

Florida Citrus Freezes and Polar Anticyclones in the Great Plains

JEFFREY C. ROGERS

Department of Geography, The Ohio State University, Columbus, Ohio

ROBERT V. ROHLI

Atmospheric Sciences Program, The Ohio State University, Columbus, Ohio

(Manuscript received 16 November 1990, in final form 14 May 1991)

ABSTRACT

Severe Florida citrus freezes since 1880 are identified and described in terms of the horticultural damage, overall frequency of occurrence, and association with polar anticyclone outbreaks in the plains of southern Canada and the United States. The most severe "advective" freezes are associated with strong cold anticyclones having tracks southward across the plains to Texas with subsequent northeastward movement. Other anticyclones move in a track somewhat east of this and ultimately pass over Florida or the eastern Gulf of Mexico. Over 80% of the worst Florida citrus freezes are associated with anticyclones with central pressures in excess of 1045 mb moving along these paths. However, anticyclones of similar intensity with more zonally oriented paths across higher latitudes are associated with minor citrus damage. The major freezes tend to be clustered in time in the 1890s and since 1977. On interdecadal time scales, the recent freezes are not linked to higher winter mean pressure in the northern plains, and there has not been an unusually high frequency of strong anticyclones in recent decades, compared to earlier this century. Compared to the freeze-free period of 1948–57, the winters of 1977–86 are characterized by a more amplified 500-mb mean standing wave pattern across North America. This is linked to changes in the Pacific/North American upper-air teleconnection pattern, the index for which had much lower values (characterized by zonal flow) prior to 1958.

1. Introduction

The Florida citrus industry has recently suffered production setbacks due to six major freezes occurring since January 1977. Cold spells in the Januarys of 1977, 1981, and 1982 caused widespread crop loss and longer-term damage to some citrus trees. These freezes were but precursors to the severe cold wave of December 1983 that destroyed nearly one-quarter of the orange crop and produced extensive damage to or destruction of citrus trees, of which many had been weakened by the earlier freezes. The severe freeze of January 1985 caused extensive damage to young growth and new trees that had emerged or started within the preceding 13 months. The back-to-back freezes are considered among the worst on record and, with a post-1983 southward shift in Florida citrus production (Winterling 1984), citrus acreage by late 1985 was at a 29-year low (Whittaker 1985). The freeze of December 1989 is the third severe freeze in six years, further hindering a return to the steady growth enjoyed by the industry before 1977 (Haddock 1981). Table 1, which will be discussed in much more detail in section 2, shows how

extraordinary the freezes of 1977–89 have been in terms of historical Florida citrus production.

An outbreak of bitterly cold polar air, moving southward across the plains of North America, precedes each Florida citrus freeze. The polar outbreaks produce numerous adverse socioeconomic impacts across many parts of the United States, including loss of lives, cattle, fisheries, vegetable crops, and grains, and they have numerous effects within cities and on land and water transportation (Quiroz 1984). Polar outbreaks in the Decembers of 1983 and 1989 helped make them the coldest and fourth coldest (respectively) on record since 1895 across the contiguous United States (Climate Analysis Center 1990).

Polar outbreaks have long attracted the attention of weather forecasters, especially the aspect of rapid temperature change or "cold waves" (Garriott 1906; Wendland 1987). Cox (1916) describes the surface and atmospheric conditions determining the severity of polar outbreaks:

It is obvious that the degree of cold recorded in a cold wave depends upon the intensity of the cold in the high and the temperature in the low in front of the high, the magnitude of the high, the barometric gradient between the high and the low and the consequent wind force, the direction of movement of the high and also the low or lows which it is following, the general

Corresponding author address: Dr. Jeffrey C. Rogers, Department of Geography, The Ohio State University, Columbus, OH 43210-1361.

TABLE 1. Historical hard and severe citrus freezes in Florida since 1880, including two earlier freezes of historical note. The freezes are especially destructive on the mornings of the dates indicated, and the sea level pressure is the highest value over the northern Plains on the daily synoptic charts or (prior to 1899) from *Monthly Weather Review* charts. Descriptions of the freezes that are unreferenced are taken from the general summaries in *Weekly Weather and Crop Bulletin*.

