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POLAR OUTBREAKS IN SOUTH AMERICA: SYNOPTIC CLIMATOLOGY OF CYCLONE/ANTICYCLONE BEHAVIOR, EXTREME CASES IN HIGH LATITUDES AND FROST EVENTS OVER 1888-2005 IN SÃO PAULO

Alexandre B. Pezza*, Tércio Ambrizzi** and Ian Simmonds*
The University of Melbourne*, Victoria, Australia and São Paulo University**, São Paulo, Brazil

1. INTRODUCTION

Polar air outbreaks associated with severe frosts in the subtropical region and snowstorms at higher latitudes are very important for the economy of South America, a continent in which most of its countries strongly depend on agriculture and primary products.

The Portuguese word *friagem* is used to describe the invasion of very cold air of extratropical origin well into the tropics. This is the most studied case of polar outbreak in the literature, given its enormous impacts over regions that are usually unprepared to handle very cold temperatures (Hamilton and Tarifa 1978, Fortune and Kousky 1983, Girardi 1983, Marengo et al 1997, Vera and Vigliarolo 2000, Garreaud 2000, Lupo et al 2001, Muller et al 2003, Muller et al 2005, Pezza and Ambrizzi 2005a,b).

The Patagonia region of Chile and Argentina to the south of 40^{o}S may experience extreme cold conditions with temperatures as low as -30^{o}C and heavy snowstorms closing airports and sometimes isolating whole communities during particularly severe winters. This type of "high-latitude mode" of cold waves tends to be associated with subtropical blocking characterized by high pressure and dry/warm conditions at subtropical latitudes (Pezza and Ambrizzi 1999).

Corresponding authors address: Dr. Alexandre Bernardes Pezza. School of Earth Sciences, The University of Melbourne. Victoria 3010, Australia.
E-mail: apezza@unimelb.edu.au.

Marengo et al (1997) studied the classical mode of polar outbreak reaching the Equatorial region as exemplified by a dramatic case occurred in June 1994. Freezing temperatures affected a large part of the subtropical and tropical continental area during that event, severely damaging the coffee growing areas and other vegetables in south-eastern Brazil.

The severe impacts of polar outbreaks on the multi-million market of the Arabic coffee in Brazil are just one of the several examples of negative consequences of cold surges in South America (Marengo et al 1997, Marengo et al 2002).

In this paper we present a synoptic climatology of cyclone/anticyclone behaviour associated with polar outbreaks affecting the south-eastern region of Brazil, a very important and sensitive area for Arabic coffee and other vegetables with enormous economic significance.

We use an automatic tracking scheme to study each individual synoptic trajectory associated with the cold waves in order to achieve a fully reproducible and non-biased approach. The climatology of frost events in São Paulo (1888 – 2005) and some insights into the polar air outbreaks occurring at high latitudes over the Patagonia region are also discussed.

2. METHODOLOGY

Twice a day mean sea level pressure from the NCEP/NCAR Reanalysis (Kalnay et al 1996, Kistler et al 2001) is used from May – August 1973 to 2000. The Melbourne University automatic tracking scheme (Simmonds et al 2003) was used to generating the synoptic climatology of cyclone and anticyclone behavior. The Melbourne University tracking scheme was chosen because previous studies have shown its reliability in capturing the most evident climatic features in the Southern Hemisphere (Murray and Simmonds 1991a,b, Jones and Simmonds 1993, Simmonds et al 1999, Simmonds and Keay 2000 a,b, Pezza and Ambrizzi 2003, 2005a,b). All settings and empirical parameters within the automatic scheme were the same as described in Pezza and Ambrizzi (2003).

The synoptic climatology of those particular trajectories associated with cold surges in São Paulo is presented for the 1973 – 2000 period by simply superposing every track on the same map, creating a "cloud" of associated paths.

Daily extreme minimum temperatures from the meteorological station of the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo (IAG/USP), located in a preserved green area at the southern part of the São Paulo city (23.7ºS, 46.6ºW, 799 m), are used for the 1950 – 2005 period. The cold outbreaks are divided according to the intensity of the minimum temperatures and the occurrence of frost. The events were classified as extreme ($T < 0^o$ C, all cases with frost), strong ($0 < T < 2.5^o$C with or without frost) and moderate ($T > 2.5^o$C with frost), but here only the results for all composites together are shown.

