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Modelling apple tree bud burst time and frost risk in Iran

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ABSTRACT: The bud burst phase of orchard trees is the most critical phase in relation to low temperature and frost since the most parts of the bud, especially the ovary, are very sensitive to low temperatures. Therefore, predicting the time of bud burst is important. If a model can predict the time of budding, it would be possible to protect buds from late spring frosts. In this study, the budding time of apple trees at two agrometeorological stations in northeast and northwest Iran was predicted by using a chilling and forcing model. Data for years 2002–2006 were used to calibrate the bud burst prediction model and respective information for the years 2007 and 2008 was used to validate it. For this purpose, five threshold temperatures (T_C) and 11 chill requirements (C_R) were used. Among 55 combinations of T_C and C_R, the combination with minimum Root Mean Square Error (RMSE) was selected for predicting bud burst of apple for each region. Meanwhile, the probability of last date of frost in spring was estimated by statistical distribution. By comparing the probability of frost occurrence with the date of predicted bud burst, the risk of frost damage on apple budding was estimated. Copyright © 2009 Royal Meteorological Society

KEY WORDS chill accumulation requirement; chill days; bud burst; late frost; Iran; apple tree

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1. Introduction

The apple tree is one of the oldest fruit trees in the world and is compatible to different climatic conditions. Two major origins for the apple tree in Asia have been found with characteristically high temperature in summer and low temperature in winter (Porteous, 1996).

Late spring frosts that occur in the beginning of the growing season may cause damage to fruit trees that are already in the flowering stage (Vestal, 1971; Bagdonas *et al.*, 1978). Frost is the most important cause of damage to fruit trees in Iran. According to a report of the Iran Agricultural Bank, the last frost in spring 2004 in Iran caused losses to apple production estimated at over US$600 million. The Iran Agricultural Insurance Company paid US$300 million to frost-affected growers in this year (IAB, 2005). There are important agricultural regions in the northeast and northwest of Iran, with late spring frosts causing a lot of damage on agricultural plants, especially fruit trees. Late spring frosts occur every year at the time of apple budding which cause a lot of financial losses to the growers.

The budding phase is the most critical phase of fruit tree development (Bagdonas *et al.*, 1978). Floral bud-break for orchard crops depends mainly on air temperature and its variation during the winter season. The exposure to a particular duration of lower temperature (called vernalization) is needed to meet chilling requirements and release dormancy, followed by a spring growth. However, the effectiveness of time-temperature combinations on meeting chilling requirements varies between species. Each tree species has specific chilling requirements related to the accumulated hours that are weighted for temperature effectiveness at breaking dormancy (Cesaraccio *et al.*, 2004). Furthermore, for complete budding, most fruit trees need exposure to suitable day lengths (Lahooti, 1997).

Several models have been developed to calculate chill units for fruit trees. Richardson *et al.* (1974) quantified required chilling degree days as cumulative hourly temperatures for a variety of crop species, including peaches, in the state of Utah in the United States. This approach became the basis of other methods. Kobayashi and Fuchigami (1983) developed an empirical model for prediction of bud burst time in Red-Osier Dogwood (*Cornus sericea* L.) based on thermal requirement for bud development. Rattigan and Hill (1986) estimated the chilling requirements for dormancy break in flower buds and the heat sum requirements for floral development in 12 almond cultivars over 7 years. Orlandi *et al.* (2002) developed a practical method to evaluate the relationship between the amount of winter chilling and plant development in two olive (*Olea europaea* L) cultivars (Ascolana and Giarraffa). De Melo-Abreu *et al.* (2004) carried out an investigation, testing three different models, to predict

