix 1). The resulting data sets containing temperature values from 10 to 30°C were used for GDD calculation with a second program in FORTRAN (Appendix 2).

3.2. Model

T_{MIN} and T_{MAX} for each of the 40 stations were tabulated in separate tables for each calendar year. From these tables we chose the data covering the period April 1 to November 30 (244 consecutive days). These 40 tables contained 244 rows and 10 columns comprising the input dataset for the model.

After the model was run, we constructed separate tables of GDD for each of the 40 stations. The daily mean for each station was estimated for each calendar day of the 10 yr period.

There were no significant fluctuations from year to year, as the SD of daily values was very small compared with the 10 yr mean daily value. This small SD of the GDD is due to the cut-off of extreme values $<10^{\circ}\text{C}$ and $>30^{\circ}\text{C}$. Thus the daily temperature range was 20°C , resulting in small SD values. The coefficient of variation (CV) was small as well ($<5^{\circ}\text{C}$ for GDD values up to 2500°C)

3.3. Interpolation

The Greek Meteorological network is sparse and the data have a local focus, due to the mountainous landscape. Thus, statistical estimation of the GDD alone does not provide farmers with reliable information. To address this problem and provide a more powerful tool for planners, we introduced a second modelling step to interpolate the 'point information' on each station into 'area information', so that every spot in the country will be characterized by a unique value of GDD. The statistical product it is not a simple interpolation, as a number of parameters were taken into account. Similar methods have been applied for data on radiation or heating degree days (Matzarakis & Balafoutis 2004, Matzarakis & Katsoulis 2006). The parameters used were longitude, latitude, elevation, and slope aspect; distance from the coastline and the percentage of land and sea in the area were also taken into account. The country was divided into $1'$ grids.

To construct maps of the GDD distribution we selected data from the following growing periods: (1) April 1 to November 30, (2) May 1 to November 30, (3) April 1 to October 31, (4) May 1 to October 31, (5) April 1 to September 30, (6) May 1 to September 30 (Table 2).

Using these data as input files in a statistical procedure, which includes the GDD of the stations as dependent variable and latitude, longitude, elevation, distance to the sea and ratio of land and sea area of the surrounded grids as independent variables, we constructed maps for the above-mentioned time periods. The correlation coefficient r ranges from 0.83 to 0.89 and the standard error varies between 112 and 134

GDD. The calculated values in the maps do not differ from those obtained from the climate network. The maximum differences between measured and calculated values are $<10\%$ (4% for Larissa, 7% for Orestias, 1% for Florina, and 2% for Ierapetra).

4. RESULTS AND DISCUSSION

Interannual variability was small; e.g. in Kalamata, the southernmost station of the mainland, estimated values of GDD for the 10 yr period ranged from 2265 in 1978 to 2480 in 1986. There is a trend of increasing GDD at Florina during the study period (Fig. 2). GDD tended to increase during the study period, confirming the global warming trend.

The mean accumulated daily values were tabulated for the 40 stations over the period from April 1 to November 30 (data not shown). From this table we estimated the GDD for periods ending on August 31, September 30, October 31, and intermediate dates. GDD values for April to November ranged between 1656 in Florina to 2934 GDD in Rhodes.

It is possible to estimate GDD for any time period. If, for example, the starting date is April 25, we subtract the accumulated value corresponding to the previous day (April 24) in the corresponding column of values (e.g. Table 3 for Larissa, chosen because it is located at the geographic midpoint of Greece). For example, during the period from May 10 to September 30 the accumulated GDD are 1637°C , and from April 20 to August 31 the accumulated GDD are 1506°C .

Fig. 3 shows the geographic distribution of GDD for April 1 to November 30. In mountainous regions up to 1800 m the accumulated GDD are <1600 . In the southernmost coastal regions of the mainland and on the shores of Crete and many islands of the south Aegean Sea the GDD are >2800 . The magnitude of GDD in-