The composites are independent, and frost occurrence was also supported by in situ observations at the meteorological station during the whole period of analysis. In order to assure that the chosen days do not mix different synoptic stages, only one day per cold front was chosen.

3. RESULTS AND DISCUSSION

Table 1 shows the climatology of daily cold events with extreme minimum temperatures below or equal to 2.5ºC between São Paulo city, which is located at 45 km from the ocean, and Campinas city, about 100 Km further inland, for the period of 1888 – 2005. For the early record some of the observations in São Paulo were taken at different sites, which are indicated on the table.

The results show that the minimum temperatures in São Paulo and Campinas are very similar, with small differences due to local effects. The most severe frost and black frost cases according to the Agronomic Institute of Campinas are indicated in bold. Black frost is here defined as significant damage to the plants without ice deposition on the ground. It is seen that August 1898 and July 1981 presented severe black frost, and August 1902, June 1918 and July 1975 had severe frost. The August 1898 case can be considered the most intense ever measured in the city of São Paulo, with a minimum temperature of -2.5ºC in downtown area and -4.0ºC in the outskirts.

With regard to the coffee growing areas in southeastern Brazil, there was observed more than thirty cases of widespread damage over the whole period (not shown). Frost damage is a complex parameter because it depends on the actual protection used against frost and on the general improvements in agriculture, and similar weather situations can produce different degrees of damage.

From table 1 it can also be seen that during the 1990s there were nine cases of low temperatures in São Paulo, against seven cases during the 80s and eight cases during the 70s, thus suggesting that extreme events continue to be frequent despite the warmer temperatures on average and a global tendency for less cold nights during the recent decades (Alexander et al 2006).

Year	**Date or Period**	**Minimum temperature in Campinas (IAC) and São Paulo (LUZ, REP, PAV and IAG)**
1889	June	0.9 (LUZ)
1889	August	2.0 (LUZ)
1889	Sept.	0.7 (LUZ)
1890	August	0.7 (LUZ)
1891	May	2.4 (LUZ)
1892	14 July	0.2 (IAC); 0.7 (LUZ)
1893	June	1.0 (LUZ)
1894	June	2.4 (LUZ)
1894	14 July	1.0 (IAC); 1.5 (LUZ)

1895	25 June	1.0 (IAC); 0.0 (REP)
1898	May	1.5 (REP)
1898	05 July	2.4 (IAC); 0.9 (REP)
1898	**24 Aug.**	**-2.5 (REP)**
1899	June 18	1.6 (IAC); 2.8 (REP)
1901	June	2.4 (REP)
1902	Aug. 18	0.5 (PAV)
1902	**19 Aug.**	**0.2 (IAC); -2.0 (PAV)**
1904	June	1.3 (PAV)
1904	12 Aug.	1.5 (IAC); 4.0 (PAV)
1904	13 Aug.	1.5 (PAV)
1905	July	-0.2 (PAV)
1905	August	0.5 (PAV)
1910	18 July	2.1 (IAC); 3.5 (PAV)
1910	19 July	-0.2 (PAV)
1911	23 June	2.2 (IAC); 3.2 (PAV)
1911	24 June	0.0 (PAV)
1912	03 Sept.	1.8 (IAC); 4.4 (PAV)
1912	04 Sept.	1.5 (PAV)
1917	August	2.0 (PAV)
1918	**25 June**	**-1.5 (IAC); -1.2 (PAV)**
1918	26 June	-1.2 (PAV)
1918	July	1.2 (PAV)
1919	August	2.0 (PAV)
1920	June	-0.4 (PAV)
1920	Sept.	2.2 (PAV)
1921	June	0.2 (PAV)
1921	July	-0.3 (PAV)
1923	July	-0.2 (PAV)
1924	August	1.0 (PAV)
1925	June	1.2 (PAV)
1925	July	1.1 (PAV)
1926	July	0.6 (PAV)
1930	July	2.0 (PAV)
1931	29 June	2.0 (IAC); 1.1 (PAV)
1931	30 June	1.5 (PAV)
1932	June	1.9 (PAV)
1933	June	1.9 (PAV)
1933	14 July	1.4 (IAC); 1.2 (PAV)
1935	30 July	1.6 (IAG)
1936	07 Aug.	0.8 (IAG)
1936	10 Aug.	2.3 (IAG)
1938	08 July	2.0 (IAG)
1939	24 July	1.4 (IAG)
1939	31 July	1.9 (IAG)
1939	01 Aug.	2.1 (IAG)
1940	04 July	2.4 (IAG)
1941	04 Sept.	2.0 (IAG)