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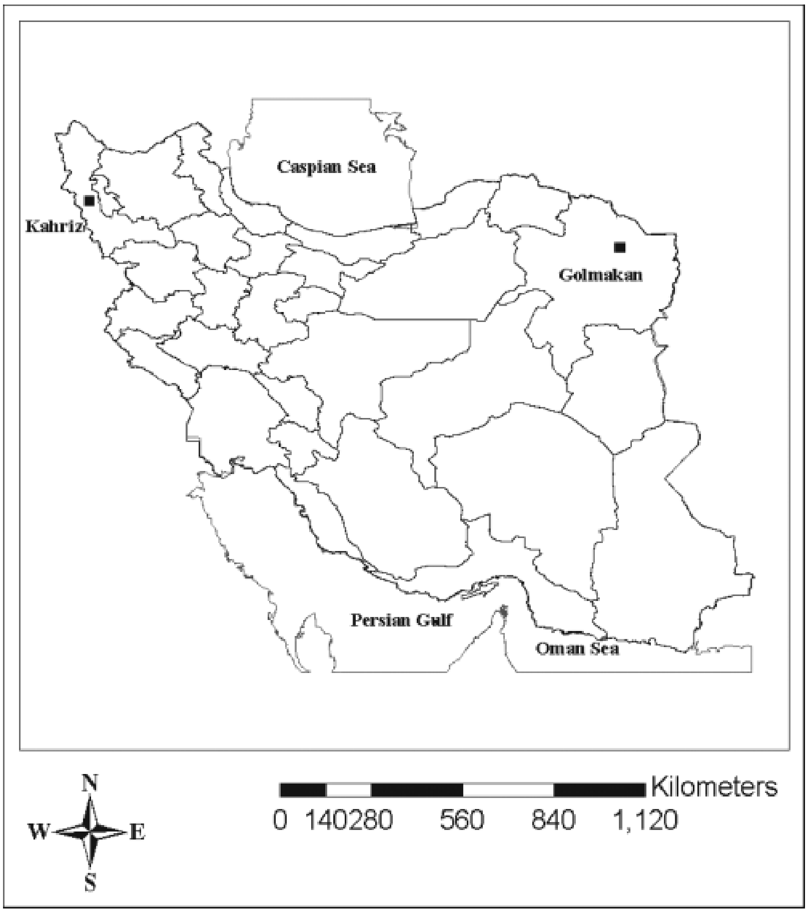

Figure 1. Study stations (Kahriz and Golmakan).

flowering of 15 varieties of olive in Spain and Portugal over the period 1975–2002.

The purpose of the present study was not to compare different methods for bud burst prediction but to develop a model for bud burst of apple trees in two places in Iran. Predicting the time of bud burst and comparing it with the frost risk at that time, using a chilling and forcing model, could potentially be used in preventing frost damage on trees using appropriate methods and machinery (such as wind machines, heaters and sprinklers).

2. Methods and materials

2.1. Study area

Two agrometeorological stations were selected for this study: Golmkan and Kahriz (Figure 1). Both stations have an appropriate climate for producing apples. Golmkan, located in northeast Iran (36°29′N, 59°17′E, elevation 1176 m ASL), has an average air temperature of 13.3 °C and presents 85 days with frost every year (for the period 1994–2007) (IRIMO, 2007). Kahriz station, located in northwest Iran (37°53′N, 44°59′E, elevation 1325 m ASL), has an average air temperature of 12.7 °C and presents a mean of 94 days with frost every year (during 1994–2007) (IRIMO, 2007). Phenological observations (observing the start and end times of each phase) and biometric measurements (i.e. number of buds in each branch, fruit weight and diameter) are obtained on apple trees every year at these agrometeorological stations.

2.2. Meteorological data

Daily maximum and minimum air temperatures for the period 2002–2007 were provided from the meteorological stations, which were located about 50 m from the apple tree gardens (IRIMO, 2007). However, there is debate about how many years of data are necessary to describe data characteristics adequately, and the minimum number of years required is a complex issue. For example, Porth *et al.* (2001) developed a technique to determine adequate sample size using a non-parametric technique that applies sub-sampling and return interval. They applied this technique to 51 years of streamflow record. Subsamples of consecutive streamflow record ranging in size from 5 to 25 years were used to estimate empirically the 1.5, 5, and 15 year return intervals. These subsample estimates were compared to the 'true' return intervals, which were calculated using the entire record period. Results showed that an ability to estimate these return intervals within 50% of the true return interval levels required only 5–10 years of data. Increasing the sample size to 15 years provided estimates with up to a 25% error rate, and 25 or more years of data were

