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GIS-based analysis of spatial distribution patterns of growing degree-days for agricultural applications in Iran

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Abstract

The geographical distribution of growing degree-days (GDDs) within Iran was studied using GIS-based maps. GDDs were calculated using daily thermal parameters (daily maximum and minimum air temperature). Based on the purpose of the study and climatic conditions of Iran, the average value of 5°C was chosen for GDD calculation. The calculations were carried out using daily weather data of 113 meteorological stations throughout Iran. The clustering of the 113 point stations' data were achieved by using statistical models combined with a digital terrain model. The final outcomes were five GDD maps (two for start and end of heating period, one for January, one for cold season and the last one annual growing degree days). The relationships between calculated GDDs and key variables that may affect temperature were carefully studied. (e.g. geographical data of latitude and longitude, elevation, nearest grid distance from the sea) Geographical distributions of GDDs were found to be correlated closely with the climatic types of different regions that are mainly based on relief. The distribution of the GDDs presented in the maps showed that the calculated values were close to the measured ones, which confirmed the validity of the GIS-based approach. In few cases significant differences between predicted and calculated values were observed, mostly in the regions with less number of weather stations. Consequently, the highly accurate generated maps can be used as a useful tool for prediction of crops and pests phonological events and crop modeling.

Keywords: Temperature; Growing Degree-Days; Iran; Digital Terrain Model; GIS

1. Introduction

Since 1730 when Reaumur introduced the concept of heat units (thermal time), many methods of calculating heat units have been used successfully in the agricultural sciences. Generally, a degree-day is a measure of heat accumulation used by agricultural scientists to predict the date of blooming or a crop reach maturity. It gives the value of quantity and duration when the air temperature becomes lower or higher than a determined threshold value, which is known as its basic temperature (Hitchen, 1981). Particularly in the areas of crop phonology and development, the concept of heat units, measured in growing degree day (GDD, ºC/day), has vastly improved description and prediction of phonological events compared to other approaches such as time of year or number of days (e.g. Cross and Zuber, 1972; Gilmore and Rogers, 1958; Klepper et al., 1984; Mc Master, 1993; Mc Master and Smika, 1988; Russelle et al., 1984; Hargy, 1982; Yang et al., 1995; Mc Master and Wilhelm, 1997; Roltsch et al., 1999; Cesaraccio et al., 2001).

Several studies have revealed that the air temperature is a major factor controlling crop development. Ghasemi Pirbalouti and Golparvar (2008) evaluated agro-climatological indices to identify suitable areas for rapeseed cultivation using GIS in two provinces of Iran. The results indicated that the main affecting factors were accumulated GDD from sowing to physiological maturity and sowing to first day of frost period.

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According to Bazgeer, (2005), multiple regression models, which considered climatic parameters as independent variables, indicated that 69% wheat yield had a significant relationship between changes' in daily minimum temperature and growing degree-days in Punjab India. Esfandiary et al., (2009) used agro meteorological indices including daily temperature, accumulated difference of maximum and minimum temperature and growing degree days (GDD) for wheat yield prediction in Ardebil province. Accordingly, in the final statistical models, 83% of wheat yield variability was the result of variation in referred agro meteorological indices.

In addition, GIS can be effectively applied to handle such kind of work and to reach the objectives of the study. Integrated models incorporating satellite based vegetation indices, agro meteorological indices, biophysical indices and time trend predicted well yield (Pinter et al., 2003; Deosthali and Akmanchi, 2006). Hutchinson et al., (2006) indicated strong relationships between pasture growth rates and GDDs. They also had asked the participating farmers to use topoclimate (south soil) and GDD maps in order to ensure the accuracy of the gathered information. Richards, (2000) presented aspects of ongoing topoclimate and spatial mapping research to map growing degree-days in Southland, New Zealand. In Iran, the duration of the heating systems' operation and the total amount of the GDDs varies from one location to the others as the air temperature (apart from the prevailing atmospheric circulation conditions) strongly depends on latitude, longitude, altitude, slope, aspects and etc. With using the meteorological station data, the GDDs were calculated and regionalized by means of statistical methods. The main and final goal of this data processing was to construct GDD maps considering geographical factors in Iran. This material is very useful for the calculation of dates of sowing and dates of harvest and useful method of predicting weed emergence. The main purpose of this study was performing a spatial analysis of GDD pattern across Iran using GIS and regression models. Attempts have been made to introduce to most significant affecting variables on GDD changes over time in study stations. These changes have already had and continue to have impacts on different aspects of society, agriculture, and energy demand. Therefore, it is important to investigate observed changes in GDDs so that future GDDs predictions can be validated and put into context.