1941	05 Sept.	0.4 (IAG)
1942	19 June	1.1 (IAG)
1942	20 June	-0.6 (IAG)
1942	05 July	2.3 (IAG)
1942	06 July	-1.2 (IAG)
1942	11 July	1.5 (IAG)
1942	12 July	-0.2 (IAC); -1.2 (IAG)
1943	15 Sept.	2.0 (IAC); 0.9 (IAG)
1945	11 June	2.1 (IAG)
1946	04 June	2.4 (IAG)
1946	22 July	0.4 (IAG)
1948	16 June	2.1 (IAG)
1948	09 Aug.	1.6 (IAG)
1951	06 July	2.2 (IAG)
1953	05 July	1.2 (IAC); -0.1 (IAG)
1953	11 July	0.3 (IAG)
1953	08 Aug.	1.3 (IAG)
1955	01 Aug.	0.9 (IAG)
1955	02 Aug.	1.1 (IAC); -1.2 (IAG)
1955	03 Aug.	2.1 (IAG)
1957	21 July	1.2 (IAC); 3.3 (IAG)
1962	07 July	2.0 (IAC); 1.8 (IAG)
1963	21 June	2.8 (IAG)
1963	22 June	2.5 (IAC); 3.0 (IAG)
1963	06 Aug.	1.3 (IAG)
1964	28 July	2.4 (IAC); 2.9 (IAG)
1964	04 Sept.	1.7 (IAG)
1965	11 July	2.1 (IAG)
1965	12 July	1.0 (IAG)
1965	21 Aug.	0.6 (IAC); 2.8 (IAG)
1968	17 May	2.5 (IAG)
1969	11 July	2.4 (IAC); 0.2 (IAG)
1972	09 July	1.6 (IAC); 1.4 (IAG)
1975	07 July	2.2 (IAC); 2.2 (IAG)
1975	17 July	1.2 (IAG)
1975	**18 July**	**0.6 (IAC); -1.1 (IAG)**
1975	19 July	2.3 (IAG)
1979	31 May	0.2 (IAC); 1.4 (IAG)
1979	01 June	1.0 (IAC); -0.2 (IAG)
1979	18 July	1.3 (IAG)
1981	20 June	2.2 (IAG)
1981	**21 July**	**0.2 (IAC); 3.2 (IAG)**
1981	22 July	2.9 (IAG)
1984	27 Aug.	1.6 (IAG)
1985	08 June	1.4 (IAC); 4.4 (IAG)
1988	05 June	1.8 (IAC); 3.8 (IAG)
1988	06 June	1.9 (IAG)
1990	28 July	2.4 (IAG)

1990	29 July	2.0 (IAC); -0.4 (IAG)
1990	30 July	1.7 (IAG)
1993	12 Aug.	1.9 (IAG)
1994	26 June	0.3 (IAC); 1.2 (IAG)
1994	27 June	0.6 (IAC); 0.6 (IAG)
1994	28 June	2.0 (IAC); 3.0 (IAG)
1994	09 July	2.3 (IAG)
1994	10 July	2.4 (IAC); 1.5 (IAG)
2000	17 July	1.6 (IAC); -0.2 (IAG)
2000	18 July	2.2 (IAC); 2.0 (IAG)

Table 1: Cold events with extreme minimum temperatures (at 1.5 m) below or equal 2.5ºC at Campinas (Campinas Agronomic Institute - IAC) and São Paulo (Jardim da Luz - LUZ, República Park - REP, Paulista Avenue - PAV and Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo at Água Funda - IAG), for the period of 1888 – 2005. Data from 1890 to 1920 and 1929 to 2003 for IAC, 1888 to 1894 for LUZ, 1895 to 1901 for REP, 1902 to 1933 for PAV and 1934 to 2005 for IAG. Black frost and extremely severe frosts with extensive damage to the agriculture are in bold.

Figure 1 shows the mean sea level pressure on the 16th of July 1973 at 12 UTC (I) and on the 17th of July 1975 at 12 UTC (II) for Argentina and south Brazil. These cases describe well the configuration of extreme situations associated with severe polar outbreaks affecting high (I) and low (II) latitudes.

