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Evaluation of Frost Days Continuity Using Markov Chain Model: Case Study of Zabol city in Iran

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Background: Extreme temperature events can impose serious impacts on environment and societies. Since the outbreak of cold and frost are one of the important factors of climate in many parts of Iran, utilization of a new model for predicting the continuity of these factors is necessary.

Materials and Methods: This paper uses high-order categorical non-stationary Markov chains to study the occurrence of extreme cold temperature events by transition and probabilities matrixes in Zabol, southeast of Iran. The occurrence of frost days, homogeneity, continuity and spatial duration were analyzed for 30 years (April 1982- April 2012). The multivariate regression was used to modeling and mapping the statistical characteristics of frost and Kriging interpolation method in Arc/GIS was applied for its relationship.

Results: The occurrence of frost days in Zabol was in conformity with Markov model characteristic that showed the continuation of frost days depended on the weather of preceding days.

Discussion and Conclusions: Heavy frost in Zabol is expected to occur in Jan and Feb. Thus, frost-free day cycle duration was more than frost cycle and occurrences of frost in short term were more than long term in the studied period.

Keywords: Auxiliary variable methods, Daily temperature, Frost periods, Zabol

1. Background

A frost day is defined as a day in which the minimum temperature goes below the temperatures at which ice melts (0°C), while above that falls under the frost-free day (1). The frost period is the average period of the first or last light freeze that occurs in spring or fall. Frost phenomenon brings about great economic losses every year around the world. Various protection methods have been applied to reduce the losses. Application of these methods is more effective before the occurrence of frost. For this purpose, prediction of frost occurrence is required.

The earlier created data assumed no alternative in the model for various years and just the seasons or months of a year were considered. Thus, there is expanding knowledge of long term continuity in the climatic data in the structure of frost and frost-free day cycles.

Markov chain model is a random process that is subjected to spatial transitions. This approach process is commonly reserved for various set of times. A discrete-time of process engages a structure which is in an absolute state at each step by the randomly changing state. In Markov chain models, the current state of a system depends on its previous state and Markov models of first, second or third orders can be used for each classified process.

A few studies have been done on random process productions that have been based on monthly or seasonal data within a year, but year by year alternative has been disregarded. Klemes and Bulu (1) showed that this common procedure to create random data underrated the limit of mean and variance of the possible future chains. The concept of performing random processes theory in meteorology belongs to Ladoy (2) who has expanded a Markov chain model for the daily rainfall in Sweden by applying a batch of data including the daily mean values of departmental rainfall over 11 years of observations.

The Markov chain model has been effectively used in various fields throughout the world in recent years (3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13). It has also been applied in Iran in a wide range of areas, including drought prediction (14, 15, and 16), rainfall estimation (17, 18, 19, and 20), frostbite (21, 22), climate change (23) and its biological consequence (24), and temperature fluctuations (25).

2. Objective

The aim was to develop a framework in assessing the frequency and continuity of frost, based on analysis of a 30-years period data in Zabol city from various descriptors taken from the assessed transition matrix, in order to catch the features of the cycles (unexpected temperature changes and slight fluctuations), while also containing the associated uncertainty in the recognition of climate states.
Continuation and the effective number of frost or freeze days affect natural and managed ecosystems (26), human activities (27) and is an indicative merit of changes in extreme weather and climate events over time (28 and 29).

3. Materials and Methods

Frost indices such as number of frost days and frost-free days, last spring freeze, first fall freeze, and growing-season length (GSL) were calculated using daily minimum air temperature (T_{min}) from meteorological station of Zabol city during April 1982- April 2012. Defining the frost day as days with $T_{min} < 0$ °C, the long- and short-term trends in frost indices were analyzed at monthly, seasonal, and annual timescales.

Zabol is located in Sistan-Baluchestan province, east of Iran (61˚ 29΄ E and 32˚ 2΄ N), at an altitude of 489 meters above sea level (Figure 1). Long-term average annual rainfall is 61.3 mm, the highest monthly average of which is received in Jan (15.6 mm), Feb (14.4 mm) and Mar (and13.9 mm), while the lowest is in June, July, Aug and Sep.

According to the 30-years data, trend of frost frequency shows this phenomenon occurs during late fall to late winter (Figure 2).