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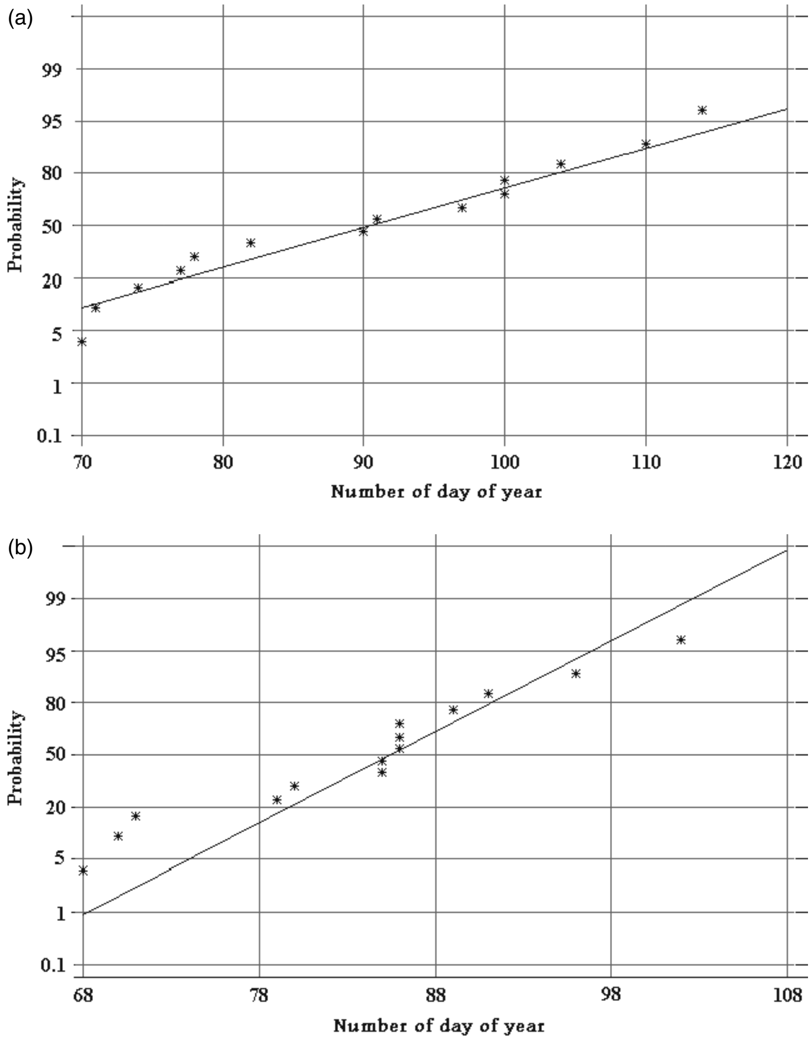

Figure 2. (a) Probability paper fit with Pearson type III distribution for the late frosts at Golmakan station. (b) Probability paper fit with Pearson type III distribution for the late frosts at Kahriz station.

required to provide estimates with less than a 20% error. Nevertheless, minimum daily temperature is a less temporally dynamic variable (Hunter and Meentemeyer, 2005) and it appears that to make a good estimation of frost risk not many years of data are required. In this regard the Mackus test method was conducted in this study to test data adequacy (Alizadeh, 1995). According to Mackus's method, the minimum number of required years, Y, is determined as:

$$Y = (4.3t\ Log R)^2 + 6 \tag{1}$$

where t is the Student's t test value at the desired confidence level (here 90%) and (Y-6) degrees of freedom and R is the ratio of Y value based on 100 year return interval to Y value based on a 2 year return interval. Y is estimated using a trial and error procedure until agreement between Y and t is fulfilled (Alizadeh, 1995). Both stations passed this test, indicating that the length of the available data is enough for a meaningful analysis. The data were also checked for homogeneity using the run test method (e.g. Castiglioni and Di Rienzo, 2004), proving that all data series were homogeneous.

2.3. Providing phenological data

The time of bud burst and leaf drop for apple trees for 5 years (2002–2007) were observed at the Golmakan and Kahriz agrometeorological stations. The variety of apples in Golmakan is Golden Delicious and in Kahriz it is Malling. Determining leaf drop and bud burst phases of apple trees was performed by sampling of 16 trees in four points in the field (4 trees in each point) in such a way that four branches of each trees were used for observation (overall 64 branches). Every other day branches were observed to see leaf drop or bud burst phases during the growing season. The percentage of each phase was calculated:

$$PF = \frac{NB}{64} \times 100 \tag{2}$$

where PF is the percentage of buds in each phase and NB the number of branches in each phase.