Fig. 2. Growing degree day (GDD) values at Florina from 1978 to 1987

Table 2. Accumulated GDD starting April 1 and May 1 for map construction

Stn	April 1 to			May 1 to		
	Nov. 30	Oct. 31	Sep. 30	Nov. 30	Oct. 31	Sep. 30
Agrinio	2318.0	2185.0	1936.9	2160.0	2027.0	1778.9
Alex/polis	2001.4	1928.8	1746.4	1894.0	1821.4	1639.0
Andravida	2360.3	2215.6	1952.1	2221.3	2076.6	1813.1
Argostoli	2569.5	2394.5	2083.4	2420.2	2245.2	1934.1
Arta	2354.8	2221.1	1964.1	2205.1	2071.4	1814.4
Athens	2681.9	2531.2	2247.1	2522.7	2372.0	2087.9
Chalkis	2658.3	2523.9	2247.3	2481.9	2347.5	2070.9
Chania	2649.2	2475.2	2131.2	2464.5	2290.5	1946.5
Chios	2386.6	2261.5	2024.7	2238.4	2113.3	1876.5
Filadelfia	2609.2	2486.3	2222.1	2438.7	2315.8	2051.6
Florina	1655.7	1701.6	1523.5	1548.1	1594.0	1415.9
Heraklion	2624.8	2433.3	2126.5	2444.7	2253.2	1946.4
Ierapetra	2881.8	2669.4	2328.4	2701.1	2488.7	2147.7
Ioannina	1979.2	1804.1	1628.7	1867.0	1691.9	1516.5
Kalamata	2380.9	2225.4	1958.1	2231.9	2076.4	1809.1
Kavala	1986.5	1921.6	1737.7	1871.8	1806.9	1623.0
Kerkyra	2422.5	2271.0	1994.6	2279.2	2127.7	1851.3
Korinthos	2676.8	2498.2	2229.3	2513.3	2334.7	2065.8
Kozani	1795.4	1708.1	1577.5	1700.5	1613.2	1482.6
Kythira	2532.2	2404.3	2122.0	2393.2	2265.3	1983.0
Lamia	2455.2	2349.3	2111.3	2297.1	2191.2	1953.2
Larissa	2201.1	2124.9	1919.8	2059.0	1982.8	1777.7
Lesvos	2540.1	2416.4	2163.0	2377.9	2254.2	2000.8
Limnos	2197.7	2102.8	1896.4	2077.6	1982.7	1776.3
Methoni	2491.2	2327.7	2028.2	2343.1	2179.6	1880.1
Mikra	2388.3	2307.5	2089.0	2246.4	2165.6	1947.1
Milos	2516.7	2366.7	2093.6	2356.4	2206.4	1933.3
Naxos	2531.2	2356.1	2068.5	2359.8	2184.7	1897.1
Orestias	1979.0	1925.1	1759.4	1854.3	1800.4	1634.7
Patra	2609.1	2444.7	2141.6	2449.8	2285.4	1982.3
Rhodos	2933.9	2725.6	2373.2	2730.4	2522.1	2169.7
Samos	2649.2	2508.4	2230.2	2488.2	2347.4	2069.2
Serres	2211.7	2155.9	1962.7	2065.2	2009.4	1816.2
Siteia	2721.0	2520.5	2209.9	2525.4	2324.9	2014.3
Skyros	2373.2	2250.2	2004.8	2225.3	2102.3	1856.9
Thira	2560.5	2392.2	2119.9	2396.9	2228.6	1956.3
Trikala	2421.5	2335.8	2112.3	2258.8	2173.1	1949.6
Tripoli	1813.5	1742.4	1569.4	1706.4	1635.3	1462.3
Volos	2495.3	2401.5	2162.8	2334.1	2240.3	2001.6
Zakynthos	2512.8	2349.4	2058.1	2369.1	2205.7	1914.4

Table 3. Accumulated growing degree units (°C) for different starting and ending dates in Larissa

Ending date		Starting date				
		April 1	April 10	April 20	May 1	May 1
November	30	2201.1	2161.0	2114.2	2059.0	1918.0
	20	2180.8	2140.7	2093.9	2038.7	1897.7
	10	2156.2	2116.1	2069.3	2014.1	1873.1
October	31	2124.9	2084.8	2038.0	1982.8	1841.8
	20	2074.8	2034.7	1987.9	1932.7	1791.7
	10	2004.8	1964.7	1917.9	1862.7	1721.7
September	30	1919.8	1879.7	1832.9	1777.7	1636.7
	20	1816.3	1776.2	1729.4	1674.2	1533.2
	10	1706.6	1666.5	1619.7	1564.5	1423.5
August	31	1593.2	1553.1	1506.3	1451.1	1310.1
Values subtracted from original table to calculate above data values						
Starting dates						
May	10	292.6	252.5	205.7	150.5	9.5
	1	148.2	108.1	61.3	6.1	
April	20	90.6	50.5	3.7		
	10	45.8	5.7			
	1	3.3				

creases from north to south, and from elevated areas to the lowlands.

If the growing season ends 30 d earlier on October 31 (Fig. 4), the distribution of GDDs is geographically the same, but GDD is 200 units lower; the reduction is more pronounced in the mountains. For April 1 to September 30, areas >700 m have <1200 GDD (Fig. 5). The lowland area of the country shows predominance of 1800–2000 GDD. In elevations ≤650 m, 1400–1600 GDD are common. Peloponnesus, Crete and south Aegean islands have higher values.

For a more complete description of the distribution of the accumulated GDD, 3 more periods starting on May 1st were considered with the ending day remaining the same as in the previous analyses (Table 3, last 3 columns). Using these data we constructed 3 maps (Figs. 6, 7 & 8) showing the geographical distribution of the GDD over Greece for these shorter and warmer periods.

