INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **27**: 349–356 (2007)
Published online 9 October 2006 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1405

RMetS
ROYAL METEOROLOGICAL SOCIETY

Short Communication

Risk analysis of first and last frost occurrences in the Central Alborz Region, Iran

M. Rahimi*,[a] S. Hajjam,[b] A. Khalili,[c] G. A. Kamali[d] and C. J. Stigter[e]
[a] *Agrometeorological Department, I. R. of Iran Meteorological Organization (IRIMO), Airport St., Tehran, I. R. of Iran*
[b] *Institute of Geophysics, University of Tehran, Tehran, Iran*
[c] *Faculty of Agriculture, University of Tehran, Karaj, Iran*
[d] *Atmospheric Science and Meteorological Research Center (ASMERC), Tehran, I. R. of Iran*
[e] *Agromet Vision, Bruchem, The Netherlands*

Abstract:

Central Alborz is one of the important agricultural regions of Iran. Occurrence of the first frost in fall and the last frost in spring causes damage to the crops in this region every year. Information about the probable dates of frost occurrence helps farmers in preventing or reducing the damages caused by frost. Six stations, with 34 years of daily minimum temperature data, were selected at various elevations. Dates of frost occurrences in three degrees of severity (mild, moderate, and severe) and frost-free periods were obtained for each year. Appropriate distributions were determined for each frost series (dates of frosts and frost-free periods) on the basis of relevant statistical methods. It was found that the Pearson type III distribution was most appropriate. Probability distribution was constructed for each frost series. Frost occurrences up to a given date and maximum lengths of frost-free periods, with their probabilities, were determined. Correlations between the dates of frost occurrence and elevation, and between the maximum lengths of frost-free periods and elevation were identified in some probability levels. Our results show a positive correlation between the frequency of frost and elevation, and a significant negative correlation between the duration of frost-free period and elevation. Frost is more frequent in higher areas. The shortest and the longest frost-free periods occur on top of high mountains and on low altitude areas, respectively. Copyright © 2006 Royal Meteorological Society

KEY WORDS central Alborz; frost risk; frost-free period; growing season; Iran; Pearson type III distribution

Received 4 December 2005; Revised 27 May 2006; Accepted 11 July 2006

1. INTRODUCTION

Agricultural meteorology, beyond the basic understanding of all its aspects, has only one aim: providing agrometeorological services and information to farmers and other decision makers in agricultural production. The need for such services is obviously different for different production systems, with different inputs in different climates. These services are sorely missing, particularly for sustainable agriculture with lower external input in warmer climates; however, they can be used effectively at all places where environmental conditions are an important factor in yield determination (Stigter, 2006).

Extreme temperature events can have serious impacts on our environment and society. The first fall and the last spring frosts usually cause damages to plants (Rosenberg *et al*., 1983; Geiger *et al*., 1995). Occurrence of the first fall frost, at the beginning of the freezing period, damages crops that are still in the field. The last spring frost at the end of the freezing period, which occurs at the beginning of the growing season, causes damage to seedlings and young plants and to those that are already in the flowering stage (WMO, 1963, 1997; Vestal, 1971). Late frosts in spring and early frosts in autumn can be devastating to all fruits. In autumn, an earlier than normal frost can damage actively growing shoots. In spring, a later than normal frost can cause a variety of damages, depending upon the development stage of the fruit (Tait and Zheng, 2003). Frost can cause a rapid decline in net photosynthesis and stomatal conductance rates. Young expanding leaves, reproductive organs, and other rapidly differentiating tissues of trees are most sensitive to freezing temperatures (Taschler *et al*., 2004). Chloroplasts are the most severely impacted organelle during frost occurrence (Kratsch and Wise, 2000). Reversible frost-induced reductions of photosynthesis are common during spring and autumn (Gaumont *et al*., 2003). During freezing, cellular dehydration and destabilization of membrane are the key processes leading to frost damage

* Correspondence to: M. Rahimi, I. R. of Iran Meteorological Organization (IRIMO), Airport St., Tehran, I. R. of Iran.
E-mail: mrahimi@irimo.ir

Copyright © 2006 Royal Meteorological Society

WILEY InterScience® DISCOVER SOMETHING GREAT

(Pearce, 2001). Central Alborz is one of the important agricultural regions of Iran (Figure 1). High-value horticultural and fruit crops grown in this region, such as cereals, sugar beet, cotton, almond, apricot, cherry, grape, pear, and poppy, are subject to frosts that occur in the beginning and end of the growing season. The damage in terms of economic costs due to frost are considerable for the area. As an example, in 2002, as much as 400 hectares of agricultural area in Tehran was affected by frost. Information about the probable dates of frosts helps farmers in preventing or reducing frost damages (Mavi, 1996).

