CHAPTER

3

Polar Air Outbreaks in the Americas: Assessments and Impacts During Modern and Past Climates

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Abstract

Polar outbreaks have long attracted the attention of meteorologists and climatologists. They are described here in terms of their air temperatures, air mass central pressures, and wind characteristics, as well as in relation to the atmospheric circulation and their trajectories over the continents. Outbreaks of polar air into low latitudes tend to organize tropical convection and rain in summer, while the cold air tends to produce cooling in lower latitudes and freezes in the subtropics during winter. Cold waves accompanying polar outbreaks have other significant impacts in the Americas, including adverse effects on coffee production in South America and on citrus production in North America. Synoptic events leading to cold waves are somewhat similar in the Americas, particularly in terms of the upper air patterns and forcing, but the intensity of the outbreaks in terms of temperature and pressure is larger in North America. Typically, they are associated with an amplified ridge lying across the western edge of the continent. Records of freezes in coffee- and citrus-growing areas are used to reconstruct subtropical climate variability and to identify linkages to low-frequency variability mechanisms in the atmospheric circulation. Results suggest that there is little link between the occurrence of El Niño and cold waves and freezes in either hemisphere. Citrus freeze occurrences in Florida are linked to the long-term variability in the Pacific–North American (PNA) teleconnection pattern, and they appear to occur in clusters concentrated near the end of each century. Comparisons are made of possible paleoclimate scenarios for the occurrence of cold waves based on evidence reconstructed from pollen and lake sediment samples collected in southeastern and central Brazil.

Resumen

Incursiones de aire frío de origen polar han atraído la atención de meteorólogos y climatólogos desde ya hace mucho tiempo. Estas incursiones de aire polar han sido estudiadas y caracterizadas en base a sus características de temperatura, intensidad del centro de alta presión atmosférica, y del comportamiento de la circulación y trayectorias del aire frío una vez que entran al continente. Las irrupciones de aire polar hacia latitudes más bajas tienden a organizar la convección y producir lluvia en verano, mientras que en invierno el aire frío tiende a producir enfriamiento y a veces, hasta heladas en latitudes subtropicales. Ondas de frío que acompañan las incursiones de aire frío tienen un impacto significativo en las Américas, incluyendo efectos adversos en la producción de café en América del Sur, y de naran-

jas y otros cítricos en América del Norte. Los eventos sinópticos que preceden a las ondas de frío son similares en ambas América del Norte y del Sur, particularmente en relación a las forzantes y a la circulación en altura, pero la intensidad de estas irrupciones y el enfriamiento que producen es mayor en América del Norte. Las ondas de frío muestran como característica general la amplificación de una cresta localizada a lo largo del extremo oeste del continente. Registros de ocurrencias de heladas que afectaron al café y cítricos son usados como indicadores climáticos, para reconstruir la variabilidad climática en la región subtropical, y para identificar los mecanismos de variabilidad climática de baja frecuencia en la circulación atmosférica, asociada a las ondas de frío. Resultados de los estudios realizados sugieren de que hay poca relación entre la ocurrencia del fenomeno El Niño y la presencia de ondas de frío en invierno de ambos hemisferios. Ondas de frío y heladas que afectan a los cítricos en el estado de Florida, U.S.A. estan asociados a la variabilidad de largo plazo del patrón de teleconección identificado como Pacífico–América del Norte (Pacific–North American, PNA), y parece de que se concentran en grupos y eventos al final de cada siglo. Se hacen comparaciones con posibles escenarios paleo-climáticos caracteristicos de episodios fuertes de ondas de frío, basados en reconstrucciones a partir de muestras de granos de pólen y de sedimentos de lagos, colectados en las regiones del sureste y central de Brasil.

3.1. INTRODUCTION

The North and South American atmospheric circulation is characterized by interactions occurring between warm, moist air masses of tropical latitudes and cold, dry air of higher latitudes. An *air mass* is a large dome of air, typically thousands of kilometers across, that has similar horizontal temperature and moisture characteristics acquired from the underlying surface of the Earth. Five basic air masses affect the Americas' weather: continental Arctic (or Antarctic), continental polar, maritime polar, maritime tropical, and continental tropical. North American continental polar air masses originate to the south of the Arctic Circle over northwestern North America and dominate the winter weather across the United States, while continental Arctic masses originate over the Arctic Ocean or even over Siberia. In South America, cold air masses of Antarctic or polar oceanic origin can reach deep into the core of the tropics, affecting the regional agriculture in southern Brazil and sometimes producing cooling that can be detected in the western Amazon region.

Polar outbreaks occur when polar air masses clash with continental or maritime tropical air. The transition regions between these air masses are *frontal boundaries*, narrow zones where temperature changes substantially within short horizontal distances of between 10 and 150 km. Typically, cold air pushes and lifts the warm air due to its greater density, and the leading *cold front* boundary separating warm and cool air is identified on weather charts in places where the dense air is advancing to replace the warm air at the Earth's surface. In general, *polar outbreaks* represent a thrust of cold air from higher to lower latitudes, affecting the weather and climate in certain regions of the planet. They are noticeable features of the distribution of low-level temperature, circulation, and rainfall over both North and South America. Evidence suggests that these air mass and frontal exchanges existed in climates of the past, but with different intensities than at the present.

We interchangeably use other common phrases for polar outbreaks in this chapter, including *cold waves*, *cold surges*, and *cold spells*. Polar outbreaks have long attracted the attention of forecasters, especially the rapid temperature change or cold waves. Cox (1916) described the basic atmospheric factors defining the severity of polar outbreaks, factors that go beyond temperature changes:

> 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 and the low and the consequent wind force, the direction of the movement of the high and also the direction and movement of the high and low or lows which it is following, the general character of the sky, the humidity, whether there is snow on the ground, and the season of the year; in a word, all the atmospheric conditions, sometimes even within an area of 3000 or 4000 square miles or more.

Transient incursions of polar and midlatitude air into subtropical and tropical latitudes are a distinctive feature of the synoptic climatology of the Americas. These incursions are a year-round phenomenon, with relatively modest seasonal changes in their structure, and have their largest impact on summer precipitation and on the wintertime temperature field. Meridional exchanges of air masses between lower and higher latitudes in South America are the most intense in the entire Southern Hemisphere, mainly due to the presence of the Andes Mountains. The effects of these polar outbreaks are mainly regional, and studies of cold surges have focused on southeastern Asia bounded by the Himalayan Plateau (Wu and Chan 1995, 1997); the east side of the Rocky Mountains, including impacts on the western side of the Great Plains in North America (Colle and Mass, 1995); and Central America and the Caribbean (Schultz et al., 1997, 1998). In South America, episodic cold surges into the east of the subtropical

Andes sometimes result in freezing conditions in southeastern Brazil during winter (Hamilton and Tarifa, 1978; Fortune and Kousky, 1983; Marengo et al., 1997a,b; Bosart et al., 1998; Seluchi and Marengo, in press) or in enhanced convection and rainfall during summer (Kousky, 1979; Garreaud and Wallace, in press; Liebmann et al., 1998). Cold frontal passages and cold surges have also been documented in Australia (Baines, 1983; Smith et al., 1995).

This chapter examines polar outbreaks in the Americas and their societal impacts, focusing on their meteorological and climatological characteristics, on the proxy climate evidence available in citrus (North America) and coffee (South America) production, and on the freeze statistics dating to the nineteenth century. Citrus and coffee crops are important to the economy of tropical regions, and freezes associated with polar air outbreaks compromise their production and subsequent prices in world markets. Records of damages to these crops also serve as an indicator of the cold wave severity occurring at higher latitudes along the paths of polar air masses. We document (1) weather patterns of wintertime polar outbreaks in the Americas and their interannual and interdecadal variability, (2) circulation features and mechanisms typical of polar outbreaks and their variability in time, and (3) the impact of these polar outbreaks on coffee and citrus production in South and North America. On paleoclimatic scales, information deduced from fossilized pollen and lake sediments (indicators of vegetation distribution) has been used to detect the potential variability of polar outbreaks in the early Holocene. It will be shown that the presence of relicts of *Araucaria* forests in southern Brazil may be an indicator of variability in the frequency of cold fronts and related polar outbreaks during the late Quaternary period. Our topic fits the scope of this book, covering present and past interhemispheric climate linkages between the Americas and their societal impacts. For a more complete review of the meteorological and dynamics aspects of the polar outbreaks, as well as several case studies in North, Central, and South America, the reader should refer to the papers by Schultz et al. (1997, 1998), Garreaud, R. D. (2000), Seluchi and Marengo (in press), Garreaud and Wallace (in press), Marengo et al. (1997a), Konrad (1996), and Colle and Mass (1995), among others.

3.2. REVIEW OF LOWER- AND UPPER-LEVEL CIRCULATION IN THE AMERICAS

In this section, we show the mean seasonal summer and wintertime ensembles of near-surface (925 hPa [hectoPascal]) and upper level (200 hPa) atmospheric circulation for December–February and June–August, drawing upon the studies of Hastenrath (1996) and Kousky and Ropelewski (1997).

The seasonally varying mean circulation features are intimately linked to the horizontal gradients in temperature. The tropics are heated strongly throughout the year, while middle and high latitudes experience considerable variation in heating from summer to winter due to variations in solar insolation. As a result, mean meridional temperature gradients, and consequently the strength of the low-level zonal winds, vary considerably from summer to winter (Figs. 1A and 1B and 2A and 2B). The strongest meridional temperature gradients and strongest zonal winds are generally observed in middle latitudes of the winter hemisphere, especially the Southern Hemisphere. The Southern Hemisphere winter jet stream (maximum in zonal winds, Fig. 2A) is closer to the equator than the corresponding Northern Hemisphere winter jet stream (Fig. 1A), reflecting the asymmetry in heating occurring between the hemispheres. Zonal asymmetries in atmospheric circulation in the Western Hemisphere arise primarily due to the difference in thermal capacity between land and water. Continental areas are often warmer during the summer and cooler during the winter compared to neighboring oceanic regions.

The subtropical highs over the South Pacific and the South Atlantic display very little seasonality in either central pressure or position between winter and summer (Figs. 1B and 2B). However, there is a seasonal cycle in the sea level pressure (SLP) over central South America, with the lowest pressures occurring during December–February and the highest pressures occurring during June–August (Figs. 1B and 2B). This pattern is consistent with the seasonal variation in the low-level meridional flow, which features strong flow from the Amazon basin southward to northern Argentina during austral summer (December–January–February, DJF), and much weaker flow from the north but stronger flow from southern latitudes into lower latitudes during winter (June–July–August, JJA). An important feature of the upper level summertime circulation over South America is the presence of an anticyclonic circulation over the Bolivian Plateau that is absent during winter (Fig. 2A).

