Vol. 2: 225-233, 1993 | CLIMATE RESEARCH Clim. Res. | Published July 27

Potential impact of winter temperature increases on South Carolina peach production

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ABSTRACT: Two scenarios of climatic change were examined to determine the potential impact of winter-season warming on peach production in South Carolina, USA. The daily maximum and minimum temperatures from 1961 to 1990 were increased by 2 °C and 4 °C at 26 stations to simulate how increased winter temperatures could affect chilling during the dormant season and the last spring frost date. An average winter temperature increase of 2 °C would decrease chilling hour accumulation by approximately 400 h and approach the minimum required chilling hours of most peach varieties currently grown in the state. A 4 °C warming would result in average chilling hour accumulation ranging from 775 h in coastal regions, to 1350 h in the Piedmont. If growers continued to use current peach varieties, such warming would substantially decrease the probability of achieving sufficient chilling hours during the dormant season. However, the scenarios of winter temperature increases must also be viewed with regard to the hazards of spring frost. Our analysis shows that the date of the mean spring frost could occur approximately 2 and 4 wk earlier than at present for 2 °C and 4 °C winter warming scenarios, respectively. Future work assessing the vulnerability of peaches to climatic change will require greater insight into the expression of climatic change, the relationship between environmental variables and peach phenology, and the adjustment strategies that growers could use to adapt to certain changes.

INTRODUCTION

Results from general circulation models (GCMs) have shown that projected increases in atmospheric greenhouse gas concentrations could cause substantial changes in the earth's climate (Manabe & Wetherald 1987, Wilson & Mitchell 1987, Hansen & Lebedeff 1988, Hansen et al. 1988, Washington & Meehl 1989). While some controversy exists over how much temperature and precipitation patterns would be altered and how such changes would be expressed (Katz 1988, Lindzen 1990), projected climatic changes are significantly large to warrant concern over their potential impacts (Smith & Tirpak 1989, Jäger & Ferguson 1991, National Academy of Sciences 1991).

This concern has prompted impact studies relating climatic change to sea level rise (Eid & Hulsbergen 1991), marine resources (Beukema et al. 1990), water resources (Waggoner 1990), and agriculture (Parry & Carter 1985, Peart et al. 1989, Ritchie et al. 1989, Adams et al. 1990, Cooter 1990, Rosenzweig 1990), among other topics. Agricultural impact studies have shown that potential climatic changes could alter crop yields, cause a shift in the location of broad agricultural regions, or lead to changes in agricultural practices. Because of their importance to world food supplies, major grain crops (such as wheat, maize, and soybeans) have been the focus of most agricultural impact studies. Clearly, climatic variability and change could affect other crops both positively and negatively, and could lead to impacts on regional economies.

This study examines how climatic change could influence peach production in South Carolina, USA. We examine the sensitivity of the peach crop to recent climatic change projections for the southeastern United States in order to measure how average winter temperature increases would threaten the important winter chilling period for peach trees, yet simultaneously mitigate the threat of freeze damage to the peach crop. In addition, we examine how adaptation to current inter-annual variability could buffer the impact of climatic change.

PEACHES AND CLIMATIC HAZARDS

Peach trees require a period of winter dormancy, or chilling, to resume normal spring growth (Weinberger 1967). This chilling, or rest requirement, is achieved during the relatively cool winter months. While some evidence suggests that winter rest can occur at temperatures as high as 12.8 °C (55 °F) for some peach varieties (Aron & Gat 1991), most researchers have considered 7.2 °C (45 °F) as a critical threshold temperature for rest (Weinberger 1967, Sanders 1975, Scalabrelli & Couvillon 1986). The required amount of chilling varies widely among peach varieties. While growers choose varieties based on some non-climatic factors, such as market season, shipping, and resistance to pests and diseases, they also must consider local winter temperatures. Two specific hazards influence their decisions: insufficient winter chilling and spring freeze. Insufficient chilling occurs when temperatures during the dormant season are anomalously high, inhibiting rest. Insufficient chilling disrupts spring growth, causing sporadic bud break and leaf development, and non-uniform fruit growth (Kish et al. 1973, Kish & Purvis 1975, Ridley et al. 1986, Linvill et al. 1989). Freeze damage occurs when temperatures fall below −2.2 °C (28 °F) after bud break, and is most likely during years when cold weather fulfills chilling requirements early in the winter season and anomalously warm late winter temperatures occur. Under these conditions the dormancy requirement is satisfied early, promoting premature spring growth and increasing the threat of frost losses.