There seems to have been little statistical treatment of frost or freeze data prior to the excellent works of Reed and Tolley in 1916 (Rosenberg and Myers, 1962). They concluded that their series of frost data fitted a normal distribution best. Nevertheless, there are some papers that are related to the direct modelling of the temperature data. Stone *et al.* (1996) examined the daily temperature series for several stations in eastern Australia and found significant decrease in the number of days with minimum temperatures below 0 °C, and the dates of last frosts, over the twentieth century. Lana and Burgueno (1996) investigated the climatic diversity of Catalonia from the point of view of extreme minimum temperature records using the Jenkinson formulation. They later estimated a parameter of the Jenkinson formulation by means of likelihood analysis and usual least square criterion. They concluded that both the ranking options and the estimation procedures should lead to the same prediction of extreme temperatures when data quality is good enough and the likelihood criterion was slightly better (Lana and Burgueno, 1999). Statistical characteristics of accumulated extreme low and high daily mean temperatures have been investigated for Hungary by Domonkos (2001). Recurrence frequencies of extreme anomalies were computed at 1, 2,……, 75 days after the initial anomalies, and compared with the respective characteristics of an appropriate second order autoregressive model. The estimation of freeze probabilities from complete freeze-data series has been treated by Thom and Shaw for Iowa (Thom, 1958). Furthermore, as Linkosalo *et al.* (2000) and Root *et al.* (2003) stated, an increased risk of damage to trees of North European areas due to the existence of below freezing temperatures (early frosts) is expected, as events of spring phenology occur earlier with climate warming. Frost is more common on the top of high mountain ranges where the air temperature is coldest (Tait and Zheng, 2003). The first frost of the year at an inland basin area is often earlier than that on the surrounding slopes, because of cold air drainage and pooling. Bootsma (1976) stressed that the date of the mean spring last frost (autumn first frost) is as much as 34 days later (39 days sooner) near the bottom of valleys compared to elevated grounds in Canadian mountainous areas. Tait and Zheng (2003) have produced detailed maps of frost variables for the Otago region of New Zealand. Vincent *et al.* (2005) have pointed out that, for the United States, the number of frost days has slightly decreased over 1910–98.

The central Alborz region is unique and susceptible to frost, and therefore it is essential to closely monitor the occurrence of frost in this region and to search for evidence of changes in climate extremes. However, there are no nationally or internationally published results related to temperature changes and extremes in the central Alborz region. This study aims to analyse frost occurrence because knowledge of the frequency and timing of frosts is necessary to minimise the risk of frost damage in frost susceptible areas. Frost damage to fruit trees is a significant concern in the studied area. In the present study, we do not analyse the risk levels for specific species. However, our results can be used by farmers as an indicator of the risk of frost damage to their crops.

2. METHODS AND MATERIALS

2.1. Climate data

Minimum air temperature data from six standard climatic stations throughout the studied area are used

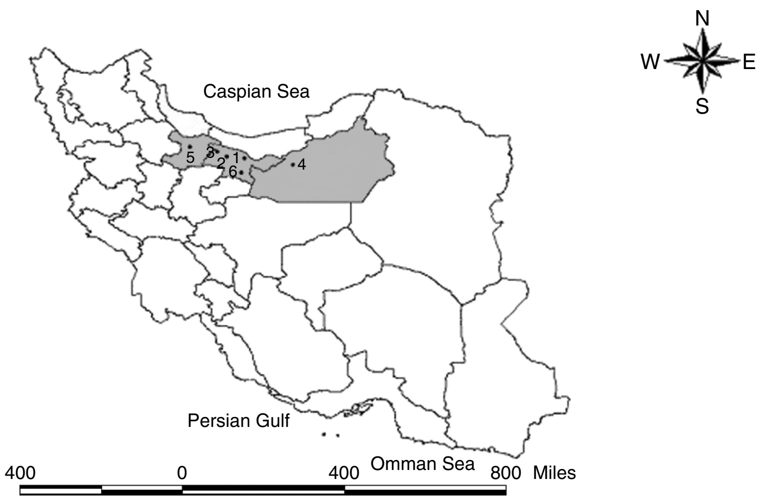

Figure 1. Map of Iran with the area of study and selected stations: Abali (1), Tehran (2), Karaj (3), Semnan (4), Gazvin (5), Varamin (6).

Copyright © 2006 Royal Meteorological Society
DOI: 10.1002/joc

(Figure 1). The period of record varies slightly, but it generally covers 1962–1995 (34 years). Information about the stations is given in Table I.