Seasonal variations in SLP are evident over the middle and high latitudes of the North Pacific and North Atlantic Oceans. There is a marked northwestward shift from winter to summer (Figs. 1B and 2B) in the central positions of the oceanic anticyclones, and their central pressure increases somewhat during summer in response to the relative coldness of the underlying surface. High pressure dominates continental North America during winter, and lower pressure dominates

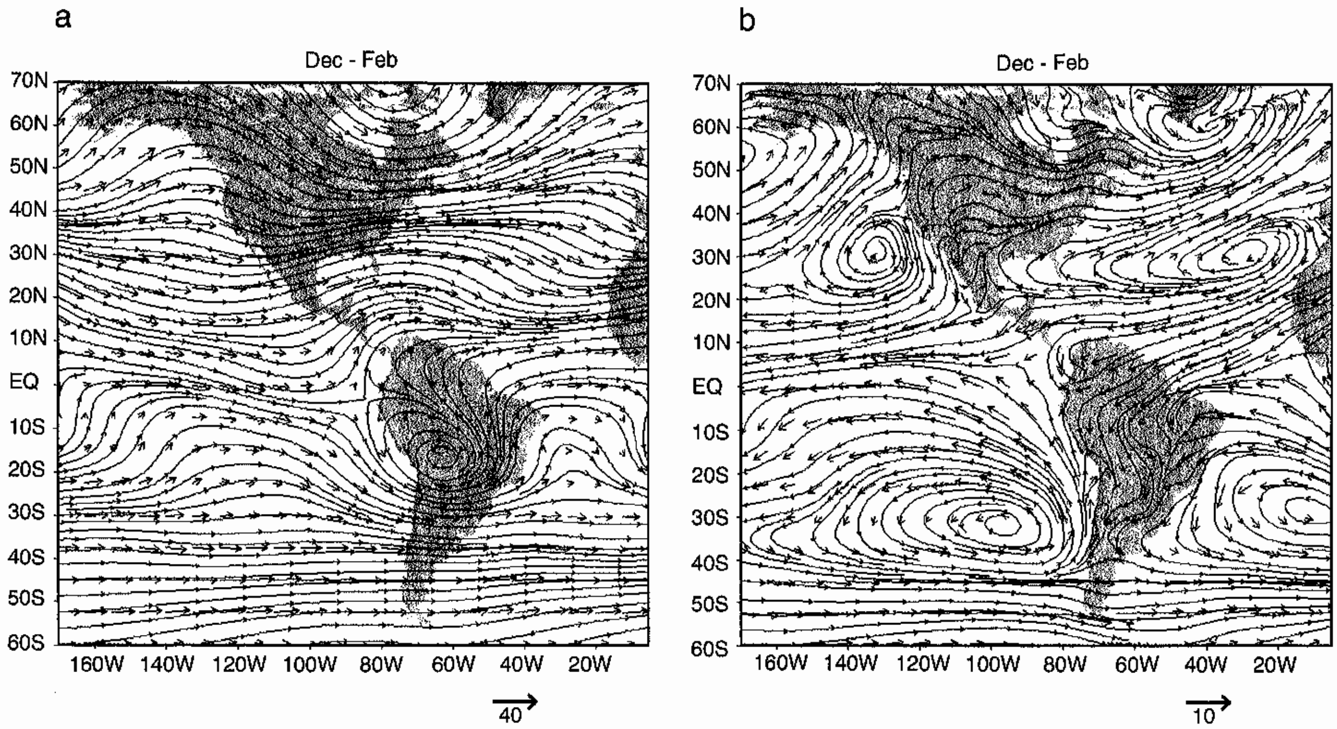

FIGURE 1 Mean seasonal summer and wintertime ensembles for December–February, (A) Upper level circulation (200 hPa) over the Americas, and (B) near-surface circulation (925 hPa) over the Americas.

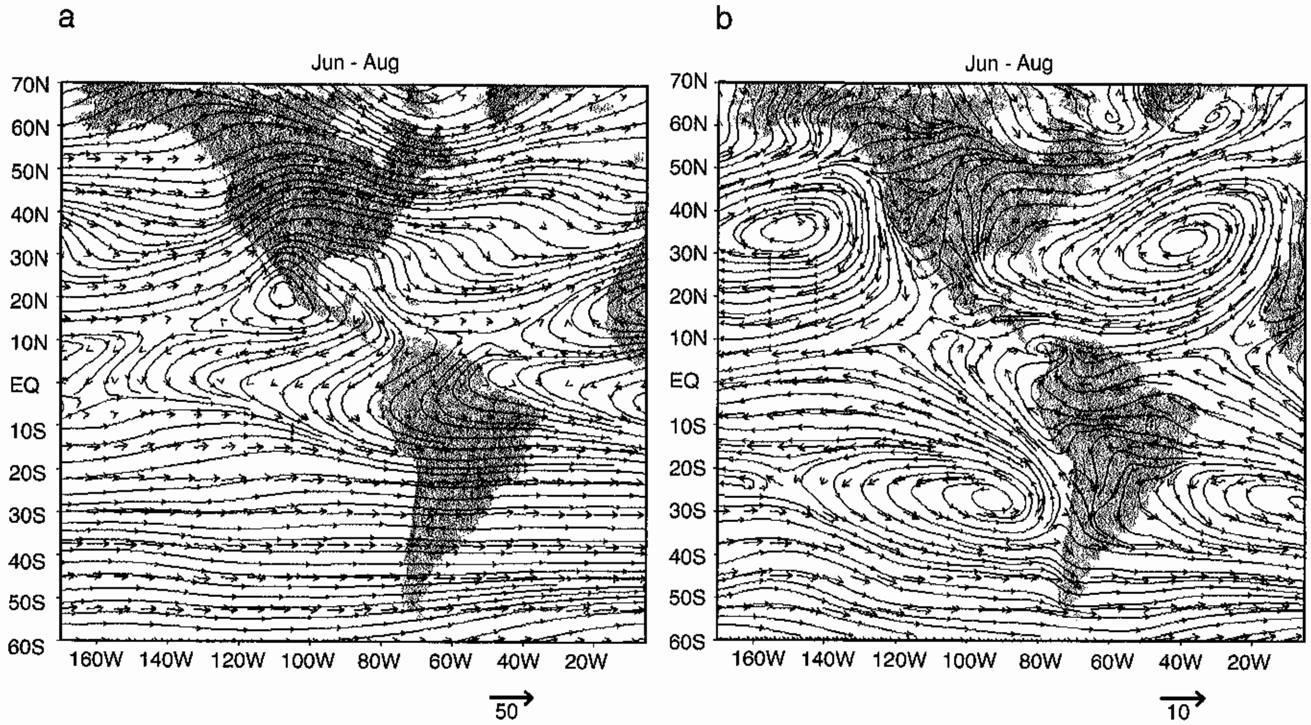

FIGURE 2 Mean seasonal summer and wintertime ensembles for June–August, (A) Upper level circulation (200 hPa) over the Americas, and (B) near-surface circulation (925 hPa) over the Americas.

it during summer; however, the seasonal variations in surface winds are not as apparent as over tropical South America.

Throughout the year a mean westerly (zonal) flow dominates much of the middle latitudes of both hemispheres (Figs. 1A and 2A). The zonal flow is strongest in each hemisphere's winter and weaker in the summer. However, the zonal flow is strongest in both hemispheres in the southern winter (Fig. 2A), and the weakening occurring in the southern summer reaches an intensity that still approximately matches the mean strength of the flow during the northern winter (Fig. 1A). The mean flow during the northern summer is seasonally the weakest on the planet. Comparison between hemispheres in Figs. 1A and 2A also reveals a greater wavelike structure, or meridionality, to the flow in the Northern Hemisphere. Northern winters are occasionally beset by periods in which the westerly flow decreases or becomes blocked, and meridional (north-south) flow begins to dominate the circulation. This flow is accompanied by an amplification of the wave ridges, notably the ridge visible at higher latitudes over western North America and the eastern Pacific (Fig. 1A). During periods of blocked westerlies, unusually cold weather persists over North America for 2–4 weeks. These long cold spells can have cold waves (2–6 days duration) embedded within them, although their severity may not always be nearly as great as those of some of the events described later in this chapter. The persistent cold meridional flow periods have created some extraordinarily cold winters, especially east of the Rocky Mountains, that are long remembered by many people. Some of these in recent memory include the winters of 1962–63, 1968–69, 1976–77, 1978–79, and 1981–82. The 1968–69 and 1978–79 winters did not, however, witness the occurrence of strong, well-known severe polar outbreaks. Blocking ridges can also occur in the Southern Hemisphere around and over the Andes, producing cold waves in South America, but the hemispheric climatological flow (Figs. 1A and 2A) gives little hint of their existence.

3.3. POLAR OUTBREAKS AND THEIR SIGNIFICANCE IN THE CLIMATE OF THE AMERICAS

3.3.1. South American Polar Outbreaks

Synoptic-scale incursions of midlatitude air moving into tropical and subtropical latitudes east of the Andes (leeward side) are observed all year long in two preferred regions: the first is located close to the mountains between 20° and 30°S, and the second region is located in southern Brazil, extending into the adjacent Atlantic.

In summer (December–February), cold air from higher southern latitudes moves into tropical latitudes behind a cold front and organizes tropical convection. This movement has a large influence on climatological rainfall patterns over central Brazil and eastern Amazonia. At this time of the year, there is a strong southward advection of warm and humid air coming from the northern Amazon that creates favorable conditions for the development of mesoscale convective systems linked to abundant rainfall over Paraguay and northern Argentina. On the leeward side of the Andes, incursions of polar air toward lower latitudes accompanying a cold front are favored by the channeling effect of the mountains. During these incursions, cold fronts move northward and merge with the South Atlantic Convergence Zone (SACZ), a region of convergence of moist air from the Amazon and cold air from the south, generating convection that is enhanced by the assimilation of the cold fronts. Because of this convergence, the SACZ is more intense in summer (Garreaud, in press a,b,; Liebmann et al., 1998; Seluchi and Marengo, in press).

In winter (June–August), polar air masses move from higher to lower latitudes and the cold front sometimes becomes stationary, allowing an intense nocturnal cooling of the surface, associated with low humidity and a lack of clouds. This cold air has undergone modifications along its path, but still may be cold enough to produce freezing conditions and snow in the subtropical parts of Brazil. Freezing weather in southeastern Brazil is caused by these polar air outbreaks in May–August. Events like these are known by the Portuguese name of *friagem* (plural: friagems) or *Surazo* in the Amazon region, where they have a marked effect on tropical and extratropical weather. These cold surges occur several times per year (from zero to eight times), producing low temperatures in the midlatitudes, and are sometimes so strong that extensive freezes affect southeastern Brazil (see reviews in Marengo et al., 1997a). In some episodes, the cold surges produce considerable cooling in central and northern Amazonia (Morize, 1992; Serra and Ratisbona, 1942; Parmenter, 1976; Fortune and Kousky, 1983; Satyamurty et al., 1990; Seluchi and Nery, 1992; Marengo et al., 1997a,b; Seluchi and Marengo, in press).