2. Materials and Methods

In order to manage the biological crop and pest processes, basic thermal units (GDD) were used in this research was a basic thermal unit called a GDD. Daily values of GDD can be obtained only by means of calculations. Daily GDD values statement the differences between the air temperature and the basic temperature, when the basic temperature is higher than the air temperature. Many approaches and techniques were developed with scientists to calculating GDDs (e.g. Snyder, (1985); McMaster et al., (1997); Yang et al., (1995)). Simple approaches use the mean daily temperature compared with the basic temperature.Nowadays, more complicated equations and relatives were used to determine it. In this Study, the GDD was calculated based on the daily data of the maximum and minimum air temperatures were collected from the 113 main meteorological stations of Iran, which had complete daily maximum and minimum air temperature observations from 1978 to 2004 (Fig.1). This period of 28 years was considered as a sufficient length to be significantly influenced by climatic change. Some missing data were estimated objectively by a weighting algorithm based on actual measurements from nearby weather stations when possible to ensure completeness of record. The data has undergone quality control. Based on the literature review and recommended values, 5ºC was fixed as the base temperature, T_b for wheat, which corresponds realistically to the climatic conditions of Iran territory. This value has been reported and confirmed by farmers in the most populated agricultural areas of Iran determination of begging and end of growing period.

The calculation of GDD has been carried out by means of different equations; it depends on the relationship between the base temperature T_b and the mean, T_{mean}, minimum, T_{min} and the maximum, T_{max} daily air temperatures. The equation is as follows (Perry, 2006)

$$\text{Growing Degree Days (GDD)} = \Sigma \text{daily } T_{mean}-5 \text{ for } T_{mean}>5^{\circ}C \quad (1)$$

As a physiological rule, the base temperature should be similar for a given crop development stage in any growing season. Goyne et al., (1977) used a range of temperature from -6ºC to 9ºC to calculate the base temperature for sunflower (*Helianthus annuals*.). Perry et al. (1986) selected the base temperature among these values, 0ºC, 10ºC, 13ºC, 18ºC and 25.5ºC for predicting harvest time of cucumber

(Cucumis Sativus L.). Values of GDDs obtained from this equation 1, were used for the generating the maps representing the geographic distribution of the GDDs over the entire Iran up to elevation of 2500 m.