2.2. Determining dates of the last spring, the first fall frosts, and the frost-free period

For each station and for each year, the first and the last frost day (i.e. the last and the first days when frosts occurred in the year) and the frost-free period (i.e. the number of consecutive days from the date of the last frost with minimum air temperature greater than 0 °C) were identified. It means that the frost-free period was determined as the time between the last day with a temperature of 0.0 °C or lower in spring and the first day with a temperature of 0.0 °C or lower in autumn. In addition, three categories of frost severity were defined according to the WMO proposals (WMO, 1963):

(1) Mild frost: daily minimum temperature of 0.0 to −1.1 °C
(2) Moderate frost: daily minimum temperature of −1.2 to −2.2 °C
(3) Severe frost: daily minimum temperature below −2.2 °C

By using these definitions, three last spring and three first fall frosts were determined for spring and autumn of each year. For each category of frost severity, the last date that the daily minimum temperature in late winter/early spring fell between the above defined thresholds was the date of last spring frost (Bootsma, 1976). After determining the frost dates, it was necessary to change them into a form that we could analyse statistically. For this purpose, Julian days were used.

2.3. Control tests of data

Researchers often question how many years of record are necessary to adequately estimate data characteristics. Deciding on the minimum number of years for which data is required is more complex and has been studied by several researchers. Among them, Porth *et al.* (2001) developed a technique to determine adequate sample size using a non-parametric technique that applies sub-sampling and return interval. Nevertheless, minimum daily temperature is a less temporally dynamic variable (Hunter and Meentemeyer, 2005), and it appears that 34 years of data is enough to have a good estimation of the frost risk. However, a simple test (Mackus's method) is conducted here to investigate data adequacy. Following Mackus's method, the minimum number of years, required Y, is determined as

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

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 the Y value based on a100-year return interval to the 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).

All stations passed this test, indicating that the length of the available data is enough for a meaningful analysis. Before the analysis, the data were checked for homogeneity using the run test method (e.g. Castiglioni and Di Rienzo, 2004), proving that all data series were homogeneous. Some missing data of daily minimum temperature was estimated using data from the Iranian Meteorological Organization archives (IRIMO, 1997). Number of years from which data was taken, means, medians, standard deviations, latest occurrence, earliest occurrence, and the range between them for the last spring frosts and the first fall frosts are given in Table II, along with this data the maxima and minima and the range between them for the frost-free periods are also given.

2.4. Estimating suitable distribution for the data

For choosing a suitable statistical distribution for each series of data (frost dates and frost-free season), we used a hydrological frequency analysis (HYFA) computer software programme (Alizadeh, 1995). HYFA computes parameters of the seven most frequently used frequency distributions as listed in the following text. Curve fitting is assessed by both the method of moments and the maximum likelihood (ML) procedure. 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, theoretical j-th moment equal to empirical j-th moment (e.g. Toksoz *et al.*, 1990). Maximum likelihood estimation begins by 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). HYFA estimates the variate value(s), the standard error of estimation and confidence intervals corresponding to a set of selected return periods. HYFA performs the goodness of fit test according to the Chi-square test and the deviation method. Deviation method is a measure of dispersion, computed by taking the arithmetic mean of the absolute values (mean related deviation) or arithmetic mean of the square (mean square related

Table I. Selected stations of central Alborz region.

Station name	Altitude (m)	Eastern longitude	Northern latitude	Years
Abali	2465	51°, 53′	35°, 45′	1962–1995
Karaj	1321	50°, 58′	35°, 56′	1961–1995
Gazvin	1287	50°, 00′	36°, 15′	1961–1995
Tehran	1190	51°, 19′	35°, 41′	1961–1995
Semnan	1171	53°, 33′	35°, 33′	1965–1995
Varamin	1000	51°, 39′	35°, 19′	1962–1995

Copyright © 2006 Royal Meteorological Society

Table II. Statistical characteristics of frost series of the studied area. The units used are Julian days.

Spring Frosts							
Station	Number of years	Mean	Median	Standard deviation	Latest	Earliest	Range
Abali	34	190	190	18.8	224	141	83
Karaj	35	92	90	15.8	126	55	71
Gazvin	35	95	93	13.5	126	62	64
Tehran	35	77	80	15.1	104	44	60
Semnan	31	68.7	69	13.9	92	38	54
Varamin	34	77	77	10	105	56	49
Fall Frosts							
Station	Number of years	Mean	Median	Standard deviation	Latest	Earliest	Range
Abali	34	305	305	12.5	329	280	49
Karaj	35	321	318	11.6	340	295	45
Gazvin	35	314	314	20.2	395	284	111
Tehran	35	336	335	14.5	372	309	63
Semnan	31	339	339	13.6	362	311	51
Varamin	34	324	323	11	347	306	41
Frost-free Period							
Station	Number of years	Mean	Median	Standard deviation	Maximum	Minimum	Range
Abali	34	190	190	18.8	224	141	83
Karaj	35	229	225	18.8	465	200	265
Gazvin	35	219	216	24.7	307	181	126
Tehran	35	259	258	20.4	304	216	88
Semnan	31	269.7	270	18.2	306	230	76
Varamin	34	247	249	16	283	210	73

deviation) values of the deviation of the observed values from the corresponding curve value of a distribution.

