The Freeze Risk to Florida Citrus. Part II: Temperature Variability and Circulation Patterns

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ABSTRACT

Severe freezes are a serious problem for the citrus growers of central Florida. To investigate possible climatic causes of intermittent freezes, this paper examines the influence of several atmospheric circulation patterns on winter temperatures in Florida. The Pacific/North American pattern is shown to be particularly influential and the North Atlantic Oscillation also to be significant, while the Southern Oscillation does not show a direct effect. A decreasing trend in Florida winter temperatures since 1947 can be explained by fluctuations in the former two circulation patterns. Climate model studies to investigate possible changes in the frequency or location of these circulation patterns could suggest potential changes in the freeze risk associated with climatic change.

1. Introduction

In a companion article, we showed that accurate assessment of the probability of severe freeze could be helpful in the investment decisions of Florida citrus growers (Miller and Downton 1993). A series of devastating freezes in the 1980s has raised questions about the commercial viability of citrus in previously productive counties and created speculation about whether the freeze risk is changing (Gerber 1985; Miller 1991). Clearly it would be useful for citrus growers to have an estimate of future freeze probabilities that would take into account both historical climate and emerging climate changes.

While recent interest in "greenhouse warming" might lead one to suppose that freezes will soon become less common in Florida, such a conclusion may be too simplistic. Intermittent fluctuations or changes in "climatic regime" affect regional climate (Dickson and Namias 1976; Diaz and Quayle 1980; Yarnal and Leathers 1988). Such fluctuations have been attributed to changes in atmospheric circulation. The potential effects of greenhouse warming on patterns of global circulation, and associated regional impacts, have not yet been established. Although global average temperatures are expected to rise, in some areas local seasonal temperatures may fall and the frequency of extreme events may change. Understanding of large-scale climate mechanisms that affect local climate is essential for predicting local changes. Given the regional variation in possible effects of climate change, the unusually frequent freezes of the 1980s bear further study even in a context of global warming.

This article examines possible climatic causes of the apparent change in freeze risk in Florida. The hypothesis is investigated that alterations in the frequency of freezes are related to variations in three atmospheric circulation phenomena: the Pacific/North American pattern (PNA), the Southern Oscillation (SO), and the North Atlantic Oscillation (NAO).

2. Climate regimes and regional temperature

Atmospheric scientists have attributed regional temperature variations to changes in atmospheric circulation, noting that a particular circulation pattern may dominate for an extended period of years. Van Loon and Rogers, after analyzing the relationship between temperatures and sea level pressures in Greenland and northern Europe, concluded:

> In the 130 years for which we have observations in Greenland, the circulation anomalies were seemingly not randomly distributed in time. They happened such that one anomaly would prevail over the other for several decades in a row. . . . Long-term regional trends of mean temperature in winter are intimately associated with changes in the frequency of circulation types (van Loon and Rogers 1978, p. 310).

Some climatologists have described such circulation changes in terms of an abrupt step change between warm and cold "climate regimes." Kalnicky (1974) and Balling and Lawson (1982) attribute abrupt temperature changes in the United States to a change in

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the winter circulation over the Northern Hemisphere in the early 1950s from predominantly zonal (west–east) upper airflow to more frequent meridional (north–south) flow. Zonal (west to east) flow of the westerlies in the Northern Hemisphere midlatitudes provides minimal mixing of tropical and polar air. Meridional flow, on the other hand, has a wavelike pattern with a substantial amount of north–south flow. In response to pressure differences, cold polar air moves southward in some regions resulting in negative temperature anomalies, while warm air moves northward in other regions resulting in positive temperature anomalies (Kalnicky 1974).

In the absence of a physical mechanism to justify it, however, the identification of a step change is subjective. Opinions differ on when step changes have occurred. Step changes in winter temperature in the eastern United States were identified by Kalnicky (1974) as occurring about 1950; by Diaz and Quayle (1980) as occurring in 1920 and 1954; and by Dickson and Namias (1976) as occurring in 1957 and 1970.