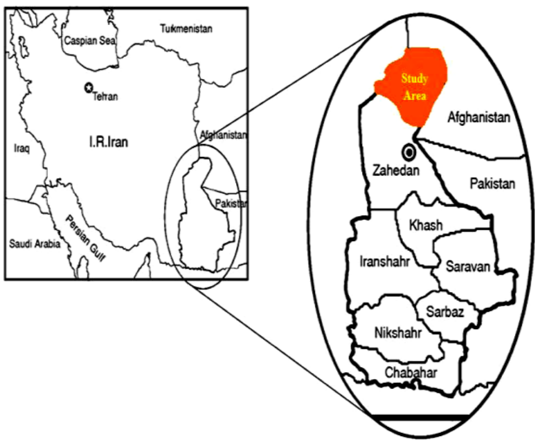

Figure 1 Location of Zabol in Iran

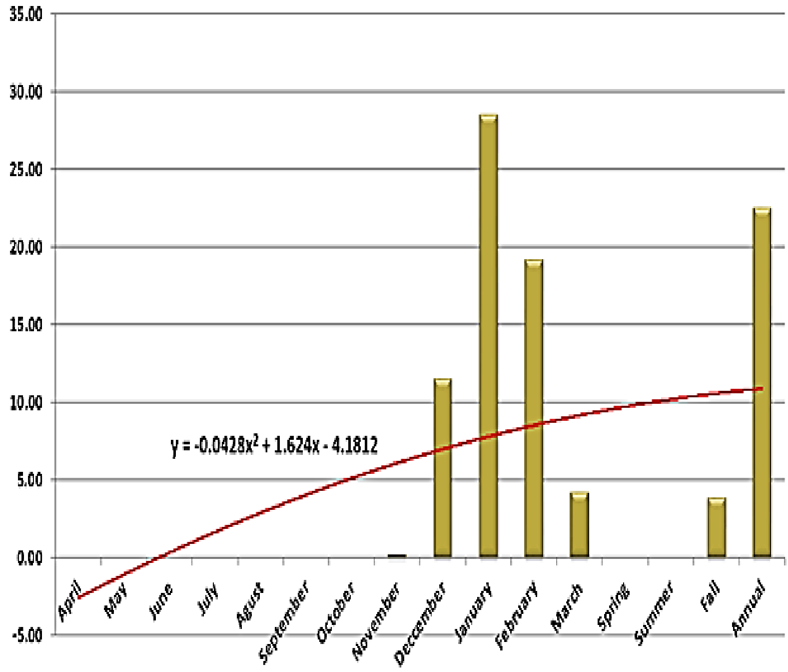

Figure 2 Hierarchy of frost frequency percentage for 30 years

Markov chain method was used for frost prediction, which is characterized by the number of status and its transition/ transmission probabilities, such as frost- and frost-free days. The probabilities associated with various status changes are called transition matrix. Therefore, the Markov chain is a mathematical technique for modeling in relation to possible processes (8).

Suppose that (X_n, n=0, 1, 2…) is a stochastic process where (Xn) can be any number of possible countable value. If (X_n=*i*), this process will be reflection state of *i* in time of n. Therefore, it will be concluded that when the process is in status of *i*, by a fixed probability (p_{ij}), its status change can be estimated to j in the future as:

$$\text{Probability}\ (X_{n+1}=j \mid X_n=i,\ X_{n-1}=i_{n-1}\ldots,\ X_0=i_0)=P(X_{n+1}=j \mid X_n=i) = (p_{ij}) \qquad (1)$$

That is true for all states i_0, i_1... i_{n-1}, i, j and n≥0. So, the conditional distribution of any future state X_{n+1}, regarding to the present state of X_n and past states of , X_0, X_1, ..., X_{n-1} only depends on the present state and is independent of the past states. It means that climate conditions for tomorrow are only related to condition of today and independent of climatic conditions of the past days. In this process, p_{ij} as a constant probability is the expression of transition from state *i* to state *j*".

The procedure is specified by a state space, a transition matrix illustrating the probabilities of special transitions, and a primary state (or initial distribution) across the state space. By convention, we suppose that all feasible states and transitions have been contained in the definition of the procedure, so there is always a next state, and the process does not terminate.

The first step in adaptation of data with the Markov chain is analyzing them to obtain the frequency of occurrence of frost days and

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relative percentage of them in months, seasons and annually separately. For this purpose, the first order of matrix 2+2 from the data frequency of the last and next day regarding to event is formed according to Eq. 2 and then the frequency and percentage of condition frequency for each data were calculated. Figures of this matrix is effective for calculation of the next relationship.

$$\begin{bmatrix} n_{00} & n_{01} \\ n_{10} & n_{11} \end{bmatrix} \quad (2)$$

Calculating chain probability (p) for the first order of two states is as follow: matrix frost-free day (0) and frost day (1). (P_{11}) is frost day probability after another same day and (P_{00}) probability of frost-free day after another same day (30). Seasonal values of conditional transfer probability for Zabol station (Table 1) were studied according to the Eqs. 3 to 5:

$$P_{01} = \frac{n_{01}}{n_{01} + n_{00}} \quad (3)$$

$$P_{00} = 1 - P_{01} \quad (4)$$

$$P_{10} = \frac{n_{10}}{n_{10} + n_{11}} \quad (5)$$

Then, the consecutive frost day periods and frost free n days in a series of observations were determined from the Eqs. 7 and 8, respectively.