The selected statistical distributions tested were (Thom, 1959):

- The Normal distribution
- The two parameter lognormal distribution
- The three parameter lognormal distribution
- The two parameter Gamma distribution
- The Pearson type III distribution
- The Log Pearson type III distribution
- The Gumbel distribution

Probability density functions of these distributions are defined by Kite (1977). For each station and for each frost variable (i.e. the last spring frost date, the first autumn frost date, the frost-free period), HYFA is run separately for mild, moderate, and severe frost. In each run, mean related deviation, mean square related deviation, and the Chi-square criteria were calculated for each distribution. These criteria are ranked individually for moments and maximum likelihood parameter estimation methods. Table III shows summary results of the application of the above mentioned distributions to the frost variables in all stations using mean square related deviation criterion. Some remarkable results are as follows:

- Maximum likelihood (ML) method is not able to identify parameters of the three parameter lognormal, the Log Pearson type III, the Gumbel and almost the Pearson type III distributions (based on the number of zeros in Table III), while moments (M) method is able to estimate all parameters of the distributions.
- The accuracy of the ML method is less than, or at most same as, that of the M method.
- The chi-square criterion to distinguish different distributions is not as good as the related deviation criteria. The ability of the mean related deviation, and the mean square related deviation are almost the same, although the mean square related deviation is sometimes superior to the mean related deviation (the chi-square and the mean related deviation criteria are not presented in Table III).
- According to the mean square related deviation criterion, the best-fitted distribution is the Pearson type III, which is the first in 67% of total first ranks (in

Copyright © 2006 Royal Meteorological Society

Table III. shows the performance comparison of the different distributions using moments (M) method, maximum likelihood (ML) fitting method, and mean square related deviation criterion for total frost variables. Numbers 1 to 12 are the ranks, and the values in the table show the percentage of each rank in different distributions.

Distribution	Rank Method	1	2	3	4	5	6	7	8	9	10	11	12
Normal	M	1.65	3.29	3.57	0.0	1.37	0.83	0.55	0.0	0.0	0.28	0.0	0.0
Normal	M.L.	1.65	3.57	3.57	0.0	1.10	0.83	0.55	0.0	0.0	0.28	0.0	0.0
2 Lognormal	M	0.55	1.10	0.55	0.83	2.20	2.32	2.20	0.55	0.0	0.0	0.0	0.0
2 Lognormal	M.L.	0.55	1.10	0.55	0.55	2.20	3.84	2.20	0.55	0.0	0.0	0.0	0.0
3 Lognormal	M	0.0	0.0	0.0	0.0	0.0	0.0	0.28	0.0	0.0	0.0	0.0	0.0
3 Lognormal	M.L.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2 Para Gamma	M	0.28	0.0	1.10	3.57	4.67	1.37	0.55	0.0	0.0	0.0	0.0	0.0
2 Para Gamma	M.L.	0.0	0.28	0.0	1.92	2.47	1.65	2.75	2.20	0.28	0.0	0.0	0.0
Pearson III	M	7.69	1.37	1.10	0.83	0.0	0.0	0.0	0.0	0.28	0.0	0.0	0.0
Pearson III	M.L.	0.0	0.55	0.28	0.0	0.55	0.0	0.55	0.0	0.0	0.0	0.0	0.0
Log Pearson III	M	1.37	2.47	0.28	0.0	0.0	0.28	0.0	0.28	0.0	0.28	0.0	0.0
Log Pearson III	M.L.	0.0	0.0	0.0	0.28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gumbel	M	0.0	0.0	0.0	0.0	0.0	0.0	0.28	5.49	4.94	0.28	0.28	0.28
Gumbel	M.L.	0.0	0.0	0.0	0.28	0.0	0.0	0.28	0.0	0.0	0.0	0.0	0.0