Year	Dates	Pressure (mb)	Description
1766	3 Jan	Unknown	Earliest recorded freeze, ". . . frost destroyed all the tropical fruits except oranges" (Blodget 1857) including limes, citron, and banana trees destroyed around St. Augustine (Fairbanks 1895).
1835	7-8 Feb	Unknown	"Many kinds of fruit killed, many of them never started again, even from the roots" (Fairbanks 1895). Destroyed all oranges/lemons to 28°N. A violent northwest wind for three days (Blodget 1857).
1880	30 Dec	1048.7 (26th)	Coldest since 1857 at Jacksonville, where oranges were frozen on trees (<i>Mon. Wea. Rev.</i>).
1886	10-12 Jan	1047.4 (7th)	Estimated over \$3 million citrus damage, which was largely frozen. Many young trees killed, old trees little damage. The coldest period since 1835 (Hazen 1886; Garriott 1906; Mitchell 1917).
1894	28-29 Dec	1054.5 (27th)	Most fruit frozen, unharvested orange crop lost, estimated at 2-3 million boxes (Abbe 1894).
1895	8-9 Feb	1055.9 (7th)	Majority of orange trees killed (which were unprotected/defoliated in December 1894 and had started actively growing in intervening warm weather) (Wilder 1948).
1899	12-13 Feb	1059.3 (11th)	Severe damage in many millions of dollars throughout the southeastern United States, most young citrus damaged in northern, central Florida. Prior warm weather had encouraged tree growth, many killed or badly injured (Abbe 1899).
1905	26-27 Jan	1053.8 (25th)	Considerable loss of unprotected fruit, some young trees lost, but generally oranges only suffer defoliation (Garriott 1905).
1909	30 Dec	1032.4 (29th)	Many oranges frozen in central and northern Florida, young growth cut back but no orange trees were killed (von Herrmann 1909).
1917	3-5 Feb	1056.9 (1st) and 1052.8 (4th)	Citrus frozen in north, central, some damage in south. Trees defoliated, much grapefruit damage, and 50% of pineapples destroyed. Many young trees killed back to their protective earthen banks.
1928	3-4 Jan	1052.5 (31st)	Unprotected citrus (especially central Florida) and that in low-lying northern and interior areas frozen; defoliation, many young trees and new growth killed but not older groves.
1934	12-13 Dec	1030.7 (10th)	Heavy losses of citrus, oranges frozen; many young trees killed, older ones frozen back, shedding fruit and foliage.
1940	28-29 Jan	1051.9 (24th)	Most severe Florida freeze since 1917. Defoliation and near-total loss of tangerines and grapefruit, over half the oranges lost. Trees "were in the best possible shape to withstand the cold" due to drought-induced semidormancy.
1947	10-11 Feb	1052.1 (7th)	\$50 million damage to citrus and truck crops, central and northern Florida. Low-lying areas hardest hit.
1957	12-13 Dec	1046.3 (10th)	The worst of several freezes this winter. Trees defoliated with heavy losses, especially in low-lying areas. Production reduced by several million boxes after seven active cold fronts in January (O'Connor 1958) and more in February.
1962	9-13 Jan	1059.3 (10th)	Damage to low-lying, young/new growth citrus, especially in the north. Florida damage minor compared to severe damage in Texas and Louisiana. "Worst cold wave since 1899" (Stark 1962).
1962	13-14 Dec	1045.3 (11th)	Most damaging Florida freeze this century; 50 million boxes lost, 50 million salvaged, 7-10 million trees killed (Turrell 1973).
1977	19-21 Jan	1039.9 (18th)	Extensive fruit injury and leaf kill, but limited wood damage. Citrus trees had developed considerable coldhardiness preventing extensive wood damage. 98% of all oranges frozen.
1981	13-14 Jan	1040.1 (9th)	Widespread citrus and foliage damage; some bark splitting and wood damage in the north but trees were generally well coldhardened. Up to 80% leaf/fruit drop in some areas, overall a production loss of 30 million boxes.
1982	11-12 Jan	1054.1 (10th)	Hard freeze to most of Florida where citrus and vegetable damage was severe; defoliation and wood damage reported.
1983	25-26 Dec	1058.7 (24th)	Trees were not coldhardened. Severe freeze all areas, fruit frozen, defoliation, and wood damage, considerable tree mortality in the north. Total fruit loss of 51 million boxes.
1985	21-22 Jan	1048.0 (20th)	Severe freeze; fruit leaf and wood damage occur even after a distinct southward shift in Florida citrus production since 1983.
1989	24-25 Dec	1054.9 (22nd)	Hard freeze all citrus areas, minimal damage in south Florida and variable foliage/fruit damage elsewhere. Approximately a 20% reduction in Florida citrus production from previous year similar to preceding freezes of the 1980s.

character of the sky, the humidity, whether there is snow on the ground, and the season of the year; in a word, all of the atmospheric conditions, sometimes even within an area of 3000 or 4000 miles or more.

The evolution and movement of the polar anticyclones accompanying the polar outbreaks of recent citrus freezes has been documented (Haddock 1981,

1984; Mogil et al. 1984). Somewhat typical is the polar anticyclone of December 1989, which crossed the eastern Beaufort Sea on the 19th and began to intensify over Alaska and northwestern Canada on the 20th. When the anticyclone entered the U.S. High Plains on the 21st, its central pressure had reached 1057 mb and the temperature at Havre, Montana, was -35°C . By

1200 UTC 22 December (Fig. 1), the high remained over 1052 mb in the northern plains and the leading edge of the polar air had already crossed Texas and was entering central Florida. By 23 December, over 250 minimum temperature records were broken across the United States. Subfreezing temperatures prevailed across Florida by Christmas Eve morning.

The purpose of this paper is to describe some characteristics of Florida citrus freezes occurring over the last 110 years, including their temporal variability, and to describe some aspects of the apparent association between freezes and strong polar anticyclones in the Great Plains of North America (with their accompanying extreme cold air). This linkage associates meteorological events and developments at the very highest latitudes of the continent and one aspect of their socioeconomic consequences along its southeasternmost fringe. The associations are examined not only on the synoptic scale but on interdecadal time scales, examining longer-term changes in frequencies of polar highs and upper-air patterns. The study is limited to freezes in Florida since it is the primary citrus-producing area in the United States and because more extensive discussion would be needed if freeze-prone citrus-producing areas such as Louisiana, Texas, and California were also included. Our intention is to concentrate on the role of polar anticyclones; some of the factors alluded to in the quote from Cox (1916), such as surface conditions (snow cover) and airmass temperature, were not analyzed.

2. Hard and severe Florida citrus freezes

Several different adjectives are typically used to describe the intensity of Florida citrus freezes (Haddock 1981, 1984). These are presented in Table 2. "Light" and "moderate" freezes produce little lasting damage to the citrus trees. Frosts and light freezes can have beneficial effects on fruit color and other developmental characteristics (Wolford 1955). Compilations of Florida monthly minimum station air temperatures (Leavitt 1978; Martsolf et al. 1984) indicate the months that have had less damaging light and moderate freezes. "Hard" and "severe" freezes are those in which citrus trees often need multiyear recovery periods before citrus production is back to prefreeze levels. These are the focus of this study since crop damage is the heaviest.