3. Atmospheric circulation patterns affecting temperatures in the southeastern United States

Three large-scale circulation patterns have been shown to affect winter temperatures in the eastern or southeastern United States. They are the ENSO phenomenon, the NAO, and the PNA pattern (Dickson and Namias 1976; Wallace and Gutzler 1981; Rogers 1984; Ropelewski and Halpert 1986; Moses et al. 1987; Yarnal and Leathers 1988). This study examines their relative importance and interactions in affecting temperatures in Florida.

The SO involves a negative correlation between sea level pressures in the eastern South Pacific and the Australia–Indonesia region. The negative phase of the SO (involving below-normal pressure centered in the southeast Pacific and above-normal pressure centered north of Australia) tends to correspond to El Niño "warm events," in which the sea surface warms in the eastern equatorial Pacific. During composite ENSO events, described by Rasmussen and Carpenter (1982), the region of anomalously warm sea surface temperature expands westward toward the central Pacific over a time span of four to eight months, apparently contributing to the remarkable persistence over several seasons of the pressure anomalies associated with the SO (Horel and Wallace 1981). The positive phase of the SO (above-normal pressure centered in the southeast Pacific and below-normal pressure centered north of Australia) tends to correspond to "cold events," in which the sea surface cools in the eastern equatorial Pacific. A variety of tropical and midlatitude climate anomalies have been associated with the SO (Rasmusson and Carpenter 1982). Studying ENSO warm events of 1875–1980, Ropelewski and Halpert (1986) found that both precipitation and temperature in the southeast United States respond to El Niño, with a tendency toward more rain and cooler temperatures than normal during warm events.

The PNA pattern is a configuration of the upper airflow over North America that is frequently, but not exclusively, associated with ENSO in winter. Its positive phase involves negative geopotential height anomalies and lower than normal pressures in the area of the Aleutian Islands in the Pacific, positive geopotential height anomalies over western Canada, and negative geopotential height and pressure anomalies over the southeastern United States (Horel and Wallace 1981). This positive PNA pattern tends to cause meridional flow in the upper-air westerlies. The negative phase of the PNA (sometimes called "reverse PNA") involves a reversal of the anomalies in the three regions, making the flow over the eastern United States more zonal (Wallace and Gutzler 1981). The positive PNA pattern generally brings warmer than average winter temperatures to the western United States and Canada and colder than average winter temperatures to the southeastern United States. The negative PNA pattern produces the opposite results—cold temperatures in the western United States and Canada and warm temperatures in the southeastern United States (Yarnal and Leathers 1988; Leathers et al. 1991). Polar anticyclones associated with the positive PNA pattern have been shown to be related to Florida citrus freezes (Rogers and Rohli 1991).

Positive and negative PNA patterns show a statistically significant relationship with ENSO warm and cold events, respectively, in winter (Yarnal and Diaz 1986). Categorizing winter months of 1947–79 as "PNA months" and "reverse PNA months" based on a PNA index, Yarnal and Diaz found that the positive PNA pattern occurred in 54% of warm event winter months and in only 25% of non–warm event winter months. Similarly, the negative PNA pattern occurred in 50% of cold event winter months and only 25% of noncold event winter months. However, these data indicate that extremes of the PNA pattern occur fairly frequently in non-ENSO winters as well. Indeed, Yarnal and Diaz note a tendency for temperature departures on the west coast of the United States and Canada to be greater during extremes of the PNA that are not associated with ENSO.

The NAO involves a negative correlation between sea level pressures in the vicinity of the Icelandic low (near 65°N) and a broad east–west belt (near 40°N) in the northern Atlantic Ocean (Wallace and Gutzler 1981). This north–south seesaw in relative pressures causes a fluctuation of the zonal wind strength across the Atlantic Ocean. The positive phase of the NAO (above-normal pressure in the vicinity of the Azores and below-normal pressure in Iceland) is associated with strong zonal flow (Rogers 1984). The extreme negative phase of the NAO involves a reversal in the usual pressure differences between Iceland and the Azores, with high pressure centered over the usual location of the Icelandic low and a low pressure center to the south, establishing meridional flow (Moses et al. 1987). Yarnal and Leathers (1988) show winter temperatures in Pennsylvania to be associated with both the NAO and the PNA.

