

Functional Analysis of Air Temperatures as Related to Chilling Requirements of Perennial Fruit Crops

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Abstract

After more than two centuries of observation and research on chilling requirements of perennial fruit crops, there remain unresolved aspects concerning relationships between chilling condition and ambient air temperatures. The purpose of this ongoing study was to further explain association between chilling temperature and plant functions: growing, chilling, and freezing. Temperature data consisted of 5-year averages for 50 Mesonet weather sites randomly located throughout Kentucky. Based upon the Chilling Hours Model analysis, available chilling hours exceeded requirements of commonly grown perennial fruit crops. In the extended study, max and min daily temperatures were processed separately permitting their comparisons within plant functional classes. Nearly twice as many min as max temperature days were included within the chilling class function. Most consecutive days of chilling temperatures ranged from 1 to 3 days and were more clustered with min than max temperatures. Using multiple-year averages especially when the temperatures were near freezing point, resulted in a high percentage of individual years with freezing temperatures that were not reflected in the group average. Separating max and min temperatures in functional classes permitted greater focus on critical temperature-chilling relations. Within the chilling range, impact of min on chilling was nearly twice that of max. Contrariwise, widely reported research literature confirms that global warming has greater influence on min than on max or mean temperatures.

Keywords

Chilling Hours, Diurnal Temperatures, Chilling Metrics, Global Warming

1. Chilling Is an Essential Process in Perennial Fruit Production

Since Knight's 1801 report on breaking plant dormancy, more than two centuries of research and observation have provided a workable knowledge of the genetic and physiological processes involved [1] [2]. However, given the added challenges resulting from the great diversity of plants and their environments, the increase in human population, and the presence of global warming, the need to understand and manage dormancy continues to be a critical factor in perennial fruit and nut crops. Winter dormancy is both a fruit production and a survival requirement for these crops. During the chilling period the plant undergoes changes necessary for flower and fruit production in the following season. Specific temperature levels and duration are required to break the chilling period permitting resumption of normal growth in the spring. When chilling temperature requirements are not met, plants may produce irregular leaves and flowers resulting in reduced or no crop production.

1.1. Chilling Models

Commonly used models for quantifying winter chill are based upon hourly temperature records. Four models, among several, have gained acceptance due to ease of use and adaption to different environmental conditions [3].

1) Chilling Hours Model equates a chilling hour with a clock hour in which the air temperature is between 0°C and 7.2°C (32°F and 45°F). Freezing temperatures are not factored into winter chill calculation.

2) Utah Model is similar to Chilling Hour but assigns different chilling efficiencies to different temperature ranges.

3) Positive Utah Model is a modified version of the Utah developed for use in warmer climates.

4) The Dynamic Model postulates that chilling is a two-step process initiated by cool temperature and continuing into an intermediate product (chill portion) under warmer temperature.

1.2. Comparability of Chilling Models

Luedeling *et al.*, (2009) [4] compared the four major models over 100 years of synthetic weather data. All models showed decrease in winter chill for all sites, but the extent of decrease varied with model. Luedeling and Brown (2011) [5] compared three models (Chilling Hours, Utah, and Dynamic) at 5078 weather stations around the world. The results varied substantially among models. The models were not proportional for chilling hours at different locations. They suggested need for conversion factors between winter chill models, and that further research efforts are needed to identify appropriate chilling models against the imminent effects of climate change.

1.3. Temperature Measurements

Hourly temperatures utilized in chilling models may be based upon recording

schedules and statistical reporting units that affect validity of the outcome. Based upon testing of 12 climate models, Lobell *et al.* (2007) [11] found that weather change depended more upon changes in mean daily min or max than in combined daily means. Association between daily min was slightly greater than with daily max which was consistent with historical trends. Wilkens and Singh, (2001) [6] reported for quantities such as accumulated chill hours, response is different for min and max temperature as compared to mean daily temperature. Based upon global studies of maximum and minimum temperature trends, Easterling *et al.* (1997) [7] determined that daily minimum temperature is increasing at a faster rate or decreasing at a slower rate, than the daily maximum, resulting in a decrease in diurnal temperature range for many parts of the world.

Objectives of the extended study were 1) To analyze air temperatures by plant functions: growing, chilling, and freezing. 2) To compare the impact of daily max and min temperatures on chilling hour production, and 3) To explore the effect of duration and frequency of chilling days on chilling hour production.

2. Materials and Methods

The present treatise is an extension of the study reported by Xue *et al.* (2016) [8] and is based on the same data for years and sites. Site identification numbers are identical for both studies permitting cross referencing. Additional relevant information for both studies included local and international locations of sites, elevation, precipitation, air temperature, and chilling hour production.