During the period May 1 to November 30 (Fig. 6) GDD values range from 2600 on Crete and Rhodes to <1200 in mountainous areas. The geographical distribution of the GDD of a shorter period (May 1 to October 31; Fig. 7) shows a lower upper limit of GDD in comparison with Fig. 6. Data for a period of 5 mo (May 1 to September 30) are given in Fig. 8.

There are no comparable data in the literature on climate regions that have similar characteristics or are located at the same latitude.

5. CONCLUSIONS

The method used to calculate GDD and the mapping method applied showed that it is possible to use high- or low-density climate networks together with geo-statistical techniques, to produce reliable spatial data (maps) and valuable information for agriculture management.

The shortest period studied, May 1 to September 30, can be characterized climatologically as a time period that permits achievement of crop maturity in corn, cotton, tobacco, sugar beets and other plants without temperature limitations, as the entire lowland area has GDD >1600. Land up to an altitude of 650 m has GDD >1200.

Fig. 3. GDD (°C) in Greece for April 1 to November 30

Fig. 4. GDD (°C) in Greece for April 1 to October 31

Fig. 5. GDD (°C) in Greece for April 1 to September 30

Fig. 6. GDD (°C) in Greece May 1 to November 30

Fig. 7. GDD (°C) in Greece May 1 to October 31

Fig. 8. GDD (°C) in Greece May 1 to September 30

If the cultivating period is extended by 1 mo at the beginning and 1 mo at the end (Fig. 4), the distribution of accumulated GDD shows that all cultivated areas of the country tend to have very high values (1600 to 2400), which covers the demands of all the plants cultivated in the country.

According to these results, Greece is characterized by favorable thermal conditions for the cultivation of high productivity crops.

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Appendix 1. FORTRAN code for calculation of growing degree days

```

WRITE(*,*)'GIVE THE NUMBER OF ROWS AND COLUMNS'
READ(*,*) N,L
DO 81 I=1,N
81 READ(7,2)KODE(I),(TEM(I,J),J=1,L)
2 FORMAT(I5,31F4.1)
DO 100 I=1,N
DO 101 J=1,L
IF(TEM(I,J).LT.10.0) GOTO 700
IF(TEM(I,J).LE.30.0) GOTO 701
IF(TEM(I,J).GT.30.0) GOTO 702
700 TEM1(I,J)=10.0
GOTO 101
701 TEM1(I,J)=TEM(I,J)
GOTO 101
702 TEM1(I,J)=30.0
GOTO 101
101 CONTINUE
100 CONTINUE
do 555 I=1,N
555 WRITE(8,3) KODE(I),(TEM1(I,J),J=1,L)
3 FORMAT(I5,31F5.1)
CLOSE(7)
CLOSE(8)
STOP
END

```

Appendix 2. FORTRAN code used to estimate cumulative daily values of growing degree days using daily maximum and minimum air temperature

```

REAL ELEM1(30,31),ELEM2(30,31), S(1000)
INTEGER YEAR(30)
CHARACTER*20 NAME1,NAME2,NAME3
WRITE(*,*) 'GIVE THE NAME OF THE output FILE'
READ(*,*) NAME1
WRITE(*,*) 'THE NAME OF THE MAX DATA FILE'
READ(*,*) NAME2
WRITE(*,*) 'THE NAME OF THE MIN DATA FILE'
READ(*,*) NAME3
OPEN(9,FILE=NAME1,STATUS='NEW')
OPEN(8,FILE=NAME2,STATUS='OLD')
OPEN(7,FILE=NAME3,STATUS='OLD')
WRITE(*,*) 'GIVE THE NUMBER OF ROWS AND COLUMNS'
READ(*,*) N,L
write(*,*) 'GIVE THE TOTAL OF THE PREVIOUS MONTH'
READ(*,*) VALUE
m1=0
S1=0.0
DO 100 I=1,N
READ(8,1)YEAR(I),(ELEM1(I,J),J=1,L)
100 READ(7,1) YEAR(I),(ELEM2(I,J),J=1,L)
1 FORMAT(I5,31F5.1)
DO 101 I=1,N
DO 102 J=1,L
M1=M1+1
IF(I.GT.1) GOTO 5
IF(J.GT.1) GOTO 5
S(M1)=VALUE+(((ELEM1(I,J)+ELEM2(I,J))/2)-10.0)
GOTO 6
5 S(M1)=S(M1-1)+(((ELEM1(I,J)+ELEM2(I,J))/2)-10.0)
GOTO 6
6 CONTINUE
102 CONTINUE
101 CONTINUE
M=N*L
DO 113 I=1,M
113 WRITE(9,333) S(I)
333 FORMAT(F7.1)
CLOSE(9)
CLOSE(8)
CLOSE(7)
STOP
END

```