When the PF for each phase reached 75%, that date was used in the model (Hashemi, 1977).

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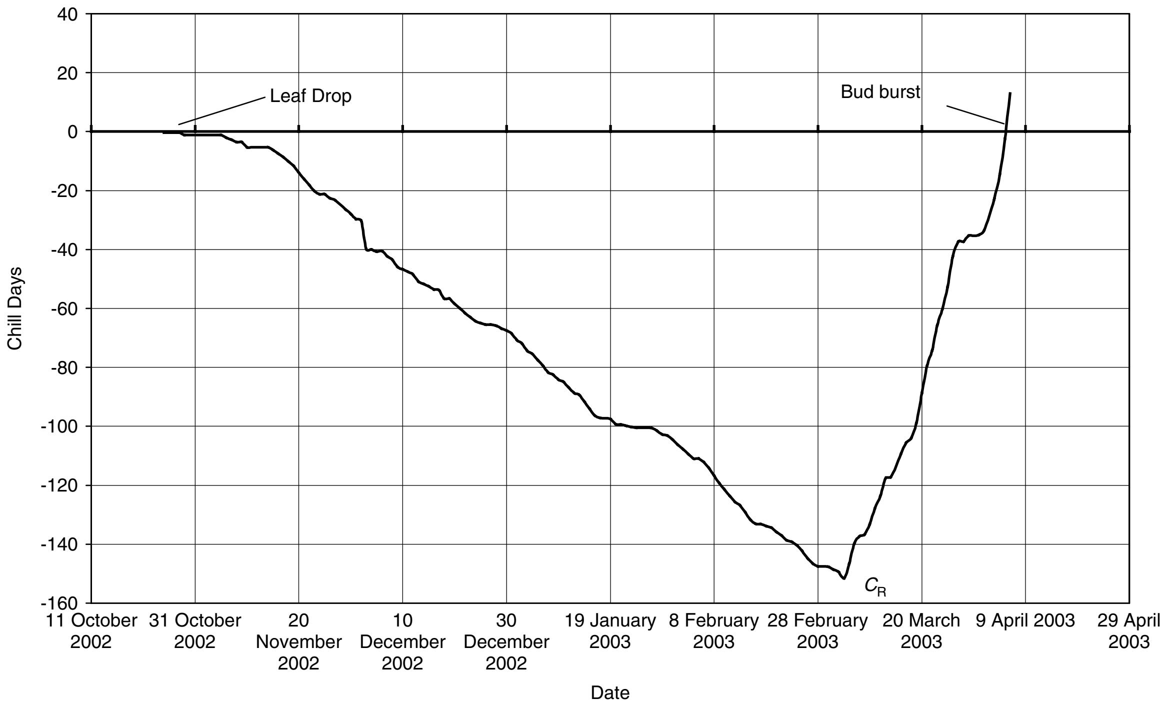

Figure 3. Chill (C_D) and anti-chill (C_A) accumulation from leaf-out to bud burst for 2003 ($T_c = 5$, $C_R = -150$) for Golmakan, in 2002 (as an example).

2.4. Determining last spring frost dates

The date of the last spring frost (air temperature of 0 °C or lower) was determined for each year of the long term period (1994–2007) as described by Rahimi *et al.* (2007). In order to be able to analyse frost dates statistically, these were expressed in calendar form (January 1 = 1, January 2 = 2, etc).

A hydrological frequency analysis software (HYFA, Alizadeh, 1995) was employed to choose a suitable statistical distribution for each series of data (frost dates and frost free season). The statistical distributions tested for were: the normal distribution, the two parameter log normal distribution, the two parameter Gamma distribution, the Pearson type III distribution, the log Pierson type III distribution and the Gumbel distribution (Thom, 1959). Probability density functions of these distributions are defined by Kite (1977). Curve fitting was performed by the method of moments and the maximum likelihood procedures. For a distribution defined in terms of r parameters($\theta_1, \theta_2, \ldots\ldots.., \theta_r$), the method of moments estimator of the parameter values is found by solving r equations as the theoretical j-th moment equal to the empirical j-th moment (e.g. Toksoz *et al.*, 1990). Maximum likelihood estimation begins with writing a mathematical expression known as the likelihood function of the sample data. The likelihood of a set of data is the probability of obtaining that particular set of data, given the chosen probability distribution model (Gould *et al.*, 2006).