In the second study, the highest hourly temperature for each day in the month was averaged to give the max temperature per month; the lowest hourly temperature for each day in the month was measured to give the min temperature per month. These max and min temperatures were classified into three functional ranges and related to chilling requirements as follows:

aa-Growing, both max and min above 7.2°C; bb-chilling, both between 0°C and 7.2°C; cc-freezing, both below 0°C; ab-max above 7.2°C, min between 0°C and 7.2°C; ac-max above 7.2°C, min below 0°C; bc-max between 0°C and 7.2°C, min below 0°C. Homo classes (aa, bb, cc) indicate that both max and min temperature were within the same range; hetero classes (ab, ac, bc) indicate that max and min temperature were in different ranges. Also, first and second letters specify max and min daily temperature; respectively. This classification system was applied to 5-year temperature means for each of the 50 Mesonet sites.

Linear correlation (Steel and Torrie, 1980) [9] was used to estimate relationships between chilling hour production (first study) and frequencies of max and min temperatures included in the different functional groups. For the bb chilling temperature range (0°C - 7.2°C), frequencies of inclusion of max and min were compared based on data for 8 months (September through April) at 11 sites (1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50). For the cc, freezing temperature range (below 0°C), which may kill flowers and fruit buds, frequency was based on individual years in addition to 5-year averages.

3. Results

Temperature classification by plant function was applied to data from the 50 sites resulting in 26.8% aa, 1.2% bb, 0.1% cc, 36.2% ab, 13.8% ac, and 22.0% bc (**Table 1**). For the homo classes, aa days were most frequent reflecting the wider temperature range, 7.2°C and above. All the days in September and about one half of the days in October and April had max daily temperature in the aa range accounting for approximately one fourth (26.8%) of the total days. The other two homo classes (bb and cc) included fewer max and min temperature days in their ranges. The bb range (0°C - 7.2°C) occurred between November and March and accounted for 1.2% of days. The cc class was lowest (0.1%) indicating a near absence of days in which both max and min temperatures were below freezing (0°C). Hetero classes (ab, ac, bc) occurred more frequently reflecting the diurnal cycle. The ab class (max, above 7.2°C, min between 0°C - 7.2°C) included more days than any class (36.2%) and was most prevalent in November and March. Both hetero classes involving c were limited to November through March with the more frequent bc likely being more impacted than ac by diurnal fluctuations.

Average daily max and min temperature by month are presented in **Table 2**. Max and min temperatures had their highest average in September (24.4°C to 13.3°C) and their lowest average in January (5°C and -2°C). Max and min temperatures by month were significantly correlated indicating that changes in one were positively associated with changes in the other.

Temperatures within the chilling range (0°C - 7.2°C) were further analyzed in relation to potential chilling hour production. Frequencies and durations of max and min temperatures within the chilling range were compared (**Table 3**). For the 242-day period, total chilling days (115.4) included 72.0 from min and 43.4 from max temperatures within the range. This relationship was present over single and multi-day (2, 3, 4 or more) durations.

Linear correlations based on data in **Table 1** with 50 sites resulted in positive statistically significant ($P \leq 0.05$) coefficients between chilling hour production and frequencies of temperature classes aa ($r = 0.785$), ab ($r = 0.207$), ac ($r = 0.342$), bc ($r = 0.378$) (Number of days in the bb and cc classes were insufficient for correlation analysis). A further analysis of data from 11 sites, resulted in positive significant coefficients between chilling hours and frequency of max temperatures in the b range ($r = 0.892$), frequency of min temperature ($r = 0.706$) and combined max/min temperatures ($r = 0.986$). Correlation was generally higher between temperature within the chilling range than with the total range.

It was observed that class c (freezing) occurred among some of the 5 years but was not apparent in the means for those years. Rather, the freezing temperature was masked by other years of larger, warmer temperatures. Since a single freezing temperature may kill developing buds, this phenomenon was explored using daily temperature in each of 5 months (December through April) for 5 years at 11 sites (**Table 4**). The results indicated that approximately 30% of individual

Table 1. Functional classification of max and min daily temperature means for 8 months (September through April) over 5 years (2010-11 through 2014-15) at 50 Kentucky Mesonet sites¹.