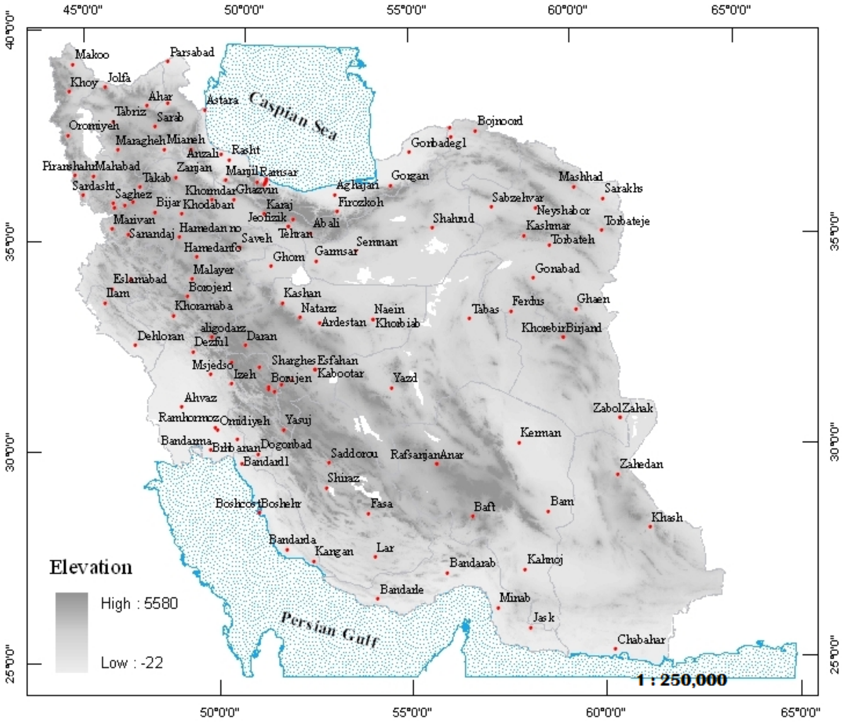


Fig.1. Spatial distribution of studied stations

There was an issue of how to fit special statistical models in order to transfer specific information from point observations (113 stations) in space. This was solved by using the spatial interpolation methods. Available interpolation methods are including geostatistics, e.g. kriging, inverse-distance weighting (IDW), and smoothing splines. Kriging has been used for the interpolation of temperature and precipitation regression residuals across a wide region in the Mediterranean (Agnew and Palutikof, 2000). Holdaway (1996) used residual kriging for the interpolation of temperature in a forest area. Brown and Comrie (2002) used ordinary kriging for the interpolation of monthly temperature anomalies, but they showed the priority of IDW for precipitation. A distance-weighted method was also used by New et al. (1999) for interpolating monthly global climate anomalies, and Willmott and Robeson (1995). Splines were used by Vicente-Serrano et al. (2003) for annual precipitation and temperature estimation in a small area and Jarvis and Stuart (2001) for daily temperature over England and Wales, in comparison with other methods. The spline functions are suitable for generating unrealistically smooth surfaces from primary data which can cover the wide range of variables and environments. Although Kriging method as a computer- intensive method gives unbiased optimal estimates based on the spatial correlation between values, it may produce too smooth surface. (Brown and Comrie, 2002) IDW was chosen for this study due to the fact that it can capture local variations well, and draws values at co-located grid points exactly. It is also a simple way to implement, which can be important considering the size of this task and may end in good results being used for a large range of different variables .

Finally, GDDs maps were correlated with topography, which was also reported in previous studies (Gordon, and Bootsma, 1993, Perry et al., 2005) for the subsequent statistical analysis the calculated GDDs were regarded as the dependent variable. The independent variables were the magnitudes of Elevation, longitude, latitude and nearest from the sea. (Perry et al., 2005)

3. Results and discussion

Analysing the calculated data provided by the previously reported relationships showed that the mean value of GDDs varies considerably from one region to other ones. The highest value of GDDs (8165.9˚ C) for the whole cold period was recorded in the dry city of Hormozgan, located in south Iran (figure2). This value is almost four times higher than corresponding value of 2103.0˚ C were observed in the cold snow forest climate city of Ardebil, located in northwest Iran, where the minimal thermal requirements of the country were observed. This large difference in GDD values between Hormozgan and Ardebil showed the intense contrast in the climatic characteristics between these two extreme geographic paints; and gave an idea about the recipient energy. A farmer working in Hormozgan receives roughly four times more heating unit comparing with a farmer in Ardebil, using the same heating unit. Also, southwest hinterland stations, e.g. Ahvaz (7799.5˚ C)and Masjedsoleyman (7495.2˚ C), had high values of GDDs, denoting that the southern and mainland of Iran has beneficially regarding to air temperature along the southern shores that cold invasions are common in this area during the cold period. Ardebil (2103.3˚ C) and Abali (2230.4˚ C) both located in high elevation, have considerably decreased energy and heat united, due to the intense topography. In Khorasan-e-shomali province, northeast of Iran, Bojnord station (3383.7˚ C) was considered as a cold spot due to its high elevation and long distance from the sea.