4. Data

a. Atmospheric indices

The Southern Oscillation index (SOI) is usually computed as the difference between standardized mean sea level pressures at Tahiti and Darwin, Australia (Horel and Wallace 1981). A commonly used index of the North Atlantic Oscillation is the difference between standardized mean sea level pressures at Ponta Delgada, Azores, and Akureyri, Iceland (Rogers 1984; Yarnal and Leathers 1988). At each location, monthly or seasonal mean sea level pressures are standardized by subtracting the long-term mean for 1895–1986, then dividing by the standard deviation:

$$z_{\mathrm{SLP}} = \frac{\mathrm{SLP} - \overline{\mathrm{SLP}}}{s_{\mathrm{SLP}}}.$$

The indices are computed from the equations

$$\text{SO index} = z_{\mathrm{SLP}}(\text{Tahiti}) - z_{\mathrm{SLP}}(\text{Darwin})$$

$$\text{NAO index} = z_{\mathrm{SLP}}(\text{Azores}) - z_{\mathrm{SLP}}(\text{Iceland}).$$

In this study, index values for 1895–1986 are used. For the NAO, only the winter season is considered. For the SO, both fall and winter seasons are examined because the high autocorrelation in the SOI implies that its fall values could potentially be useful as predictors of winter temperatures. The sign of the SO and NAO indices corresponds to the "positive" and "negative" phases of the oscillations described in the previous section. Negative values of the SOI tend to occur during El Niño episodes.

The PNA-related teleconnection between the Aleutian area, western Canada, and the southeastern United States is much stronger in 500- and 700-mb height data than in sea level data (Wallace and Gutzler 1981). An index of the PNA has been developed by Horel and Wallace (1981) using 700-mb heights at three key points in Alberta, Canada, the North Pacific, and northern Florida. It is computed using 700-mb height data on a 5°lat–long grid from the equation

$$\text{PNA index} = Z(55°\text{N}, 115°\text{W}) - \frac{Z(45°\text{N}, 165°\text{W}) + Z(30°\text{N}, 85°\text{W})}{2},$$

where Z is the standardized departure of the 700-mb height from its long-term mean at a particular grid point. A high positive value of the monthly or seasonal PNA index indicates a strong positive PNA pattern; a highly negative value indicates a strong negative PNA pattern. The Horel and Wallace PNA index was computed using standardized 700-mb height anomalies for the winters of 1947–86.

The sea level pressure data used to compute the SO and NAO indices comes from the World Monthly Surface Climatology dataset, combining data from *World Weather Records* through 1967 and *Monthly Climatic Data for the World* for succeeding years. The gridded 700-mb height data used to compute the PNA index comes from the National Meteorological Center. Both datasets are archived at the National Center for Atmospheric Research (Jenne 1975, 1989).

Winter season (DJF) values of the three indices, based on seasonal anomalies, are the primary focus of this research and are shown in Fig. 1. In using seasonal averages, however, it must be noted that values of the PNA and NAO indices may not reflect circulation patterns during the entire winter season. The PNA, in particular, can be strongly positive one month and strongly negative the next. Therefore, monthly values of the indices for December, January, and February were also computed, using monthly anomalies, to allow examination of shorter cold spells that might be missed in a seasonal average.

b. Florida temperatures

The temperature data series are described in the accompanying article by Miller and Downton (1993). In brief, time series of monthly mean minimum temperatures averaged over eight central Florida weather stations were calculated for December, January, and February of 1931–85. The three monthly series were then averaged to produce a time series of winter mean minima for central Florida, 1932–85. (The eight stations are shown on a Florida map in Miller and Downton 1993.) For coverage of a longer time span, monthly and winter mean temperatures for the entire state of Florida for 1896–1983 were also obtained.

The winter season temperature series are shown in Fig. 2, with dashed lines showing the 9-year running means to highlight any underlying decadal trends. In the longer record, 1896–1983, there is no statistically significant trend. Indeed, Fig. 2 shows an extended cool period in 1896–1906 not unlike that of 1977–85. Other extended periods of predominantly warm or cool temperatures can also be noted. In Miller and Downton (1993), it was shown that severe freeze events have occurred somewhat more frequently in winters having low mean and mean minimum temperatures. (Throughout this paper, winters are identified by the year of their January–February.)