Site Number	County	Coordinates Latitude Longitude	Chilling hours	Plant response code ²						
				aa	bb	cc	ab	ac	bc	
1	Adair	37.14	-85.29	1552	69	6	0	95	30	42
2	Allen	36.74	-86.22	1464	81	7	0	92	32	30
3	Barren	37.01	-86.11	1527	68	7	0	98	32	37
4	Boone	38.96	-84.72	1508	65	3	3	77	12	82
5	Breathitt	37.54	-83.34	1680	49	3	0	94	57	39
6	Breckinridge	37.71	-86.49	1529	96	0	0	57	24	65
7	Bullitt	37.92	-85.66	1572	60	2	0	92	30	58
8	Caldwell	37.1	-87.86	1521	81	1	0	76	30	54
9	Calloway	36.61	-88.34	1499	83	4	0	81	31	43
10	Campbell	39.01	-84.47	1544	64	6	5	77	15	75
11	Carroll	38.69	-85.14	1632	58	2	1	85	27	69
12	Casey	37.28	-84.96	1595	52	3	0	99	41	47
13	Christian	36.95	-87.52	1463	81	2	0	81	26	52
14	Clark	38.03	-84.2	1579	61	4	1	91	27	58
15	Clinton	36.71	-85.13	1522	57	5	0	95	39	46
16	Crittenden	37.38	-88.04	1495	85	1	0	74	22	60
17	Cumberland	36.8	-85.43	1636	47	1	0	102	60	32
18	Fayette	37.97	-84.53	1555	70	1	0	83	19	69
19	Franklin	38.12	-84.88	1571	59	2	0	88	23	70
20	Fulton	36.57	-89.15	1526	97	4	0	69	37	35
21	Graves	36.69	-88.72	1519	67	1	0	91	36	47
22	Grayson	37.46	-86.34	1532	58	0	0	91	32	61
23	Hardin	37.67	-85.97	1573	65	0	0	85	28	64
24	Harrison	38.49	-84.34	1623	64	3	1	61	40	73
25	Henderson	37.82	-87.5	1571	59	4	2	77	39	61
26	Hopkins	37.27	-87.48	1468	78	0	0	86	22	56
27	Jackson	37.36	-83.97	1587	52	0	0	98	39	53
28	Johnson	37.83	-82.88	1662	42	0	0	92	57	51
29	Knott	37.4	-82.99	1474	74	12	0	92	24	40
30	Knox	36.87	-83.83	1613	55	1	0	100	49	37
31	Lewis	38.58	-83.42	1632	42	0	1	87	52	60
32	Lincoln	37.58	-84.62	1600	58	2	0	95	28	59
33	Logan	36.85	-86.92	1966	74	2	0	90	32	44
34	Madison	37.72	-84.15	1607	51	1	0	87	47	56
35	Marshall	36.92	-88.34	1499	82	1	0	78	37	44
36	Mason	38.62	-83.81	1595	56	4	1	88	22	71
37	McCreary	36.77	-84.47	1537	68	3	0	101	26	44

Continued

38	Mclean	37.59	-87.32	1565	59	1	0	92	27	63
39	Mercer	37.81	-84.84	1533	63	2	0	91	25	61
40	Metcalf	36.98	-85.7	1496	79	6	0	89	21	47
41	Morgan	37.9	-83.27	1594	64	2	0	82	41	53
42	Nicholas	38.27	-84.1	1590	54	2	1	94	20	71
43	Ohio	37.46	-86.86	1513	64	0	0	93	37	48
44	Owen	38.55	-84.74	1542	60	2	1	84	21	74
45	Owsley	37.45	-83.68	1627	52	2	0	90	54	44
46	Rowan	38.22	-83.48	1648	49	2	0	90	36	65
47	Taylor	37.36	-85.46	1580	56	3	0	95	36	52
48	Trigg	36.82	-87.86	1533	67	4	0	91	39	41
49	Union	37.69	-87.84	1533	66	12	0	94	16	54
50	Warren	36.93	-86.47	1549	72	5	0	91	29	45
Mean				1577	65	3	0.3	8	33	53
%					26.8	1.2	0.1	36.21	3.8	22.0

¹Far additional physiographical characteristics of sites, see Xue, Y., *et al.* (2016) [8]. ²Plant response code (°C). aa-Growing, both max and min above 7.2°C; bb-Chilling, both between 0°C and 7.2°C. cc-Freezing, both below 0°C; ab-max above 7.2°C, min between 0°C and 7.2°C; ac-max above 7.2°C, min below 0°C; bc-max between 0°C and 7.2°C, min below 0°C.

Table 2. Mean number of days by classification of max and min air temperature responses for 5 years (2010-11 through 2014-15) at 50 Kentucky Mesonet sites.