$$w_f = 1 + \frac{(N-n)(P_{01})(P_{10})(1+P_{10})^{n-1}}{(P_{01}+P_{10})} \quad (7)$$

Where, (W_f) is frost day period number for a specific period, (N) is statistical days for research and (n) is duration of Frost period.

$$d_f = 1 + \frac{(N-n)(P_{01})(P_{10})(1+P_{01})^{n-1}}{(P_{01}+P_{10})} \quad (8)$$

Where, (d_f) is frost-free day period number for a specific period, (N) is statistical days for research and (n) is duration of Frost period.

In this paper, Eqs. 8 to 10 were used to calculate the air cycle (total Frost day and frost-free day periods) and expected Frost day and frost-free day periods as well as continuity parameters that reflected autocorrelation of frosty days to each other.

$$E_c = E_0 + E_1 \quad (8)$$

$$E_0 = \frac{P_{10}}{(1+P_{01}) - P_{11}} \Rightarrow E_1 = 1 - E_0 \quad (9)$$

$$r_1 = P_{11} - P_{01} \quad (10)$$

Where, **(**E_0) is duration of expected Frost period, (E_1) is duration of expected non-Frost period, (E_c) is total air cycle and (r_1) is duration of Frost period.

Finally, reverse period of n days by separation of monthly, seasonal and annual for times of Frost were calculated according to Eq. 11 that is shown in Table 6. Result of calculation determine the reverse period of Frost and statues of average return of phenomenon (31).

$$T = \frac{1}{P} \quad (11)$$

$$P(no\ \ u^n) = P_{00}{}^{n-1} \times P_{01} \quad (12)$$

$$P(f^n) = P_{11}{}^{n-1} \times P_{10} \quad (13)$$

Where (n) is duration of specified period, (u) is duration of frost-free day period and (F) is duration of frost day period.

Multivariate regression models were used to model and map the statistical characteristics of frost day, based on the data related to the minimum daily temperature for a 30-years period from Apr 1982 to Apr 2012. The

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relationship among five statistical characteristics, including the mean days of the first fall frost, the last spring frost, number of frosty days per year, length of the frost period, and mean length of growing season were modeled by three geo-climate factors of elevation, longitude and latitude. The precision of each model was explored by four hypotheses: linearity of the relationship between independent variables and the dependent variable, normality of errors, constancy of error variance and lack of correlation of errors were tested, and their precisions were confirmed. The regionalization maps of statistical characteristics of frost were obtained using Kriging interpolation method in GIS.

4. Results and Discussions

By checking the homogeneity of the daily temperature data in autumn and winter through Chi-Squared test, high level of homogeneity was accepted and zero degrees as the threshold frost free days and frost days were separated. Then, frost day's frequency and frost free days were carried out. In the next step, transition states matrix of binary consecutive days (00), (01), (11), (10) are set and occurrence probability of conditional states (P_{01}), (P_{11}), (P_{00}) and (P_{10}) were calculated (Table 1).

For considering expected continuity of frost days and frost free days and air cycle periods in Zabol, frequency matrix and climate probability matrix and continuous index were estimated by monthly, seasonal and annual (Tables 2 and 3).

According to Table 2, the highest expected Frosty day period in autumn season is in Nov and the lowest is in Oct and in winter season is Feb and Dec, respectively.

Coefficient continuity is explanatory of auto correlated values of frosting days to each other. Derived positive result shows that probability of a frosting day to another Frost day is more than the frost-free day. If the time series are not properties of auto correlation, it will be out of regulations of the conditional probability. The forecasting frost day periods for n days till 10 days indicate short term frost day periods have more frequency than longer period (Table 4, Figures 6 to 12. The number of frequencies gradually declined and reduction in the frequency and number of forecasted frost day periods became more intensive. For example, the number of frost day periods of 5, 6, 7 days in months of Dec and Mar are severely declined.