5. Results

a. Year-to-year autocorrelation

The discussion of recurrence of circulation regimes on a decadal scale (section 2) suggests the possibility of autocorrelation from year to year in temperature

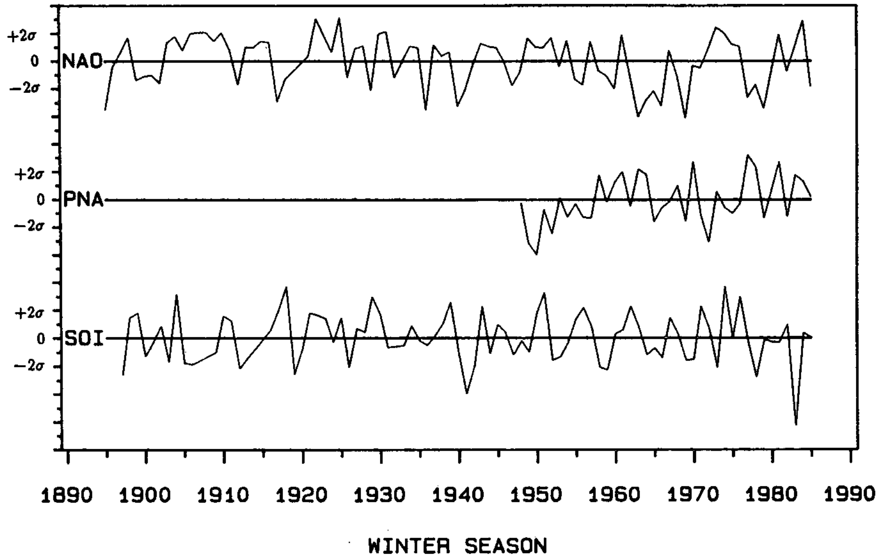

FIG. 1. Winter atmosphere indices: the NAO, PNA, and SO. Each tick mark on the vertical axis represents one standard deviation of sea level pressure (for NAO and SO) or 700-mb height (for PNA). Each index is the difference between two standardized variables, so values are generally between −5.0 and +5.0.

and pressure data. Therefore the temperatures and climate indices were checked for autocorrelation.

The first 10 lags of the autocorrelation function (ACF) were computed for the seasonal time series of temperature and the three climate indices. The only time series that appears to differ from white noise is the winter NAO index, which has significant lag 1 autocorrelation (0.245 for the period 1895–1986) and should be considered a first-order autoregressive process. For the other variables, the autocorrelations have no discernable pattern and are seldom significantly different from zero at a 95% confidence level.

In particular, the winter temperature series have minimal year-to-year autocorrelation. This indicates that year-to-year persistence of circulation regimes, if it exists, is either irregular in its effect on Florida or small relative to other sources of variability.

b. *Cross-correlations between temperatures and climate indices*

Correlations between the seasonal time series are shown in Table 1, using the longest possible time span for each pair of variables. Both mean and mean min-

