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COLD WAVES IN SOUTH AMERICA AND FREEZING TEMPERATURES IN SÃO PAULO: HISTORICAL BACKGROUND (1888 – 2003) AND CASE STUDIES OF CYCLONE AND ANTICYCLONE TRACKS

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RESUMO

Neste trabalho, realizou-se uma compilação das ondas de frio mais intensas que atingiram a América do Sul desde o final do século retrasado até os dias atuais (1888 – 2003), com ênfase em casos extremos na Argentina e no Brasil. Para o Brasil, utilizou-se dados de ocorrência de neve nas serras gaúcha e catarinense e também na serra da Mantiqueira, além de temperaturas mínimas extremas para o país. Especificamente em São Paulo e Campinas, destaca-se a ocorrência de geadas severa e negra, e os eventos mais importantes de prejuízos agrícolas nas zonas cafeeiras do Sudeste. Para a Argentina, foram considerados casos de anticiclones com pressão recorde (acima de 1040 hPa), ocorrência de temperaturas mínimas extremas e tempestades de neve com elevado impacto social. Tal levantamento complementa as referências existentes na literatura e contribui para um melhor conhecimento da climatologia da ocorrência de massas polares na América do Sul. Dentre outros fatores notou-se que, apesar do aumento da temperatura média em boa parte do continente, continua-se registrando ondas de frio intensas com temperaturas baixas recordes tanto na Argentina quanto no Brasil, como, por exemplo, o ocorrido no inverno de 2000.

Numa segunda etapa, utilizou-se um esquema automático traçador para encontrar-se as trajetórias dos ciclones e anticiclones extratropicais associados a todos os casos de ondas de frio que resultaram em temperaturas mínimas abaixo de 1.0ºC em São Paulo. Os resultados mostraram que as trajetórias obedecem a um padrão definido de propagação, com anticiclones sendo formados em latitudes médias no oceano Pacífico leste, cruzando os Andes entre 35 e 50ºS apresentando um deslocamento meridional pronunciado na Argentina e finalmente, deslocando-se para o Atlântico entre 23 e 35ºS. Em um caso em particular, entretanto, a alta foi monitorada com mais de vinte dias de antecedência desde a região da Nova Zelândia. De forma geral, após passar para o Atlântico, as altas migratórias agregam-se à Alta Subtropical, atuando como um suposto mecanismo de realimentação daquele sistema. Por outro lado, a importância dos ciclones no processo, ainda pouco difundida na literatura, ficou marcada neste trabalho, com a ocorrência típica de ciclogênese na costa Atlântica e ciclólise na costa da Antártica e trajetórias bastante variáveis com duração de 3 a 21 dias.

Palavras-chave: Geadas, Ondas de Frio, Ciclones e Anticiclones Extratropicais, Algoritmos de Traçado de Trajetórias

ABSTRACT: A historical compilation of intense cold waves affecting South America from 1888 to 2003 is performed, with emphasis on extreme cases in Argentina and southern Brazil. For Brazil, extreme minimum temperatures and significant snow accumulation data in the mountainous regions of Rio Grande do Sul, Santa Catarina, São Paulo, Rio de Janeiro and Minas Gerais States are used. Frost and black frost are also considered for the cities of São Paulo and Campinas in particular, and the occurrence of widespread damage in the coffee growing areas of the southeastern part of the country is discussed. For Argentina, record minimum temperatures, record anticyclones (above 1040 hPa) and intense snowstorms with severe social impacts are considered. This background complements the previous references found in the literature, and adds a new perspective to the climatology of polar waves in South America. Among other results, it was shown that recent occurrence of extreme cold events such as the 2000 case, with record low temperatures in Brazil and Argentina, is relatively frequent, despite the average temperature warming trend that is taking place in many parts of the continent.