With regard to the aforementioned climatic hazards, the choice of appropriate peach varieties represents an adjustment to the opposing threats of spring freeze and insufficient chilling. Growers must choose varieties with chilling requirements high enough to avoid premature spring growth which increases the threat of spring freeze; but must not overcompensate by choosing varieties whose chilling requirements would not be met during most winter seasons. Under current climatic conditions, growers have achieved a balance between the 2 threats through experience, and with the help of agricultural experiment station studies reporting average temperature and consequent chilling at stations across the state (Kish et al. 1973, Kish & Purvis 1975, Linvill et al. 1989). Growers and researchers commonly use the concept of accumulated chilling hours, defined as the number of hours during the dormant season that are below a critical threshold temperature, to match peach varieties to typical climatic conditions.

Over 50 different peach varieties are grown in South Carolina. There are 3 general peach growing regions in the state: the Upper State, Ridge, and Coastal Plains (Fig. 1). Table 1 lists the top 10 varieties grown in each region with their associated chilling hour requirements, and the weighted mean chilling hour requirement for all varieties (Ridley et al. 1986, South Carolina Agricultural Statistics Service 1991). This survey shows that, even within relatively small regions, peach varieties have a wide range of required chilling hours. However, because average winter temperatures in the Upper State region are cooler (Fig. 2), varieties with higher chilling hour requirements tend to be located there. This insures that chilling requirements will not be satisfied prematurely, leaving peaches vulnerable to spring frost damage.

METHODS

Growers protect themselves against the threat of insufficient chilling by selecting varieties whose chilling hour requirements provide a buffer against interannual climatic variability. It is unclear whether this buffer is sufficient against the threat of increased winter temperatures. To test this, we calculated 1961–1990 average chilling hour accumulation, and contrasted it with chilling hour accumulation derived from 2 scenarios of winter-time warming. We con-

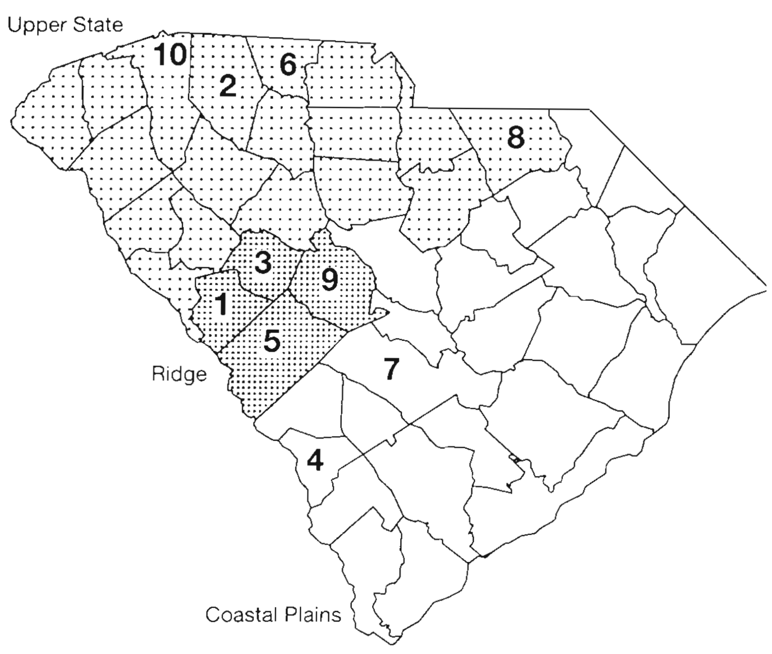

Fig. 1. South Carolina (USA) peach growing regions and the 10 most productive counties

Table 1 Predominant peach varieties in South Carolina and their chilling hour requirements

Variety	%	Chilling hour requirement
Upper state		
Redglobe	10.8	850–950
Blake	8.3	850
Redhaven	7.8	950
Rio-Oso-Gold	4.4	900
Monroe	4.1	850
O'henry	3.5	750
Jerseyqueen	3.2	850
Loring	3.2	750–950
Tyler	3.0	950
Coronet	2.6	700–900
Weighted mean chilling hour requirement:		**865.2**
Ridge		
Harvester	8.9	750
Redglobe	7.7	850–950
Redhaven	6.2	950
Coronet	6.0	700–900
Jefferson	5.4	850
Blake	4.6	850
Cresthaven	3.7	850
Loring	3.2	750–950
Springcrest	2.9	650
June Gold	2.5	650
Weighted mean chilling hour requirement:		**835.4**
Coastal plain		
June Gold	14.0	650
Florida King	13.7	450
Harvester	12.5	750
Redglobe	7.4	850–950
Cary Mac	6.6	750
Windblo	6.0	800
Monroe	3.4	850
Coronet	3.2	700–900
Jefferson	3.0	850
Cresthaven	2.0	850
Weighted mean chilling hour requirement:		**782.1**

sidered 2 scenarios of climatic change for the purpose of assessing the hazards or benefits that warmer winter temperatures might pose to peach production if no adjustment occurred, or if adjustment occurred too slowly. In addition, we examined how winter temperature increases could change spring frost dates and potentially reduce this important hazard to peach growers.