The HYFA program computed the parameters of the six frequency distributions. Computations included the variate's value(s), the standard error of estimate and confidence intervals corresponding to a set of selected return periods, mentioned in Section 2.4. The goodness of fit test according to the Chi-square test was also performed. For each station's late frost dates, HYFA was run separately. In each run, Chi-square criteria were calculated for each distribution.

2.5. Estimating chilling requirements for predicting bud burst time

Cesaraccio *et al.* (2004) developed a model to predict bud burst for deciduous fruit trees in Italy. In this model, chill days (C_D), which are defined as the cumulative number of hours below a threshold temperature (T_C) divided by 24 h, are used to quantify chill unit accumulation. Anti-chill days (C_A), which are defined as the cumulative number of hours above the same pre-selected threshold temperature divided by 24 h, are also used to predict chill accumulation. The C_D values are assigned a negative sign and the C_A values a positive sign. In the model, the C_D values are accumulated until they reach a pre-selected value that is identified as the chill requirement (C_R). The C_D values are negative, so C_R is also negative. The chill requirement is met on the day when $\Sigma C_D \leq C_R$. On the following day, the model begins to add anti-chill days to C_R. Bud burst occurs when $C_R + \Sigma C_A \geq 0$ (Cesaraccio *et al.*, 2004).

Chill days and anti-chill days are calculated using the daily maximum (T_X) and minimum (T_N) temperature data and the single triangle method (Zalom *et al.*, 1983).

When $T_X \leq T_C$, there are no hours above T_C so the heat units are $H_1 = 0$ (chill units are = 0). When $T_C < T_N$, the

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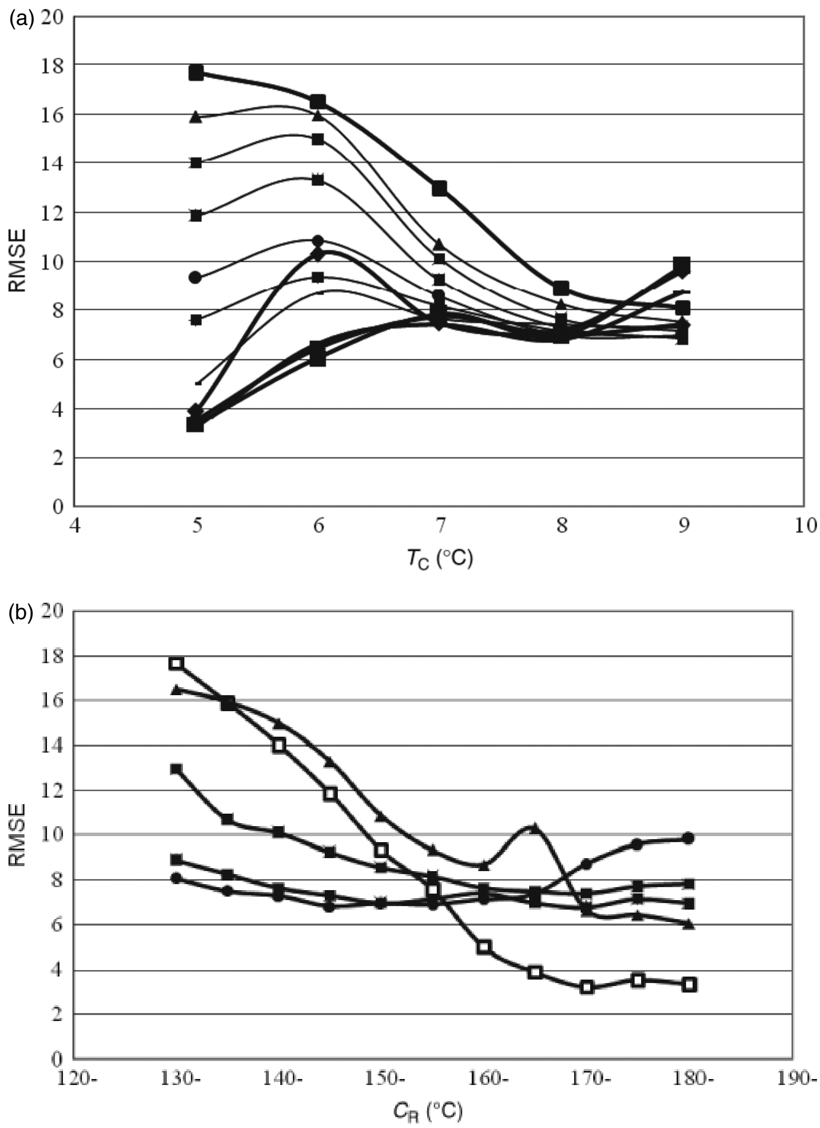

