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Flowering phenology change and climate warming in southwestern Ohio

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1 **Abstract** Global surface temperature has increased markedly over the last 100
2 years. This increase has a variety of implications for human societies, and for
3 ecological systems. One of the most obvious ways ecosystems are affected by
4 global climate change is through alteration of organisms' developmental timing
5 (phenology). We used annual botanical surveys that documented the first
6 flowering for an array of species from 1976 to 2003 to examine the potential
7 implications of climate change on plant development. The overall trend for these
8 species was a progressively earlier flowering time. The two earliest flowering
9 taxa (*Galanthus* and *Crocus*) also exhibited the strongest shift in first flowering.
10 We detected a significant trend in climate suggesting higher temperatures in
11 winter and spring over the sampling interval and found a significant relationship
12 between warming temperatures and first flowering time for some species.
13 Although 60% of the species in our study flowered earlier over the sampling
14 interval, the remaining species exhibited no statistically detectable change. This
15 variation in response is ostensibly associated with among-species variation in the
16 role of climate cues in plant development. Future work is needed to isolate
17 specific climate cues, and to link plant phenology to the physiological processes
18 that trigger plant development.

19

20 **Keywords** climate change · global warming · first flowering · minimum
21 temperature

22

23 **Introduction**

24

25 Reports issued over the past 20 years by the Intergovernmental Panel on Climate
26 Change (IPCC) have been increasingly clear about changes currently occurring in
27 Earth systems (Houghton et al. 2001). Most recently, the Fourth Assessment
28 Report (AR4) concluded that “warming of the climate system is unequivocal”
29 (Solomon, et al. 2007, p. 7) and that “observational evidence from all continents
30 and most oceans shows that many natural systems are being affected by regional
31 climate changes, particularly temperature increases” (Parry et al. 2007, p. 8).

32 Climate warming has been shown to initiate a complex of ecological responses. In
33 some instances, ecosystem structures may be altered substantially, and
34 ecosystem-climate system feedbacks have been identified (Chapin et al. 2008).

35 The spatial distribution of some plants is expected to shift in a warmer climate
36 (Iverson and Prasad 1998, Walther et al. 2002, Woodall et al. 2009), and
37 alterations in migration timing have been documented for a number of animal
38 species (Bradley et al. 1999, Parmesan 2006). These shifts have important
39 ecological implications as some interdependent community relationships could be
40 disrupted (Walther et al. 2002, Parmesan 2006).

41 Alteration of plant phenology is one of the most readily observable
42 ecosystem reactions to climate change. Numerous studies have indicated shifts in
43 plant phenology related to climate warming (e.g., Orlandi et al. 2005, Nordli et al.
44 2008). For instance, Fitter and Fitter (2002) found an average advance of 4.5 days
45 in flowering date among the 385 species sampled in a study from south-central

46 England over the four decades prior to the 1990s. Bradley et al. (1999)
47 documented overall changes of 1.2 days per decade in the phenology of various
48 species in recent years compared to the dates measured six decades earlier.
49 Increasingly early plant development has been documented in a number of species
50 and study systems (Abu-Asab et al. 2001, Menzel et al. 2006, Parmesan 2006,
51 Nordli et al. 2008).

52 Multi-species assessments have yielded some particular hypotheses
53 about the nature of plant phenology change in a warming climate. First, species
54 that flower early in the growing season tend to exhibit a greater shift in flowering
55 time. In some species, this shift may be related to maintaining the adaptive
56 advantage of development in advance of potential competitors in early spring
57 (e.g., Muller 1978). Second, species' reactions to climate change are non-
58 uniform. Bradley et al. (1999) found that while many species had substantially
59 earlier flowering times, other species were "non-responders" that did not change
60 in response to climate warming. The latter likely include species with flowering
61 triggered by photoperiod. This non-uniform response across species has
62 important ecological implications as it creates the potential for climate-response
63 mismatches between ecologically interdependent species (Bradley et al. 1999,
64 Walther et al. 2002, Parmesan 2006).

65 We examined a 28-year data set of first flowering observations in
66 southwestern Ohio, USA. Our objective was to investigate potential influences of
67 global change processes on plant phenology and to identify variation in response
68 among species. We hypothesized that (H_1) plants in our study would flower

69 increasingly early in association with a warming climate. We further hypothesized
70 that (H_2) plants that flower in the early spring would change more substantially than
71 species flowering later in the year.