1961–1990 average chilling hour accumulation

We used maximum and minimum temperatures during the period 1961–1990 to calculate winter chilling hours under present climatic conditions. The chilling hour accumulation period extended from October 1

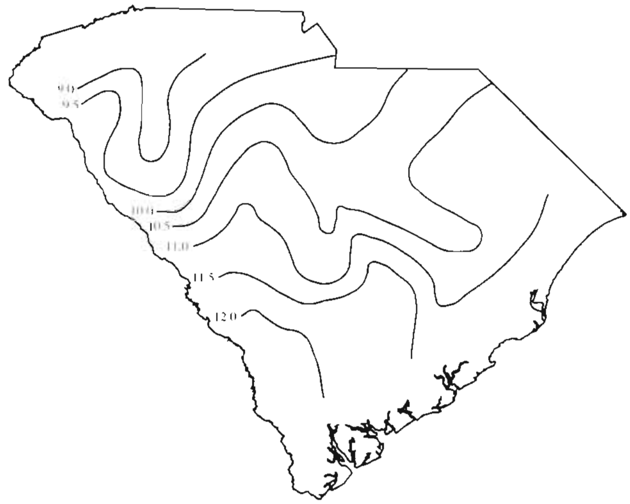

Fig. 2. Average chilling season (Oct 1 to Feb 28) temperature (°C), 1961 to 1990 normal

through February 28. Twenty-six stations were chosen according to the quality of their records during this period, and to achieve a state-wide distribution (Fig. 3).

Chilling hours were computed for each site and individual year using the common 7.2 °C (45 °F) threshold and a variation on the method developed by Linvill (1990). Hourly temperatures were computed from

$$T(t) = (T_{max} - T_{min}) \times \sin\left[\frac{(\pi \times t)}{(DL + 4)}\right] + T_{min} \quad (1)$$

where $T(t)$ = temperature at time t hours after sunrise; T_{min} = daily minimum temperature (°F); T_{max} = daily maximum temperature (°F); DL = daylength.

Daytime chilling hours (CH) were calculated by:

$$CH = \left[\frac{(DL + 4)}{\pi}\right] \times \arcsin\left[\frac{T_c - T_{min}}{T_{max} - T_{min}}\right] \quad (2)$$

where T_c = threshold critical temperature (45 °F), and nighttime chilling hours (CH) were calculated by:

$$CH = (24 - DL) - \exp\left[\frac{T_s - T_c}{T_s - T_{min}}\right] \times \ln(24 - DL) \quad (3)$$

where T_s is sunset temperature (°F).

Climatic change scenarios

We considered 2 scenarios of climatic change in our analysis – average winter-time temperature increases of 2 °C and 4 °C. These values are based on winter-season temperature changes from equilibrium runs of the Goddard Institute for Space Studies (GISS), Geofluids Dynamics Lab (GFDL), and Oregon State University (OSU) GCMs (Hansen et al. 1984, Manabe

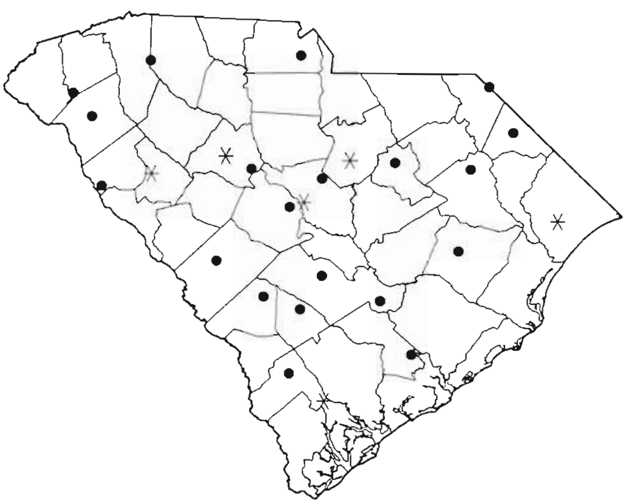

Fig. 3. Weather stations used in analysis. ⚹: long-term 'century' stations

& Wetherald 1987, Schlesinger & Zhao 1989). The models showed CO_2-induced temperature changes in the southeastern U.S. that ranged from 3.5 to 4.0°C (Smith & Tirpak 1989).