Mean number of days (24-hr period) within months												
Response Class ¹	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Yearly		Range in % over 50 sites	
									Total	3%		
aa	30	15.5	0.8	0.9	0.1	0.2	1	16.5	65	26.8	17.3 - 40.0	
bb	0	0	0.3	1.8	0.4	0.2	0.1	0	2.8	1.2	0.0 - 4.9	
cc	0	0	0	0	0.2	0.1	0	0	0.3	0.1	0.0 - 2.1	
ab	0.1	15.6	20.1	9.5	2.1	3	23.8	13.5	87.7	36.2	23.6 - 42.1	
ac	0	0	7.1	3.4	7.9	10.2	4.7	0	33.3	13.8	5.0 - 24.8	
bc	0	0	1.2	15.4	20.7	14.8	1.6	0	53.7	22	8.7 - 33.9	
Daily temperature (°C)									Mean		Correlation (r)	
Max	24	19	13	7	5	7	13	21	14		Max vs. Min	
Min	13	7	1	-1	-3	-2	2	7	3	r = 0.378**		
Difference	11	12	12	8	8	9	11	14	11			

¹See **Table 1** footnote 2 for explanation of plant response class code. ²Each daily response value is a mean for 5 years over 50 sites. ³Percentage is the yearly total for a class divided by the total number of days (242) in the 8 months.

freezing days were masked in their 5-year means. The percentage varied among sites (23.8% - 35.8%) and months (2.5% - 20.4%).

4. Discussion

The previous study [8], resulted in preliminary findings that chilling production

Table 3. Analysis of chilling temperatures (class b, 0°C - 7.2°C) frequency and duration of occurrences of daily max and min temperatures within the chilling range by months (Sep - April) over 5 years (2010-11-2014-15) and 11 sites¹.

Mean duration of daily max and min temperatures within chilling range												
Max temp consecutive days	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total	Weighted	Days %2	
1	0	0.3	1.3	1.2	1.8	1.3	1.4	0.1	7.4	7.4	3.0	
2	0	0	0.7	1.1	1.8	1.1	1.5	0	6.2	12.4	5.1	
3	0	0	0.2	0.6	0.5	0.6	0.5	0	2.4	7.2	3.0	
4 or more	0	0	0.4	1.2	1.3	1	0.2	0	4.1	16.4	6.8	
Total	0	0.3	2.6	4.1	5.4	4	3.6	0.1	20.1	43.4	17.9	
Min temp consecutive days	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total	Weighted	Days %2	
1	0.9	1.5	3.1	2.4	2.8	2.1	2.7	2.2	17.7	17.7	7.3	
2	0.5	0.9	1.3	1.2	0.9	1.4	1.8	1.5	9.5	19	7.8	
3	0.2	0.5	0.9	0.9	0.4	0.3	0.8	0.7	4.7	14.1	5.8	
4 or more	0.1	1.6	0.9	0.6	0.2	0.4	0.8	0.7	5.3	21.2	8.8	
Total	1.7	4.5	6.2	5.1	4.3	4.2	6.1	5.1	37.2	72	29.8	
Combined temp days	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total	Weighted	Days %2	
1	0.9	1.8	4.4	3.6	4.6	3.4	4.1	2.3	25.1	25.1	10.4	
2	0.5	0.9	2	2.4	2.6	2.5	3.3	1.5	15.7	31.4	13	
3	0.2	0.5	1.1	1.5	0.9	0.9	1.2	0.7	7	21.3	8.8	
4 or more	0.1	1.6	1.3	1.9	1.5	1.4	1	0.7	9.5	37.6	15.5	
Total	1.7	4.9	9	9.3	9.6	8.2	9.7	5.2	57.3	115.4	47.7	

¹Data are based upon 11 sites (Table 1, numbers 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50). ²Percentage of days equals number observed divided by number of days (242) in the 8-month period.

Table 4. Number of days within months (December through April) in which one or more freezing temperatures (Class c) occurred among the 5 years but were masked by positive temperatures included within the mean.