Table 1 Probability of conditional transmission frost days and frost-free days

Time epoch	Condition												
	n_{00}	n_{00} %	n_{01}	n_{01} %	n_{10}	n_{10} %	n_{11}	n_{11} %	P_{00}	P_{01}	P_{10}	P_{11}	n
Nov	868	99.8	1	0.1	1	0.1	0	0	1	0	0	1	870
Dec	726	83.4	44	5.1	37	4.3	63	7.2	0.94	0.06	0.37	0.63	870
Jan	546	62.8	86	9.9	84	9.7	154	17.7	0.86	0.14	0.35	0.65	870
Feb	620	71.3	71	8.2	78	9	101	11.6	0.9	0.1	0.44	0.56	870
Mar	813	94.3	16	1.9	18	2.1	15	1.7	0.98	0.02	0.55	0.45	864
Fall	2464	94.4	45	1.7	38	1.5	63	2.4	0.98	0.02	0.38	0.62	2610
Winter	1979	75.8	173	6.6	180	6.9	270	10.3	0.92	0.08	0.4	0.6	2604
Annual	4443	85.2	218	4.2	218	4.2	333	6.4	0.95	0.05	0.4	0.6	5214

Although the observed periods in months of Jan and Feb were expected to continue for ten days, six or seven days were more frequent. frost day period frequencies for the selected seasons in stations indicated that the short term forecasted periods were more than the short-term observed ones and were continues to a long-term period.

Derived results from Table 4 are shown in Figures 6 to 12 that are separated by monthly, seasonal and annual for more comparison and survey of relative concepts. Outcome of relative data in Table 5 indicates that proportion of correlation in observation and predicted frost are meaningful that shows high precision research trend which confirms the application of Markov chain model in relative studies.

Table 2 Air cycle of frost day and frost-free day periods

Parameter	Nov	Dec	Jan	Feb	Mar	Fall	Winter	Annual
E_1	0.36	2.7	2.83	2.29	1.04	2.66	2.5	0.4
E_0	0.36	17.5	7.35	9.73	16.29	55.76	12.44	0.05
E_c	0.72	20.2	10.18	12.03	17.3	58.41	14.94	0.44

F.I * = Frost day persistence index, D.I ** = frost-free day persistence index, R_t = Total persistence coefficient

Table 3 Climate probability of frost day and frost-free day periods and continuous index

Parameter	Nov	Dec	Jan	Feb	Mar	Fall	Winter	Annual
F.I*	0.5	0.87	0.72	0.81	0.97	0.95	0.83	0.89
D.I**	0.5	0.13	0.28	0.19	0.03	0.05	0.17	0.11
R_t	1	0.57	0.51	0.46	0.44	0.61	0.52	0.56

Table 4 Frequency of n-day period for observed frost days

	Days period	1	2	3	4	5	6	7	8	9	10
Nov	Seen frequency	2	0	0	0	0	0	0	0	0	**0**
	Predicted frequency	1	1	1	1	1	1	1	1	1	**1**
Dec	Seen frequency	20	9	3	3	1	2	2	0	0	**1**
	Predicted frequency	44	28	18	11	8	5	4	3	2	**1**
Jan	Seen frequency	34	24	13	4	8	2	7	0	0	**1**
	Predicted frequency	86	56	37	24	16	11	7	5	4	**3**
Feb	Seen frequency	36	20	12	1	2	4	1	0	0	**1**
	Predicted frequency	73	42	24	14	8	5	3	2	2	**1**
Mar	Seen frequency	10	5	1	2	1	0	0	0	0	**0**
	Predicted frequency	17	8	4	2	2	1	1	1	1	**1**
Fall	Seen frequency	21	9	3	3	1	2	2	0	0	**1**
	Predicted frequency	46	29	18	11	8	5	4	3	2	**1**
Winter	Seen frequency	76	45	26	7	9	36	5	1	0	**1**
	Predicted frequency	175	105	64	39	24	15	9	6	4	**3**
Annual	Seen frequency	97	56	24	8	11	7	9	1	0	**2**
	Predicted frequency	219	133	81	49	30	19	12	7	5	**3**

Table 5 Meaningful amount of frost day observed and predicted frequency

Issue	Monthly					Seasonal		Annual
	Nov	Dec	Jan	Feb	Mar	Fall	Winter	Annual
Correlation Coefficient	0.94	0.96	0.97	0.99	0.98	0.96	0.91	0.99

Table 6 Occurrence probability of Frost for 10 days

Days		1	2	3	4	5	6	7	8	9	10
Dec	Occurrence	17.5	18.56	19.69	20.88	22.14	23.49	24.91	26.42	28.02	29.72
Jan	Occurrence	2.83	4.38	6.77	10.46	16.16	24.98	38.6	59.66	92.2	142.5
Feb	Occurrence	2.29	4.07	7.21	12.77	22.64	40.13	71.11	126.03	223.36	395.86
Mar	Occurrence	1.83	4.03	8.87	19.52	42.95	94.48	207.86	457.3	1006.06	2213.33
Fall	Occurrence	2.66	4.26	6.83	10.95	17.56	28.15	45.13	72.34	115.98	185.94
Winter	Occurrence	2.5	4.17	6.94	11.57	19.29	32.15	53.58	89.31	148.84	248.07
Annual	Occurrence	2.53	4.18	6.92	11.45	18.95	31.35	51.87	85.83	142.02	235