The relationship between air temperature and freeze severity is complicated by several factors, including the age of the citrus trees, current climatic conditions (such as periods of drought), and factors such as irrigation and measures used in combating the freeze. The cold-hardiness of a citrus tree is considered a very critical factor in determining the relative severity of a freeze (Yelenosky et al. 1984), as is the degree of tree dormancy at the time of the freeze (Wilder 1948). In general, the citrus trees become dormant at temperatures below 12°C, and they develop cold-hardiness (which they effectively retain for life) if temperatures remain between 0° and 7°C for an extended period during the cold season (and especially prior to subfreezing tem-

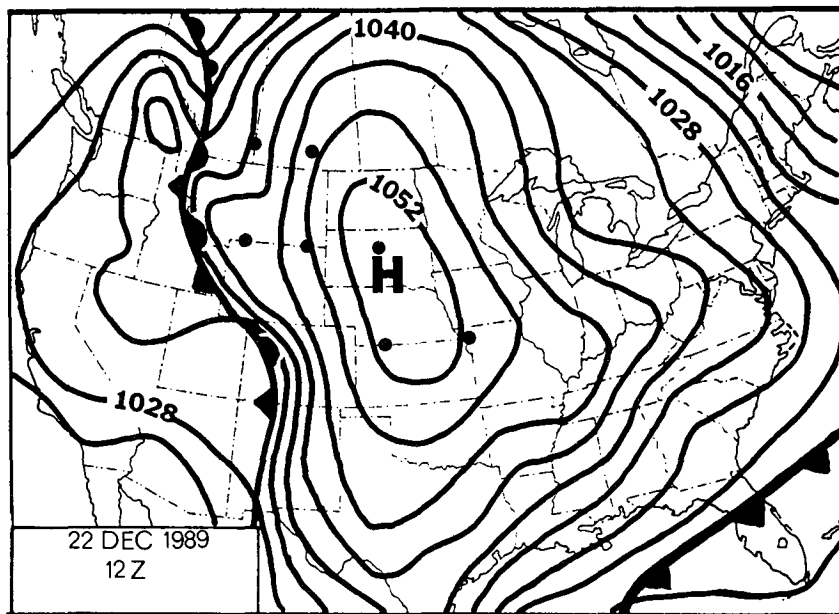


FIG. 1. The mean sea level pressure distribution for 1200 UTC 22 December 1989. Isobars are at 4-mb intervals and the location of the polar front is indicated in the Rockies and in Florida. The seven dots represent grid points used in locating strong polar anticyclones occurring since 1899.

TABLE 2. The association between freeze type, minimum air temperature ($^{\circ}\text{C}$), and number of years typically required before citrus production recovers to preefreeze levels (from Haddock 1981, 1984).

Type of freeze	Minimum temperature ($^{\circ}\text{C}$)	Citrus recovery period (years)
Light	0 to -2.0	0
Moderate	-2.0 to -4.0	0
Hard	-4.0 to -6.5	1–3
Severe	<-6.5	3–7

peratures). If a severe freeze takes place while the tree is not in dormancy, or before much cold-hardening develops (i.e., in young trees or those with new or recent growth), the damage is much greater. Citrus fruit vary in their ability to withstand subfreezing temperatures. Dormant oranges are able to withstand temperatures down to about -4°C for about one hour without injury, but below -5.5° to -6.5°C , twigs will generally begin to die back and leaves will brown and fall (Wolford 1955). Once they are frozen, oranges can be salvaged for production of juice concentrate.

Table 1 is a list of hard and severe Florida citrus freezes since 1880. It is compiled from agricultural and meteorological summaries in *Monthly Weather Review*, from the 1880s to the 1920s; the *Weekly Weather and Crop Bulletin*, available to us since 1927; and reports in articles or books on horticultural aspects of citrus freezes. In order to qualify for inclusion in Table 1, evidence had to indicate that the cold spell induced either 1) freezing of citrus on the trees, 2) defoliation of the trees, 3) a substantial reduction in citrus production, and/or 4) damage to citrus trees (limbs or bark) resulting in injury or death, all occurring over extensive portions of northern and central Florida and possibly farther south. The crop damage-related features frequently occur together, making the major freezes rather easy to distinguish.

Back-to-back severe freezes, such as those of 1894–95 and 1983 and 1985 in Florida, and those that occurred in 1949 and 1951 in Texas, can be especially destructive. The late nineteenth century freezes kept Florida production below 1894 levels until 1909–10 (Wilder 1948) and, as in recent years, contributed to a net southward migration in the citrus production belt (Winterling 1984; Chen and Gerber 1985).

Among the citrus freezes in Table 1, those of 1835, the 1890s, 1962, and 1983–89 are the most destructive according to horticultural studies (Fairbanks 1895; Wilder 1948; Zeigler and Wolfe 1975; Yelenosky et al. 1984) and recent summaries in *Weekly Weather and Crop Bulletin*. These events are generally regarded as “advective” freezes, characterized by cold dry winds of up to 50 km h^{-1} causing additional defoliation, death of twigs, and loss of fruit due to excessive transpiration and the mechanical force of the wind (Wolford 1955).

Frost protection procedures are much less likely to reduce the damage wrought by advective freezes. It is also possible to have “radiation” freezes, those associated with light winds and clear skies behind the polar front.

The three severe Florida citrus freezes of the 1890s, and those since 1983, may be the only ones to have occurred in clusters over the last two centuries. The severe freeze of December 1962 was preceded by one of about equal intensity in January 1962 (included in Table 1), which was very destructive in the citrus-growing regions of Texas but did little damage in Florida. The severe freeze of 1835 is also apparently a lone event in Florida. Tropical fruits had been uninjured in more than half a century at St. Augustine at the time of the freeze of 1835 (Blodget 1857). The *Autobiography of Thomas Douglas* (printed in 1856; Chen and Gerber 1985) indicates that many of the trees destroyed in 1835 around St. Augustine were nearly 100 years old. The closest cluster of severe winters prior to 1835 over the eastern and southeastern United States may well be those of the last quarter of the 18th century, including 1776/77, 1779/80, 1783/84, 1786/87, 1796/97, and 1798/99 (Blodget 1857; Ludlam 1966), and these may be linked to undocumented severe citrus freezes. The cold spell and freeze of 1886 is considered the worst since 1835 (Hazen 1886). Table 1 shows that hard and severe citrus freezes have occurred about once per decade in the last 110 years, but more frequently in the 1890s and since 1977.