The cases leading to minimum temperatures below 1.0ºC in São Paulo are analyzed in terms of the associated cyclone and anticyclone tracks, through the use of an automatic tracking algorithm. The results showed that the trajectories described a well defined pattern of propagation, with most anticyclones appearing in eastern Pacific, crossing the Andes between 35 and 50ºS and presenting a pronounced meridional displacement from southern

to northern Argentina, and finally migrating to the Atlantic between 23 and 35ºS. However, a high variability is observed, and a particular case study shows a migrating anticyclone near the New Zealander sector with more than 20 days in advance with regard to frost occurrence in São Paulo. Over the Atlantic, most tracks are aggregated to the Subtropical High, suggesting a feeding-like mechanism. On the other hand, the cyclones apparently are an essential ingredient for triggering the cold waves because of the associated cold and dry advection (in the case of São Paulo). This fact is not commonly mentioned in the literature. Most cyclogenesis take place near the Atlantic coast and the cyclolisis occur around the Antarctic coast, with tracks lasting from 3 to 21 days.
Key words: Frosts, Polar Waves, Extratropical Cyclones and Anticyclones, Automatic Tracking Schemes

1. INTRODUCTION

The literature about polar waves in South America (SA) has undergone significant improvements particularly in the last decade, when important articles dealing with dynamics of case studies, statistics and climatological composites which led to the knowledge of the "*friagem*" in the Amazon River Basin have been published (Marengo *et al* 1997, Garreaud and Wallace 1998, Krishnamurti *et al* 1999, Garreaud 1999 and 2000, Vera and Vigliarolo 2000, Lupo *et al* 2001, Marengo *et al* 2002, Muller *et al* 2003 and Pezza and Ambrizzi 2005). However, a comprehensive historical background of severe cold cases affecting Brazil and Argentina is still lacking, probably because of the sparse surface data and the enormous difficulties faced by anyone who attempts to prepare such compilation.

Marengo *et al* (1997) is one of the few references which addressed this problem, showing a climatological list of intense cases that badly damaged the coffee growing areas of southeastern Brazil from 1892 to 1996. According to the authors, the cold surges in SA occur from zero to eight times a year, but major events with pronounced cooling in central and northern Amazon and widespread severe frost in south and southeastern Brazil are relatively rare, with about 46 events producing intense damage in the coffee growing areas during the studied period. On the other hand, speculation can also take place as for instance in the morning after the 1994 cold event (when minimum temperatures reached the freezing point in and around São Paulo city), when the prices of the Arabic coffee increased almost 70% in the New York stock market (Marengo *et al* 1997).

Souza (1998 a, b and 2002) described heavy snowfall in the mountains of southern Brazil as a relatively common phenomenon, with many social impacts such as on tourism and communications. In his works, the author associated the presence of snowfall in the upper plains of Rio Grande do Sul and Santa Catarina States with the passage of migratory anticyclones further inland (continental highs) and extratropical cyclones near the southern Brazilian coast. Furthermore the city of São Joaquim, located at 1300 m above the sea level in the eastern part of Santa Catarina State, was pointed out as being one of the Brazilian sites with more snowfall days per year. A comprehensive list of cases with intense snow accumulation in São Joaquim and other typical snowy sites in southern Brazil is also available from Climaterra (www.climaterra.com.br, personal communication) and some other sources that, unfortunately, have not been published yet (Cabral 1997 and references therein). For Argentina, Celemín (1984) made a historical compilation of record anticyclones with central pressure above 1040 hPa, apart from heavy snow occurrence and record minimum temperatures all over the country, developing a simple conceptual model for anticyclone tracks associated with polar outbreaks.

Concerning the dynamic of case studies, Marengo *et al* (1997) also studied the polar outbreak occurred in June 1994, when freezing temperatures affected a large part of the subtropical area of SA, severely damaging coffee and other vegetable growing areas. The contribution of each individual term within the quasi-geostrophic equation was analyzed, and a feedback like mechanism between the low and high level circulation in the Andes region was proposed during the preliminary phase, which could contribute to intensify the trough further to the east, therefore enhancing the cold advection itself.

Garreaud and Wallace (1998) studied a composite of summer time outbreaks of midlatitude air into tropical and subtropical South America, showing a pattern very similar to the one described by Marengo *et al* (1997), i.e., the presence of a relatively cold migrating anticyclone at the surface accompanied by a well defined quasi-geostrophic wave pattern above. The importance of the Andes Mountains in favoring the cold air advection on its eastern side through an ageostrophic wind component directly from the south was carefully discussed, complementing the previous studies found in the literature (Gan and Rao 1994, Seluchi 1995 and Seluchi *et al* 1998).