As can be seen in Table 6, the longer the continuity period, the longer is the reverse period. Based on the reverse period data provided in Table 6, appropriate plan and strategies can be implemented to prevent the probable loss as the result of frost. It seems that distribution of average number of frost free days was increased, and thus the return of frost-free day periods was raised both seasonally and annually. It's observed that return periods up to four days at this scale are close to each other. As a matter of fact, the area is influenced by the long-term Frost periods in the months of Jan, Feb and autumn season. The short term frost-free days period occurred sooner than the short term frost days period, while the long term frost days period occurred sooner than long term frost-free days period. Meanwhile, the factor of night cooling was a reason for early frosts in Dec that that could be attributed to the topography of Zabol region being influenced by Siberia and far away from moisture sources (32). Regarding the late frosts at the end of the year, it is derived from the synoptic patterns as the result of displacements of pressure systems from higher latitude, such as the North Europe and Siberian high pressure and their counter-clockwise rotation that cause severe and pervasive frosty periods. However, it shouldn't be forgotten that the displacement of pressure system from lower latitude and their clockwise circulation causes the weak and semi-pervasive frost in the area that cool the land surface.

The trend of daily temperature changes in studied months for twenty eight years shows the high potential for frost occurrence and cold climate in the area.

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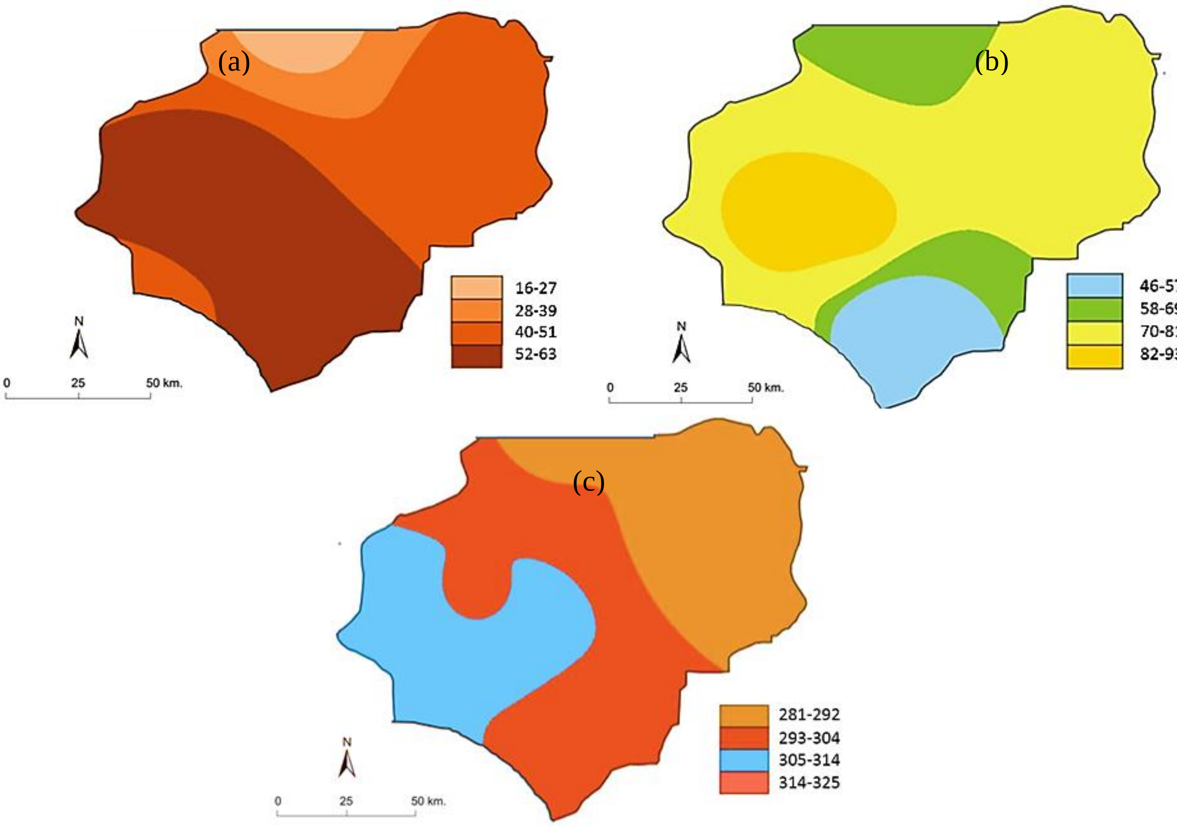