The lowest GDDs were estimated in northwest, north and northeast regions, where cold air masses coming from the Mediterranean sea and Siberia are frequent. In the center of the low mainland there are high value like south of Iran because of their location, this area located between two mountains Zagros and Alborz and those mountains act like wall for mainland so this area have high values of GDDs because of a few entrance air current. Finally the lowest GDDs indicated in local with highest elevation (the Alborz and Zagros elevations) that those are against cold air masses coming from Mediterranean sea. Based on the mean period values, as well as on the mean monthly values of each station, Maps of the geographic distribution of the GDDs were constructed, and some of them are analysis below. Figure3 is the geographic distribution of the GDDs for the entire study period. Regions with smaller GDD are the highland areas, northern, coastal regions of Caspian Sea, northwest Iran, as well as many parts of the high-altitude hinterland. A slightly higher heating unit was observed in the other parts of Iran. The growing degree days (GDD>1500) were observed in the highlands of north of Khorasan, the mountainous western mainland, the east regions of Caspian sea, lowlands neighbor Caspian sea and the coast of the Persian Gulf with lowland mostly have high GDD. The most heating unit region, with GDD>4000˚ C, are the central and southeast and southern coastal this analysis showed a comprehensive description of the differences in thermal receipts in the various regions of Iran.

However, more practical interest is the annual variability of the seasonal GDDs in the various parts of Iran (these graphs are not included). Values of GDDs higher than 100˚ C appeared first in January (especially at the end of January) in the mainland and southeast. In April, values lower than 100˚ C are common in the mountainous regions and northern coastal regions. During cold winter months (December to February) the geographic distributions of the GDD values were very similar; hence the analysis of the geographical distribution for January (figure3) could be used, with high precision, for rest of the winter period. In the January (and the other two winter months) lowest GDDs (<200˚ C) were observed over all northwest Iran, in the mountainous areas of central and western and three smaller extent in northeast, in the mountain range of Khorasan. The interior lowlands of southern and southeast, at the fringes of the mountains and elevated areas of the center and south of Iran have relatively higher GDDs. Where the total amount of the GDDs ranges were between 1000 to 3000˚ C. the coastal regions of the mainland are characterized by milder conditions and the monthly totals of the GDDs were limited between 0 to 3000˚ C.

Favorable conditions for plant growing do exist in middle and southern parts of the country. In March, the geographic distribution of the GDDs is quite similar to that of January, with a reduction in the absolute values of GDDs by at least of 200˚ C in the most of country. In April the GDDs' values were lower than 500˚C in the entire country, except the higher mountainous regions. Concerning the May pattern, the GDD values were lower than 700˚ C in entire of Iran except around the Persian Gulf. An arbitrary monthly limit of 100˚ C for GDDs below was proposed when heating is not required. The analysis of the maps in figures 4 and 5, which presented the beginning and the end date of the heating period, reveals which regions had reduction for heating and which regions continue. These estimations will help the authorities to identify those areas of the country where are suitable for Several times a year in crop cultivation.