Admittedly, there are some drawbacks to using GCM results at the regional scale. GCMs are global models and the accuracy of regional scenarios presently is not guaranteed by modelers (Mitchell et al. 1990). In addition, the temporal and spatial resolution of GCM output is quite coarse. However, GCMs remain our best tool for estimating potential climatic change, and guidance from 3 different models presents a range of possible future scenarios. Furthermore, we used seasonal temperature projections, one of the more reliable elements of current climatic change projections, and, therefore, one appropriate for a climate impact study (Schneider 1984, Riebsame 1990).

We examined how higher mean winter temperature could change the vulnerability of peaches by comparing average chilling hour accumulation under present conditions to chilling hour accumulation under the 2 climate change scenarios. These scenarios were created by adjusting the daily time series of maximum and minimum temperatures for each station and each year from 1961 to 1990. In the first scenario, daily maximum and daily minimum temperatures were both increased by 2°C. In the second scenario, they were both increased by 4°C. This method assumes that winter season warming would be expressed as an equal change in maximum and minimum temperatures and does not consider potential changes in climatic variability and extreme temperatures.

It is likely that disproportionate changes in maximum or minimum temperature would affect chilling hour accumulation. As a test of the sensitivity of chilling hour accumulation to the nature of climatic change, we altered 139 yearly time series from 2 long-term stations (Yemassee and Newberry) and recalculated chilling hours under 3 different scenarios. A 2°C temperature increase was expressed as: (A) a 4°C increase in minimum temperature with no change in maximum temperature; (B) a 4°C increase in maximum temperature with no change in minimum temperature; and (C) a 2°C increase in both minimum and maximum temperatures. Our results show that changes in minimum temperature most dramatically decrease chilling hour accumulation (Table 2). This result is significant in the context of previous research showing greater increases in minimum temperatures than maximum temperatures during the past century (Karl et al. 1984, Folland et al. 1990, Idso & Balling 1992) and GCM results suggesting similar expression of future climatic change (Mitchell et al. 1990).

Our decision to consider equal changes in maximum and minimum temperature results from uncertainties about future diurnal temperature changes, and analysis of the historical record from 6 long-term stations across the state (Fig. 3). In our analysis of the empirical record, we constructed an analog for warming at each station by examining pairs of years that had an average winter season temperature difference of 2°C. We then calculated the difference in average winter season maximum and minimum temperatures between the 2 years in order to measure their relative contribution to the corresponding average temperature difference. Table 3 shows that the contribution of the maximum and minimum temperatures to average temperature differences is approximately the same when averaged over all possible pairs of years.

Table 2. Influence of various expressions of a 2°C climatic change on chilling hour accumulation

Scenario	Mean temperature change (°C)	Change to minimum temperature (°C)	Change to maximum temperature (°C)	Mean chilling hours
A	+2	+4	0	908.7
B	+2	0	+4	1135.8
C	+2	+2	+2	1026.1
D	None	0	0	1334.9

Table 3. Analog of a 2 °C chilling season temperature difference, and relative contribution of maximum and minimum temperature

Station	Average temperature difference (°C)	Maximum temperature difference (°C)	Minimum temperature difference (°C)	n
381310	+2	1.55	2.45	22
381944	+2	2.37	1.63	40
381997	+2	1.96	2.03	55
383754	+2	1.76	2.22	35
386209	+2	2.03	1.97	59
389469	+2	1.88	2.11	40
Average	+2	1.96	2.03	251

While comparison of average chilling hour accumulation may measure the impact of mean winter temperature change, peach growers use stricter standards when choosing varieties. Therefore, we also calculated the number of chilling hours achieved 90% of the time under current conditions, and compared these values to those that would be achieved 90% of the time under the 2 scenarios of change. The 90% probability level was calculated using the mean, standard deviation, and *Z*-scores assuming a random Gaussian distribution of chilling hours (Kish & Purvis 1975).

Changes in frost dates

It is possible that increasing winter temperatures would decrease the occurrence of frost and move the average date of the last spring frost earlier in the season. Assuming, as we are in our construction of new time series, that there is no accompanying change in climatic variability, and that the climatic change is expressed as equal changes in the maximum and minimum temperatures, the threat of damaging frosts could decrease. We examine this idea by comparing average last spring frost dates under current conditions to these average dates under our 2 scenarios of change. We use −2.2 °C (28 °F) as a threshold for a frost event.