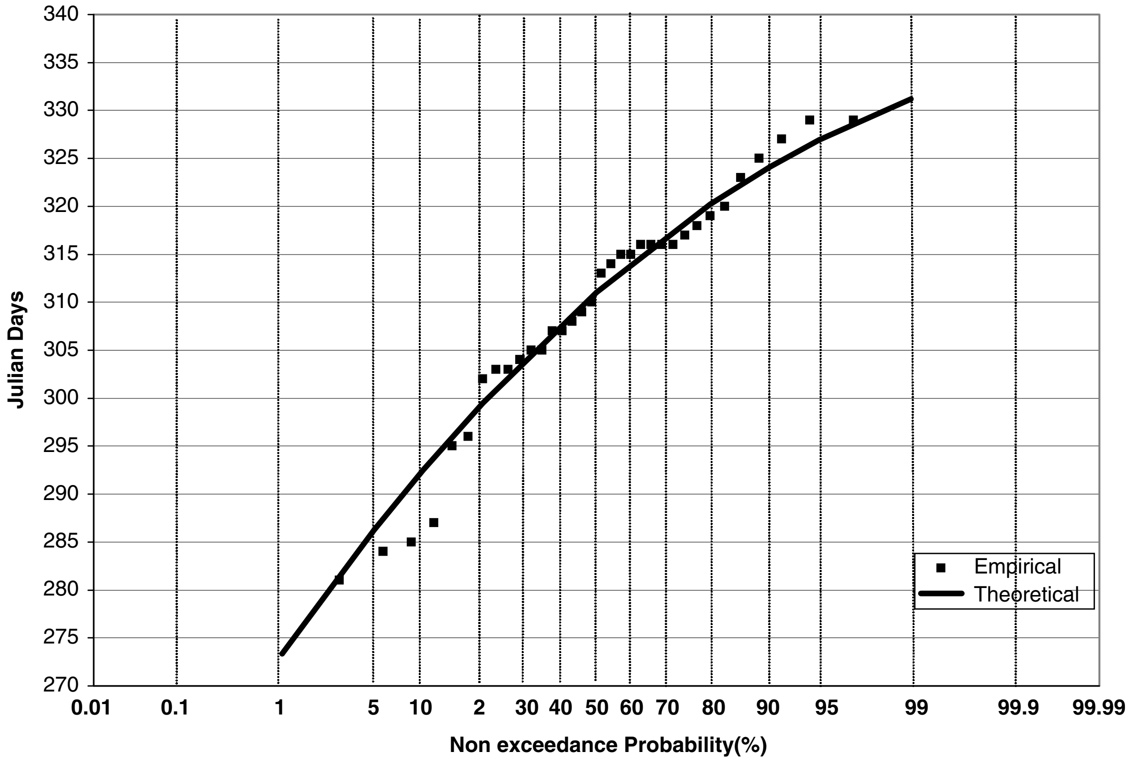

Figure 2. Probability paper fit with Pearson type III distribution for the moderate fall frosts of Abali station (as an example).

7.69% of total ranks). The second best distribution is the Normal distribution with 14.3% and 1.65%, respectively. The worst fitted distribution is the Gumbel distribution, which is ranked last in 90.7% of total ranks. Therefore, the Pearson type III distribution is used to analyse the risks (probabilities) of the first and the last occurrences of frosts and the frost-free periods based on the moments parameter estimation method and mean square related deviation criterion.

- The Pearson type III probability density function is as follows:

$$p(x) = \frac{1}{\alpha\Gamma(\beta)} \left\{ \frac{x-\gamma}{\alpha} \right\}^{\beta-1} e^{-\frac{(x-\gamma)}{\alpha}} \quad (2)$$

Where α, β, and γ are parameters of distribution, $p(x)$ is probability and $\Gamma(\beta)$ is the Gamma function of β.

In Figure 2, a Probability paper fit with Pearson type III distribution for the moderate fall frosts of Abali

Copyright © 2006 Royal Meteorological Society

station is presented as an example that has been produced by HYFA software using moments parameter estimation method.

3. RESULTS AND DISCUSSION

3.1. Probability of occurrences of the last spring frosts

The last spring frost dates, for several probabilities and for the three classes of frost severity as derived using the Pearson type III distribution, are presented in Tables IV and V for the station with highest altitude (Abali, 2465 m) and the station with lowest altitude (Varamin, 1000 m). The probabilities are non-exceeding frost occurrence. It means that the data is set out from the least extreme to the most extreme, and the probability of a data below a threshold value (x) is calculated and expressed as $(1-p(x))$ and the corresponding return period will be its inverse. As an example, according to Table IV there is a 96% chance that the last mild spring frost in Abali occurs on 13 May or earlier. As we go towards the summer, the risk of last spring frosts occurring after a given date decreases. According to the same table, at 75% probability level, the last mild spring frost occurs on day 123 (2nd of May) or earlier than that, and at 50% probability level it will be on day 115 (24th of April) or before that. On average, in 4 years there are 3 years with the last mild spring frost occurring before 3 May, and 1 year with such a frost occurring after 2 May.

3.2. Probability of occurrences of the first fall frosts

Tables IV and V show examples of the dates of occurrence of the first fall frost (the probabilities are exceedance) for several probabilities and the three frost severities for Abali and Varamin, respectively. Table IV shows that the chance of occurrence of the first fall frost increases in Abali as autumn progresses. For example, at 75% probability level the first mild fall frost occurs on or after day 297 (23 October) and at 50% probability level it will be on or after day 307 (31 October). Usually the first severe and moderate fall frosts occur closer to winter, after the mild ones.