3.3.1.1. Conceptual Model of South American Polar Outbreaks

Most of the literature on South American polar outbreaks has focused on descriptions of the circulation and dynamics of individual episodes (see reviews in Marengo et al. 1997a; Garreaud, 1999, 2000; Marengo, in press), while more recent work has focused on the

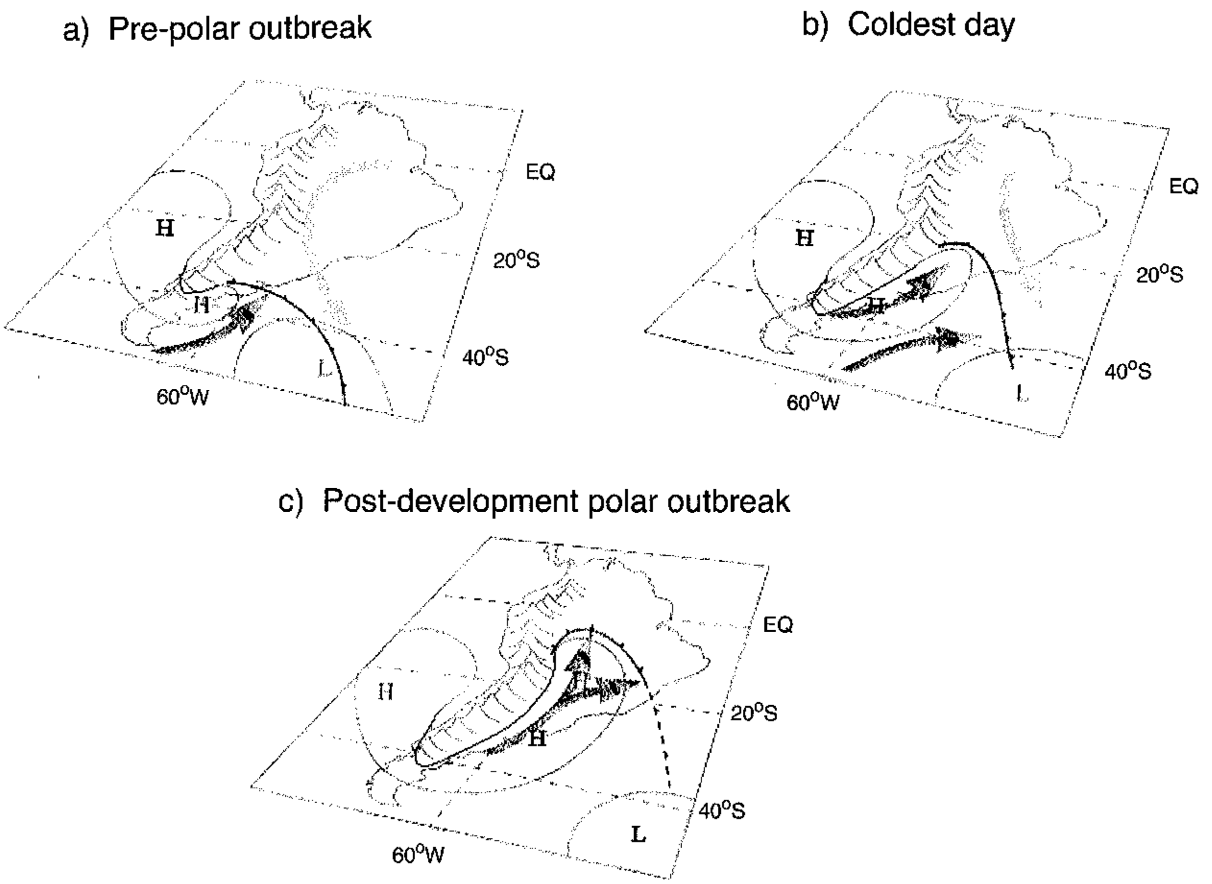

FIGURE 3 Conceptual model of wintertime polar outbreaks in South America. (Adapted from Marengo et al., 1997a; Garreaud, in press b.)

mean structure, evolution, and dynamics of these phenomena (Garreaud, in press a,b; Seluchi and Marengo, in press; Kousky and Cavalcanti, 1997). Based on literature published from early work by Morize (1922) to the most recent work by Garreaud (1999, 2000) and Marengo et al. (1997a) describing general features and discussing individual case studies, a simple conceptual model for wintertime polar outbreaks is shown in Fig. 3.

Several case studies have shown that cold outbreaks and some freeze events in southern Brazil are preceded by a slow eastward-moving long wave in the South Pacific Ocean, which is amplified greatly some days before (see review in Marengo, in press) and exhibits large meridional displacements of the flow (see Table 1 for some cold events in the state of São Paulo, Brazil). When at maximum amplitude, the wave ridge is usually located near the southern Andes, while the next downstream trough lies over the South Atlantic in Brazilian longitudes. This typical configuration allows air originally from higher latitudes to be channeled equatorward. Frontogenesis is associated with the wave amplification, and a freeze occurs east of the polar anticyclone. In South American cold waves, an anticyclone–cyclone couplet causes the associated southerlies to transport colder air from high latitudes, contributing substantially to the cooling. The conceptual model (Garreaud, 1999; Marengo et al., 1997a) shows the evolution of near-surface circulation patterns. Key elements include the cold core anticyclone that moves from the southeastern Pacific into southern Argentina near the extreme southernmost region of South America, as well as the cyclone over the southwestern Atlantic. South of 30°S these two pressure systems grow due to upper level vorticity advection. During the pre-polar outbreak period, before the coldest day in southeastern Brazil (Fig. 3A), the geostrophic southerly winds between the high- and low-pressure systems produce low-level cooling along the east coast of South America and farther inland as far north as 25°S.

Closer to the tropical Andes, the low-level flow is blocked during the developmental period, leading to ageostrophic, mountain parallel flow (Fig. 3B) and cold

TABLE 1 List of Cold Events in the State of São Paulo, Brazil and Their Intensity

Date	Intensity (min. temp., °C)	Damage
14 July 1892	0.2	Severe
14 July 1894	1.0	Severe
25 July 1895	1.0	Severe
18 June 1899	1.6	Moderate
19 August 1902	0.2	Very intense
12 August 1904	1.5	Severe
3 September 1912	1.8	Severe
25 June 1918	−1.5	Very intense
12 July 1923	2.0	Weak/absent
4 July 1925	2.0	Weak/absent
29 June 1931	2.0	Moderate
14 July 1933	1.4	Moderate
12 July 1942	−0.2	Severe
15 September 1943	2.0	Moderate
5 July 1953	1.2	Severe
2 August 1955	2.0	Severe
21 July 1957	1.2	Moderate
7 July 1962	2.4	Severe
21 August 1965	0.6	Moderate
11 July 1969	2.4	Severe
9 July 1972	1.6	Moderate
18 July 1975	0.6	Very intense
31 May 1979	0.2	Severe
21 July 1981	0.2	Severe/very intense
8 June 1985	1.4	Moderate
5 June 1988	1.8	Moderate
27 June 1994	0.3	Severe/very severe
10 July 1994	0.1	Severe/very severe

Adapted from Marshall, 1983 and updated by J. Zullo (Centro de Pesquisas Agricolas [CEPAGRI], Universidade de Campinas, São Paulo, Brazil). No cold events that affected coffee were registered after the ones in winter 1994.

air damming. As the cold air moves into lower latitudes (Fig. 3C), the blocking effect of the Andes diminishes (due to a more zonal orientation of the Andes to the north of 18°S). Cold advection produced by the southerly wind produces most of the local cooling at the leading edge of the surge, and the cooling is felt in southeastern Brazil and on the west side of Brazil adjacent to the Andes. Thus, the advance of the polar air outbreak along the subtropical Andes is set up by the topographic blocking of the flow.

Accompanying the cold surge is an area of surface high pressure. The highest pressure detected in central South America with a cold spell was 1044 hPa during the event of 15 July 1975 (Tarifa et al., 1977; Marengo, in press), which was considered the strongest in the twentieth century. Cold wave central pressure intensities in southern Brazil rarely exceed 1038 hPa: e.g., 1035 hPa (June 1994, Marengo et al., 1997a) and 1033 hPa (July 1981, Haddock et al., 1981).

3.3.2. North and Central American Polar Outbreaks

Cold waves have long attracted the attention of North American weather forecasters and climatologists (Garriott, 1906; Cox, 1916). Cold waves have been defined by meteorologists in terms of (1) severity or rapidity of the drop in air temperature (Wendland, 1987), (2) the numerical values of the low temperatures or temperature departures that ultimately occur, and (3) the duration of the cold wave (varying time spans can be used) per the Cox (1916) quotation in the Introduction. To a lesser extent the cold wave can be characterized by the intensity of the polar anticyclone accompanying it (Rogers and Rohli, 1991). In North America, polar outbreaks are frequently observed east of the Rocky Mountains–Mexican Sierras. The most visible feature of the winter polar outbreaks is the surface anticyclone moving from its Alaskan/Yukon source region and associated with the southward transport of cold air across its core and eastern flank (Rogers and Rohli, 1991). SLPs associated with the core of the air mass can exceed 1070 hPa in northwestern Canada, but the central pressure decreases steadily with the southward movement of the polar outbreak, seldom exceeding 1055 hPa once the central high-pressure area enters the United States and 1040 hPa by the time it reaches the United States East Coast or the Gulf of México. The December 1983 and 1989 cold waves and citrus freezes were associated with polar highs with central pressures in excess of 1055 hPa when the anticyclones entered the northern Great Plains of the United States (Rogers and Rohli, 1991). Some examples of anticyclone central pressures in the northern Plains for severe cold events are given in Table 2.

The polar outbreaks are typically associated with record low temperatures (Konrad and Colucci, 1989) and produce numerous adverse socioeconomic impacts across many parts of the United States, including loss of vegetable crops and citrus, damage to homes and plumbing, human mortality, and disruption of transportation systems, among other problems. Air temperatures in the northern Great Plains reached −35°C during the 1989 polar outbreak, and it broke over 250 minimum temperature records across the United States, ultimately producing a citrus freeze in Florida (Rogers and Rohli, 1991). Colle and Mass (1995) have documented northerly surges of cold air that often move equatorward along the eastern side of the Rockies into México and have described the strongest surges that developed in the midwinter of 1994, with temperature decreases of 20°–30°C and pressure rises of 15–30 hPa within 24 hr. These cold surges have several regional names in North and Central America: *Blue*

TABLE 2 Strongest Anticyclones Detected over the Northern Great Plains on 1200 UTC (Universal Time Zone) Synoptic Charts for the Period 1899–1989 and Associated Agricultural Damage in Florida

Date	Intensity (pressure, hPa)	Damage
3 January 1766	Unknown	Severe
7–8 February 1835	Unknown	Very severe
30 December 1880	1048.7	Severe
10–12 January 1886	1047.4	Severe
27 December 1894	1054.5	Severe
7 February 1895	1055.9	Severe
11 February 1899	1059.3	Severe
25 January 1905	1053.8	Moderate
30 December 1909	1032.4	Moderate
1–4 February 1917	1056.9	Severe
28 December 1917	1060.3	Vegetables
20 February 1918	1053.8	None
24 January 1920	1056.5	None
14 February 1923	1056.2	Some
20 December 1924	1057.2	None
27 December 1924	1054.5	None
27 December 1925	1055.2	Vegetables
14 January 1927	1053.2	Citrus
3–4 January 1928	1052.5	Moderate
12–13 December 1934	1030.7	Severe
28–29 January 1940	1051.9	Moderate
3 January 1947	1052.1	None
10–11 February 1947	1052.1	Severe
12–13 December 1957	1046.3	Severe
24 January 1961	1052.3	Severe
10 January 1962	1059.3	Moderate
13–14 December 1962	1045.3	Very severe
9–12 January 1977	1039.9	Moderate
13–14 January 1981	1040.1	Moderate
11–12 January 1982	1054.1	Severe
25 December 1983	1058.7	Severe
21–22 January 1985	1048.0	Severe
5 February 1988	1052.3	None
3 February 1989	1058.5	None
17 February 1989	1057.8	None
23–25 December 1989	1054.9	Severe

Modified from Rogers and Rohli, 1991.