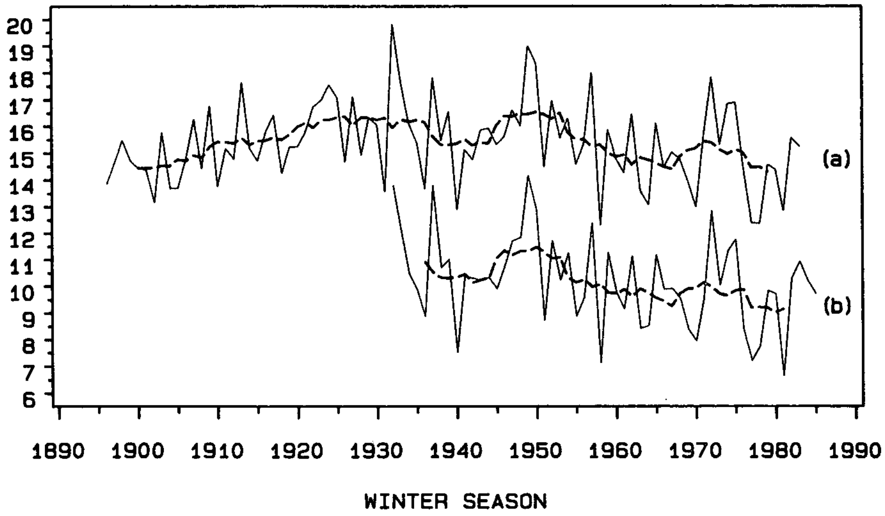

FIG. 2. Florida winter temperatures (°C). (a) Mean winter temperatures, entire state. (b) Mean minimum winter temperatures, eight central Florida stations.

TABLE 1. Correlation between winter temperatures, climate indices, and linear trend (number of seasons of available data is given in parentheses).

	Mean minimum $T_{\min}$	Mean T_F	PNA	NAO	SOI	Preceding fall SOI
Mean Florida temperature, T_F	.96* (52)					
PNA index	−.76* (38)	−.83* (36)				
NAO index	.37* (51)	.37* (83)	−.20 (36)			
SOI	.07 (53)	.20 (83)	−.32* (39)	.21 (81)		
Preceding fall SOI	.12 (53)	.27* (83)	−.37* (39)	.20 (81)	.75* (85)	
Trend, 1947–86	−.37* (39)	−.41* (37)	.43* (39)	−.04 (37)	−.12 (40)	−.10 (40)

* Correlation is statistically significant at a 95% confidence level.

imum temperatures are highly correlated with the PNA index, and also significantly correlated with the NAO index. The mean temperatures are also weakly (but significantly) correlated with the SOI for the preceding fall, though the minimum temperatures are not.

Correlations between the PNA, NAO, and SO indices are relatively low, although the PNA index is significantly related to the SOI.

c. *Winter temperature trends explained by multiple regression*

A test for linear trend in the winter mean Florida temperatures of 1896–1983 reveals no statistically significant long-term trend (correlation is $r = -0.06$ between mean temperature and the trend variable t). Both positive and negative short-term temperature trends are evident within the longer time span, however (see Fig. 2). Here we focus on 1947–85 since that is the period for which the PNA index is available.

During 1947–85, there is a statistically significant decreasing trend in both the mean and mean minimum temperatures and a significant increasing trend in the PNA index, as shown in the last line of Table 1. Trends in the NAO index and the SOI are insignificant. (Note that a linear trend model is used for convenience although the actual changes may not be linear. Other trends or step changes can also appear as a statistically significant linear trend.)

Multiple regressions of the temperatures were performed, using the PNA index with other climate indices and trend as predictor variables. The significant results are shown in Table 2. The coefficient of determination, R^2, is shown for each regression, together with the adjusted R^2 (which is adjusted for degrees of freedom to allow comparison of regressions containing different numbers of predictors). For both mean and mean minimum temperatures, the PNA is the most significant predictor, and inclusion of the NAO improves the regression fit over that obtained with the PNA alone. Inclusion of either the fall or the winter SOI does not improve the fit (not shown in the table). Use of the trend variable does not improve the fit over that obtained with both PNA and NAO.

The models containing PNA and NAO (but not trend) were selected as the best models for both of the temperature series. Residuals of the models were then analyzed and found to be approximately normally distributed with no patterns of autocorrelation.

After correcting for the effects of the PNA and the NAO, no significant temperature trend remains. It appears that the decreasing trend in Florida's winter temperatures during 1947–85 is related to the increase in the PNA index during that period. More frequent high

TABLE 2. Multiple regression of Florida winter temperatures on climate indices, 1948–85.