First Frost =323.836+(−4.703×Latitude)+(−1.106×Longitude)+(−0.042×Elevation)
Late Frost =−57.804+(5.321 ×Latitude)+ (0.011 ×Longitude)+(0.037×Elevation)
Frequency of Frost Length=17.161+(3.382×Latitude)+(−2464×longitude)+(0.056×Elevation)
Duration of Frost=−317.214+(7.736×Latitude)+(1.641×Longitude) +(0.056×Elevation)
Growing Season Length= 632.363+(−7.699×Latitude)+(−0.682×Longitude) +(0.056×Elevation)

Figure 3 Map of the mean frequency of frost days (a), map of mean length of frost days period (b), map of mean length of growing season (c)

The Figure 5 shows the monthly frost (crosses) and average frost (black line). Periods of deficit relative to average frost are indicated in red. On average, the complete period cycle of the occurrence of a frost- and frost-free day was less than 50% at Dec and Jan. Regionalization map of statistical characteristics of the frost phenomenon, was drawn up by using the Kriging interpolation method.

The geo-climate factors of elevation and latitude had the greatest role in spatial arrangement of this frost characteristic in Zabol. So, it can be concluded that, in addition to elevation, synoptic systems had a great role in days of the last frost. Therefore, the late-winter frosts can be a type of advection frosts (33).

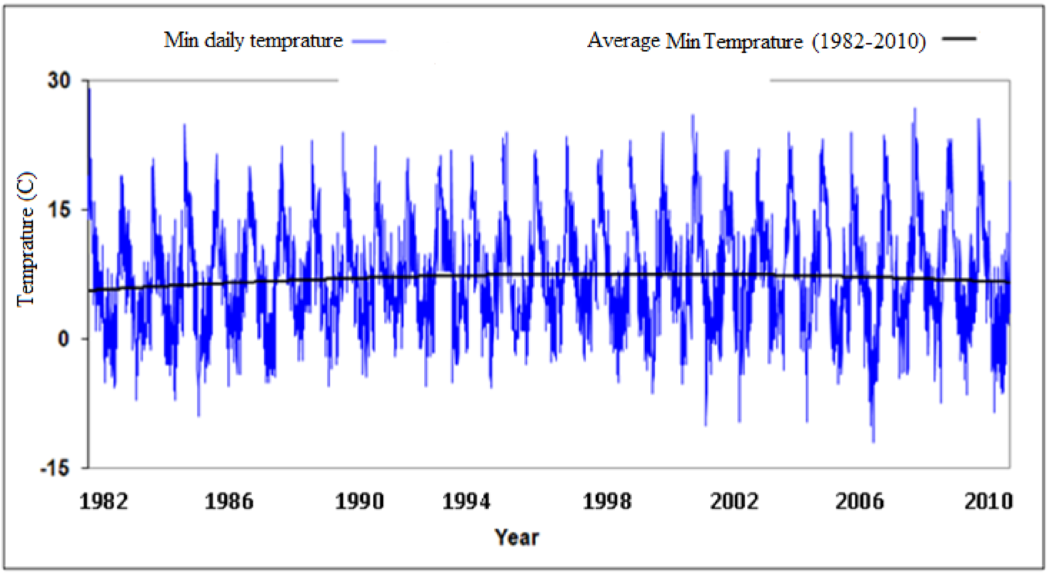

Figure 4 The changes in the minimum daily temperature

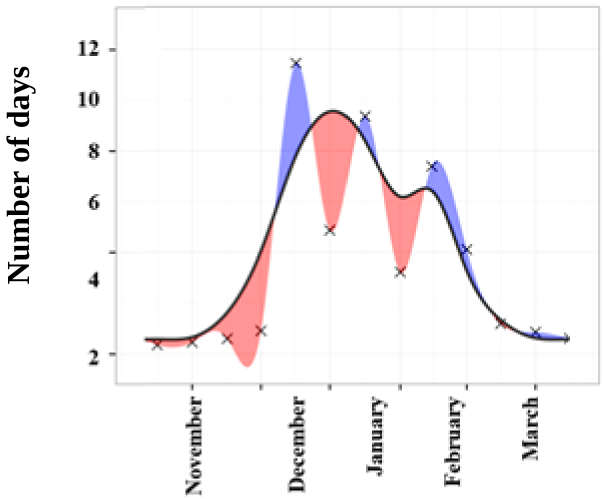

Figure 5 The mean of monthly frost for 30 years period

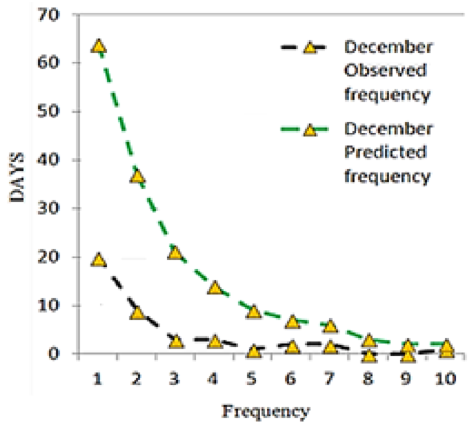

Figure 6 Comparative hierarchy of observed and predicted frequency for month of Dec