Northers in Texas; *Nortes*, *Chocolatero*, and *Tehuano* in México; *Papagayo* in Nicaragua and Guatemala; *Atemporalado* in Honduras; and *Invierno de las Chicharras* in Venezuela.

Dalavalle and Bosart (1975) indicate that comparatively weak anticyclones (<1045 hPa) can also produce severe freezes over North America. The cold waves of the 1990s have been among the 10 worst events this century in the midwestern United States in terms of low temperature values (Rogers, 1997), but were associated with anticyclones of only moderate strength. The mid-January 1994 cold wave was associated with two fast-moving highs having intensities under 1040 hPa, the second of which was advected over the Plains behind an intense cyclone that moved across the Great Lakes. The early February 1996 cold wave was ushered in by the cold air advection behind a strong Alberta storm moving across the Midwest, producing an anticyclone that just exceeded 1040 hPa in intensity. Even the Florida freeze of 19–20 January 1997 was associated with an anticyclone of about 1042 hPa in intensity. The trajectory of this anticyclone was characteristic of that for Florida advective freezes (which are the most severe, as described in Section 3.4.2), but its intensity was vastly below normal and the bulk of the freeze damage was probably due to radiative cooling of the air.

As the cold front of a polar outbreak reaches the Gulf of México or the United States East Coast, a strong baroclinic zone is typically established in conjunction with the warm adjacent ocean that is the site of subsequent cyclone development. Thus, as the anticyclone at the core of the polar air mass enters the United States, traveling southward, cyclogenesis begins occurring along the coastal areas. The developing cyclone will frequently evolve into a ferocious *nor'easter* along the eastern coast of the United States (Kocin and Uccellini, 1990), producing tremendous snowfalls along the Atlantic coast and thereby creating many societal impacts of its own. One example is the East Coast storm accompanying what is still regarded as the worst cold wave on record in many parts of the country—that of 8–11 February 1899 (Kocin et al., 1988). The East Coast cyclone developed while the cold wave was advancing across the midsection of the continent, producing a strong baroclinic zone across the southeastern United States. Intensification of the pressure gradient occurred across the anticyclone/cyclone couplet, producing strong cold air advection and a further decline in air temperature and wind chill from the Plains to the East Coast. Schultz et al. (1997) studied the United States superstorm of 12–14 March 1993, which developed after polar air, originating over Alaska and western Canada, brought northerlies exceeding 20 m sec^{-1} and temperature decreases up to 15°C over 24 hr into México and Central America. During this cold surge, topographically channeled northerlies along the Rocky and Sierra Madre Mountains advected cold air equatorward, reaching as far south as 7°N, and the dynamical forcing associated with the low-latitude upper level trough and confluent jet-entrance region over México and Central America, in addition to the topographic channeling, favored the extraordinary equatorward incursion of cold air.

Schultz et al. (1998), Steenburgh et al. (1998), and Klaus (1973) documented midlatitude cold surges affecting México and Central America, based on observations and regional modeling. A *Central American cold* *surge* is defined as the leading edge of a cold anticyclone originating poleward of México that has penetrated equatorward to at least 20°N. Although the topographies of the Rocky Mountains and the Sierra Madre undoubtedly play an important role in channeling the cold surge equatorward, different planetary- and synoptic-scale flow patterns can also be conducive to longevity of Central American cold surges. From 177 cases studied, they concluded that 75% of the cold surges had durations of 2–6 days, the same timescale as mobile disturbances in the westerlies. There does not appear to be any relationship between the temperature drop and the duration of the event, although cold surges penetrating to low latitudes (7°–10°N) have a weak tendency to persist longer than those that do not penetrate to low latitudes (15°–20°N). In addition, cold surges tend to reach their most equatorward extent where topographic features impede the progress of cold air; the temperature decreases in the postsurge air do not appear to be related to the latitude of the cold outbreak.

3.3.3. Conceptual Model for North-Central American Cold Surges

As with the South American illustration in Fig. 3, the North American conceptual model (Figs. 4A–4C) shows the evolution of the surface circulation components of a polar outbreak, based on the work of Dallavalle and Bosart (1975), Konrad and Colucci (1989), Kocin and Uccellini (1990), Konrad (1996), and Schultz et al. (1998), for severe North American cold waves. Many different synoptic circumstances can lead to polar outbreaks around North America; we illustrate just one here, which is associated with severe cold waves over the eastern United States.

The polar outbreak begins (Fig. 4A) with a strong polar anticyclone moving away from its source region across south-central Canada into the United States. The polar high likely originates over snow-covered plains and forests of northwestern Canada, acquiring its characteristics from radiative cooling during the long polar nights. The dense, cold air is linked to a large positive

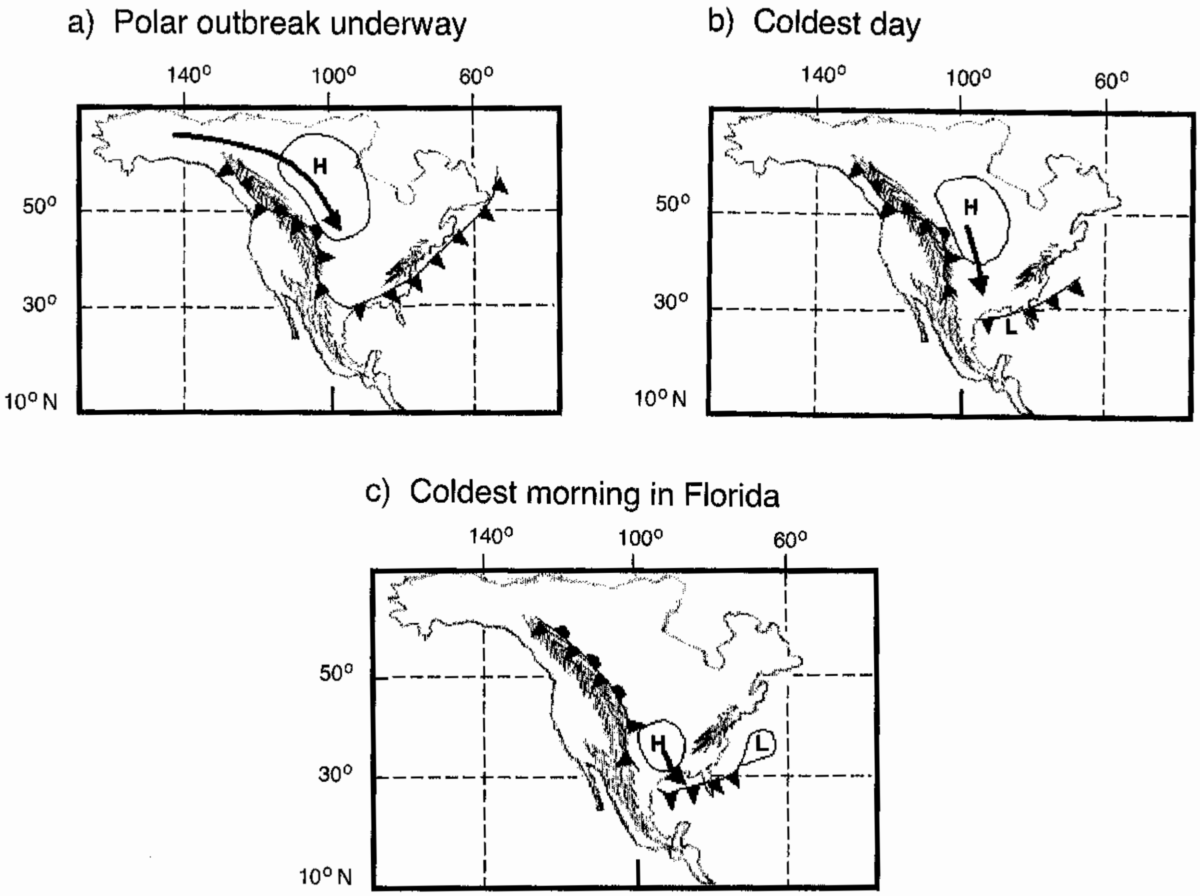

FIGURE 4 Conceptual model of wintertime polar outbreaks in North-Central America. (Adapted from Dallavalle and Bosart, 1975; Kocin and Uccellini, 1990; Schultz et al., 1998; Konrad, 1996; Konrad and Colucci, 1989.)

pressure anomaly at the core of the air mass. The baroclinic zone that is continually present south of the high encourages its south-southeastward motion by the process of cold air advection. The leading edge of the polar air approaches the Gulf of México in Fig. 4A, where strong baroclinicity is also developing. Within 12–24 hr (Fig. 4B), the cold front has entered México and a substantial cold outbreak begins in that country. Low-temperature records are also being set in the northern United States. A frontal wave develops in the Gulf baroclinic zone. The western boundary of the cold air mass is illustrated here as lying along the Rocky Mountains, a common barrier to the shallow cold air mass.

Within another 24–48 hr, the polar high reaches Texas (Fig. 4C) and is no longer supported by cold air advection. It is at its greatest peril of dissipating, especially over the relatively warm environment around the Gulf of México. It has weakened substantially, but is being maintained to some extent by the relatively cold continental surface. The cyclone developing in the Gulf in Fig. 4B has slowly migrated northeastward, undergoing a process of *secondary redevelopment* (Kocin and Uccellini, 1990) that leads to cyclogenesis off the East Coast. The East Coast cyclone will rapidly evolve as an upper air trough of cold polar air (not illustrated) begins to lend support via positive vorticity advection. Severe cold weather and windy conditions now prevail over the southeastern United States. In the final stages (Fig. 4C), both features of the anticyclone–cyclone couplet have received upper level support from the waves in the upper troposphere. The Gulf Coastal anticyclone begins redeveloping eastward, assisted by negative (anticyclonic) vorticity advection occurring ahead of another upper level ridge approaching from the west. It does not greatly reintensify due to its destabilization and proximity to the warm ocean. The cyclone has evolved into a major East Coast winter snowstorm, aided by upper air positive (cyclonic) vorticity advection east of the trough that was, in a large part, created and amplified by the preceding polar outbreak in the Great Plains and the Midwest. The warm front that marks the western boundary of the polar outbreak now tends to move eastward as new western synoptic systems push eastward.