The 1973 case produced extremely severe snowstorms in Patagonia (south of 40^{o}S), disrupting electricity and gas services and completely isolating several villages and even main cities such as Rio Gallegos in Argentina (Rusticucci and Vargas 1995; La Nacion, Buenos Aires, 17th of July 1973). On the other hand, the 1975 case produced extremely severe frost conditions over subtropical and tropical latitudes, with very extensive damage to the Arabic coffee market in Brazil.

Cases such as the winter of 1973, severely affecting the southern tip of the continent, have been much less studied in the literature, but are of importance for the economies of Chile and Argentina. They tend to occur in association with blocking-like conditions over the subtropical latitudes in the Atlantic, preventing the meridional air mass exchange and therefore significantly increasing the temperature gradient between 30 and 45^{o}S (Pezza and Ambrizzi 1999).

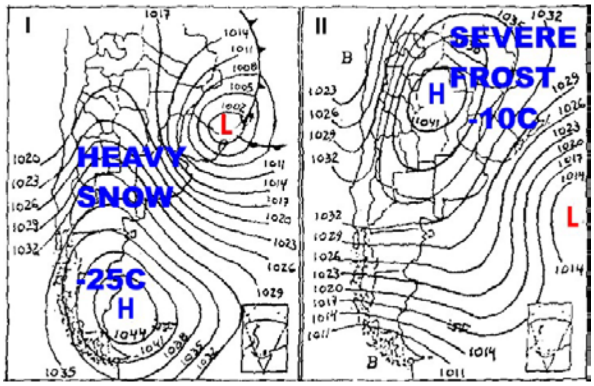

Figure 1: Synoptic maps for 16th July 1973 at 12 UTC (on the left) and 17th July 1975 at 12 UTC (on the right) showing the typical configurations respectively associated with high and low latitude polar outbreaks in South America. Adapted from Celemin (1984).

On the other hand, cases like the 1975 classical subtropical frost are widely known for having a devastating impact over agricultural areas closer to the equator. The 1975 frost is considered to be the worst ever documented polar outbreak in South America, with an impressive minimum temperature of -1.1^{o}C in São Paulo city and frost occurrence as further north as near the Equator.

The synoptic climatology associated with all extreme cold surges similar to the 1975 case affecting São Paulo with minimum temperatures below 2.5^{o}C and/or frost occurrence between 1973 and 2005 is shown in figure 2. The mean central pressure, the tracks length in days and the position of the most intense cyclone and anticyclone (full circles) are also indicated.

From this figure, two dense “clouds” of paths are seen, with anticyclones to the northwest and cyclones to the southeast. It is clear that most anticyclone tracks started between 90 and 120ºW and formed a closed area of high density to the west of SA, indicating an anticyclogenetic region associated with the dynamic reinforcement due to the Andes mountains (Bluestein 1993, Gan and Rao 1994) and also with the South Pacific Subtropical High to the north (Schwerdtfeger 1976).

It is also seen that a pronounced meridional shift to the east of the Andes is a key element of virtually all cases, and the same is true for any independent composite selecting different temperature thresholds. This is one of the most important synoptic observations related to this particular mode of polar outbreaks leading to extreme events at lower latitudes (*friagem*), but is not present for most extreme cases affecting Patagonia (figure 1 l).

Figure 2 also shows a large red region summarizing the high variability of the cyclone tracks, indicating the importance of the South America Atlantic sector as a cyclogenetic region from the Brazilian coast to the southern tip of Patagonia.

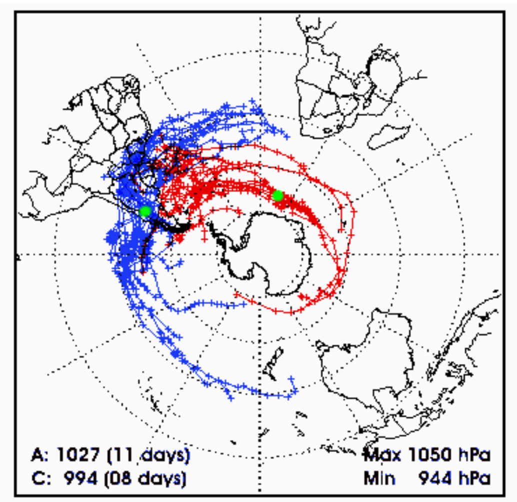

Figure 2: Synoptic climatology of all trajectories associated with severe cold surges in São Paulo (at least 2.5^{o}C in São Paulo and/or frost occurrence) from 1973 to 2005. Anticyclone tracks are shown in blue and cyclones in red, and the average and extreme pressures are indicated at the bottom. The green full circles show the positions of the strongest systems. From: Pezza and Ambrizzi (2005a).