3.3. Probabilities of frost-free periods

It was found that the Pearson type III distribution is again the most appropriate model for the analysis of the frost-free period, using the moments parameter estimation procedure. Table VI shows the example of frost-free periods probability (non-exceedance) in the Abali station. According to the table, at 75% probability, the frost-free period in Abali would be less than 204 days. Additional information about the frost-free period for each station and each probability is also presented in Table VI.

Table VI. Average frost-free periods for each selected station in the Alborz region (non-exceedance probability levels).

Probability %	Abali	Karaj	Gazvin	Tehran	Semnan	Varamin
96	224	253	295	290	302	277
90	215	243	285	281	293	267
80	207	233	276	273	286	261
75	204	230	273	270	283	258
67	199	225	268	265	278	254
50	191	216	259	257	270	247

Table IV. Dates of the last spring frosts and the first fall frosts for various probabilities in Abali (non-exceedance probability levels for last spring frost variables and exceedance probability levels for first fall frost variables).

Probability %	Last mild spring frost	Last moderate spring frost	Last severe spring frost	First mild fall frost	First moderate fall frost	First severe fall frost
96	13 May	7 May	1 May	7 Oct	10 Oct	18 Oct
90	8 May	1 May	26 Apr	14 Oct	19 Oct	23 Oct
80	3 May	25 Apr	20 Apr	20 Oct	26 Oct	29 Oct
75	2 May	23 Apr	18 Apr	23 Oct	28 Oct	31 Oct
67	29 Apr	20 Apr	15 Apr	26 Oct	31 Oct	4 Nov
50	24 Apr	15 Apr	9 Apr	31 Oct	6 Nov	10 Nov

Table V. Dates of the last spring frosts and the first fall frosts for various probabilities in Varamin (non-exceedance probability levels for last spring frost variables and exceedance probability levels for first fall frost variables).

Probability %	Last mild spring frost	Last moderate spring frost	Last severe spring frost	First mild fall frost	First moderate fall frost	First severe fall frost
96	5 Apr	29 Mar	24 Mar	2 Nov	6 Nov	11 Nov
90	31 Mar	24 Mar	20 Mar	6 Nov	10 Nov	15 Nov
80	26 Mar	20 Mar	15 Mar	10 Nov	15 Nov	20 Nov
75	23 Mar	18 Mar	14 Mar	12 Nov	17 Nov	22 Nov
67	21 Mar	15 Mar	11 Mar	14 Nov	19 Nov	25 Nov
50	19 Mar	11 Mar	6 Mar	19 Nov	24 Nov	30 Nov

Copyright © 2006 Royal Meteorological Society

DOI: 10.1002/joc

3.4. Height dependency of frost occurrences

Early frost studies have explained the relationship between minimum temperature and elevation (Laughlin and Kalma, 1987), and emphasised the role of katabatic flow and cold air accumulation. This implies that there may be a relationship between elevation and the frost variables. To investigate this, some equations between the first fall frost ($M1$ mild, $M2$ moderate, and $M3$ severe) Julian days (at the 75% exceedance probability level) and elevation (Z meters), as well as between the last spring frost ($M4$ mild, $M5$ moderate, and $M6$ severe) Julian days (at the 75% non-exceedance probability level) and elevation were constructed through the regression analysis. These relationships are presented in Equations (3-1) to (3–6), respectively.

$$M1 = 338.2 - 0.017\ \mathrm{Z} \quad (3\text{–}1)$$

$$M2 = 349.5 - 0.019\ \mathrm{Z} \quad (3\text{–}2)$$

$$M3 = 354.3 - 0.02\ \mathrm{Z} \quad (3\text{–}3)$$

$$M4 = 59 + 0.027\ \mathrm{Z} \quad (3\text{–}4)$$

$$M5 = 51.9 + 0.026\ \mathrm{Z} \quad (3\text{–}5)$$

$$M6 = 45.1 + 0.026\ \mathrm{Z} \quad (3\text{–}6)$$

Where Z is elevation in meters.

Equation (3) can only be seen as an approximation because geographical/climatological factors other than elevation, which are not included, may affect these differences. However, for farmers operating at a certain elevation in central Alborz region, it may provide the first indication. The graphical schemes of these equations are shown in Figures 3 and 4.