72

73 **Methods**

74

75 Our analysis was based on flowering phenology observations on a species rich 0.5
76 hectare tract in Beavercreek, Ohio (39°73'N, 84° 04'W) from January 1976 through
77 2003 (Carol Graff, personal communication). The observations were made every
78 day through spring and summer of each year. A transit was made each morning
79 along a path that circles through the property. Additional observations were made
80 in secondary transits during most days (Carol Graff, personal communication).

81 Across the sampling period, 270 different taxa of both native and cultivated species
82 were observed, though most were observed only a few times, and many were
83 taxonomic varieties. Because we were specifically interested in long-term changes
84 in flowering phenology, in our analyses we only included taxa that occurred in ≥ 16
85 of the observation years.

86 For the purposes of analysis, first flowering dates were converted to ordinal
87 date (mathematical sum of days beginning at January 1). Simple linear regression
88 analysis was used to test the hypothesis of no change in first flowering date (for
89 each taxon individually) over the sampling interval. In this analysis, year was the
90 independent variable, ordinal date of flowering was the dependant variable, and
91 the regression was considered significantly different from zero at $P \leq 0.05$.

92 Daily climate data were obtained from the National Climate Data Center for
93 the weather station at the Dayton International Airport (Co-op ID #332075; located
94 at 39°54'N, 84°13'W). The weather station is located approximately 35 kilometers
95 from the site of observations. We analyzed mean daily maximum and minimum
96 temperature for each month. A linear regression analysis was performed on the
97 raw monthly data to test the statistical significance of any deviation over time of the
98 temperature trend from zero. Regressions were considered significantly different
99 from zero at $P \leq 0.05$, and highly significant at $P \leq 0.01$. Since we were interested
100 in potential influences of temperature changes during the period for which we had
101 observations, we used temperature data for the period 1976 – 2003.

102

103 **Results.**

104

105 We found 15 taxa with at least 16 observations over the 28 year sampling period
106 (Table 1). These included ornamental species, natives to the region, exotic
107 ornamentals, and a variety of life forms including both woody and herbaceous
108 species. First flowering dates ranged from early March through early August
109 (Table 1).

110 In support of our first hypothesis (H_1), 9 of the 15 taxa we tested (60%) had
111 a statistically significant negative slope (Table 1; Fig. 1) indicating earlier flowering.
112 For instance, *Crocus*, *Galanthus* and *Phlox* were the three taxa with the most
113 strongly negative slope (Fig. 2) and the regression for each of these was highly
114 significant ($P < 0.001$, for all three). In contrast, species such as *Ranunculus*,

115 *Centaurea* and *Ageratum* did not exhibit detectable changes over the sampling
116 period (Fig. 2).

117 We found some support for our hypothesis (H_2) that species flowering
118 earlier in the year would have the strongest change in flowering date. *Galanthus*
119 and *Crocus* had the two most negative slopes, indicating the most substantial shift
120 in flowering time, and were also the two earliest flowering species (Fig. 1).
121 Considering only species that flowered before June (ordinal date ~150), there was
122 a highly significant positive relationship ($P = 0.003$; $r^2 = 0.6$) between flowering
123 date and flowering date change, where species that flowered later in the year also
124 had a less negative slope (Fig. 1; relationship not shown). An analysis that
125 included the whole data set, though, suggested no relationship ($P = 0.3$; $r^2 = 0.08$),
126 and this was largely caused by two taxa (*Phlox* and *Hosta*) that had significantly
127 negative slopes, but were late flowering species (Fig. 1).

128 Over the sampling period there was a distinct trend in temperature, with
129 increasingly warm temperatures especially apparent for months early in the year
130 (Table 2). Although there was substantial annual variability, mean minimum
131 temperature exhibited a significant (increasing) trend for January, February and
132 June ($P < 0.05$; Fig. 3). We also detected a significant trend in mean minimum
133 temperature averaging December through February (Table 2). Mean maximum
134 temperatures in January also increased significantly (Table 2).