3.3.4. Tracks of Cold-Core Anticyclones and Trajectories of Polar Outbreaks in the Americas

As indicated in the previous sections, there is no direct relationship between the intensity of the cold-core anticyclone and the degree of cooling in regions affected by the polar outbreak associated with that high-

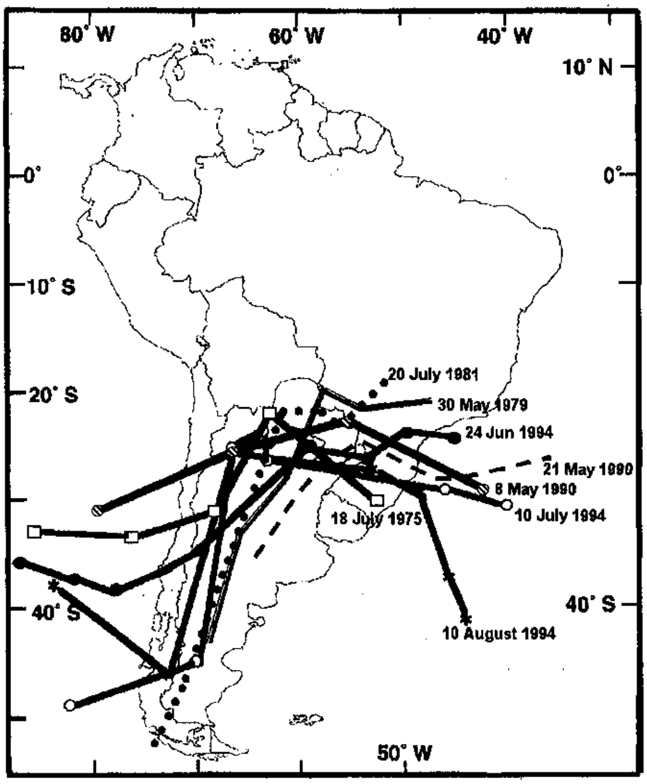

FIGURE 5 Partial track of wintertime cold-core anticyclones related to intense freeze events in southern Brazil. The track indicates the daily paths of the anticyclones from southern Chile, along the Andes, toward southern Brazil (Marengo, submitted).

pressure center. It is also important to consider the track, or path, of the anticyclone and the trajectory of the cold air moving from higher to lower latitudes.

The tracks of some South American anticyclones associated with cold surges (1975, 1979, 1981, 1990, 1993, and 1994), and occasionally freezing conditions in southern and southeastern Brazil, are presented in Fig. 5. Since it was not possible to plot the track of every anticyclone listed in Table 1 due to the lack of weather maps and surface charts for those cases, this figure should not be taken as comprehensive of all cases of major cold surge events. The most prominent characteristics of each path are the eastward trajectory coming from the Pacific, then a turn around the Andes to follow a northward trajectory until it reaches approximately 25°S; there, it turns toward the southeast and southern Brazil–northern Argentina, ultimately reaching the subtropical Atlantic where it is finally assimilated by the subtropical high. In general, the anticyclones take 24–48 hr to travel from the coast of Chile to southern Brazil. There is a tendency for the anticyclones to become somewhat stationary over southern Brazil during severe freeze events, as in 1975, 1981, and 1994.

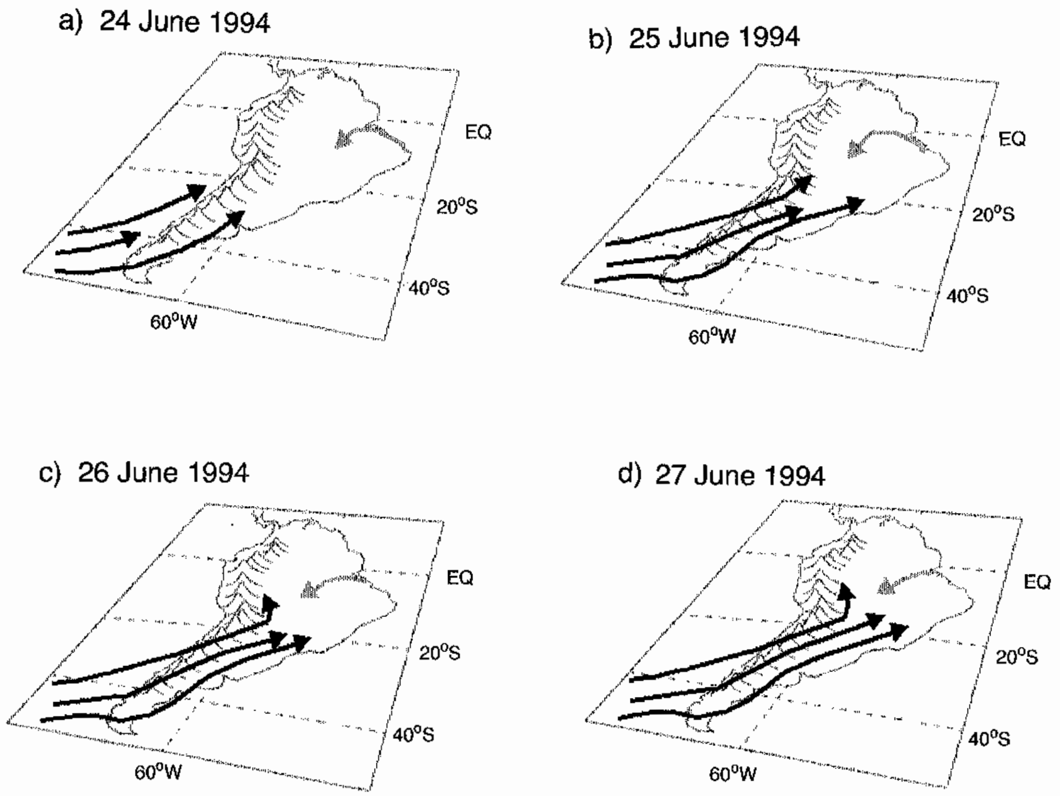

FIGURE 6 Trajectory of the cold air mass over South America during the intense cold episodes of June 1994. (A) 24 June, (B) 25 June, (C) 26 June, and (D) 27 June. Arrows indicate different pressure levels in the atmosphere. (Adapted from Sanchez and Silva Dias, 1996.)

The strong polar outbreaks of June and July 1994 can be analyzed in conjunction with Fig. 5. The case for 24–27 June 1994 is shown in Figs. 6A–6D. On 24 June (Fig. 6A), air coming from the South Pacific reached northern Argentina. On 25 June (Fig. 6B), the trajectory of cold air coming from upper levels above the Pacific turned toward the west and reached western Amazonia, affecting southeastern Peru on 26 June (Fig. 6C). It is interesting to notice that the parcel coming from the middle troposphere above the South Pacific reached central Brazil, while the air parcels from lower levels affected southeast Brazil and eventually reached the coastal region. The 7–10 July 1994 case (Figs. 7A–7D) is significantly different from the June 1994 case, considering the origin of the air parcels. The air parcels that reached western Amazonia and central and southeastern Brazil came from air masses over the South Atlantic. There are indicators that the polar air parcels did not reach such low latitudes as in the June 1994 event. Air came from upper levels of the troposphere and descended until it reached western Amazonia on July 10 (Fig. 7D). This indicates that the air mass reaching southeastern Brazil in July 1994 showed more oceanic characteristics than that of June 1994.

The tracks of surface anticyclones associated with polar outbreaks in North America (listed in Table 2) are presented in Figs. 8A to 8D. Figure 8A shows the path of the strong anticyclones associated with the severe freezes of 1894–95, 1899, 1962, 1983, 1985, and 1989, which produced extensive citrus damage in Florida. It comprises the synoptic setting associated with Fig. 4. The most prominent characteristics of each path are a southward movement across the Plains toward eastern Texas and a subsequent abrupt eastward or northeastward turn toward the Atlantic coast. In general, the anticyclones take 24–48 hr to traverse the distance from the Canadian border to Texas. Rogers and Rohli (1991) indicate that Florida freeze damage generally occurs in the mornings when the high is in Texas. Dalavalle and Bosart (1975) point out that movement of the 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 curvature and reintensification. Figure 8B shows the tracks of slow-moving anticyclones, which generally track east of those in Fig. 8A, crossing over Missouri or Arkansas. This second kind of anticyclone is associat-

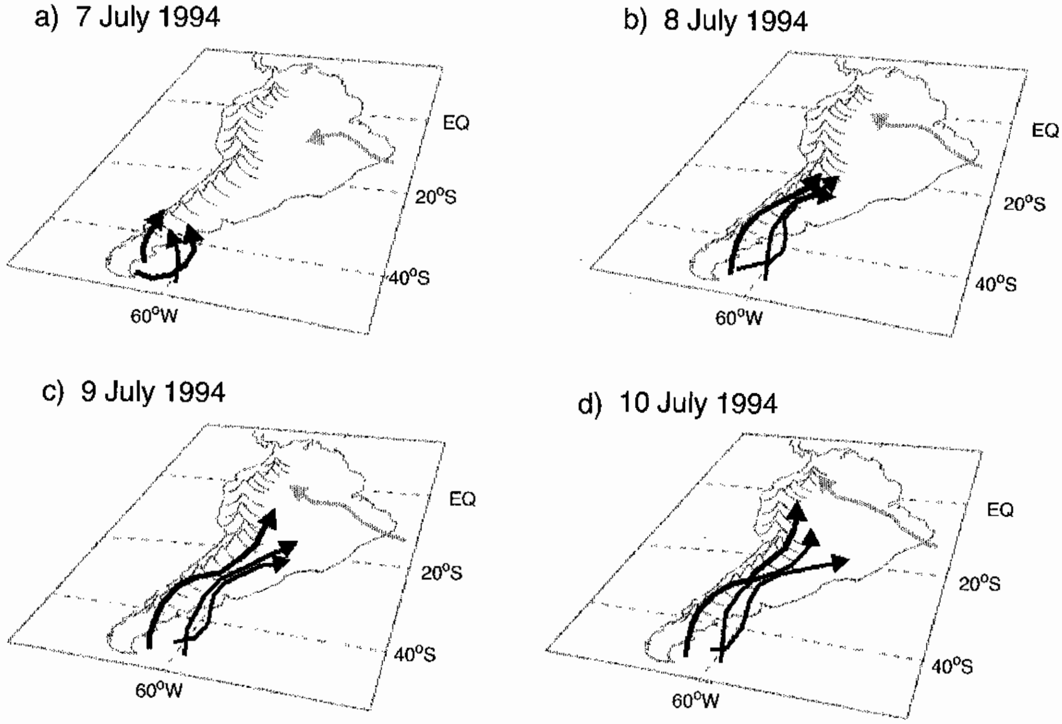

FIGURE 7 Trajectory of the cold air mass over South America during the intense cold episodes of July 1994. (A) 7 July, (B) 8 July, (C) 9 July, and (D) 10 July. Arrows indicate different pressure levels in the atmosphere. (Adapted from Sanchez and Silva Dias, 1996.)

ed with freezes caused by overnight radiative cooling in Florida. They move into the Gulf of México or Atlantic Ocean, becoming part of the warm Atlantic subtropical high. The third set of anticyclone paths (Fig. 8C) is associated with high-pressure areas that move toward Texas, but do not create severe freezes in Florida. Figure 8D shows the paths of a small subset of the many strong anticyclones that are linked to meridional winter flow and unusually cold weather across North America, but do not produce notable impacts across the southeastern United States.

3.3.5. Atmospheric Teleconnection Patterns Associated with Polar Outbreaks in the Americas and Their Interdecadal Variability

North and South American polar outbreaks that produce damaging freezes do not appear to be related to El Niño or La Niña. For southern Brazil, there is no clear signal of El Niño or La Niña impacts at interannual timescales on either the frequency or intensity of polar outbreaks in South America. The coldest events registered in July 1975 and June and July 1994 occurred during transition years between El Niño and La Niña. What is observed is a tendency for warmer than normal winters during El Niño years with a lower probability of strong polar outbreaks in those winters. However, some of the events listed in Table 1 occurred during some El Niño or La Niña episodes.