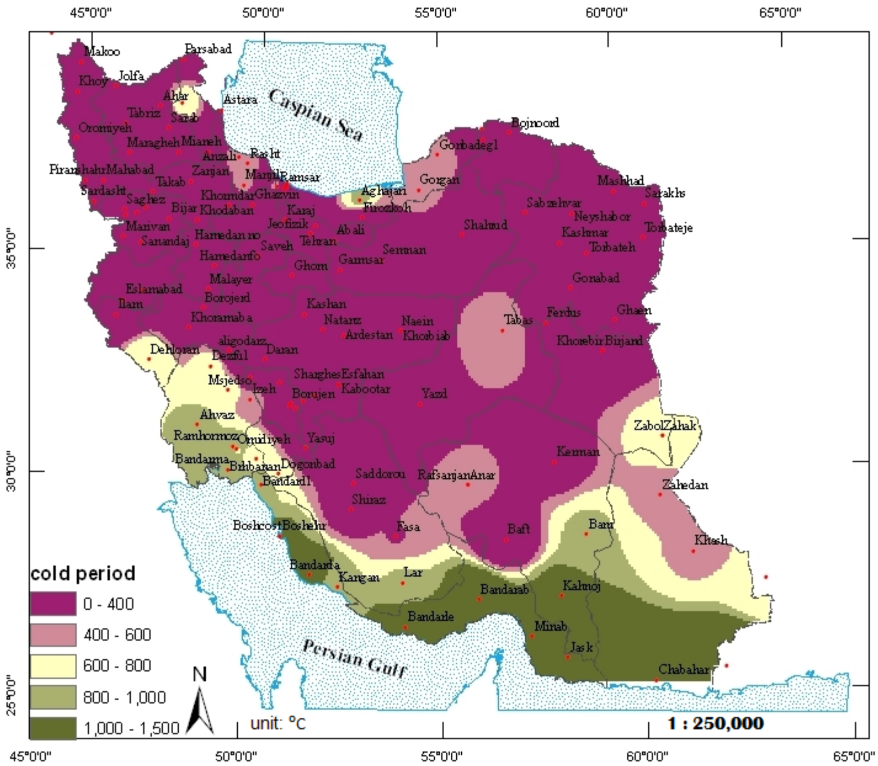


Fig. 2. Spatial distribution of GDDs during the cold period

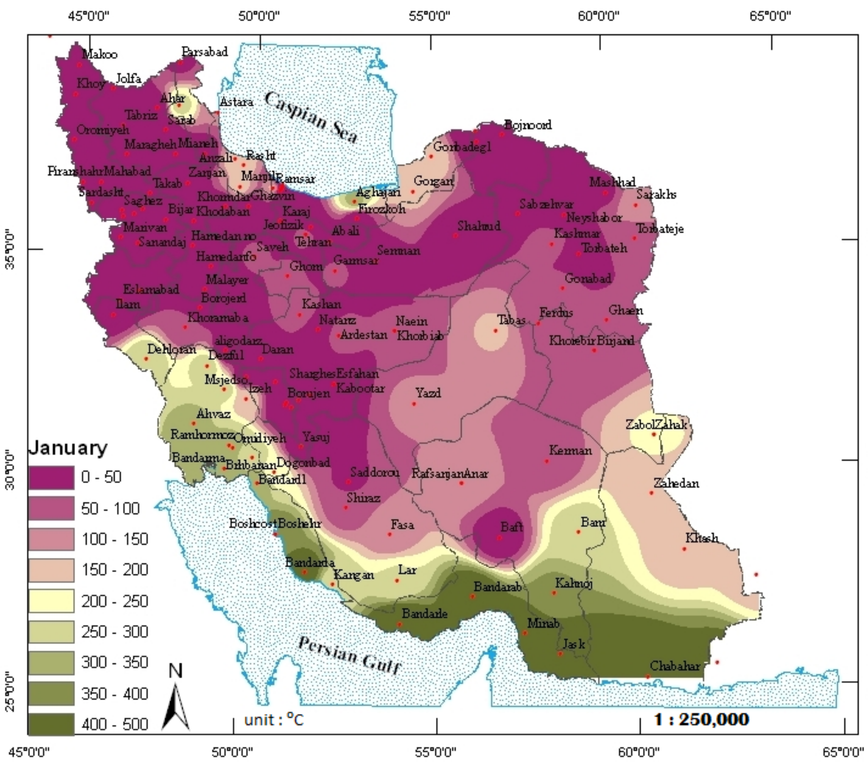
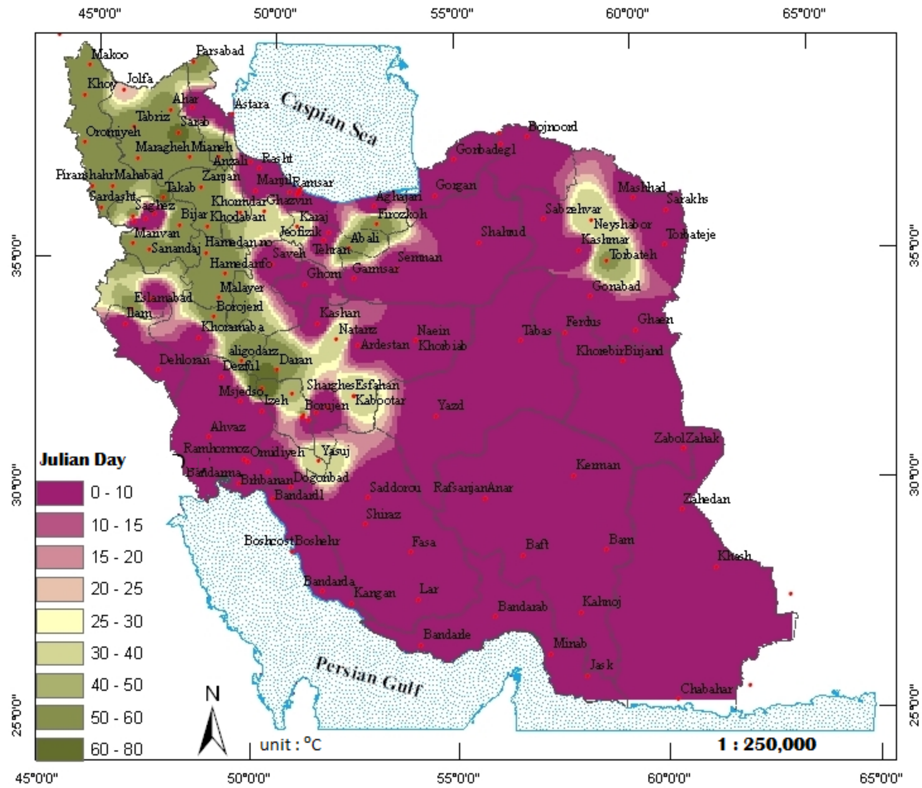