135 Early season temperature changes were strongly correlated to changes in
136 first flowering date of early flowering species (Fig. 4). Mean minimum
137 temperatures for December-February were significantly, and negatively, related to

138 first flowering date in *Galanthus* ($P < 0.001$; $r^2 = 0.61$) and *Crocus* ($P = 0.001$; $r^2 =$
139 0.33) (Fig. 4). These two species were the earliest flowering species and also
140 exhibited the strongest shifts in flowering (Table 1; Fig. 1). First flowering dates for
141 *Galanthus* ($P < 0.001$; $r^2 = 0.66$) and *Crocus* ($P < 0.001$; $r^2 = 0.39$) were also
142 significantly related to mean maximum temperature over the same three months
143 (Fig. 4).

144

145 **Discussion.**

146

147 A warming global climate has the potential to substantially influence the structure,
148 composition, and function of ecosystems (Parmesan 2006, Chapin et al. 2008).
149 Alteration in the timing of plant phenology is one important potential impact of a
150 warming climate (Bradley et al. 1999, Fitter and Fitter 2002, Primack et al. 2004,
151 Orlandi et al. 2005). Our data supported the hypothesis (H_1) that first flowering
152 time was increasingly early over the last three decades and was related to an
153 overall trend of increasing seasonal temperature. Of the species in our study, 60%
154 exhibited significantly earlier flowering over the study period. Abu-Asab et al.
155 (2001), similarly, found an increasingly early flowering time for a variety of species
156 correlated with an increase in minimum temperatures in the Washington D.C. area.
157 Similarly, Houle (2007) found an advance of 2-6 days per century in a study of
158 flowering phenology in eastern Canadian forest species. That study found that a
159 shift of 2-3 days was correlated with a change of 1°C of temperature rise, and
160 showed a stronger effect on species found in Montreal, a large urban area which

161 experiences a heat-island effect (Houle 2007). Our data add to a growing body of
162 work (e.g., Fitter and Fitter 2002, Parmesan and Yohe 2003, Nordi et al. 2008) that
163 indicates plant phenology is changing markedly in association with a warming
164 climate.

165 In addition to the overall trend of increasingly early flowering, we
166 hypothesized (H_2) that early flowering plants would exhibit a more marked change
167 in phenology than later flowering species. Hypothetically, early-spring flowering
168 species, which exploit a narrow window in time before leaf-out of other species
169 (Muller 1976), would have evolutionary pressure to track climatic conditions and
170 begin development at the earliest opportunity. A number of studies have
171 supported this concept (e.g., Abu-Asab et al. 2001, Fitter and Fitter 2002, Walther
172 et al. 2002). For instance, Parmesan and Yohe (2003) found that 62% of early
173 spring phenophases shifted earlier in response to climate warming. We found
174 some support for this postulate as the earliest flowering species also exhibited the
175 strongest change in first flowering; however, two of the latest flowering species
176 also exhibited substantially earlier flowering. Physiological work is needed to
177 understand the mechanism(s) underlying tracking of winter temperature in early
178 flowering species, and more survey work is needed to identify taxonomic patterns
179 in flowering response.

180 Beyond variation in flowering phenology across the growing season, we
181 found that some species responded to climate warming, while others were stable.
182 Bradley et al. (1999), focusing only on springtime events, found that approximately
183 1/3 of the phenophases they observed (including animals as well as plants) were

184 earlier as a result of climate change, 1/3 were later, and 1/3 remained stable. In
185 our study, plants that flowered in the range of 100-150 ordinal days (late April
186 through early June) exhibited a variety of responses including significantly earlier
187 flowering and non-response (Fig. 1). The cause of this variation is unknown.
188 These species encountered identical climatic stimuli, so the cause of these
189 differences must be linked to variation in the role of climate as a developmental
190 trigger. We hypothesize that winter and early spring warming accelerated growth
191 of some taxa such that they arrived at a requisite developmental threshold sooner,
192 while other species were either 1) not accelerated by climate warming or 2)
193 development was accelerated but flowering was unchanged because the flowering
194 trigger was photoperiod (which is stable). Bradley et al. (1999) argue that
195 flowering in many species is cued by photoperiod and therefore will not respond to
196 climate warming. This suggests the possibility of a lag effect in some species that
197 may reach a growth threshold earlier but flowering is stalled because photoperiod
198 is unchanged. Future work is needed that focuses on the particular relationship(s)
199 between temperature (and other climate cues), photoperiod, developmental
200 pathways, and physiological activity in plant species.