The importance of the cyclones on the southern Brazilian coast in leading to frost conditions over São Paulo has not been much explored in the literature, but is one of the propagation types described in Lupo et al (2001) and more recently by Hoskins and Hodge (2005). The wintertime occurrence of extratropical cyclones over that area is one of the most interesting features of the local synoptic climatology, and after the cyclone Catarina in March 2004 (Pezza and Simmonds 2005) much more attention has started to be given on the strategic importance of that region in terms of energy balance and tropical/extratropical interaction.

Considering all tracks, the anticyclones presented a mean central pressure of 1027 hPa with a length of 11 days, and the cyclones showed an average of 994 hPa with a length of 8 days. The most intense anticyclone from 1973 to 2000 reached a central value of 1050 hPa near the city of Bariloche, in Argentina (41ºS), and the most intense cyclone measured 944 hPa near the eastern Antarctic coast, as shown by the marks on the map. However, in the case of anticyclone strength over the continent during extreme cold events it is possible that the proximity of the Andes may have placed an artificial influence on the reduced pressure derived from the reanalysis, although the Argentine Weather Service has also reported estimated values of up to 1050 before (Servicio Meteorologico Nacional, personal communication).

Figure 3 presents a conceptual model for the classical cold surges affecting tropical regions in South America. It shows the most frequent cyclone and anticyclone paths superposed on a topographic map of South America and the adjacent oceans and continents, summarizing the physical processes here described. The heavy arrows indicate the anticyclone and cyclone tracks derived from figure 2, while other frequent paths are indicated by the dashed arrows. The crosses indicate the climatological position of the Pacific High (PH) and the Atlantic High (AH). The cyclogenetic (cyclolitic) and anticyclogenetic (anticyclolitic) areas and the typical sea level pressure values are also plotted. The cold front line approximately shows the furthest displacement of the cold advection, as derived from the study of each individual case occurred for the whole period.

A simplified conceptual model of the dynamical influence of the Andes in association with the migratory cyclones and anticyclones can be summarized as follows: a) at the southern tip of SA previous southerly wind anomalies take place as a result of the geostrophic balance between the developing migratory anticyclone near the southern Chilean coast and the extratropical cyclone over the Atlantic. These wind anomalies are accompanied by cold advection, and hence pressure starts to increase rapidly over the continent; b) when pressure becomes very high at the southern tip of the continent, a strong meridional pressure gradient is established and as a consequence the blocking effect of the Andes produces mass accumulation to the northwest of the high pressure cell; c) as a result, the wind speed is reduced, weakening the Coriolis effect and generating an ageostrophic component from the south (driven by the pressure gradient), therefore advecting cold air towards lower latitudes at the eastern side of the Andes; d) the anticyclone center tends to move to the north towards the region of maximum cold advection, maximum subsidence and anticyclonic vorticity advection increasing aloft; e) When the cold air reaches latitudes near 18ºS, the blocking effect of the Andes is diminished because of its shape and also due to the fact that the geostrophic adjustment is very slow in tropical latitudes (Garreaud 1999), hence the remaining cold air is inertially advected to the western Amazon river basin, characterizing the mature phase of the *friagem* event.

This conceptual model based on the synoptic climatology of cyclone/anticyclone behavior adds a new insight to the physical mechanisms associated with the classical type of cold surges leading to extreme frosts over low latitudes, as exemplified by the 1975 case (figure 1 II). However, it does not fully address the mechanisms associated with severe snowstorms in Patagonia, as shown by the 1973 cold outbreak or by the more recent winter patterns in 1995 (Pezza and Ambrizzi 1999) and also in the year 2001, as discussed below.

Figure 3: Topographic map of South America and the adjacent oceans and continents, depicting the synoptic climatology of cyclone (in red) and anticyclone (in blue) tracks associated with polar air outbreaks in subtropical South America. Regions of higher tracks density are indicated by the heavy colored areas and arrows. Other frequent paths are indicated by dashed arrows. The crosses indicate the climatological position of the permanent highs, and the cold front line approximately shows the north boundary of the cold advection. Typical cyclogenetic and anticyclogenetic regions, and sea level pressure values (hpa) are also plotted. From: Pezza and Ambrizzi (2005a).