Large-scale circulation factors controlling austral winter freeze events over subtropical and tropical latitudes are generally accompanied by major synoptic- to planetary-scale changes in the pressure systems over an extensive part of the Southern Hemisphere. These changes are reflected in a large-amplitude trough of the middle-latitude westerlies. The tropical extension (or penetration) of such large-amplitude troughs appears to be associated with synoptic- to planetary-scale events. The mechanism of downstream amplification across the Pacific into South America generally precedes heavy frost events. This is a well-known wave train of the midlatitudes that is seen to traverse across the Pacific Ocean toward South America, exhibiting the successive intensification of downstream troughs and ridges (Krishnamurti et al., in press).

The occurrence of severe North American freezes in the far southeastern United States has been linked to the positive phase of the Pacific–North American Oscillation (PNA) atmospheric teleconnection pattern

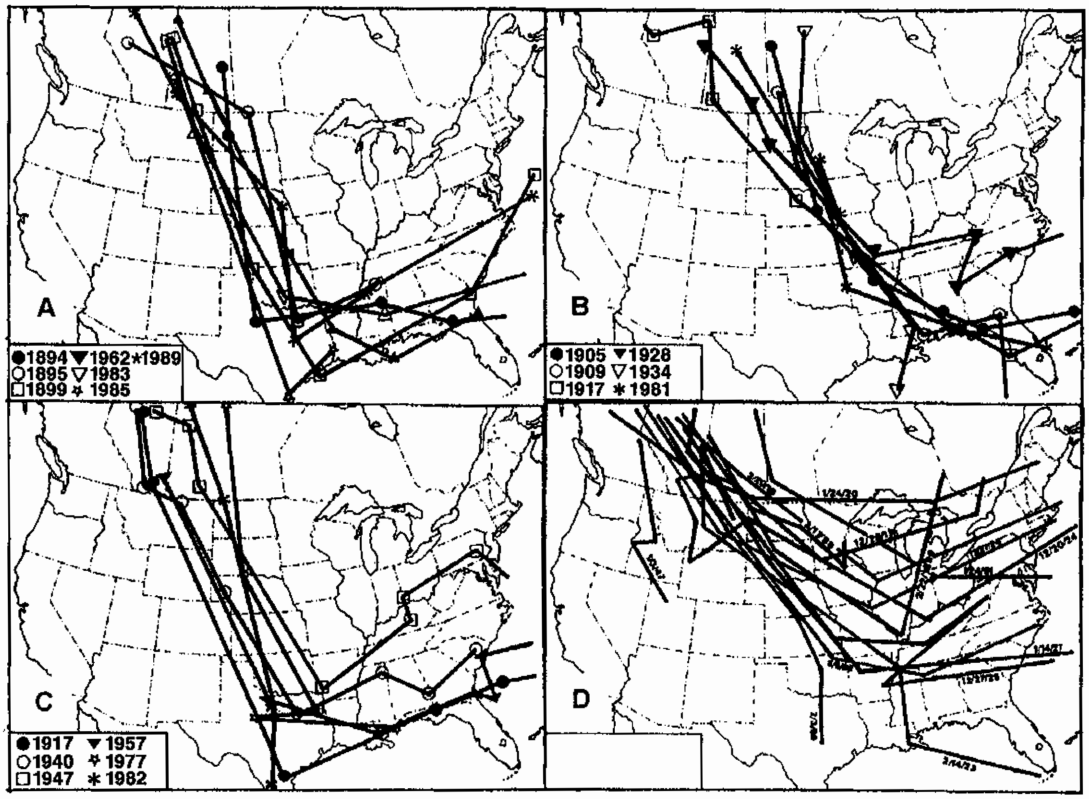

FIGURE 8 Partial track of the strongest wintertime anticyclones, beginning with points in their paths in southern Canada and then across the United States. Positions are based on 12 or 13 October Universal Time Zone (UTC) synoptic charts. The years labeled in (A)–(C) refer to years of Florida citrus freezes, while the tracks in (D) are from the remaining nonfreeze events. (From Rogers and Rolhi, 1991. With permission.)

(Rogers and Rohli, 1991; Rohli and Rogers, 1993; Downton and Miller, 1993). This prominent mode of low-frequency variability in the Northern Hemisphere extratropics is observed in all months of the year except June and July. Its positive phase is characterized by amplification of the upper tropospheric ridge off the west coast of North America (Fig. 1A), which establishes a strong meridional flow of polar air southward toward the United States and Central America. The PNA positive phase can be forced by the tropical heating associated with El Niño in the tropical Pacific. It has been shown, however, that El Niño is not the only forcing mechanism of the PNA, and while the record of freezes in Florida is dominated by the occurrence of the PNA positive mode, the occurrence of El Niño during polar outbreaks and freezes is only occasional. Cold waves are, of course, synoptic events occurring over 2–6 days, and while the presence of a ridge over the western peripheries of the continents is almost mandatory, the long-duration El Niño is not or is merely coincidental. Furthermore, the nature of winters in the eastern United States associated with El Niño has changed since 1977, with relatively mild winters consistently prevailing in events since that year. El Niño is statistically linked to colder, but wetter than normal, winters along the Gulf of México coast and in Florida. The wetter and colder weather is typically linked to the presence of skies that are cloudier than normal, conditions not generally linked to polar outbreaks.

The PNA is linked to variability in the mean surface pressure of the Aleutian Low. Around 1977, the Pacific Ocean sea surface temperatures (SSTs) underwent a remarkable regime shift that has attracted considerable attention (Latif and Barnett, 1994; Mantua et al., 1997). The climate shift produced a deepening of the wintertime Aleutian Low and moved the PNA index into an almost continuously positive phase during subsequent winters. Freezes affecting North and Central America and the Florida citrus-growing regions began occurring with great rapidity, such as in 1977, 1981, 1982, 1983, 1985, 1989, and 1997, whereas they had previously occurred only about once per decade (Rogers and Rohli, 1991). In contrast, 1948–57 was a freeze-free period characterized by anomalously high pressure in the

Aleutian Low center and anomalously low index values of the PNA. A strong, persistent PNA pattern, *within* and *among* winters, substantially increases the probability that Florida will experience a widespread, severe tree-damaging freeze. Further comments on the long-term interdecadal variability of citrus freezes appeared in the earlier discussion.

Strong cold surges in México and Central America usually possess a positive PNA and a confluent subtropical jet over the Gulf of México and southeast United States that is also found during El Niño conditions (Schultz et al., 1998). In fact, Klaus (1973) and Schultz et al. (1998) presented evidence that cold surges in this region tended to be more numerous during the cold season after the El Niño year.

In South America, research on interdecadal variability in cold surges focuses on variability in cold frontal passages. Calbete (personal communication) identified cold fronts at three different latitudinal bands over 1975–98, and noticed that the number of cold fronts reaching these latitudinal bands was larger during the period 1975–84 as compared to the period 1987–98, regardless of the intensity of the cold air masses related to the fronts. Calbete (1996) also showed that cold air masses reach southern Brazil from April to October, and in some regions at high altitudes freezes can occur all year long. Table 3 summarizes the number of cold air masses and snow events during the whole period 1988–96. However, the occurrence of very strong freezes in southern Brazil may be more of a random short-time variability event, occurring anytime even though the number of cold fronts may have been lower in recent decades.

Lemos and Calbete (1996) and Marengo (submitted) identified the number of cold fronts affecting the coastal section of Brazil from 35°–20°S, encompassing the coffee-growing areas of southeastern Brazil. The number reaching this latitudinal band was larger during 1975–84 compared to the period 1987–95. For this latter period, the number of cold fronts that affected this region in wintertime vary considerably: 40 cold fronts during 1987–90, 31 from 1991–94 (period of the extended El Niño of 1991–94), and 34 during 1995–98.

TABLE 3 Number of Cold Air Masses and Number of Snow Events in Southern Brazil during 1988–96 during the Cold Season

Month	Number of cold air masses	Number of snow events
April	10	0
May	30	3
June	33	4
July	28	12
August	28	6
September	25	2
October	13	0

Trends toward warmer climates have been detected in São Paulo and other states in southern and southeastern Brazil (Victoria et al., 1998). In fact, Marengo (submitted) has detected an upward trend since the beginning of the century, in São Paulo, Rio de Janeiro, Londrina, and Curitiba, near the coffee-growing areas in southern and southeastern Brazil. Work by Venegas et al. (1996, 1998) has shown that a positive trend in SSTs and SLP in the South Atlantic may be indicative of a systematic warming in this region.

3.4. HISTORIC POLAR OUTBREAK EVENTS IN THE AMERICAS AND THEIR IMPACT ON REGIONAL AGRICULTURE

This section documents how extreme meteorological events such as polar outbreaks can affect human activities. Statistics on coffee and orange production are used as qualitative indicators of long-term climate variability in the region, as related to interhemispheric indicators of polar outbreaks in present-day climates.

3.4.1. Chronology and Impacts of Polar Outbreaks in Coffee-Growing Regions of South America Since the Late Eighteenth Century

Coffee was introduced to Brazil from French Guiana at the beginning of the eighteenth century. The first seeds, planted in Cayenne in 1718, can be traced back to seedlings offered by the Dutch to the French from the Botanic Gardens of Amsterdam. Brazil is the world's largest coffee producer, supplying approximately 27% of the coffee consumed worldwide. It competes with Colombia as the world's largest exporter, ranking either first or second each year depending upon the volume of its output. It is also the second world consumer of coffee after the United States.

Historically, weather has played a major role in determining the world supply of coffee. For example, production increases after recovery from the 1953 Brazilian frost created big price declines. In another situation, drought is reported to have aggravated the effect of the July 1981 frost because it came after the crop damage had occurred. In many other frost incidents, subsequent abundant rain has helped damaged trees to recover very swiftly.