201 Climate change has wide ranging implications for ecosystems, and one of
202 the most important is the potential for alterations in the life-history timing of
203 individual species. Our data suggest that 1) some plant species are responding to
204 variation in climate, 2) across the growing season the reaction is non-uniform and
205 3) even within season, some species react to changes in climate while others are
206 non-responders. Given the potential importance of climate-response mismatches

207 between community members, understanding the basis of plant phenology
208 response is an important next step for research (Parmesan 2006). In particular,
209 we suggest that future work is needed that bridges the gap between pattern (plant
210 phenology response) and process (plant developmental physiology) in relation to
211 particular climatic cues.

212

213 **Acknowledgements** This analysis was made possible by three decades of
214 careful observations by Carol Graff. We are appreciative of her careful botanical
215 efforts and grateful that she was willing to share her data. Comments by Amy L.
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Table 1. First flowering date change of plant species monitored for 28 years in southwestern Ohio, USA.

First Flowering			First Flowering Change		
Date (mean)	Ordinal day (mean \pm SE)	Taxon	Days/Year (slope)	r^2	P
02 Mar	61 \pm 2.8	<i>Galanthus</i> sp. (snowdrop)	-1.10	0.36	0.001
06 Mar	65 \pm 3.2	<i>Crocus flavus</i> (crocus)	-1.22	0.33	0.001
27 Mar	86 \pm 2.0	<i>Forsythia</i> sp. (forsythia)	-0.18	0.02	0.468
18 Apr	108 \pm 1.5	<i>Viola pubescens</i> (yellow violet)	-0.58	0.35	0.001
19 Apr	109 \pm 1.5	<i>Malus</i> sp. (crab apple)	-0.45	0.25	0.014
23 Apr	113 \pm 1.6	<i>Ajuga reptans</i> (ajuga)	-0.19	0.04	0.336
25 Apr	115 \pm 1.3	<i>Delphinium consolida</i> (larkspur)	-0.37	0.20	0.019
27 Apr	117 \pm 2.2	<i>Dicentra spectabilis</i> (bleeding heart)	-0.37	0.18	0.047
27 Apr	117 \pm 1.2	<i>Geranium maculatum</i> (wild geranium)	-0.19	0.06	0.243
05 May	125 \pm 1.9	<i>Ranunculus</i> sp. (buttercup)	0.16	0.02	0.488
13 May	133 \pm 2.3	<i>Centaurea cyanus</i> (bachelor's button)	0.23	0.04	0.440
19 May	138 \pm 1.6	<i>Hemerocallis lilioasphodelus</i> (daylily)	-0.40	0.16	0.044
14 Jul	195 \pm 2.2	<i>Phlox</i> sp. (phlox)	-0.91	0.50	<0.001
08 Aug	220 \pm 1.9	<i>Ageratum</i> sp. (ageratum)	0.18	0.02	0.475
11 Aug	223 \pm 2.3	<i>Hosta plantaginea</i> (giant white hosta)	-0.64	0.20	0.039

Table 2. Temperature trends from 1976 – 2003 in southwestern Ohio, USA. Slope of the linear regression values for raw data are given (* $P < 0.05$; ** $P < 0.01$).

Month	Minimum (°C/year)	Maximum (°C/year)
Dec	0.04	0.00
Jan	0.19*	0.18*
Feb	0.17**	0.12
Mar	-0.01	-0.04
Apr	0.04	0.01
May	0.02	-0.05
Jun	0.06*	-0.03
Jul	0.01	-0.03
Aug	0.04	0.02
Dec-Feb	0.10*	0.13**

Figure Legends

Figure 1. First flowering date change (ordinal date) over a 28-year (1976-2003) observation period in southwestern Ohio, USA. Flowering date change represents the slope of the linear regression between first flowering date and year. Darkened symbols represent slopes that were statistically different from zero ($P < 0.05$), and the horizontal dashed line represents no change.

Figure 2. Response of first flowering date (ordinal date) of selected taxa over a 28-year (1976-2003) observation period in southwestern Ohio, USA. Column of figures on the left represents the three species with the most negative slopes (all significant at $P \geq 0.001$; solid lines) indicating increasingly early flowering. Figures on the right represent the three most positive slopes (none statistically significant, dotted lines). Panels in each column are ordered from earliest to latest flowering.

Figure 3. Temperature trend for selected months over a 28-year (1976 – 2003) observation period in southwestern Ohio, USA.