Dependent variable	Predictors	R^2	Adjusted R^2
Florida mean temperature, T_F (1948–83, $n = 33$)	PNA	.72	
	PNA and trend	.74	.73
	PNA and NAO	.81	.80
	PNA, NAO, and trend	.82	.81
Central Florida mean minimum temperature, $T_{\min}$ (1948–85, $n = 35$)	PNA	.62	
	PNA and trend	.64	.62
	PNA and NAO	.68	.67
	PNA, NAO, and trend	.69	.67

values of the PNA index, particularly from 1977 to 1985, imply an increase in the occurrence of the positive phase of the Pacific/North American pattern bringing arctic air into Florida.

d. Periods having positive and negative PNA indices

The strong correlation between Florida winter temperatures and the PNA index implies that climate regimes favoring the meridional positive PNA pattern should lead to a different conditional temperature distribution than regimes favoring a zonal negative PNA pattern. The winters of 1948–85 were divided into two classes depending on whether their PNA indices were positive or negative, and t tests were performed comparing first the mean temperatures and then the mean minimum temperatures of the two classes. The results are shown in Table 3. On the average, the Florida mean temperature is 2.2°C lower, and the central Florida mean minimum temperature is 1.9°C lower, when the PNA index is positive than when it is negative. Both differences are highly statistically significant. (In both cases, an F test indicates that the variances of the two classes do not differ significantly.)

The PNA pattern often persists for several weeks but is not usually sustained throughout an entire winter, so effects are more pronounced in monthly rather than seasonal data. The temperature difference is especially large when the Januarys of 1947–85 are divided into positive and negative PNA classes, as shown in the lower part of Table 3. On the average, the January mean temperature is 3.4°C lower, and the mean minimum temperature is 3.2°C lower, when the January PNA index is positive than when it is negative. Again, both differences are highly statistically significant (and again, the variances do not differ significantly).

Thus, both mean and mean minimum temperatures are strongly dependent on the state of the Pacific/North American pattern.

e. Strong PNA pattern and severe freeze

A monthly PNA index of 2.0 or above is rare and indicates that a strong positive PNA pattern occurred during that month. Only 18 of the 117 winter months of 1947–85 had a PNA index that high. Those months are listed in the first column of Table 4. Ten winter months in the same period have been identified as months of widespread severe freeze that caused damage to citrus trees (Miller and Downton 1993). They are shown in the last column of Table 4 with their PNA index values. Six of the severe freeze months had a PNA index of at least 2.0, while four of the severe freeze months had much lower PNA values (Dec 1957, Jan 1971, Jan 1982, and Dec 1983; though the Dec 1957 freeze was part of the 1958 freeze season with a high PNA index the following month).

We will show that there is a statistically significant relationship between a high PNA index and the incidence of severe freezes. The test was performed on winter seasons instead of individual months, because the month-to-month autocorrelations (Table 5) indicate that the monthly data are not independent. A winter was classified in the high-PNA category if at least one month had a PNA index of 2.0 or more. The resulting 2 × 2 contingency table is shown in Table 6. Five of the 12 high-PNA winters had severe freezes (42%). Only 3 of the 27 winters that were not high PNA had severe freezes (11%). Because one cell of Table 6 has a frequency of less than 5, the usual asymptotic approximation based on chi squared is not sufficiently accurate. Using Fisher's exact method for 2 × 2 tables (Fisher 1958, pp. 96–97), the probability of obtaining three or fewer cases in the upper-right cell of the table by chance is $p = 0.043$. At a 95% confidence level, we can reject the hypothesis that the two variables are independent: widespread severe freezes in Florida are significantly more likely in high-PNA winters.

Some comment is needed on the three winters that had severe freeze damage without a high-PNA index. In the months of those freezes, the PNA indices did not exceed 0.5 (Table 4) and the mean minimum temperatures were close to the long-term averages. However, severe freeze damage to citrus trees can occur after only a few hours of temperatures below 20°F, depending on the acclimation of the trees. When cool temperatures prevail for two or more weeks before a

TABLE 3. Comparison of Florida temperatures in periods when the PNA index is positive and negative (1947–85).