RESULTS

Under current climatic conditions (1961 to 1990 normals) mean winter-season chilling hours range from 1050 to 1700 h across South Carolina (Fig. 4). These values exceed those required by peach varieties grown in the state by 600 to 750 h. Since growers make variety choices using more conservative criteria, the distribution of the 90% probability of chilling hour accumulation provides more relevant information about the buffer against inter-annual variability that growers rely upon. These values range from 800 to 1550 h (Fig. 5), and exceed the chill hour requirements by 350 to 600 h in most parts of the state.

Under the 2 °C warming scenario, mean chilling hour accumulation would drop substantially (Fig. 6). Average values would range from 775 on the southeastern Coastal Plain to 1350 h in the northwestern portion of the state. Despite the marked decrease, mean chill hours still exceed the requirements in most regions of the state. However, if growers use a 90% probability threshold, a 2 °C warming reduces chilling hour accumulation to a range between 525 to 1175 h (Fig. 7). These values are very close to the chilling hour requirement of peaches grown in many parts of the state.

The effect of a 4 °C warming is more drastic. Average chilling hour accumulation under this scenario drops below 550 h on the Coastal Plain and 1000 h in the northwest (Fig. 8). In nearly all parts of the state growers could expect average chilling hour accumulation to be at or below that required for normal spring growth. The 90% probability of chill hour accumulation under the 4 °C warming scenario ranges from 325 to 825 h (Fig. 9).

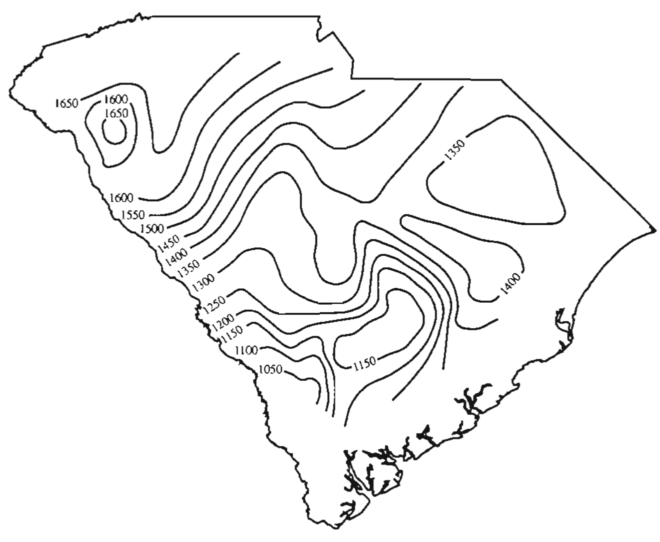

Fig. 4. Mean accumulated chilling hours, 1961 to 1990 normal

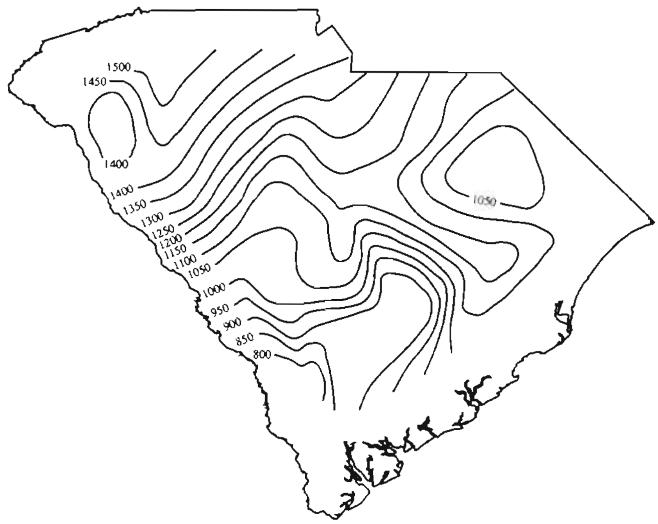

Fig. 5. Accumulated chilling hours achieved with 90% probability, 1961 to 1990 normal

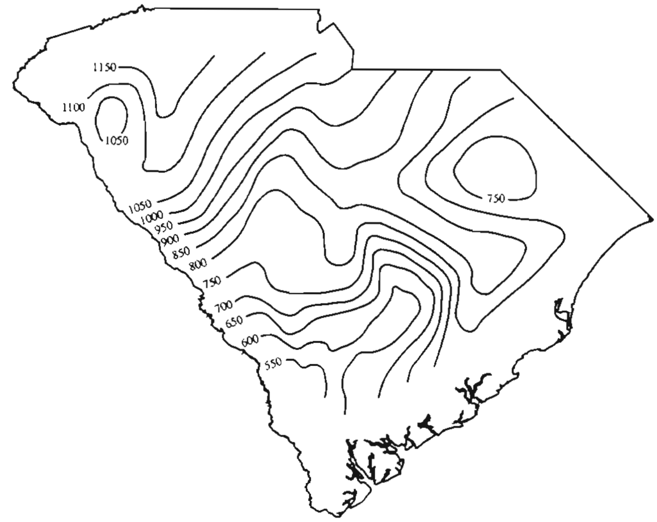

Fig. 7. Accumulated chilling hours achieved with 90% probability under 2°C warming scenario