Freezing temperatures and frost affect a large part of the harvest of wheat, coffee, soybeans, and oranges in

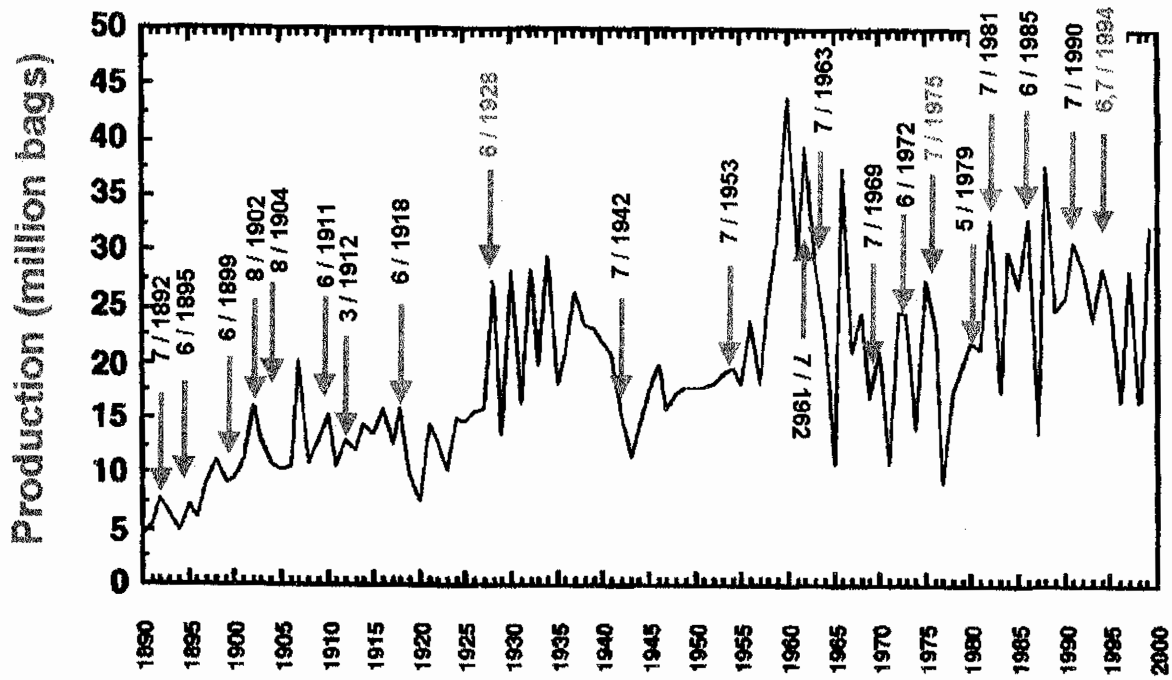

FIGURE 9 Coffee production in Brazil from 1892 to 1995 (millions of 60-kg bags) (Marengo, submitted). Arrows indicate freezes.

the agricultural lands of southeastern Brazil. For southeastern Brazil, reports issued by the United States Department of Agriculture (USDA) indicated that the freeze of July 1975 (perhaps the most intense in this century) reduced the 1976–77 harvest to 9.3 million bags (60 kg/bag), compared to the 1961–80 average of 19 million bags. The damage was severe enough to motivate the moving of some coffee plantations from the former growing region of Paraná (southern Brazil) to the northern states of São Paulo and Minas Gerais. This severe event is comparable to the intense freezes of August 1908 and June 1918. In 1975, some 75% of the trees in Brazil were affected in some degree, and the 1976 crop was a paltry 6 million bags.

Frost in mid-July claimed 60–70% of São Paulo's 1975–76 coffee crop and 5–10% of its sugarcane crop. The intense cold also hurt pastures, tomatoes, wheat, and bananas in that state. Because of the frost damage, virtually no coffee was harvested in the year following the freezes in Paraná, and only 25–33% of its normal harvest was projected for 1977–78.

Frigid air surged through Brazil's coffee regions during the third week of July 1981, killing buds and potentially causing a significant reduction in 1982–83 production (Haddock et al., 1981). The damage was not as severe as in 1975 when coffee trees were killed. Likewise, the Brazilian frosts in June and July 1994 caused a sharp drop in coffee production and dramatic increases in coffee prices (Marengo et al., 1997a).

Statistics on coffee production in the southern states of Brazil, available since the late 1800s, can be used to indirectly assess the presence and intensity of regional cold waves. Figure 9 shows coffee production in southern and southeastern Brazil, provided by the Brazilian Institute of Coffee and *The New York Times*, from 1892–1995. A steady increase is observed in production due to increases in the cultivated area. Large drops in production were observed after the freezes of June 1928, July 1975, June 1981, and June and July 1994, related largely to the cold weather. Estimates of losses in 1995 due to the frosts of June and July 1994 are 50–80% in the states of São Paulo and Paraná (Marengo et al., 1997a). For the 1995–96 production, estimates put the crop at 13.15 million bags. Marengo et al. (1997a) indicate that heavy commodity market speculation after the 24 June 1994 cold event resulted in coffee price increases of almost 70% over a few days, with the New York, London, and Chicago Stock Exchanges reacting more quickly than the Brazilian market. For 1997–98, in Brazil, mild winter weather linked to El Niño kept the top production areas free of frost, but heavier than normal rainfall in June affected the quality of the harvested crop. El Niño–induced drought in Espírito Santo failed to damage the Brazilian coffee harvest, which increased in 1997–98 to 18.86 million bags. Recently, during 16–17 April 1999, the first cold wave entered from higher latitudes and extended over central Brazil and western Amazonia. On the coffee-growing areas of southern and southeastern Brazil (western Paraná and São Paulo), air temperatures dropped to between 0° and 2°C, creating moderate and weak freezes. However, given the occurrence of these freezes during early stages, damage to the coffee plantations was not as severe as one would expect.

Table 1 shows a chronology of events and their intensities since 1892 for the coffee-growing areas of the state of São Paulo (southeastern Brazil); the most devastating events are marked as very intense. The listed frosts in coffee regions of Brazil indicate that the change over the years in temperature range is probably very small, but it takes only marginal variation and a few hours of frost one night to do real damage; as in 1975, the trees can take 2 or 3 years to recuperate. In 106 years, from 1890–1996, 18 intense freeze events brought damage to coffee production. Of these, five were considered catastrophic. On average, there has been one severe event every 6 years and one very severe event every 26 years in the coffee-growing region. Two very severe events were registered in 1892–1925 (in 1902 and 1918) and the other three in 1962–96 (in 1975, 1981, and 1994).

3.4.2. North and Central American Polar Outbreaks and Their Impacts on the Citrus Industry in the Southeastern United States

Climate has played an important role in the development of Florida's citrus industry. Florida's subtropical climate characteristics set the stage for that state to become a major producer of oranges since the eighteenth century, ultimately becoming the world's first major producer of frozen concentrated orange juice. Freeze damage to Florida's citrus industry due to intense polar outbreaks occurring since 1977 has been responsible for launching the Brazilian citrus industry into its current position as the world's leading producer and exporter of orange juice concentrate (Miller and Glantz, 1988). Studies by Rogers and Rohli (1991), Miller and Downton (1993), Rohli and Rogers (1993), and Downton and Miller (1993) describe an increase in freeze frequencies in central Florida since 1977, which have brought about a large dislocation in the Florida citrus industry, similar to the dislocation of the coffee plantations to the north of their normal places after the freeze of July 1975 in southeastern Brazil. Citrus is also grown in the Rio Grande valley region of extreme southern Texas. As in Florida, however, production in Texas has been hampered by freezes, especially those of 1949, 1951, and 1962 (Rohli and Rogers, 1993).

Descriptions of damage to the citrus crop typically focus on freezing of the citrus, defoliation of the trees, reductions in citrus production, and damage to tree limbs or bark leading to injury or death. The most damaging are advective freezes, wherein a powerful polar anticyclone migrates to Texas (Figs. 4C, 8A), and the winds around the eastern edge of the high often reach 50 km/hr, causing excessive defoliation and transpiration and breakage of twigs and branches, in addition to bringing subfreezing air. Damage becomes very severe if temperatures remain below −5.5°C for more than 1 hr. The worst advective freezes were those of 1962, 1983, 1985, and 1989, in addition to those during 1835, 1894, 1895, and 1899 (discussed in more detail later). The advective freeze is that identified in the conceptual model (Section 3.3.2 and Figs. 4A–4C) and in the anticyclone tracks of Fig. 8A. Radiative freezes occur when the anticyclone at the core of the polar air mass begins to settle over the southeastern United States and Florida (Fig. 8B). Radiative cooling in the clear winter night brings air temperatures to below freezing, with the air temperature dropping to the most dangerous levels only near sunrise, after which warming rapidly occurs. While most Florida freezes may combine elements of both the advective and radiative varieties, the less damaging events have lower wind speeds and are primarily radiative.

As was pointed out in Section 3.3.2, a devastating cluster of freezes affected a large portion of Florida citrus-growing areas in January 1977, 1981, and 1982; December 1983; and January 1985 (Table 2). Florida's citrus industry survived the first three freezes without major problems. However, the advective freezes of 1983 and 1985 occurred back-to-back in adjacent winters and sent the industry into a tailspin with serious crop and tree damage. Nearly one-third of the state's commercial citrus trees were lost. The next severe freeze, in December 1989, killed a large number of newly planted tress in areas that already had been affected by the earlier events. By 1989, citrus production in northern Florida had largely been abandoned. Citrus production in northern Florida had originally been encouraged by the relatively mild winters of that region prior to 1977. The industry had suffered only relatively minor setbacks occurring about once a decade, interspersed with some rare but substantial disasters, such as the freezes of 1917 and 1962, for the first three-quarters of the twentieth century.

Figure 10 shows Florida's orange production in thousands of 90-lb boxes since 1965, as shown by Miller and Glantz (1988), and updated to 1997–98. A general rising trend can be seen over the 1970s, but in general it is clear that freezes have had very uneven effects on Florida's orange growers. Major freeze events are noted in Figs. 9 and 10, denoted by arrows. As with coffee production in Fig. 9, the effect of the cold weather is often more pronounced in the year following the freeze. Tree damage is longer lasting, while the fruit frozen on the

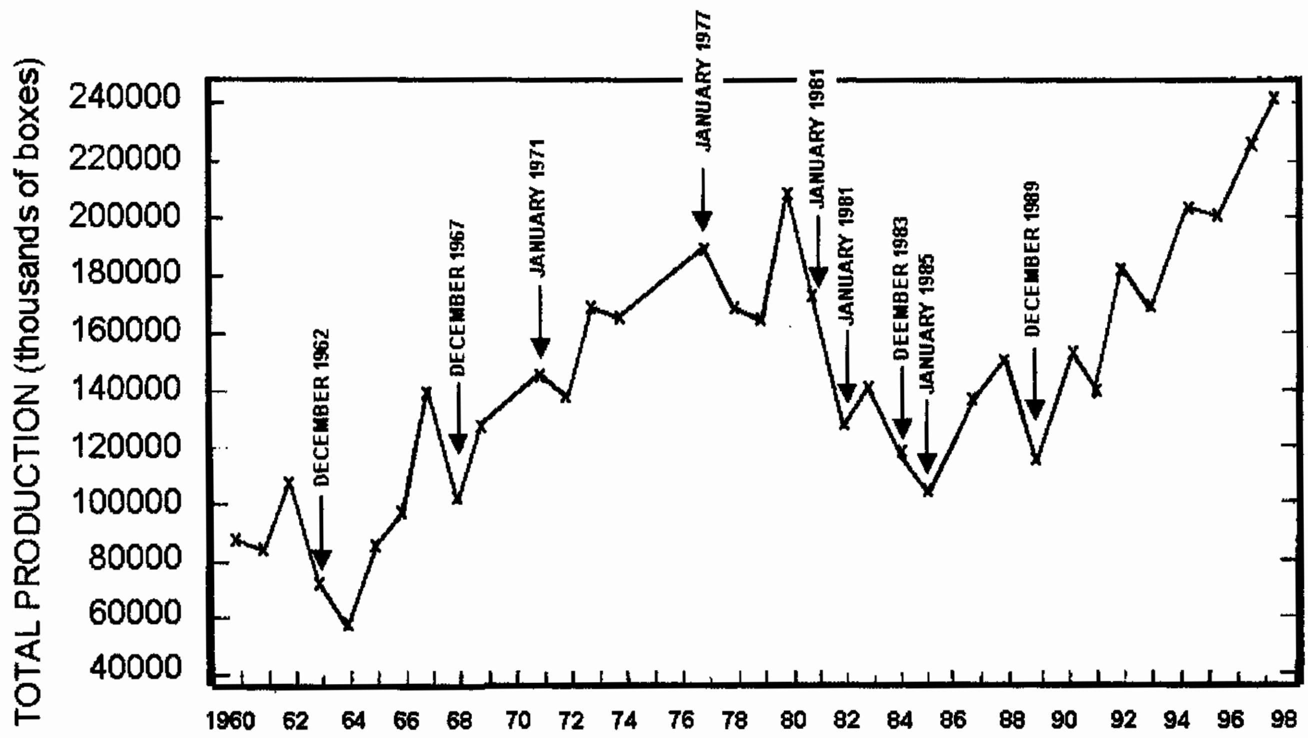

FIGURE 10 Florida orange production from 1965 to 1997 (thousands of 90-lb boxes). (Adapted from Miller and Glantz, 1988; updated with data from the Florida Department of Citrus). Arrows indicate freezes.

tree can often be salvaged, and those freezes occurring in January do not affect the harvest of early-bearing varieties. The dramatic impacts of the December 1983, January 1985, and December 1989 freezes can readily be seen. Miller and Glantz indicate that the December 1962 freeze had a striking effect on orange prices, as did that of 1977. The January 1981 and January 1982 freezes, however, had virtually no effect on prices. By the 1984–85 season, continued reductions in Florida production had succeeded in raising the price of Florida oranges to its highest levels in 20 years.