Figure 4. (a) Variation of RMSE with T_c for different amounts of C_R at Kahriz. $C_r = -130$ $C_r = -150$ $C_r = -170$ $C_r = -135$ $C_r = -155$ $C_r = -175$ $C_r = -140$ $C_r = -160$ $C_r = -180$ $C_r = -145$ $C_r = -165$ (b) Variation of RMSE with C_R for different amounts of T_c at Kahriz. $T_c = 5$ $T_c = 6$ $T_c = 7$ $T_c = 8$ $T_c = 9$.

heat units above T_C are given by: $H_2 = T_M - T_C$, where T_M is the mean temperature: $T_M = (T_X + T_N)/2$.

If $T_N < T_C < T_X$, then the anti-chill units above T_C are calculated as:

$$C_A = \left(\frac{T_x - T_c}{T_x - T_N}\right)\left(\frac{T_x - T_c}{2}\right) \tag{3}$$

When $T_C = T_N$, the number heat units (H_4) above T_C is given by $H_4 = T_M - T_N$ and $H_3 = (T_x - T_c)/2$. The number of hours *per* day below the threshold T_C divided by 24 h provides a measure of the chill days (C_D). When $T_x \leq T_C$, then $C_D = -H_4$.

If $T_C \leq T_N$, then $C_D = 0$. When $T_N < T_C < T_X$, then the chill days are calculated as the heat units within the triangle minus the heat units above T_C [e.g. $C_D = -(H_4 - H_3)$].

The anti-chill days (C_A) are calculated using heat units and the same chill threshold as used for the C_D calculations. When $T_x \leq T_C$, there are no heat units above T_C and $C_A = 0$. If $T_C \leq T_N$, then $C_A = H_2$. When $T_N < T_C < T_X$, then $C_A = H_3$.

The optimal values for T_C and for C_R are determined using trial and error until the root mean squared error (RMSE) between predicted (d_p) and observed (d_o) days between harvest or leaf drop and bud burst or leaf drop is minimized:

$$RMSE = \sqrt{\frac{\sum (d_p - d_o)^2}{N}} \tag{4}$$

where N is the number of years. Since the goal is to identify the threshold temperature and chill requirement that give the best prediction of days from harvest or leaf drop to bud burst, minimizing the RMSE provides the best possible prediction. This model was used in this study to predict bud burst time of apples.

3. Results and discussion

3.1. Estimating suitable distribution and probability of occurrence of last spring frosts

Table I shows summary results of the application of the six frequency distributions, mentioned in Section 2.4, to the frost dates in the two stations using the mean square related deviation criterion. The following conclusions are noted:

- the maximum likelihood (ML) method was not able to identify the parameters of the Pearson type III, and the Log Pearson type III distributions at both stations, and the Gumbel distributions at Kahriz station, while the moments (M) method was able to estimate all parameters of the distributions;
- the accuracy of (ML) method is less than, or at most cases, the same as that of (M) method at both stations, and,
- according to the mean square related deviation criterion the best fitted distribution was the Pearson type III. The second best distribution, at both stations, was the Log Pearson type III. The worst fitted distribution was the Gumbel distribution, which ranked last. Therefore, Pearson type III distribution was used to analyse the risks (probabilities) of the last occurrences of frosts based on the moments parameter estimation method and the mean square related deviation criterion. The probability fits with Pearson type III distribution for the frosts at Golmakan and Kahriz, using the moments parameter estimation method (Figure 2).

Last spring frost dates, for several probabilities as derived using the Pearson type III distribution before and after a given date, are presented in Tables II and III. The probability of frost occurrences on or after 30 March is 50% in Golmakan and 24 March in Kahriz, meaning that in 50% of years, the last spring frost occurs on or after 30 March in Golmakan and 24 March in Kahriz. The probabilities show the non-exceeding frost occurrence. In other words, the data are set out from the least extreme to the most extreme, and the probability of data below a threshold value (x) is calculated and expressed as $(1 - p(x))$.