3. Polar anticyclones in the Great Plains

A characteristic common to most polar outbreaks is a strong and large anticyclone near the core of the air mass. Both the December 1983 and 1989 cold waves and citrus freezes were associated with polar highs with central pressures in excess of 1055 mb when the anticyclones entered the northern Great Plains of the United States. Wave cyclones often develop and move along the polar front at the leading edge of the polar air. These will form along the Texas Coast (with an occasional “Colorado” or “panhandle” low) or along the Atlantic coast. Some of the cyclones forming along the polar front during citrus freezes can achieve considerable intensity, as in the case of the northeast coast blizzard of 12–14 February 1899 (Kocin et al. 1988). Aspects of cyclone development and movement in conjunction with the cold air outbreaks of mid-January 1977 are described by Konrad and Colucci (1989). The spatially consistent feature common to Florida citrus freezes is, however, the high-pressure cell in the Great Plains.

Daily sea level pressure maps are used to identify occurrences of strong polar anticyclones in the northern plains between November and March of each year since 1899 (when the historical weather maps of the U.S. Weather Bureau begin). An initial survey of weather

maps suggested that the intense anticyclones linked to citrus freezes enter the northern United States across the 110°–95°W longitude band. A gridded (5° latitude by 5° longitude) version of the daily pressure data, available on tape from the National Center for Atmospheric Research, is initially used to identify days when pressure exceeded 1045 mb at any of seven points in the northern plains: 50°N, 110° and 105°W; 45°N, 110° to 100°W; 40°N, 100° and 95°W (Fig. 1). One gridded map is available per day for either 1300 UTC (from 1899 to 1939) or 1200 UTC thereafter. The methodology does not include strong anticyclones, developing in subarctic and arctic regions of Alaska and the Yukon, which weaken below 1045 mb before reaching 50°N. It excludes strong highs moving across regions outside the grid, and it may miss highs passing across portions of the grid in less than 24 h between morning observations. However, none of the anticyclones occurring in conjunction with citrus freezes were overlooked.

After identifying the high pressure days with gridded tape data, the original weather maps are examined in order to determine the highest pressure on an individual station model within the grid and within 2.5° of latitude and longitude surrounding the grid. The possibility of errors in the station model maximum pressure reports is assessed by comparing the numerical values to those at nearby stations.

The station model 1200 or 1300 UTC sea level pressure maxima are given in the third column of Table 1 for the freezes since 1880. Prior to 1899, central pressures and paths of highs are from the anticyclone track charts in *Monthly Weather Review*. Table 1 indicates that the pressure was above 1050 mb in 11 (of 20) of the Florida freezes and over 1045 mb in all but four freezes. In cases where the pressure was below 1045 mb, the maximum central pressure over the grid area was identified from the synoptic charts.

Table 3 presents a list of daily anticyclone events in which the pressure exceeds 1052 mb. Considering that the pressure data are sampled only once a day, many of the pressures in Table 3 are not the actual maximum value for the anticyclone; the list is not likely in "true" descending order. Although several of the strong anticyclones in the northern plains (Table 3) are associated with subsequent Florida citrus freezes (Table 1), some are only linked to vegetable crop damage (which occurs at higher temperatures than for citrus) or instances where little or no damage occurs due to relatively mild conditions.

The tracks of anticyclones associated with citrus freezes (Table 1) and other strong highs (Table 3) are presented in Fig. 2. The anticyclone tracks are shown in four panels, emphasizing some of their qualitative differences. Figure 2a shows the paths of the strong anticyclones associated with the severe advective freezes of 1894/95, 1899, 1962, 1983, 1985, and 1989 (Fairbanks 1895; Wilder 1948; Zeigler and Wolfe 1975; Ye-

TABLE 3. The strongest anticyclones detected over the northern Great Plains grid on 1200 UTC and 1300 UTC synoptic charts 1899–1989 and associated agricultural damage in Florida (if any). The central pressure is the highest reported on any station model in the grid area. Highs associated with citrus damage in Table 1, occurring before 1899, have been added to this list.

Date of high (yr/mo/d)	Pressure	Agricultural damage (Florida)
1917/12/28	1060.3	Vegetables damaged
1899/2/11	1059.3	See Table 1
1962/1/10	1059.1	See Table 1
1983/12/24	1058.7	See Table 1
1989/2/3	1058.5	Florida temperatures stay above normal
1989/2/17	1057.8	None, high dissipated over upper midwest
1924/12/20	1057.2	None, Florida mild
1917/2/1	1056.9	See Table 1
1920/1/24	1056.5	No damage anywhere
1923/2/14	1056.2	Some vegetables, strawberries
1899/2/22	1056.2	Follows a major freeze by 10 days
1895/2/7	1055.9	See Table 1
1925/12/27	1055.2	Vegetable damage
1989/12/22	1054.9	See Table 1
1894/12/27	1054.5	See Table 1
1924/12/27	1054.5	Florida temperatures above normal
1982/1/10	1054.1	See Table 1
1905/1/25	1053.8	See Table 1
1918/2/20	1053.8	Florida seasonally mild
1927/1/14	1053.2	Citrus damage but crop recovered later
1917/2/4	1052.8	See Table 1
1947/1/3	1052.6	Stays quasi-stationary in western United States
1927/12/31	1052.5	See Table 1
1988/2/5	1052.3	No damage in Florida
1961/1/24	1052.3	Leaf burn, some complete losses
1947/2/7	1052.1	See Table 1

lenosky et al. 1984). The prominent characteristic of each path is a southward movement across the plains toward eastern Texas and subsequent eastward or northeastward redevelopment toward the Atlantic Coast. In general, the anticyclones take 24–48 hours to traverse the distance from the Canadian border to Texas, and they move northeastward more slowly. Although not shown specifically in Fig. 2a, the data indicate that Florida freeze damage generally occurs on the mornings when the high is in Texas and on the subsequent day when eastward recurvature occurs. In 1989 the freeze damage occurs on the first two mornings during recurvature. The 1895 and 1985 anticyclones dissipate before reaching the East Coast. Details of the 1899 polar outbreak are in Kocin et al. (1988).