Figure 4. Relationship between first flowering date change (ordinal date) and mean temperature December through February over a 28-year (1976-2003) observation period in southwestern Ohio, USA. All relationships were significant at $P \leq 0.001$.

Figure 1.

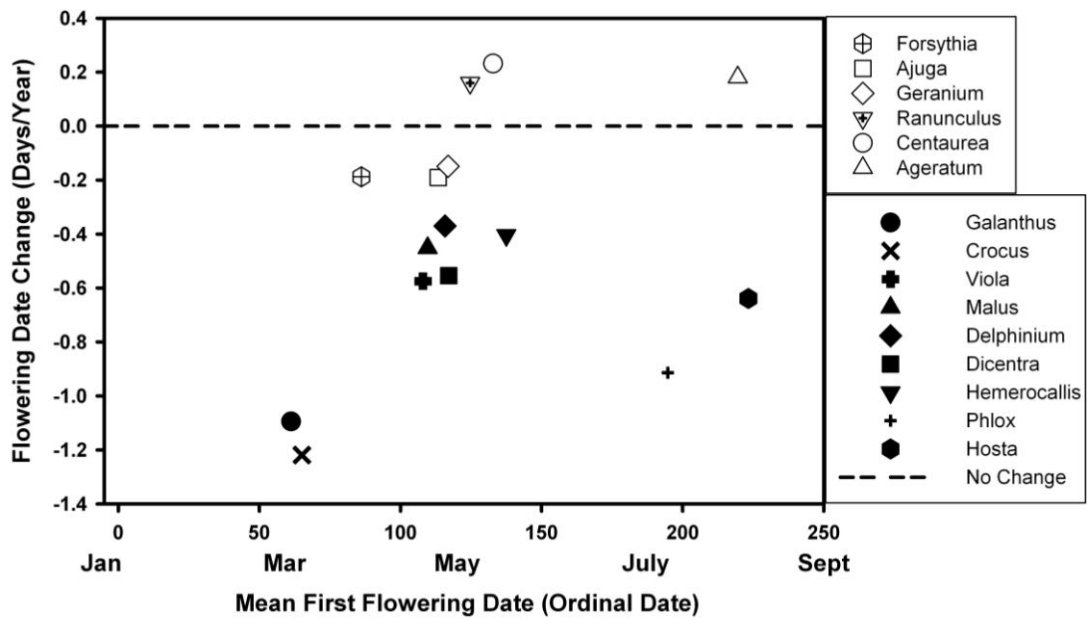


Figure 2.