Clearly, the warmed conditions would have a disastrous effect on the peach crop if growers did not choose varieties with lower chilling hour requirements.

Countering the increased threat of insufficient chilling is the possibility that killing frosts will not occur during the peach blossom season. Table 4 shows how the average date of the last spring frost changes under our 2 climate change scenarios. Under the 2 warming scenarios, the mean date (50% probability) of the last spring frost and the 90% probability of the last spring frost occur considerably earlier. While the adjustment of these dates varies among different stations, a 2°C warming generally moves the last frost date ahead by about 2 wk and a 4°C warming moves the last frost date ahead by about 4 wk.

DISCUSSION AND CONCLUSIONS

The results reported above suggest that chilling hours during the winter season could decrease substantially under the warming scenarios provided by current GCMs. Considered alone, this decrease could cause delayed or abnormal spring growth. Growers have adapted their orchard practices to current climatic normals in order to buffer themselves against inter-annual

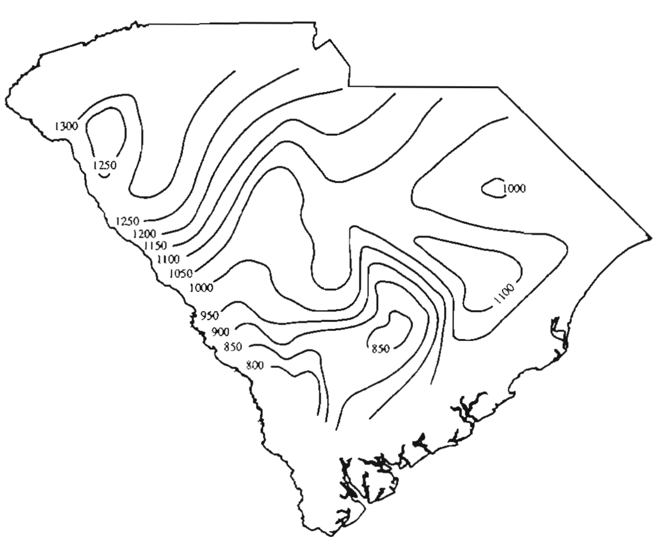

Fig. 6. Mean accumulated chilling hours under 2°C warming scenario

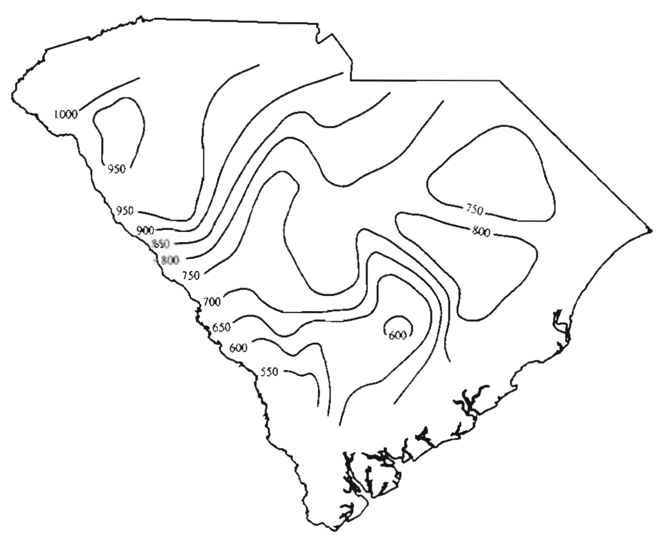

Fig. 8. Mean accumulated chilling hours under 4°C warming scenario

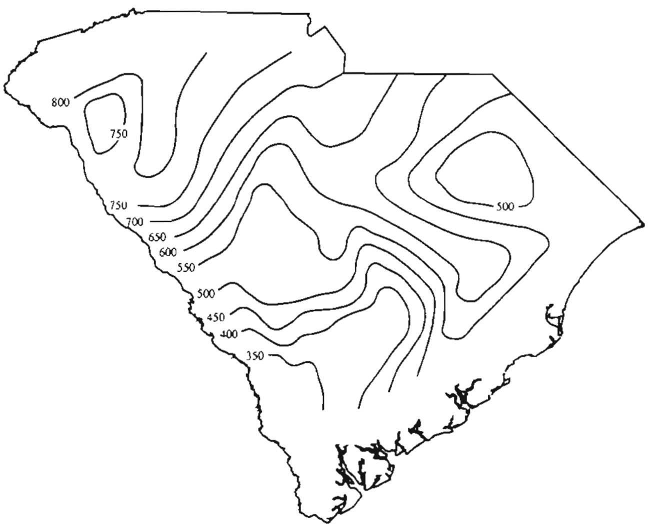

Fig. 9. Accumulated chilling hours achieved with 90% probability under 4 °C warming scenario

variability. Our results show that this buffer would be eroded with a 2 °C warming during the chilling season. Growers in certain portions of the state would experience greater frequency of insufficient chilling if cultivars with the same chilling requirements were used. A 4 °C warming would significantly increase the probability of insufficient chilling and could affect growers across the entire state.

In order to put these results into an historical perspective, we examined the climatological record of 6 long-term South Carolina stations (Fig. 10). During the 20th century, 6 years had winter temperature anomalies greater than +2 °C (1932, 1937, 1949, 1950, 1957, 1974). Chilling hour accumulation during these same years was at least 400 h below the 1961 to 1990 normal. While peach yields in each of these years was reduced, it is unclear whether insufficient chilling was solely to blame. In fact, several factors can cause reduced peach yields. What is clear, however, is that insufficient chilling of the degree proposed by our scenarios has been relatively infrequent. This could cause growers to be cautious about changing varieties based on scenarios of winter warming.