	Mean temperature, T_F (°C)			Mean minimum temperature, $T_{\min}$ (°C)		
	N	Mean	Std dev	N	Mean	Std dev
			Winter season			
PNA index > 0	14	13.83	1.18	16	8.93	1.28
PNA index < 0	22	16.05	1.40	22	10.81	1.56
		($t = -4.90$, $p = .0001$)			($t = -3.92$, $p = .0004$)	
			January			
PNA index > 0	19	12.99	1.60	21	7.91	1.92
PNA index < 0	18	16.42	2.12	18	11.15	2.19
		($t = -5.57$, $p = .0001$)			($t = -4.92$, $p = .0001$)	

TABLE 4. Months having high PNA index and/or severe freeze.

Winter season*	Months having PNA index ⩾ 2.0	Months of widespread severe freeze (with PNA index values)
1947	February 1947	
1958	January, February 1958	December 1957 (−1.3), January (2.8), February 1958 (2.0)
1961	December 1960, January 1961 (2.0)	
1963	December 1962, February 1963	December 1962 (2.0)
1964	December 1963	
1968	February 1968	
1970	December 1969, February 1970	
1971		Janury 1971 (−0.8)
1977	January, February 1977	January 1977 (2.6)
1978	January, February 1978	
1980	February 1980	
1981	January 1981	January 1981 (4.1)
1982		January 1982 (−1.5)
1984		December 1983 (0.5)
1985	January 1985	January 1985 (3.4)

* January year.

severe freeze, freeze resistance develops and freeze injury tends to be decreased (Yelenosky 1985). Conversely, warm temperatures before the December 1983 freeze apparently reduced the freeze hardiness of the trees and an abrupt drop in temperature produced extensive damage. Called "the freeze of the century" at the time, it was more damaging than other December freezes having equally low temperatures (Chen 1985). The January freezes of 1971 and 1982, though less abrupt, also had unseasonably high temperatures in the three weeks before the freeze (Crosby 1985).

In summary, during 1947–85, the majority of severe tree-damaging freezes occurred during cold spells of several weeks (Crosby 1985). These freezes were associated with a strong positive PNA pattern. The tree-damaging freezes that occurred in months of near-normal or negative PNA indices generally involved short severe cold spells preceded by normal or above-normal temperatures.

6. Discussion

Clearly, Florida winter temperatures of 1947–85 were strongly influenced by the Pacific/North American pattern. The North Atlantic Oscillation also had an influence. The decreasing trend in temperature since 1947 is accounted for in a regression model by the PNA and NAO indices. Unfortunately, the 700-mb height data required to compute the PNA index were not collected prior to 1947, so we are unable to determine whether the PNA pattern occurred in a similar configuration and with comparable frequency in the cold periods of the 1890s and the 1980s. Certainly the PNA pattern occurred more frequently and persistently in 1977–86 than in any other decade since 1947.

Florida winter temperatures are only weakly related to El Niño and the Southern Oscillation, probably through the increased frequency of the PNA during ENSO warm episodes (Horel and Wallace 1981; Yarnal and Diaz 1986). In a multiple regression model containing the PNA index, the SOI does not explain any additional temperature variance. Indeed, the strong ENSO of 1982–83 was not associated with the usual PNA pattern and its effect in the southeastern United States was offset by a strong positive NAO (Rogers 1984). Winter 1983 was the only winter of 1981–85 that did not produce a severe freeze in Florida.

It appears that the probability of a severe freeze in Florida depends upon the state of the Pacific/North American pattern. Mean and mean minimum winter temperatures are significantly lower when the PNA index is positive. Furthermore, a strong persistent PNA pattern (monthly PNA index ⩾ 2) substantially increases the probability that Florida will experience a widespread severe tree-damaging freeze. These findings

TABLE 5. Month-to-month autocorrelation.

	Dec–Jan	Jan–Feb	Dec–Feb
$T_{\min}$ (1931–85)	.41*	.25	.10
T_F (1895–1983)	.43*	.30*	.18
PNA index (1947–85)	.29	.23	.39*

* Correlation is statistically significant at a 95% confidence level.

TABLE 6. Winters of 1947–85 classified by PNA index and freeze category.