Northern Florida was abandoned as a citrus-growing region once before, during an earlier cluster of freezes that culminated in the nineteenth century, from 1880–1899. During this spell, the most lethal events were two severe freezes that occurred within ca. 8 weeks of each other during the 1894–95 winter. These freezes were preceded by a freeze in 1886, widely considered the worst since 1835 (see Rogers and Rohli, 1991). The 1894–95 pair of freezes was followed by the extraordinarily severe freeze of 1899 (associated with the famous East Coast blizzard described earlier), which killed both old and new citrus trees in the northern half of Florida. The late nineteenth-century freezes kept Florida citrus production below 1894 levels until 1909–10 and, as with the recent cluster, contributed to a net southward migration in the citrus production belt (Chen and Gerber, 1985).

The milder decades between the severe citrus freeze clusters appear to have been associated with a gradual northward migration in citrus production (Miller and Glantz, 1988). During these mild periods the severe freezes were sporadic (e.g., those of 1835, 1917, and 1962), and other freezes that occurred were relatively benign radiative events. The December 1962 freeze was described as the "worst since 1899" (Rogers and Rohli, 1991). Very strong cold waves occurred in 1835 and 1857 (Pardue, 1946). Since the beginning of systematic weather observations, severe cold waves have been experienced in January 1866, December 1894, February 1895, 12–13 February 1899, 2–6 February 1917, 3–4 January 1928, 12–13 December 1934, 25–29 January and 16–17 November 1940, 2 March 1941, and 15–16 February 1943. Similarly, in the nineteenth century, the 1880 freeze was the coldest since 1857, but the far more severe freeze of 1886 at the start of the nineteenth century cluster is compared to the event of 1835, which is among the worst known. The data suggest that at least half a century of comparatively milder winters precedes each severe cold-wave cluster.

Tropical fruits had also been uninjured in more than half a century at St. Augustine, FL, at the time of the freeze of 1835 (Blodget, 1857). The *Autobiography of Thomas Douglas* (published in 1856; Chen and Gerber, 1985) indicates that many of the trees destroyed in 1835 around St. Augustine were nearly 100 years old. A cluster of severe winters over the eastern and southeastern United States is also known to have occurred during the last quarter of the eighteenth century, including the winters of 1776–77, 1779–80, 1783–84, during the United States Revolutionary War, and 1786–87, 1796–97, and 1798–99 (Blodget, 1857; Ludlam, 1966). If the St. Augustine, FL, reports are characteristic, however, either any cold waves during these winters may not have greatly affected Florida citrus production or the citrus trees may have been able to withstand them due to their age, the timing of the freeze, or other factors such as abundant soil moisture. It is interesting to note that many of the worst winter freezes in the southeastern United States have been clustered in the final quarter of each of the recent three centuries.

3.5. PALEOCLIMATIC EVIDENCE OF LONG-TERM VARIABILITY IN SOUTH AMERICAN POLAR OUTBREAKS

Our understanding of the climatic history of the South American tropical lowlands is more limited than for other regions of South America. It is not possible to use the available surface meteorological observations (especially those from southeastern tropical South America) to describe variations at century or longer timescales. The statistics for coffee and oranges help to identify years with possible intense freezes since the late nineteenth century, but only qualitatively. Climate proxy data covering longer timescales are available from a few sites in the South American tropics based on paleoenvironmental records, primarily pollen records (Ledru, 1993; Ledru et al., 1994; Servant et al., 1993; Suguio et al., 1997; Behling and Lichte, 1997; Bush et al., 2000). These records identify possible mechanisms of past atmospheric circulation, including cold air outbreaks.

Today, for the Southern Hemisphere, the Earth is farthest from the Sun in June (winter) and closer to the Sun in December (summer) (Martin et al., 1997). As a consequence, seasonal differences in insolation are strong with warm summers and cold winters, and the seasonal shifts of the Intertropical Convergence Zone (ITCZ) are strong. Equatorward extents of cold advections under present-day conditions are shown in Fig. 11A. In contrast, at ca. 11,000 B.P., for the Southern Hemisphere, the Earth was closer to the Sun in June and farther from it in December, resulting in relatively colder summers, but relatively warmer winters than now and reduced seasonality. As a consequence, the continent was not warming as much then as during today's southern summer, and the ITCZ was probably located farther north than it is today. A weaker ITCZ, on the other hand, would have helped cold advections to penetrate further equatorwards in spring and autumn and possibly even in summer (Fig. 11B).

Numerous paleoecological studies found evidence in the South American tropics of well-developed dense forests during late glacial and early Holocene times (Behling, 1996; Servant et al., 1993; Ledru, 1993; Ledru et al., 1994; Behling and Lichte, 1997; Ledru and Mourguiart, 2000). The main features that characterized the tropical forests during those times were (1) montane Andean forest elements, such as *Podocarpus*, and southern forest elements, such as *Araucaria*, expanded into the tropical lowlands and equatorwards, respectively, and (2) the reduction of climate seasonality prior to 7500 B.P. according to the vegetation composition at that time. All these aspects, inferred from paleoecolog-

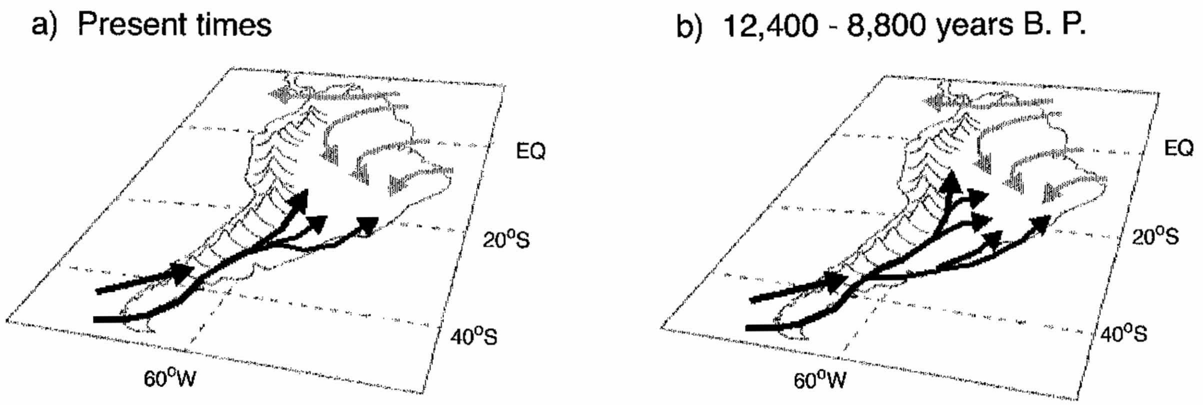

FIGURE 11 Position of the polar outbreaks for (A) present times and (B) 12,400–8800 B.P. (Adapted from Martin et al., 1997 and Servant et al., 1993.)

ical evidence, suggest climates colder than today during the glacial/interglacial transition. The most likely explanation is that polar air masses reached tropical regions more frequently during those times than they do today (Figs. 11A and 11B). Currently, climate in the region is influenced by polar outbreaks from the south only occasionally, but overall the climate is not cold enough to support the presence of either Andean forest elements or *Araucaria* forests in these lowland regions.

Climatic conditions during full glacial times were apparently too dry and too cold for large *Araucaria* populations (Ledru, 1993; Ledru et al., 1994; Behling and Lichte, 1997; however, see discussion in Bush et al., 2000). Dry climatic conditions with reduced cloud cover might have favored frosts during winter nights. Cold air associated with cold fronts and polar outbreaks might have reached farther north and had a significantly stronger influence in southeastern Brazil during the last glacial maximum than it does today (see also Bradbury et al., 2000).

Increases in temperature and moisture content of the air masses after 8000–6000 B.P., interpreted from paleoecological records, are probably due to a reduction in the influence of cold fronts (Suguio et al., 1997). Thus, throughout the late Quaternary, variations in the intensity and trajectory of the polar outbreaks affected the climate of southern and southeastern Brazil.

3.6. CONCLUSIONS

At several timescales, from the interannual to the long term, interpretations of climatic and proxy climatic data have demonstrated that changes in weather and climate patterns can have strong impacts on human societies, exemplified here by the production of coffee and citrus in South and North America, respectively. From timescales of days to decades and beyond, there are associations between the frequencies and intensities of polar outbreaks and freezes and atmospheric circulation anomalies in both hemispheres. Observed negative trends in wintertime temperatures in central Florida and positive trends in southern South America (and less frequent cold fronts) seem to be linked to decadal changes in the PNA pattern and the SST in the South Atlantic. Features such as clusters of freezes in the Florida citrus areas or hard-hitting freezes in southeastern Brazil in the middle 1990s, even though the winter of 1994 was relatively warm, are indicators of the large climate variability in the Americas.

The marked similarity in meteorological aspects of the polar outbreaks in the southeastern United States and Brazil has long been noted. The near-surface and upper level circulations, as well as the role of the mountain ranges, favor the thrust of polar air toward subtropical and tropical latitudes in both the Americas. There are important differences, though, related presumably to geographical differences, outbreak intensities, and impacts. Both regions have different vegetation and agricultural crops that can be threatened by surges of polar air. In that sense, this chapter has used historical data and meteorological evidence to document polar outbreaks, their synoptic setting, and longer term variability.

The extreme weather events cause loss of crop production with inevitable social and economic difficulties. For the past, few observational data can be used directly to indicate climate variability on century timescales in South America, in the way that tree rings do for identifying climate variations in North America. Proxy data such as statistics on coffee and orange production and relicts of vegetation distribution are the only possible observational evidence.

In future climate scenarios, consequences of global warming and extreme climate events on many types of agricultural crops must be of major concern in ensuring continuity of the food supply. But besides climate-related effects, agricultural technology, economics, and politics will continue to have profound effects on farming in most societies, and responses to the changing environment will be included in the overall adaptation of farming.

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