Table I. Performance comparison of different distributions using moments (M) and maximum likelihood (ML) fitting methods and mean square related deviation criteria for Kahriz and Golmakan late frost date.

Distribution	Method	Golmakan	Kahriz
Normal	M	2.34	3.22
Normal	M.L.	2.34	3.22
2 Log normal	M	2.48	3.22
2 Log normal	M.L.	2.48	3.22
2 Para gamma	M	2.42	3.17
2 Para gamma	M.L.	2.49	3.42
Pearson III	M	2.31	3.11
Pearson III	M.L.	N/A	N/A
Log Pearson III	M	2.32	3.15
Log Pearson III	M.L.	N/A	N/A
Gumbel	M	3.05	3.98
Gumbel	M.L.	N/A	3.49

3.2. Calibration and validation of bud burst prediction model

The minimum and maximum air temperatures along with phenological observations made on 16 apple trees at each station for the years of 2002, 2003, 2004, 2005, and 2006 were used to select suitable C_R and T_c values for the model (Section 2.5). The model was run for threshold temperatures from 5 to 8 °C and chill requirements from −130 till −150 units. The T_c for pear is 6.8–7 °C, and for cherry 7–7.9 °C. The C_R for pear is −106 to −120 and for cherry −128 to −167 (Cesaraccio *et al.*, 2004). The RMSE for selected C_R and T_c was calculated and the results are shown in Figures 4 and 5.

The estimated accumulations of negative C_D and positive C_A values from leaf out to bud burst for the season 2002/2003 at Gomakan are illustrated in Figure 3. In this case $T_C = 5$ and $C_R = -150$. With observed leaf drop on 25 October 2002, C_R was −150 at 5 March 2003 and the predicted bud burst was on 6 April 2003.

Table II. Probability of last spring frosts before and after given dates at Golmakan between 1994 and 2004.

Date	Probability of frost occurrence on or after date (%)
13 March	90
18 March	80
24 March	67
30 March	50
5 April	33
12 April	20
19 April	10
28 April	4
4 May	2
10 May	1

Table III. Probability of last spring frosts before and after given dates at Kahriz between 1994 and 2004.

Date	Probability of frost occurrence on or after date (%)
13 March	90
17 March	80
20 March	67
24 March	50
29 April	33
2 April	20
7 April	10
12 April	4
16 April	2
19 April	1

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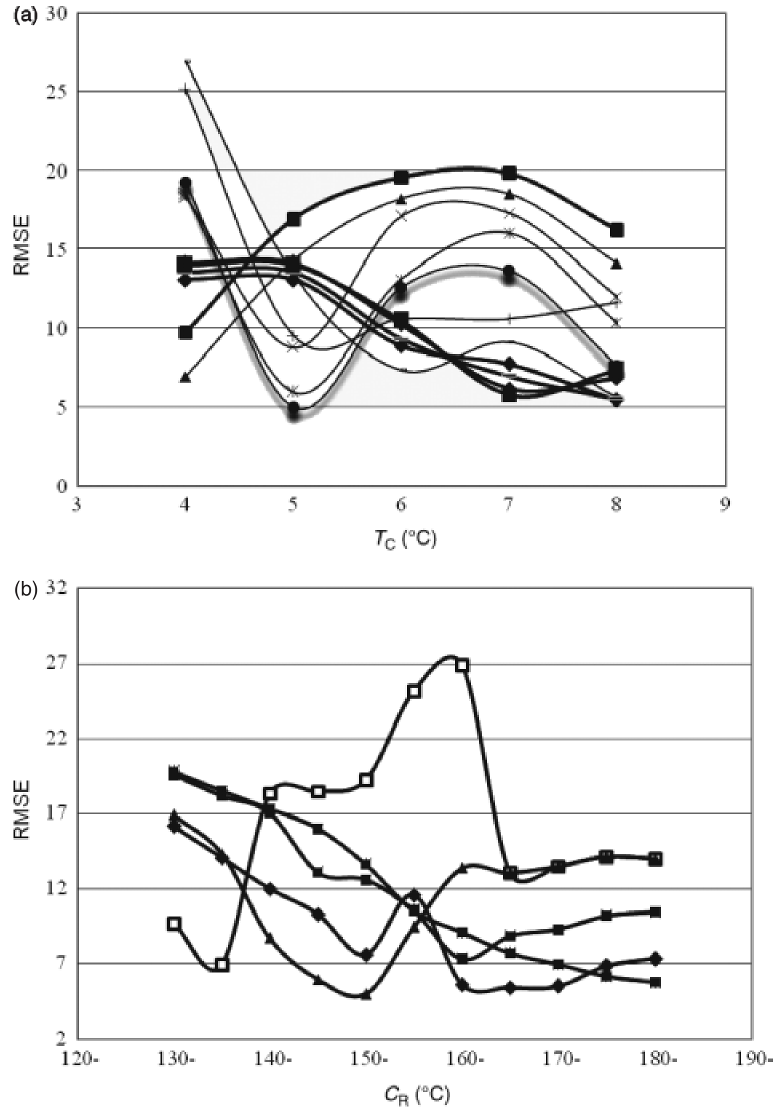