3.5. Height dependency of frost-free periods

The relationship between the frost-free periods (M7) and the elevation (Z) (at the 75% non-exceedance probability level) is found as

$$M7 = 309.5 - 0.04\ \mathrm{Z} \quad (4)$$

In many agricultural areas, there is an interest not only on when a frost might occur, but also on its spatial pattern in a certain region. Such information can assist

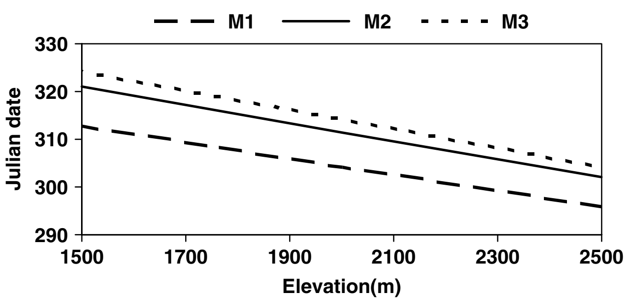

Figure 3. Graphical presentation of the first mild fall frost ($M1$), first moderate fall frost ($M2$), and first severe fall frost ($M3$) in Julian days as a function of altitude (exceedance probability levels).

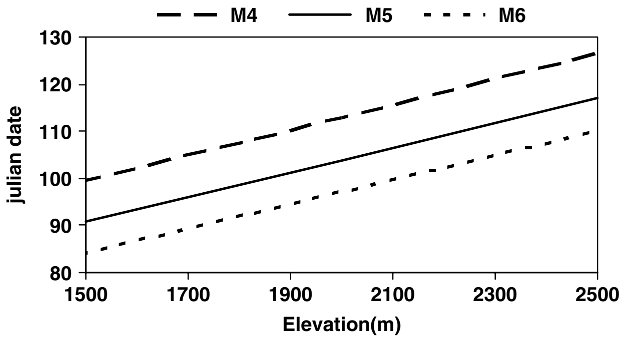

Figure 4. Graphical presentation of the last mild spring frost ($M4$), last moderate spring frost ($M5$), and last severe spring frost ($M6$) in Julian days as a function of altitude (non-exceedance probability levels).

in the development of local frost-risk maps, which is an important tool for farm planning and management (Laughlin and Kalma, 1987). However, the low spatial density of the data available here is too coarse to make a good quality map for the entire region.

4. CONCLUSIONS

Bringing risk analysis of the last and first occurrences of frost and of frost-free periods to farmers in a way understood and appreciated by them is a very useful procedure to decrease frost hazards in farm management. It is believed that information on frost, provided along with information on the properties of climate, soil, and water, can help farmers to manage their agricultural activities much better. This can be considered an agrometeorological service to such farmers (e.g. Stigter, 2005). A probability of occurrence of 75%, with a return period of 4 years, is a degree of risk that is accepted as an important yardstick when planning agricultural activities in Iran.

The frost probability distributions are determined using the moments method, ML parameter estimation method, mean related deviation, mean square related deviation, and chi-square criteria. Our results show that the ML method fails to define the parameters of most of the statistical distributions and is less accurate than the moments method. Mean square related deviation distinguishes the different distributions the best, followed by the mean related deviation; however, chi-square is not strong enough. We found that the Pearson type III distribution best fits the frost data sets in the central Alborz region. The Gumble distribution is not able to fit the distribution of these data.

Regression analysis was used successfully (through the significant test of the coefficient of determination r^2) to investigate frost, by establishing individual equations both for first fall and last spring occurrences of frost of different severities, as well as for the frost-free period. These approaches can be used as the basic tools to forecast frost risks, and thereby to prevent or decrease their hazard.

We show that the Julian days of the first mild, moderate, and severe fall frosts, as well as the last spring

Copyright © 2006 Royal Meteorological Society

DOI: 10.1002/joc

frosts and the mean frost-free period can be estimated using the regression equations provided. According to the provided equations, frosts occur more frequently on the higher areas, where the air temperature is lower. The shortest and the longest frost-free periods are found to occur on top of high mountains and on low altitude areas, respectively. Higher areas are prone to earlier frosts in autumn and later frosts in spring.

REFERENCES

Alizadeh A. 1995. *Applied Hydrology*, 1st edn. Astane Ghodss publishing Co.: Iran; 635.

Bootsma A. 1976. Estimating minimum temperature and climatological freezing risk in hilly terrain. *Agricultural Meteorology* **16**: 425–443.

Castiglioni P, Di Rienzo M. 2004. How to check steady state condition from cardio vascular time series. *Physiological Measurement* **25**(4): 985–996.

Domonkos P. 2001. Temporal accumulations of extreme daily mean temperature anomalies. *Theoretical and Applied Climatology* **68**: 17–32.

Gaumont GD, Margolis HA, Bigras FJ, Raulier F. 2003. Characterizing the frost sensitivity of black spruce photosynthesis during cold acclimation. *Tree Physiology* **23**: 301–311.

Geiger R, Aron RH, Todhunter P. 1995. *Ed The Climate Near the Ground*, 5th edn. Vieweg: Braunschweig, Germany.