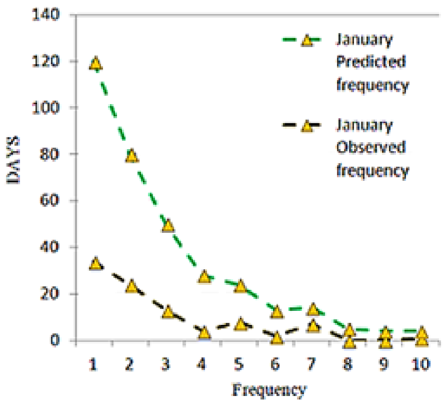

Figure 7 Comparative hierarchy of observed and predicted frequency for month of Jan

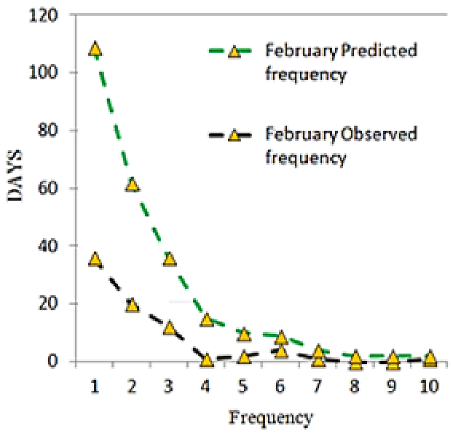

Figure 8 Comparative hierarchy of observed and predicted frequency for month of Feb

Table 7 The abstract of statistics of regression models for statistical characteristics of frosts in Zabol

Characteristic	R	F Statistic (calculated)	F Statistic (Table)	DF (1)	DF (2)	P-Value	Durbin-Watson statistic
The first day of frost	0.920	120.062	2.7581	3	65	0.05	1.839
The last day of frost	0.943	172.956	2.7581	3	65	0.05	1.876
Frequency of Frost days	0.875	70.123	2.7581	3	65	0.05	1.594
Length of frost period	0.872	68.950	2.7581	3	65	0.05	1.558
Length of growing season	0.914	110.488	2.7581	3	65	0.05	1.843

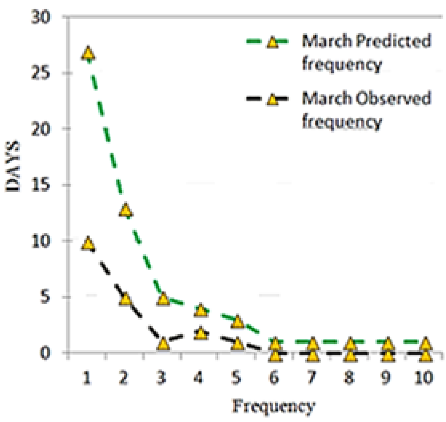

Figure 9 Comparative hierarchy of observed and predicted frequency for month of Mar