Garreaud (1999) simulated an intermediate event occurred in May 1993 and proposed the vorticity advection aloft as the main process contributing to the low and high pressure intensification at the surface, which is the mechanism associated with the low level cold advection. Furthermore, the subsidence occurring to the south of the subtropical jet also appeared as a relevant mechanism in intensifying the anticyclone, making the jet very important in the process. Finally, Garreaud (2000) complemented the previous studies showing the dynamic structure of wintertime cold waves and suggesting that winter and summertime cases are very similar but with different amplitudes.

Vera and Vigliarolo (2000) studied the dynamics of wintertime polar outbreaks, emphasizing the differences between cases associated with frosts in the subtropical area and cases confined to midlatitudes. In this work, the Principal Component Analysis (PCA) technique was used in order to extract the most relevant physical patterns. At high levels, some Rossby wave dispersion to the northeast was shown and, at the surface, the wave pattern is normally adjusted following the Rossby topographic waves due to the presence of the Andes.

Krishnamurti *et al* (1999) studied the downstream amplification in the Pacific Ocean associated with cold surges over South America, emphasizing the importance of the wave amplitude and the scale interaction among different waves in the whole process. The interaction between baroclinic and barotropic processes was also discussed, and it was shown to be relevant during the preliminary phase.

Lupo *et al* (2001) classified polar outbreaks in South America according to the synoptic pattern responsible for the low level cold advection and showed that the extratropical cyclones also play a crucial role in pushing the cold air into the Brazilian coast. It is interesting to notice that this concept was not present in the classical thinking, according to which the strength and positioning of the anticyclone were the only essential ingredients leading to frost in southeastern Brazil.

Recently, Marengo *et al* (2002) performed a composite of polar waves considering temperature deviations around the coffee growing area in southeastern Brazil (22.5^o S, 60^o W). They showed some persistent positive geopotencial anomalies to the southwest of South America during the preliminary phase up to twelve days in advance. The possibility of a connection with tropical convection near Indonesia was discussed through the linear wave theory. Furthermore, the authors have also pointed out the complexity of extended cold wave forecasts, since there is not only one preliminary observed pattern in the Pacific Ocean leading to intense surges.

Using PCA, Muller *et al* (2003) studied the synoptic patterns associated with frosts in the Argentine Wet Pampas (central Argentina). In this article, the authors obtained patterns very similar to those previously described but for cold surges taking place at higher latitudes, exemplifying the physical grounds of most PCA modes with real synoptic charts related to cold surges. Other studies addressing cold waves and cyclones and anticyclones in South America can also be seen in Ambrizzi and Pezza (1999), who made a review of the most important articles published during the last century.

As far as monitoring cyclone and anticyclone tracks is concerned, it is important to notice that, in the past, this process demanded a lot of operational time because of its manual nature. Nowadays, however, the situation is completely different due to recent developments on automatic tracking schemes such as the ones described in Murray and Simmonds (1991a, b) and Sinclair (1994). An automatic procedure can be applied for finding and tracking highs and lows from operational numerical analyses. The main advantage is the possibility of handling a large amount of information in a shorter time frame and producing results that can be easily compared among them.

Murray and Simmonds (1991a, b) developed an automatic procedure to find and track surface pressure systems. Jones and Simmonds (1993) evaluated the performance of this particular tracking scheme through different datasets and concluded that it is a very useful tool for meteorological applications. They were able to reproduce and complement some previous results found in the literature. Nowadays, the large number of studies using cyclone/anticyclone tracking schemes have shown their reliability (e.g., Sinclair 1994; Sinclair *et al* 1997; Simmonds and Keay 2000a, b and Pezza and Ambrizzi 2003 and 2005 and references therein).

In the present work, a compilation of historic cases of freezing temperatures, severe frosts and snowfall occurrence in Brazil and Argentina is presented for the 1888-2003 period, adding a new climatology in the literature. In the second part, the cyclone and anticyclone tracks associated with very strong cold cases leading to temperatures below 1.0ºC with frost in São Paulo are presented. The results are obtained from the use of the NCEP/NCAR Reanalysis data applied to the Murray and Simmonds automatic scheme (MS scheme from now on). This paper adds some new insights on the well-known traditional patterns of propagation, complementing the previous works found in the literature and improving the synoptic climatology of the Southern Hemisphere.