Figure 4 shows a satellite photo composed between the infra-red and visible channels in order to enhance the snow cover on the ground over the southern tip of Patagonia on the 15th of July 2001. Although the photo is showing a single day, a succession of extremely severe cold outbreaks occurred in Patagonia during the winter of 2001, generating near-unprecedented conditions of snow cover near the sea coast for more than a month. On the other hand the subtropical latitudes presented a very mild winter, without any major frost event at low latitudes.

We are currently further investigating the synoptic climatology of tracks associated with extreme cases affecting high latitudes and not affecting the tropics, in order to better understand how it compares with the well known pattern shown in figures 2 and 3.

Figure 5 adds some insight into the understanding of this problem, showing in blue the anticyclone trajectories associated with extreme cold outbreaks affecting low latitudes (below 0^{o}C in São Paulo) and in green the anticyclones associated with cold outbreaks in central Argentina which did not affect lower latitudes. The criterion used for the cold surges in central Argentina was the same proposed by Muller at al (2005), which considers a spatial criterion selecting the occurrence of below zero temperature at more than 75% of the meteorological stations located over a wide area around the wet Pampas, which is the most important agricultural region of the country. Only events above the mean plus one standard deviation were considered.

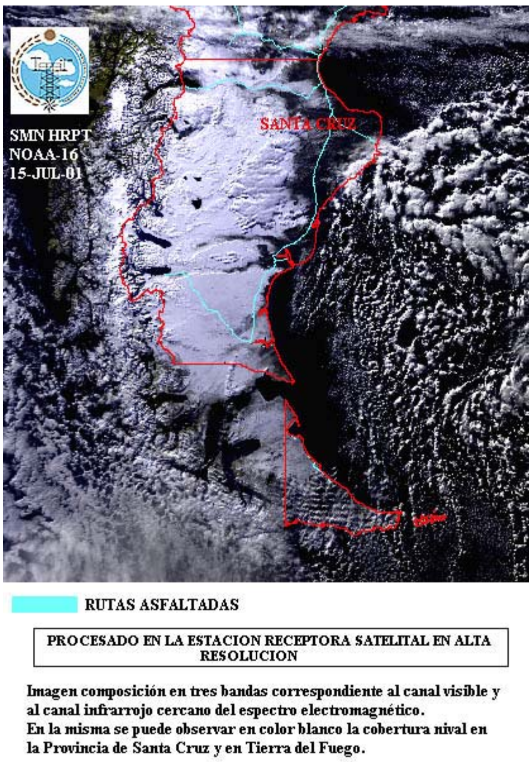

Figure 4: Satellite image showing a composite of the visible and infrared channels on 15th July 2001, indicating snow cover on the ground over Patagonia, to the south of 45^{o}S. From: Servicio Meteorologico Nacional (SMN), Argentina.

As clearly seen, there is a tendency for the tracks responsible for generalized frosts in central Argentina to be significantly displaced to the south and presenting a less important meridional component. The regions that presented anticyclones associated with both types of cold waves are shown in yellow.

More studies on the dynamics of cold waves affecting mid and high latitudes in South America are currently being conducted.

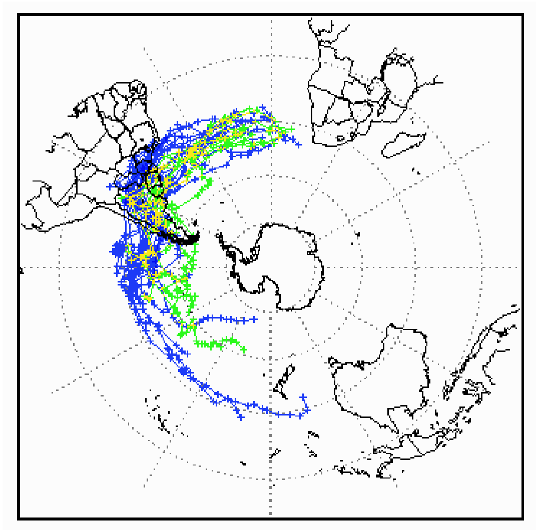

Figure 5: Synoptic climatology of anticyclone trajectories associated with severe cold surges with less than 0^{o}C in São Paulo (in blue) and of anticyclone tracks related to generalized frosts in central Argentina (in green). Regions crossed by anticyclones associated with extreme events in central Argentina and São Paulo are indicated in yellow.

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