Site ¹	Dec	Jan	Feb	Mar	Apr	Total	% of days ²
1	16	4	8	18	6	52	34.4
5	10	2	2	23	15	52	34.4
10	10	1	0	23	6	40	26.5
15	14	3	6	17	5	43	28.4
20	17	4	0	17	0	38	25.2
25	7	1	1	21	6	36	23.8
30	12	2	4	22	14	54	35.8
35	14	3	0	22	14	53	35.1
40	17	5	0	18	1	41	27.2
45	5	1	3	22	1	45	29.8
50	14	2	7	22	6	51	33.8
Mean	12.4	2.5	2.8	20.4	6.7	44.9	30.40%

¹Data are based upon 5 months 11 sites taken from the 50 included in the study. ²Percentage of days equals number observed divided by number of days (151) in the 5-month period.

over 5 years and 50 sites consistently exceeded chilling requirements for perennial fruit crops commonly grown in Kentucky. This margin could provide a buf-

fer of early protection against expected weather warning and its negative effect on chilling production. The purpose in extending the study was to explore some alterations of the temperature metrics utilized in the Chilling Hours Model and, thereby, enhance understanding of chilling conditions. A main objective was to ascertain effects of dividing daily air temperature into plant functional classes on chilling production.

Initiation of the chilling process depends upon temperatures between 0°C - 7.2°C [10]. For the 50 sites in the present study, the percentage of days in the chilling range was 59.4% composed of 1.2% homo bb and 58.2% hetero (36.2% ab, 22.0% bc). Total days in which a max or min temperature was included in the chilling range was approximately 115 (Table 3). However, these calculations are based only upon max and min and do not include other daily temperature between these extremes. Including frequencies and durations of consecutive days of chilling temperatures revealed that 25.1%, 31.4%, 21.3%, and 37.6% of the chilling periods were for 1, 2, 3, and 4 or more days; respectively. Since the common winter chill models are based upon the accumulation of hourly temperature, the chilling process must be able to circumvent gaps in temperature conditions. Furthermore, average chilling hours' production by sites (Table 1) was 1557 which by definition equals the number of clock hours or about 65 twenty-four hour days. It appeared more likely that the critical temperature initiated the chilling process which continued intermittently as temperature permitted. This explanation is further supported by the homo bb being lower than the hetero, ab and ac, and by ab being greater than ac. These observations may provide support for the Dynamic Model including a two-step process initiated by cooler weather and continuing under warmer temperature.

Different temperature metrics were compared for their influence on chilling. The highest hourly temperatures for each day in the month were averaged to get the max; the lowest hourly temperature for each day was averaged to get the min. These, temperatures were used to study relationships between max and min temperature with chilling temperature (Table 3). Of the total 115.4 days in which max and min temperatures were included in the chilling range, 62.4% were min and 37.6% were max. Thus, min contributed nearly twice that of max to chilling temperature. These findings support the emphasis on max and min indices as reported by other researchers [6] stated that daily max and min temperatures had major impact on plant growth and development. Lobell *et al.* (2007) [11] concluded that quantities such as chill hours that are used in models to predict climate changes are more related to daily max and min when used separately than when averaged.

In the present study, max and min temperatures were based on 5-year means. Since a mean is a single value that brings unequal quantities together into a best fitting number, it is possible that the impact of a critical component could be lost. Approximately 30% of freezing temperatures (class c) for individual years were masked by above freezing temperature in the 5-year means. This outcome

is especially critical for reporting of multiple-year predictions in chilling studies. A single extreme weather condition such as a freezing temperature can kill developing buds.

The greater association of min than max temperatures within the chilling range (**Table 3**) is consistent with results of other reported studies. Vos *et al.* 2004 [12] determined that min temperatures over global land areas increased approximately two times as fast as max temperatures since 1950. During this time period in California, LaDochy *et al.* 2007 [13] observed that min increased faster than max temperatures. Vincent, *et al.* 2005 [14] compiled weather summary data from eight South American countries showing that global warming effects can be attributed to rising min temperatures that have increased faster than max or mean temperatures. In summary, these results indicate that global warming has greater negative impact on min than on max or mean temperature, whereas, chilling has a higher positive association with min than with max or mean temperature. Thus, as has been experienced, warming has a negative effect on chilling.

5. Conclusion

Continued investigation into relationships between chilling and temperature is warranted in view of the warming that has occurred and the unequivocal predictions (IPCC 2014) [15] that the warming trend is continuing. A more direct focus on temperature/chilling relationships was possible by using daily max and min rather than mean temperature and by dividing daily temperatures into plant functional classes: growing, chilling, and freezing. Within the chilling class, more min than max temperatures were associated with chilling. For studies involving temperatures fluctuating around 0°C, the use of means may mask injurious freezing temperature. The smaller number of hours in the chilling class compared to the total number of chilling hours produced, may support the Dynamic Chilling Model which postulates a two-step process initiated by cooler and increased by warmer temperature. However, further research on initiation and duration of chilling conditions is necessary.

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