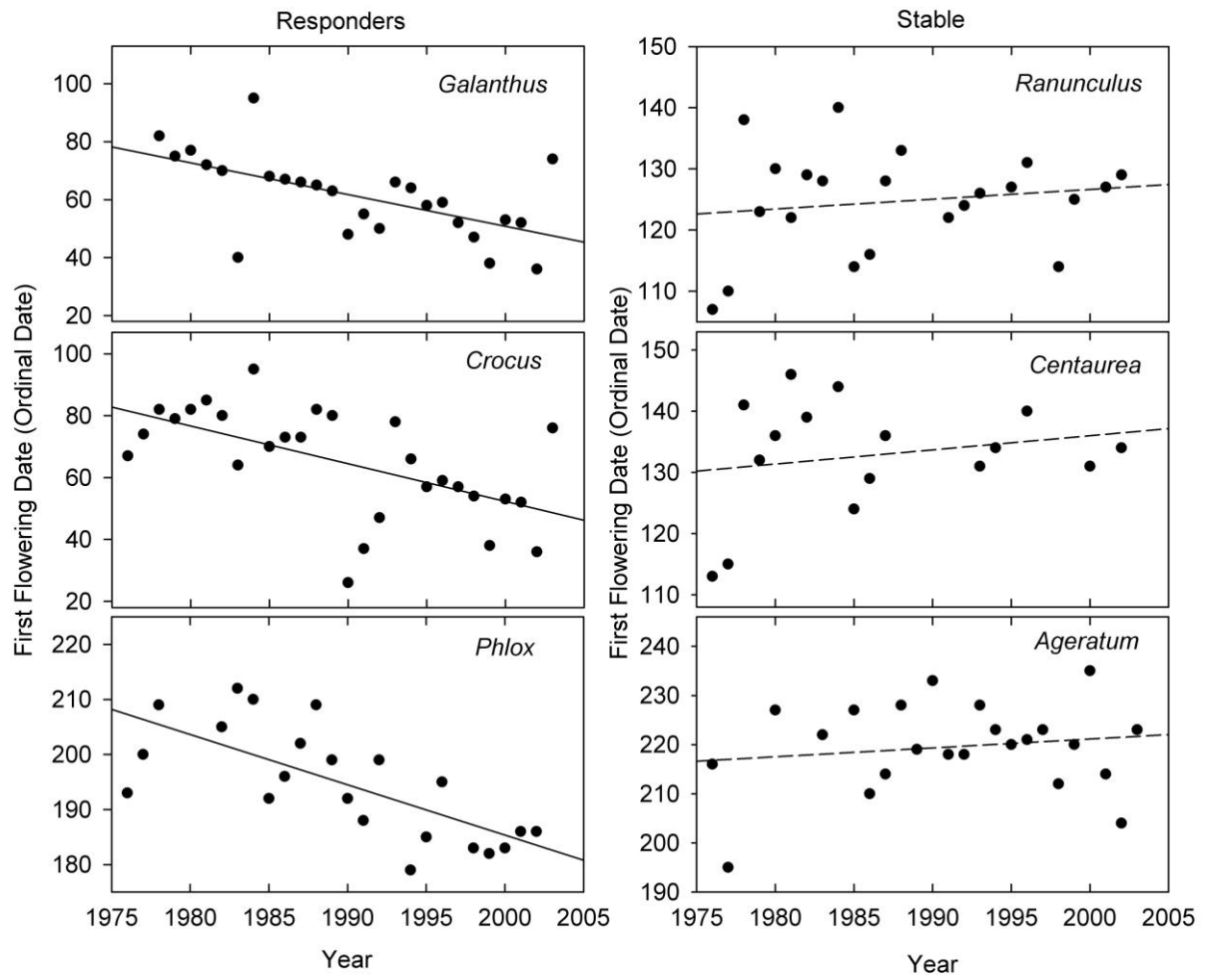


Figure 3.

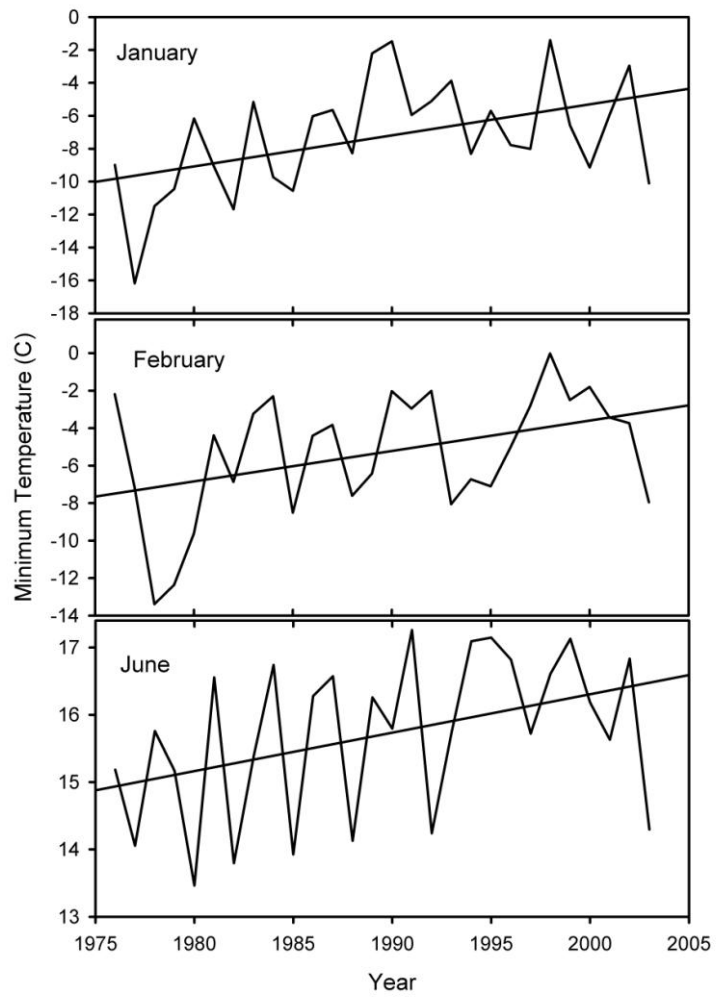


Figure 4.