Dallavalle and Bosart (1975) describe the synoptic characteristics of polar anticyclones with paths similar to those in Fig. 2a. Their composite cold core high weakens while moving rapidly southward from eastern Montana to Texas over a 24-h period. When the high

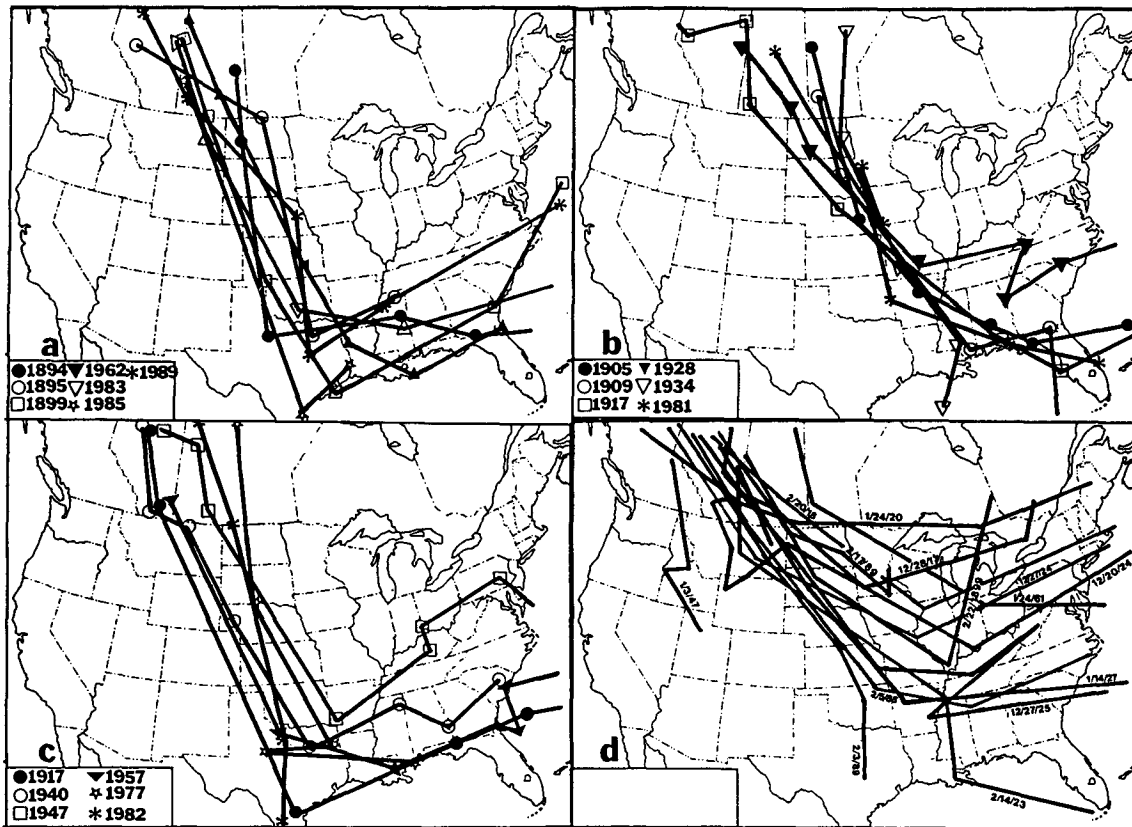


FIG. 2. Partial tracks of the strongest wintertime anticyclones (Table 3), beginning with points in their paths in southern Canada and then across the United States. Positions are based on 1200 UTC or 1300 UTC synoptic charts. The years labeled in (a)–(c) refer to years of Florida citrus freezes in Table 1, while the tracks in (d) are for some of the remaining nonfreeze events identified only in Table 3. Of the two strong highs in early February 1917 (Table 1), the first appears in (b) and the second in (c).

reaches the Gulf Coast, it recurves eastward and reintensifies as a warm dynamic system. Movement of their composite polar anticyclone is linked to changes in forcing mechanisms; cold air advection drives the southward motion, and anticyclonic vorticity advection aloft supports the eastward recurvature and reintensification. The polar highs in their study do not move southward until short-wave troughs clear the region over northwestern North America and uninterrupted northwesterly flow aloft is established. The coldest surface air typically moves rapidly southeastward and precedes the highest surface pressure. Dallavalle and Bosart's (1975) study shows that comparatively weak anticyclones (<1045 mb) can also have paths similar to those in Fig. 2a.

The freezes of 1905, 1909, 1917, 1928, 1934, and 1981 are characterized by slow-moving anticyclones (Fig. 2b) that generally track east of those in Fig. 2a, crossing over Missouri or Arkansas. They do not significantly recurve to the northeast. In these instances the freeze damage in Florida occurs when the high is in Mississippi, Alabama, or Florida, except in 1928

when it was farther north. The paths of these anticyclones are similar to Dallavalle and Bosart's (1975) second case study composite, exhibiting a track somewhat east of that described in Fig. 2a. This second type of anticyclone moves into the Gulf of Mexico and weakens, never undergoing warm anticyclonogenesis. The paths of these highs seem consistent with the notion of radiation freezes, in which strong radiative cooling occurs while Florida lies under the eastern flank of the approaching high.

A third set of anticyclone paths (Fig. 2c) is associated with citrus freezes (Table 1) that track toward Texas but have not been identified as severe advective freezes (Fig. 2a) in the literature (Fairbanks 1895; Wilder 1948; Zeigler and Wolfe 1975; Yelenosky et al. 1984). Some anticyclones in this group exhibit different characteristics than those in Fig. 2a, including one that continues into the subtropics through Texas (1982) and another that stalls and migrates westward before moving eastward (1977). The 1947 anticyclone does not go as far southward as the others and it redevelops toward much higher latitudes. The 1957 freeze occurs