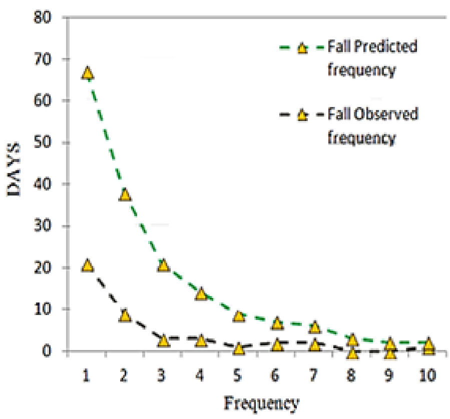

Figure 10 Comparative hierarchy of observed and predicted frequency for fall

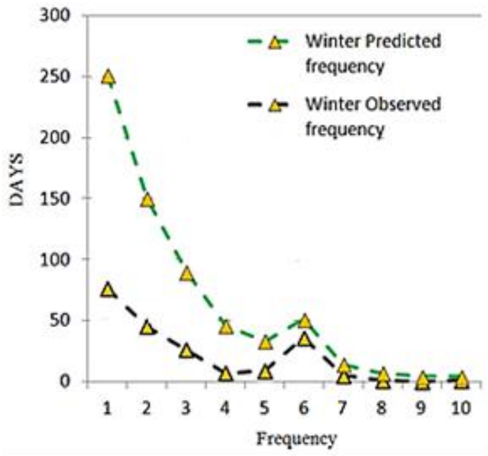

Figure 11 Comparative hierarchy of observed and predicted frequency for winter

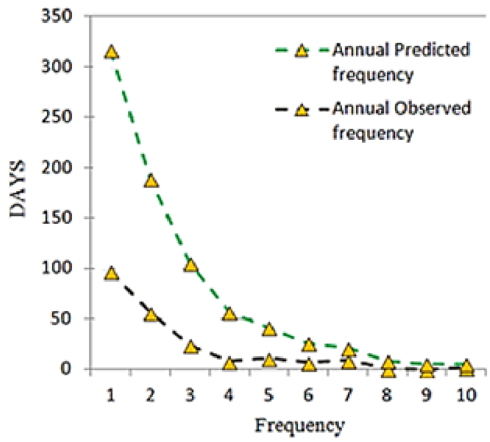

Figure 12 Comparative hierarchy of observed and predicted annual frequency

5. Conclusion

The purpose of this research was to analyze the continuity of frost days based on Markov chain model in Zabol city. The matrices of the frequency of frost days were constructed and the matrices of the probabilities of transition for months and seasons were calculated. The expected frequency of frost days, the period of frost and frost free day, and the sequence of the frost n-days for each month were calculated. Two geo-climate factors of elevation and latitude had the greatest effect in spatial arrangement of frost characteristic. Persistence of frost event continue until ten frost days in Dec that are known as the first frost days that occurs in fall. The occurrence of heavy long term frost day was dominated in Feb and Mar, hence frost return-trend goes to long term periods. The observed frost day periods in Jan and Feb were expected to have a continuation period of six, seven and even ten days. Also it was found that in the autumn, the percentage of frost free day frequency was higher than the frequency of frost day and the trend of this process was opposite in winter. Frost day period frequencies for the selected seasons (of Zabol stations) indicated that the short term forecasted periods were more than the short-term observed ones as well as long-term periods. Our twenty eight years long study revealed that the trend of daily temperature changes in studied months had a high potential for frost occurrence and cold climate in the area.

Conflicting of Interest

There are no conflicts of interest with respect to the University of Sistan and Baluchestan, or Zabol Province Authority of Conversation.

Authors' Contributions

Each of the authors contributed to the development of the paper

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ارزیابی تداوم روزهای یخبندان زابل با استفاده از مدل زنجیره مارکف

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مقدمه: پدیده‌های دمایی می‌تواند تأثیرگذاری جدی بر شرایط محیط و جوامع داشته باشد. از آنجایی‌که پدیده سرما و یخبندان به‌عنوان یکی از عوامل مهم آب و هوایی در بیش‌تر مناطق کشور در طی دوره سرد سال بروز می‌کند، بکارگیری مدل‌های جدید به‌منظور پیش‌بینی جریانات آب و هوایی و تداوم آن ضروری می‌باشد.

مواد و روش‌ها: در این پژوهش از مدل زنجیره مارکف برای مطالعه و بررسی تداوم روزهای یخبندان در زابل استفاده گردیده است. با استفاده از این مدل و بهره‌گیری از الگوهای رگرسیون چندمتغیره و درون‌یابی کیرجینگ در محیط سیستم اطلاعات جغرافیایی، ماتریس احتمالات داده‌های یخبندان روزانه از اول فروردین ماه سال ۱۳۶۱ تا اول فروردین ماه سال ۹۱ برای یک دوره ۳۰ ساله در ایستگاه هواشناسی زابل مورد بررسی قرار گرفتند و وابستگی روزهای یخبندان و غیریخبندان به یکدیگر، به همراه ایستایی و همگنی و تداوم مکانی آن‌ها مورد آزمون قرار گرفت.

بحث و نتیجه‌گیری: نتایج به‌دست آمده نشان داد که وقوع روزهای یخبندان در شهر زابل، ویژگی زنجیره مارکف را دارا هستند و تداوم روزهای یخبندان در این شهر تصادفی نیست بلکه وقوع روز یا روزهای یخبندان به شرایط اقلیمی روزهای گذشته وابسته است هم‌چنین وقوع یخبندان‌های دو ماه دی و بهمن، که به دوره یخبندان سنگین شهر زابل مشهور هستند، از زنجیره مارکف تبعیت می‌کند، یعنی وقوع یخبندان فقط به شرایط اقلیمی روز گذشته مرتبط است. به دیگر، حاکمیت با تداوم‌های دو روزه است، هم‌چنین نسبت دوره‌های عدم یخبندان به کل دوره مورد مطالعه زیاد بوده و دوره‌های یخبندان‌های کوتاه مدت بیش‌تر از دوره‌های یخبندان‌های بلندمدت اتفاق می‌افتد.

کلمات کلیدی: دمای روزانه، دوره‌های یخبندان، روش‌های چند متغیره، زابل