Gould W, Pitblado J, Sribney W. 2006. *Maximum Likelihood Estimation with Stata*, 3rd edn. Stata press; Texas, USA; 290.

Hunter Rd, Meentemeyer RK. 2005. Climatologically aided mapping of daily precipitation and temperature. *Journal of Applied Meteorology* **44**: 1501–1510.

IRIMO. 1997. *Meteorological Year Book. I. R. of Iran Meteorological Organization*. Tehran: Iran.

Kite GW. 1977. *Frequency and Risk Analysis in Hydrology*. Water resources publications: Fort Collin, CO.

Kratsch HA, Wise RR. 2000. Invited review: the ultra structure of chilling stress. *Plant Cell and Environment* **23**: 337–350.

Lana X, Burgueno A. 1996. Extreme winter minimum temperature in Catalonia (north east Spain): expected values and their spatial distribution. *International Journal of Climatology* **16**: 1365–1378.

Lana X, Burgueno A. 1999. Comments on an extreme winter minimum temperature study in Catalonia, north east Spain. *International Journal of Climatology* **19**: 803–809.

Laughlin JP, Kalma JD. 1987. Frost hazard assessment from local weather and terrain data. *Agricultural and Forest Meteorology* **40**: 1–16.

Linkosalo T, Carter TR, Hakkinen R, Hari P. 2000. Predicting spring phenology and frost damage risk of Betula spp. Under climatic warming: a comparison of two models. *Tree Physiology* **20**: 1175–1182.

Mavi HS. 1996. *Introduction to Agrometeorology*, 1st edn. Raju Prim lanifo Oxford & IBM Publishing Co.: New Delhi.

Pearce RS. 2001. Plant freezing and damage. *Annals of Botany* **87**: 417–424.

Porth LS, Boes DC, Davis RA, Troendle Ca, King RM. 2001. Development of a technique to determine adequate sample size using sub sampling and return interval estimation. *Journal of Hydrology* **251**: 110–116.

Root TJ, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. 2003. Fingerprints of global warming on wild animals and plants. *Nature (Lond)* **421**: 57–60.

Rosenberg NJ, Myers RE. 1962. The nature of growing season frost in and along the Platte valley of Nebraska. *Monthly Weather Review* **90**: 471–478.

Rosenberg NJ, Blad BL, Verma S. 1983. *Microclimate; the Biological Environment*, 2nd edn. John Wiley: New York.

Stigter Kees. 2005. Building stones of agrometeorological services: adaptation strategies based on farmer innovations, functionally selected contemporary science and understanding of prevailing policy environments. *Journal of Agricultural Meteorology (Japan)* **60**: 525–528.

Stigter CJ. 2006. From basic agrometeorological science to agrometeorological services and information for agricultural decision makers: a simple diagnostic and conceptual framework. An Editorial. *Agricultural and Forest Meteorology* in press.

Stone R, Nicholls N, Hammer G. 1996. Frost in NE Australia, trends and influence of phases of the Southern Oscillation. *Journal of Climate* **9**: 1896–1909.

Tait A, Zheng X. 2003. Mapping frost occurrence using satellite data. *Journal of Applied Meteorology* **42**: 193–203.

Taschler D, Beikircher B, Neuner G. 2004. Frost resistance and ice nucleation in leaves of five woody timberline species measured in situ during shoot expansion. *Tree Physiology* **24**: 331–337.

Thom HCS. 1958. Climatological analysis of freeze data for Iowa. *Monthly Weather Review* **86**: 251–257.

Thom HCS. 1959. The distribution of freeze-date and freeze-free period for climatological series with freeze less years. *Monthly Weather Review* **87**: 136–144.

Toksoz MN, Dainty AM, Bullit LT. 1990. A prototype earthquake warning system for strike slip earthquakes. *Pure and Applied Geophysics* **133**(3): 475–487.

Vestal CK. 1971. First and last occurrences of low temperature during the cold season. *Monthly Weather Review* **99**: 650–652.

Vincent LA, Peterson TC, Barros VR, Marino Mb, Rusticucci M, Carrasco G, Ramirez E, Alves LM, Ambrizzi T, Berrlato MA, Grimm AM, Marengo JA, Molion L, Moncunill DF, Rebello E, Anunciacao YMT, Quintana J, Santos JL, Baez J, Coronel G, Garcia J, Trebejo I, Bidegain M, Haylock MR, Karoly D. 2005. Observed trends in indices of daily temperature extremes in South America 1960–2000. *Journal of climate* **18**: 5011–5023.

WMO. 1963. *Protection Against Frost Damage*, *WMO-No. 133*. WMO: Geneva.

WMO. 1997. *Weather, Climate and Sustainable Agricultural Production and Protection*, *WMO Td 838*. WMO: Geneva.

Copyright © 2006 Royal Meteorological Society

DOI: 10.1002/joc