Figure 5. (a)Variation of RMSE with T_c for different values of C_R at Golmakan. $C_r = -130$ $C_r = -150$ $C_r = -170$ $C_r = -135$ $C_r = -155$ $C_r = -175$ $C_r = -140$ $C_r = -160$ $C_r = -180$ $C_r = -145$ $C_r = -165$ (b) Variation of RMSE with C_R for different values of T_c at Golmakan. $T_c = 4$ $T_c = 5$ $T_c = 6$ $T_c = 7$ $T_c = 8$.

The differences between observed and predicted bud burst dates (in days) and the respective RMSE values for each chill threshold (T_C)/chill requirement (C_R) combination tested are presented in Figures 4 and 5. The lowest RMSE for Kahriz (3.2 days) was found when $T_c = 8$ and $C_R = -150$. The best combination for Golmakan (RMSE = 5 days) was identified when $T_c = 5$ and $C_R = -150$.

To validate the model, the optimized T_c/C_R combinations for each station were used to predict bud burst time of apple for years 2007 and 2008. The predicted time for Kahriz for 2007 and 2008 were 3 May and 17 April and for Golmakan were 8 April and 24 March, respectively. The observed bud burst dates for 2007 and 2008 at Kahriz were 28 April and 14 April and for Golmakan were 4 April and 21 March respectively. The model deviations for Kahriz and Golmakan for year 2007 were 4 and 5 days respectively and for year 2008 was 3 days for both stations.

3.3. Frost occurrences related to predicted bud burst time

The modelled timings of bud burst in 2008 were compared with the frost probability occurrences in Figure 2. For Golmakan, the probability of a late spring frost before 10 April 2008 (Year day = 100) is 70% (Figure 2(a)) and for Kahriz the probability of a late spring frost before 1 April 2008 (Year day = 91) is 75% (Figure 2(b)). Because of the high risk probabilities, it is necessary for farmers and growers to apply appropriate means and methods/management to protect apple buds from frost damage.

4. Conclusion

Two apple gardens in two agrometeorological stations in the northwest and northeast of Iran were selected to calibrate and validate a bud burst model based on

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chilling requirements units. The distribution of late spring frosts in both places was computed with the Pearson type III probability density function. The model was calibrated based on phenological and meteorological data during 2002–2006 in two stations and was validated with data from 2007. In this regard, the combinations of five minimum threshold temperatures T_C (5, 6, 7, 8 and 9 °C) for Kahriz and (4, 5, 6, 7 and 8 °C) for Golmakan and 11 chilling requirements C_R (−130, −135, −140, −145, −150, −155, −160, −165, −170, −175 and −180) were tested to determine the combination of T_C/C_R producing the lowest RMSE. Finally, the probability of frost risk was predicted after the modelled apple bud burst time was compared with the temporal probability of frost occurrences.

Generally, bud burst will occur sooner if the winter is warmer, since anti-chill units accumulate sooner and the buds are at more risk of frost damage. The risk of damage is greater because late frosts in spring often follow warm winters.

This study is an example of combining meteorology and phenology in decreasing risk damage of a natural disaster (in this case frost), but other fruit trees or environmental changes (e.g. drought) can also be studied.

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