Fig. 3. Spatial distribution of the GDDs for January

Further analysis of two relative maps (figure 4 and 5) showed that the starting dates for GDD appeared first in the southern territory close to the Persian Gulf especially in southeast. In this part of the country the GDD appeared in all days of research period. In the mountainous range (crossing the country from northeast to southwest) 40th day of the year (9th February) marks the start of the heating period. In the main plains of the country, located in northern and central regions, the starting values of GDD appear after 20th day of year (20th January). In the Caspian Sea coasts, the first GDD appears at 10th day of year (10 January).



Figu. 4. Geographical distribution of beginning day heating period (Julian day)

Regarding the finishing time of GDD period, it was observed that, in southern Iran, 360th day of year (26 December) marks the latest date for terminating heating, a value that exceeds 320th day of year (14 November) in mountainous area. In the coastal area, the Iran plains and in the northern regions the approximate date of end of heating period ends is 350th day of year (15 December).Figure 6 shows the geographical distribution of the mean length heating period (in days) across Iran. The analysis of this map showed that the regions with the highest period for GDD, greater than 360 days located in southern Iran. Still, scattered spots with the same length were observed in the mountainous regions, in the plains of Iran there exist a period of 0-80 days for continuous heating. In the northern coastal regions and northwest of Iran, the length of GDD period varies from 300 to 350 days. A period of 0-80 days was observed along the northeast. Reduced GDD in the day was observed in the majority of 250 where the duration ranges from 200 to 300 days.

Generally, investigations in this field are rare. In a similar study by Gou-Jing (2006) the heating conditions in eastern China were analyzed. Their results were partly comparable with findings of this study. The differences might be explained by the different length of data record (30 years in eastern China) and different latitude-longitude of both regions.