It is likely that such caution could also be driven by the current problem that frost poses for peach growers in the state. Frost has reduced peach yields during several years during the past decade, and is presently seen as growers' greatest hazard. Our results show that, without changes in climatic extremes, last spring frosts would occur earlier in the season. This could reduce the likelihood of killing frosts during the peach bloom and early fruit periods. The combination of fewer chilling hours and earlier last spring frosts could have a positive effect on peach production. Scalabrelli & Couvillon (1986) have shown that reduced chilling significantly in-

Table 4. Last spring frost dates in South Carolina under current climatic conditions and climatic change scenarios

Station	Mean frost date			90% probability of last frost before date shown		
	Current	+2 °C	+4 °C	Current	+2 °C	+4 °C
Aiken	Mar 14	Mar 4	Feb 12	Mar 30	Mar 23	Mar 7
Anderson	Mar 24	Mar 10	Feb 24	Apr 8	Mar 26	Mar 10
Bamberg	Mar 10	Feb 20	Feb 4	Mar 29	Mar 12	Feb 25
Bishopville	Mar 21	Mar 2	Feb 14	Apr 9	Mar 21	Mar 8
Blackville	Mar 14	Feb 18	Feb 7	Apr 1	Mar 10	Feb 25
Calhoun Falls	Mar 12	Feb 28	Feb 13	Mar 31	Mar 16	Mar 4
Clemson	Mar 24	Mar 7	Feb 24	Apr 13	Mar 25	Mar 13
Columbia	Mar 15	Mar 1	Feb 13	Apr 4	Mar 21	Mar 8
Conway	Mar 1	Feb 13	Feb 3	Mar 23	Mar 13	Feb 25
Dillon	Mar 22	Mar 1	Feb 18	Apr 9	Mar 21	Mar 12
Florence	Mar 10	Feb 17	Feb 5	Mar 30	Mar 16	Feb 26
Greer	Mar 24	Mar 6	Feb 23	Apr 8	Mar 25	Mar 14
Greenwood	Mar 21	Mar 10	Feb 22	Apr 9	Apr 2	Mar 12
Hampton	Mar 4	Feb 16	Jan 29	Mar 22	Mar 6	Feb 27
Holly Hill	Mar 11	Feb 16	Jan 31	Mar 30	Mar 12	Feb 18
Kingstree	Mar 16	Feb 20	Feb 13	Apr 9	Mar 16	Mar 7
Little Mountain	Mar 18	Mar 1	Feb 14	Apr 7	Mar 19	Mar 12
McColl	Mar 17	Mar 2	Feb 10	Apr 7	Mar 23	Mar 11
Newberry	Mar 22	Mar 6	Feb 18	Apr 6	Mar 24	Mar 11
Orangeburg	Mar 12	Feb 15	Feb 3	Apr 2	Mar 3	Feb 26
Sandhill Exp Station	Mar 17	Feb 24	Feb 8	Apr 5	Mar 11	Feb 25
Summerville	Mar 11	Feb 20	Feb 5	Apr 5	Mar 11	Feb 25
Winthrop College	Mar 16	Mar 2	Feb 17	Apr 5	Mar 22	Mar 11
Yemassee	Mar 8	Feb 16	Feb 11	Mar 31	Mar 8	Mar 3