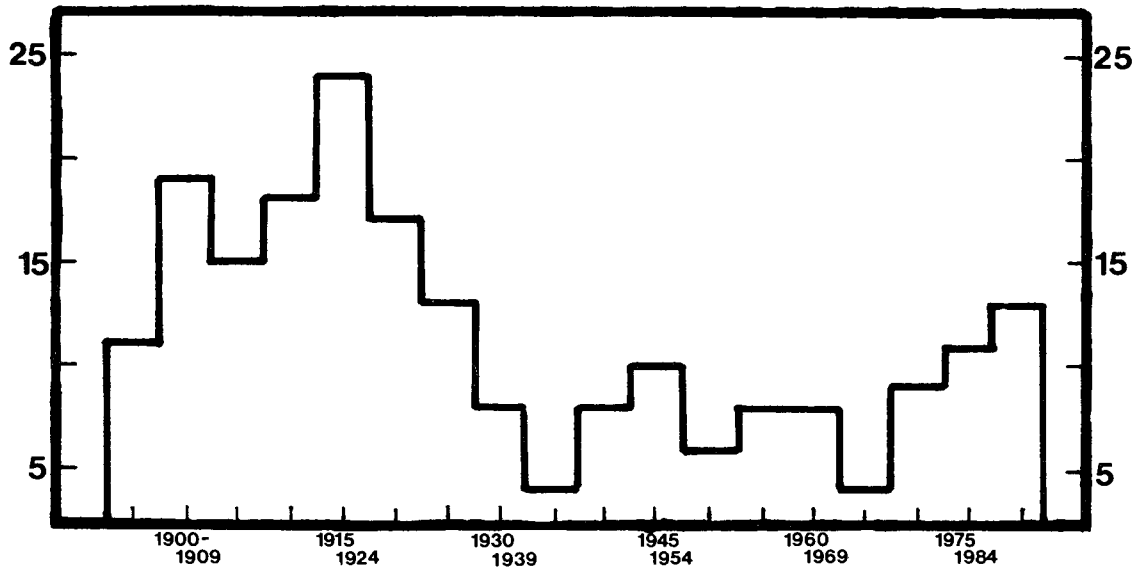


FIG. 3. The frequency of occurrence by decades, overlapping at 5-year intervals, of the number of 1200 UTC anticyclones during November–March in the Great Plains with central pressures exceeding 1045 mb, 1899–1989.

on the two nights when the high is east of Texas near Florida (more like those in Fig. 2b). The 1917 and 1940 freezes otherwise display characteristics similar to those in Fig. 2a.

Figure 2d shows the tracks of several of the strongest anticyclones in Table 3 that are not associated with hard or severe freezes in Florida. It is apparent that most of the highs stay well to the north of Florida and do not track directly southward through Texas as do those of Figs. 2a and 2c.

4. Interdecadal circulation variability associated with citrus freezes

Anticyclones with central pressures exceeding 1045 mb in the northern Great Plains grid area, during November–March, are more prevalent earlier this century than in recent decades (Fig. 3). They are most frequent in 1915–24 and least frequent in 1935–44 and 1965–74. There has been a small increase in their frequencies in the 1980s, but in general the recent cluster of citrus freezes occurs in a period of comparatively infrequent strong polar highs.

The *monthly* mean pressures in the Great Plains show a tendency similar to that of the synoptic anticyclone frequencies (Fig. 3). The February mean sea level pressure, 1899–1986, averaged at 50°N, 110° and 105°W, is characterized by a downward trend with time (Fig. 4a). The February mean pressure exceeds 1022 mb in over half of the winters from 1900 to 1925, but it exceeds this value in only seven winters since then. Similar trends (not shown) are noted in March and December data, but the January (Fig. 4b) pressure time series is characterized by more random variability

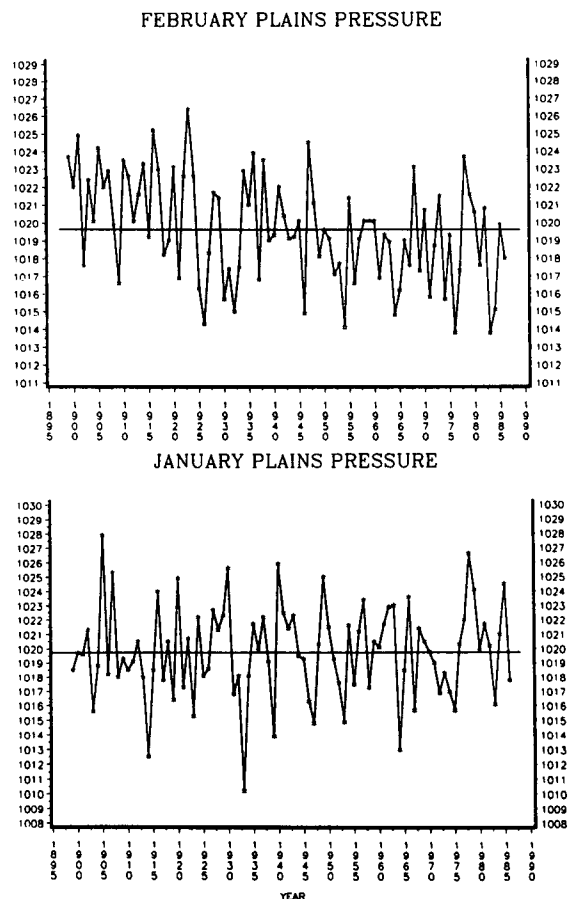


FIG. 4. The combined mean sea level pressure at grid points 50°N, 110° and 105°W for (a) Februarys and (b) Januarys, 1899–1986.