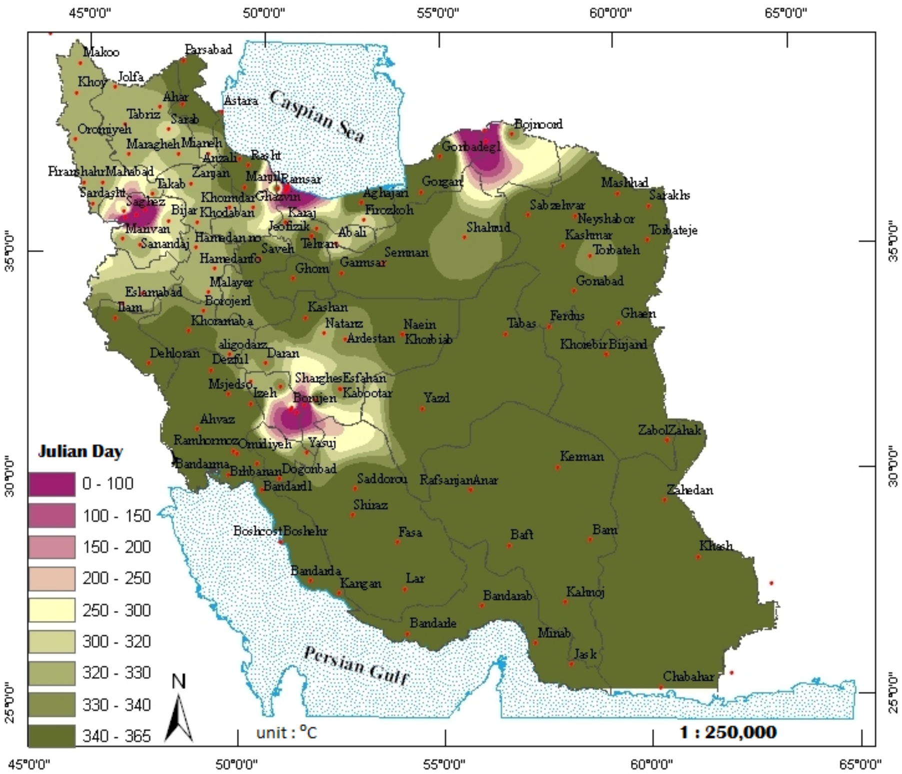


Fig. 5. Geographical distribution of last day of heating period (Julian day)

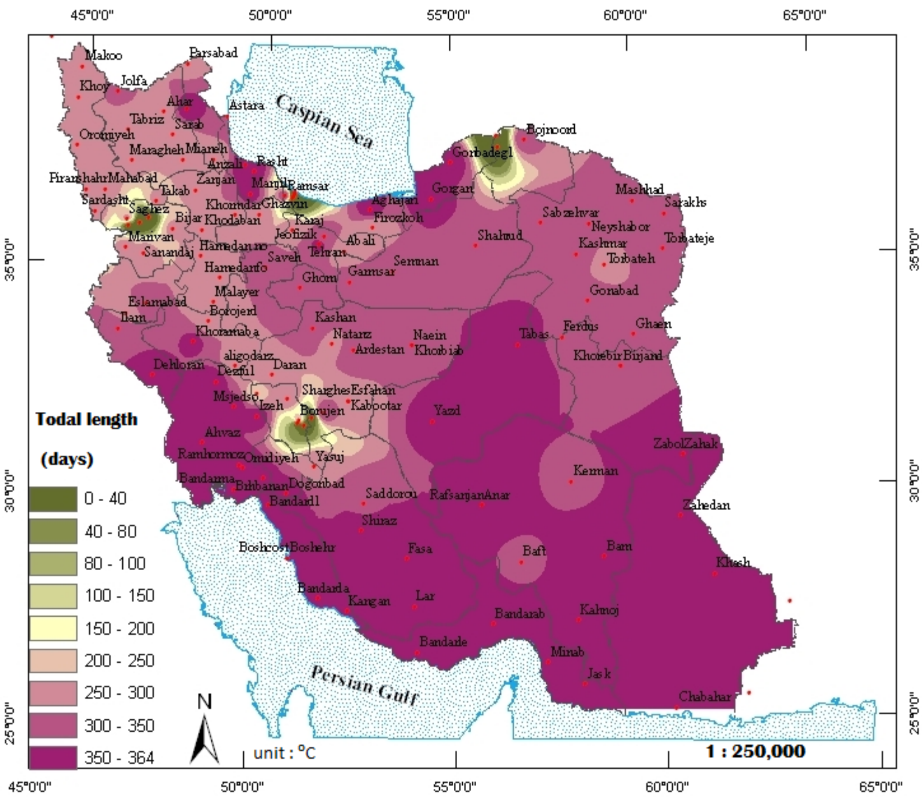


Fig. 6. Total length of heating period across Iran

4. Conclusion

GDD, provides an excellent tool regarding the quantity of heating unit in any region. Analysis of the produced maps revealed that longer period of GDD duration appears in southern Iran, with much higher GDD amounts than the rest of Iran. The GDD values are declining from south to north and from the mainland to the mountains areas. The local authorities and decision makers may consider the outcomes of this research in establishing agro-advisory systems and determination of crop sowing dates in different regions of the country. It is obvious that the distribution of sowing dates across the country is a major concern for maximizing the agricultural production. The introduced methodology is a could be used for the benefit of all farmers in different farm scales.

As the estimated values are very close to the measured ones, the represented geographical distribution of the GDDs on the maps reveals a significant statistical relation which confirms the reliability of the models applied. The small differences between the estimated and measured values can be accepted due to the conditions of stations network, sparse and limited only to areas up to 2000m above sea level, used in this study.

Offering relevant information and support, the introduced GDD maps of this study can be considered as a useful tool in applied agroclimatic studies as well as the crop modeling, decision support systems and integrated pest management

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