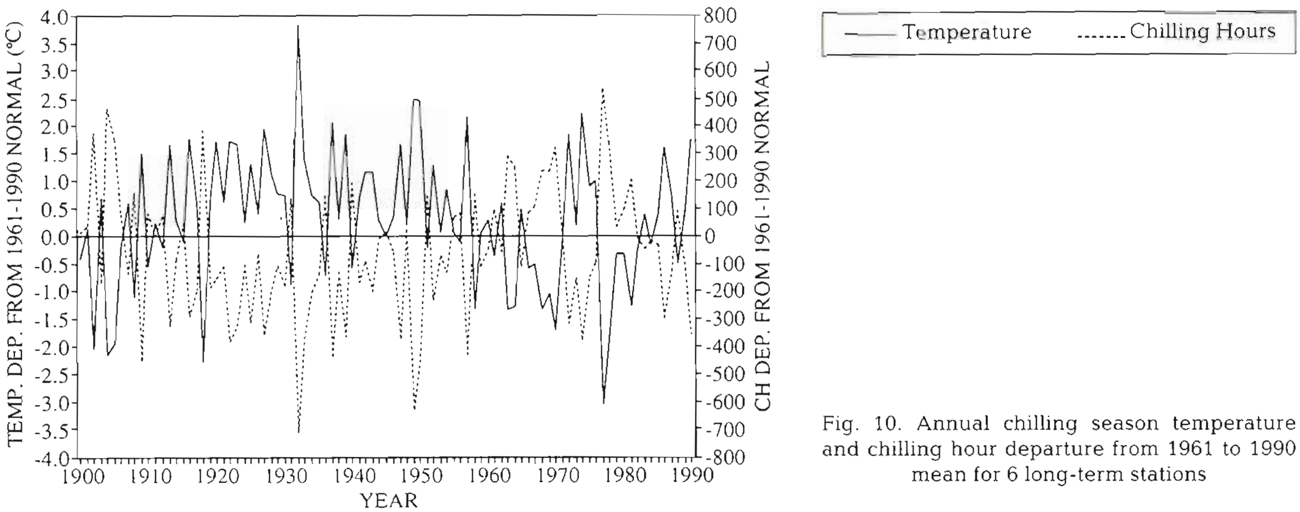

Fig. 10. Annual chilling season temperature and chilling hour departure from 1961 to 1990 mean for 6 long-term stations

creases the growing degree hour (GDH°C) requirement for budbreak in 'Redhaven' peaches. Therefore, warmer winter conditions would not necessarily accelerate the process of budbreak and fruit set during the spring. Delayed budbreak would protect peaches from killing spring frosts that would occur earlier in the season.

Our results provide a preliminary investigation into the possible impacts of climatic change on peach production. Several issues remain unanswered, and are restricted by our present knowledge of the nature of future climatic change and variability and the link between seasonal peach growth and environmental conditions. Our analysis does not include the possibility of changes in climatic variability and, particularly, changes in extreme events because of present uncertainties of future climate. We also do not address questions about how rapidly climatic change could occur. Very gradual changes (e.g. 2 °C over 100 yr) possibly would allow growers an opportunity to adjust to new climatic conditions. Further investigation in this area would involve an analysis of how growers presently make adjustments. Additionally, work directed towards the development of a broadly applicable model for predicting bloom dates would help researchers to understand the competing challenges of insufficient chilling and adjusted frost dates. Finally, our analysis could be extended to include the impacts of winter temperature increases on other fruit species and regions in the southeastern United States. We have found through a preliminary examination of selected stations from the U.S. Historical Climate Network (HCN; Hughes et al. 1992) that 2 °C and 4 °C warming scenarios could change chilling hours and frost dates across the Southeast in a manner similar to that in South Carolina.

Acknowledgements. The authors thank Karen Beidel, Michael Burdett, Jonathan Byron, Rex Cammack, Don Campbell, Yang Cheng, Dale Linvill, Brooks Tomlin, and John Winberry for their editorial comments and technical assistance in preparing this manuscript. Partial funding for this project came from the Southeast Regional Climate Center

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Editor: V. Meentemeyer

Manuscript first received: August 18, 1992
Revised version accepted: May 26, 1993