	High-PNA	Not high-PNA	Total
Severe freeze	5	3	8
Not severe freeze	7	24	31
Total	12	27	39

are consistent with the suggestion in section 2 that extended warm or cold periods may result from a recurring fluctuation between dominant circulation patterns. When the PNA index is positive, cold fronts are likely to be coming in from the north, shifting the temperature distribution downward; conversely, when the index is negative, the likelihood of cold outbreaks is reduced.

The PNA pattern is inherent in the circulation of the Northern Hemisphere, resulting from the distribution of land and water. Its strength and direction are affected by a number of different forcing mechanisms. ENSO events appear to increase the likelihood of a persistent positive PNA pattern, although we have seen above that the relationship between ENSO and Florida temperatures is weak and some of the most extreme values of the PNA index have occurred during non-ENSO winters (notably February 1968, January 1981, and January 1985).

There can be long intervals when one mode of the PNA is more frequent than others, either by forcing or by chance. The extended warm period of 1921–54 (noted in Diaz and Quayle 1980) cannot be accounted for by the 2- to 8-year recurrence interval of El Niño, although El Niños did occur slightly less frequently in that period. Dickson and Namias (1976, p. 1255) have suggested that observed warm and cold "regimes" are the result of established wave patterns sustained by feedback mechanisms. As far as we know, however, no physical mechanisms have conclusively explained such a positive feedback. The lack of year-to-year autocorrelation in the Florida temperature series indicates that the "climate regimes" are not continuous processes, or do not affect Florida continuously, over successive years. Though cold winters occur more frequently in some decades than in others, they occur intermittently without any apparent relationship to immediately preceding winters.

7. Conclusions and implications for future research

Part I of this study (Miller and Downton 1993) described an increase in freeze frequencies in central Florida in the 1980s that, temporarily at least, raised doubts about the commercial viability of citrus production in the area. A change in the apparent long-term freeze risk brought about a large dislocation in the Florida citrus industry. Future climate change may have equally important implications for citrus growers. What information from climate change research would be useful in predicting regional impacts for Florida?

The frequency of occurrence of the PNA, bringing frigid arctic air southward, appears to have a major impact on the commercial viability of citrus growing in central Florida. It would be valuable to know whether the PNA pattern is likely to occur more or less frequently in the event of climate change. Florida temperatures also were found to be related to the North Atlantic Oscillation; hence potential changes in the NAO may also be of importance.

A few climate modelers have investigated potential changes in circulation in the event of global warming. Bates and Meehl (1986), using the NCAR Community Climate Model, found decreases in the frequency of wintertime high-latitude blocking in the southern hemisphere and shifts in the centers of blocking activity in the Northern Hemisphere under a doubled CO_2 scenario. Such changes could alter the frequency or location of the PNA pattern, changing the frequency of incursion of arctic air into Florida and the southeastern United States. However, in that model, overestimation of the amount of sea ice influenced the changes in blocking (Bates and Meehl 1986). In addition, the nondynamic ocean used in that model could not produce ENSO events that, as we have seen, contribute to the PNA pattern. Some recent global coupled general circulation models have been shown to internally generate some aspects of ENSO events, including features of the associated PNA pattern (e.g., Meehl 1990). There are indications, in at least one of those models, that an increase of carbon dioxide and trace gases could affect ENSO and the associated PNA pattern (Meehl et al., 1993). It is hoped that improved atmosphere–ocean models currently under development will provide more detailed insights into what circulation changes are likely in various climate change scenarios.

In the meantime, what are the implications for growers' risk adjustment strategies? Given the virtual elimination of the groves in the northern part of the traditional citrus belt, the real question facing the owners of the destroyed groves is: What is the risk of another tree-killing freeze over the next 15 or 20 years? Until more is known about the PNA, its causes and its possible linkage to climate change, we can give growers little information about whether the freeze risk over their planning horizons may differ from the frequencies calculated from the climatic record.

Florida's winter climatic record has been marked by intermittent warm and cold periods of unpredictable length. Therefore, individuals contemplating the planting of a citrus grove in a freeze susceptible part of Florida would be well advised to couple the use of the longest available climatic record with the knowledge that freeze frequencies over the future planning horizon may differ from those calculated from the record. By acknowledging this uncertainty, prospective growers may be better able to hedge their investment risks.

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