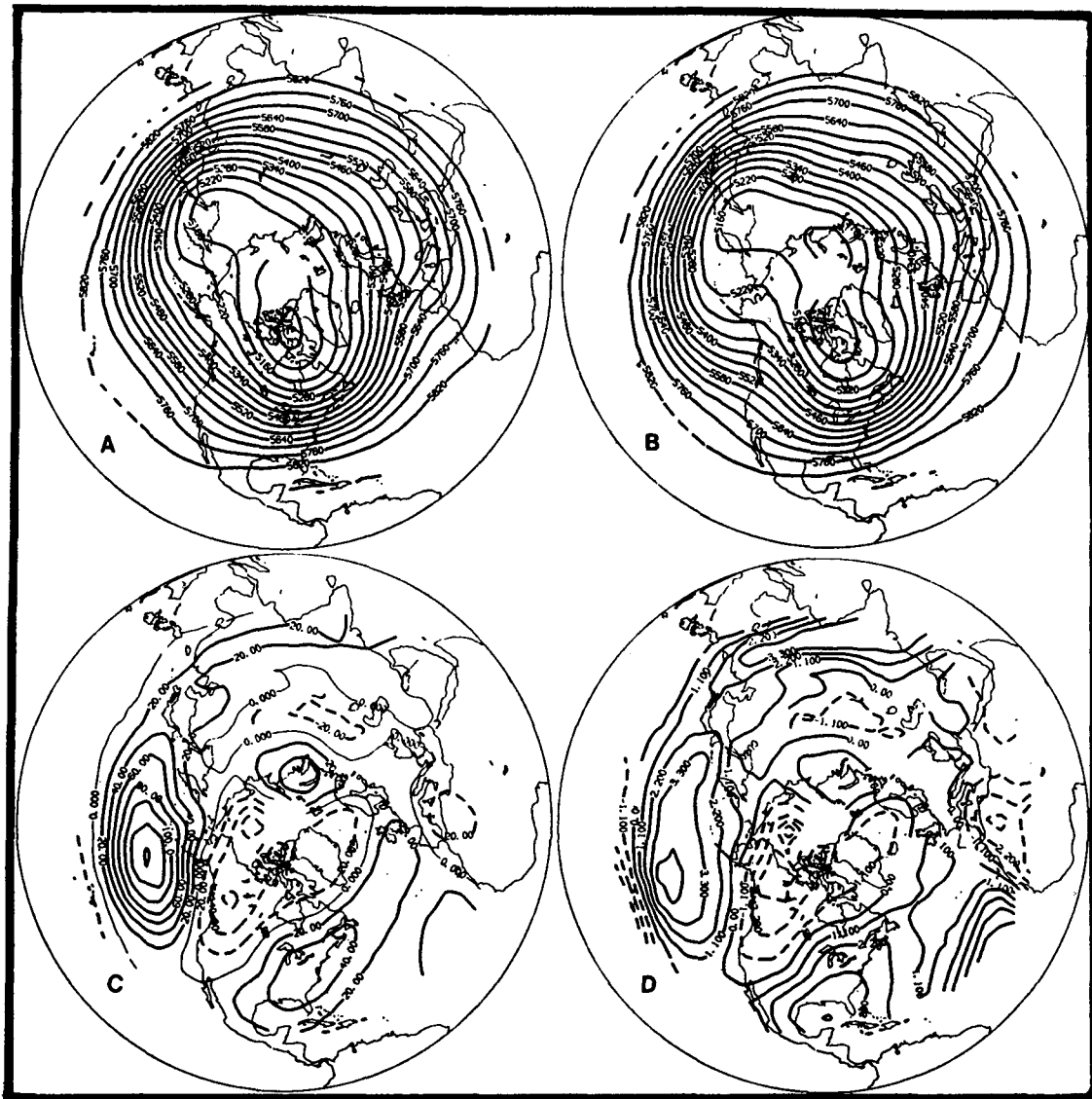


FIG. 5. The winter mean 500-mb geopotential heights for (a) 1947/48 through 1956/57 and (b) 1976/77 through 1985/86; (c) the mean difference between them (a minus b) and (d) a two-tailed t test of the height differences. The t values in excess of absolute 2.2 are statistically significant at the 95% confidence interval.

about the mean. The tendency for the highest monthly mean pressures on record to occur prior to 1925 is also noted in long-term station data at Bismarck, North Dakota, and Helena, Montana. Anticyclone passages dominate the pressure field at any given location in the plains for several days, and one or more strong anticyclones in a month may affect the monthly averages, explaining this apparent interdecadal linkage between synoptic frequencies and mean pressures.

The tendency for more frequent citrus freezes since 1977 may be related to interdecadal changes in the wintertime quasi-stationary standing wave patterns. Climatological changes in winter mean 500-mb flow are evaluated using gridded (5° latitude by 5° longi-

tude) geopotential height data. The mean 500-mb height is calculated over two 10-year periods: 1947/48 through 1956/57 (Fig. 5a), when major citrus freezes do not occur, and 1976/77 through 1985/86 (Fig. 5b). Comparison of Figs. 5a and 5b indicates that the mean flow is more zonal in the earlier period and more recently the mean quasi-stationary wave pattern across North America has greater amplitude characterized by more northwesterly flow. This is more apparent in Fig. 5c, showing the net height decreases over the southeastern United States (60 m at 35°N , 80°W) between the two periods and the height increases of about the same amount over northwestern North America (60°N , 125°W). Compared to the 40-year (1947–86)

JACKSONVILLE WINTER TEMP

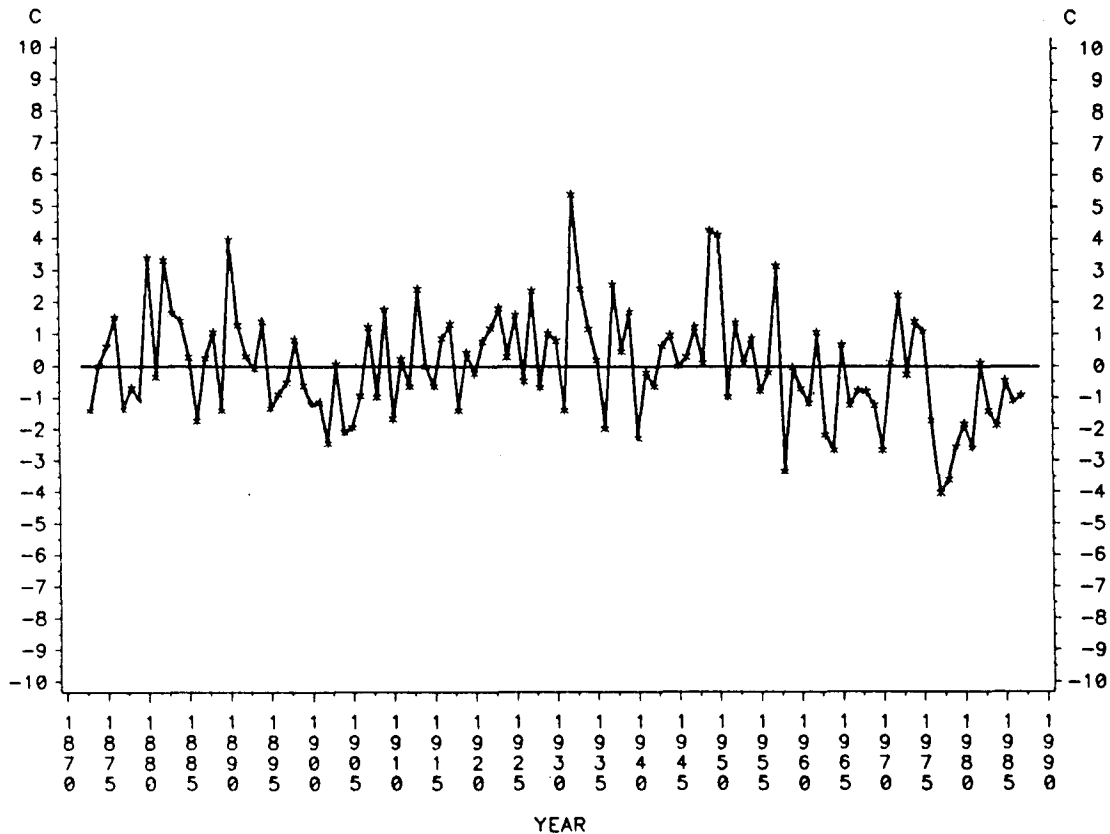


FIG. 6. The winter (December through February) mean air temperature departures from the 115-yr mean (°C) at Jacksonville, Florida, 1873–1987.

mean, the height departures at these grid points are, respectively, +40 m and -31 m in Fig. 5a and -20 m and +32 m in Fig. 5b. The largest mean decrease in heights between the two periods occurs over the northern Pacific Ocean (45°N, 165°W), where the departures in Figs. 5a and 5b are +69 m and -70 m, respectively. The differences between the mean height fields of the two periods are statistically significant (Fig. 5d), with 95% confidence, over broad areas around these centers when using a two-tailed *t* test.

Since the 1957/58 winter, mean air temperatures at Jacksonville, Florida, (Fig. 6) have been noticeably lower than in preceding decades to the 1870s. The mean winter temperature in 1977–86 is 3.1°C lower than that for 1948–57, nearly that estimated from the hypsometric equation for a mean 60-m height decrease in the thickness of the 1000–500-mb layer, assuming there is no change in mean sea level pressure. Additional discussion of the long-term Jacksonville temperature record is in Chen and Gerber (1985).

The spatial pattern of height differences occurring between the two periods (Fig. 5c) closely resembles

that associated with the Pacific/North American (PNA) teleconnection pattern (Wallace and Gutzler 1981). The PNA pattern is a preferred mode of wintertime midtropospheric variability in the Northern Hemisphere. It has been linked, along with changes in the mean Aleutian low, to interdecadal climatic fluctuations including warming around Alaska and the Yukon since 1977 (Trenberth 1990). The winter mean value of the PNA index (Wallace and Gutzler 1981) is negative in nine of the ten winters from 1948 to 1957, but it is positive in eight of the ten winters from 1977 to 1986. The winter PNA index after 1956/57 is characterized by more frequent positive values (meridional flow, Fig. 5b); this occurs concurrently with the post-1957 decrease in Jacksonville mean winter temperatures. Light or moderate citrus freezes occurred in many of the winters of the 1960s (Leavitt 1978), but the harshest freezes only begin after 1976.

The positive mode of the PNA, in which anomalous ridging occurs over western North America (Fig. 5b), has been linked to warm events in the equatorial Pacific Ocean and with the negative phase of the Southern

Oscillation (Horel and Wallace 1981) in which El Niño events occur. The period 1977–86 is correspondingly one in which the Southern Oscillation index has been persistently negative (Trenberth 1990). However, hard and severe freezes have only occurred in the El Niño winters of 1940/41, 1957/58, and 1976/77. Climatologically, Florida winters tend to be anomalously wet during El Niño events (Ropelewski and Halpert 1986), rather than anomalously warm or cold.

5. Summary

We have compiled a list of major Florida citrus freezes since 1880, based on historical evidence and agricultural reports. The most severe of these occur in clusters in the 1890s and since 1982, during what are generally known as advective freezes. Aside from these periods, hard and severe citrus freezes occur about once a decade. The advective freezes are characterized by distinctive anticyclone paths in which the strong polar high near the Canadian border usually moves quickly across the Great Plains to Texas and subsequently recurves northeastward. While most of the harshest Florida citrus freezes in Table 1 are preceded by some of the strongest polar anticyclones in the northern plains this century, strong anticyclones are not a necessary condition for hard or severe freezes. Many strong polar anticyclones (Table 3) move with a track across states north of Florida. Overall, the magnitude of the highs is not as critical a factor in severe freezes as is the path of the high.

The recent cluster of freezes is neither closely associated with a climatological period of frequent strong polar anticyclone outbreaks nor with a tendency for higher monthly mean pressures in the northern plains. In recent winters, however, the 500-mb upper-level flow has been more conducive to polar outbreaks, tending to have a more meridional orientation in the standing waves. During the freeze-free winters of 1947/48 through 1956/57, the winter mean flow was more zonal. The differences in the mean 500-mb circulation, between that period and 1976/77 through 1985/86, are associated with polarity changes in the Pacific/North American teleconnection pattern. On the synoptic time scale, the paths of the highs are closely linked to some basic aspects of freeze severity, and longer-term changes in the direction of the steering flow may be critical in determining the interdecadal frequencies of freezes.

Some aspects of citrus freezes over Florida and other southern states need more research. Further comparative analysis is warranted of the dynamics and paths of polar anticyclones driven by cold air advection and those that cause low minimum temperatures in the citrus belt primarily by radiational cooling under relatively calm conditions. In the same context, it is also of interest to examine freezes in relationship to the timing of the coldest portions of the polar air and to

explain why some hard and severe citrus freezes in southern Texas or Louisiana, such as those of 1949, 1951, and January 1962, caused relatively little damage in Florida, and conversely for events such as the Florida freezes of 1977 and 1981.

Acknowledgments. This work is supported by the National Science Foundation under Grant ATM-88-12087.

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