2. DATA AND METHODOLOGY

Daily minimum temperature data at 1.5 m are used for Campinas and São Paulo cities in Brazil, during the period of 1888 to 2003. The data for Campinas are available from Campinas Agronomic Institute (IAC) for the periods of 1890 – 1920 and 1929 – 2003 (Camargo 1997). For São Paulo city, the following data sets are used: from 1888 to 1894 at Luz (downtown area), from 1895 to 1901 at República Square (downtown area), from 1902 to 1933 at Paulista Avenue (near downtown area), and from 1934 to 2003 at Água Funda, a preserved green area located at the southern tip of the city and belonging to the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo (IAG/USP). The IAG/USP meteorological station has not undergone significant changes during the related period, having one of the most reliable climatological datasets in Brazil.

To determine the historical background of cold waves in South America as complete as possible, many additional sources are used, including official information provided by the Brazilian National Institute of Meteorology, i.e., *Instituto Nacional de Meteorologia* (INMET) and the Argentine National Weather Service, i.e., Servicio Meteorológico Nacional (SMN). Non-conventional reports such as data from private meteorological stations located in remote areas (Ronaldo Coutinho do Prado, personal communication, web site: http://www.climaterra.com.br), media information, data derived from damaged crops, and others are also included. All data used to elaborate the climatological tables were carefully checked case by case, and doubtful cases as the controversial snow occurrence in São Paulo during June 1919 (Mattos 1925) were eliminated. Finally, several "*friagem*" case studies published in the literature were also considered.

Twice a day mean sea level pressure data from the NCEP/NCAR Reanalysis (Kalnay *et al* 1996 and Kistler *et al* 2001) are used for the 1973 – 2003 period, and the MS automatic scheme is applied to find and track high and low pressure centers at the surface. The MS scheme was chosen because previous studies have shown its reliability in capturing the most important climatic features in the Southern Hemisphere (Murray and Simmonds 1991, Jones and Simmonds 1993 and 1994, Simmonds et al 1999, and Simmonds and Keay 2000 a and b and Pezza and Ambrizzi 2003 and 2005), and because it deals directly with sea level pressure, giving a synoptic meaning to the analyses.

The method is based on the physical principle that the center of a closed cyclone (anticyclone) is unequivocally identified with its point of minimum (maximum) pressure; this is normally found within one grid space of the Laplacian maximum (minimum), depending on the degree of symmetry of the system. A cyclone (anticyclone) is deemed to exist at any point at which the pressure is lower (higher) than at any of a small number of grid points (4 or 8) surrounding. In the second stage of the scheme the path of each system is tracked from the time of its appearance to its dissipation. To make the appropriate decisions, a procedure, which makes an estimate of the new position of each system, calculates the probability of associations between the predicted and realized positions, and finds the matching of these associations with the highest overall probability, was developed.

The settings and empirical parameters used within the MS automatic scheme are the same as described in Pezza and Ambrizzi (2003) who performed a sensitive calibration based on case studies of cold surges over South America (SA). For a detailed description of the physical principle and technical properties of the numerical algorithm, the reader should refer to that work and also to Murray and Simmonds (1991a, b) and references therein.

The study area is the Southern Hemisphere, and track analyses have been carried out during wintertime, i.e., June, July and August (JJA). All cold surges leading to minimum temperatures below 1.0ºC with frost in São Paulo are considered. The cyclone and anticyclone tracks directly responsible for the cold advection in the preliminary phase and for the radiative cooling leading to frost in São Paulo are plotted case by case. These cases are significant since the daily minimum temperature anomalies were above one and a half standard deviation. In addition, our tests have shown the existence of a significant large-scale pattern associated with these cases, i.e., the presence of a well developed baroclinic wave at mid and high levels leading to the cold air incursion near the surface, as seen by the composites shown in Pezza and Ambrizzi (2005).

The principle used to find each track was a manual check case by case, first identifying one single point of each cyclone and anticyclone track directly associated with the cold surges, usually during the "day 0" (lowest temperatures in São Paulo). This is made using the "synoptic experience", considering the classical polar front theory of Bjerknes and Solberg (1922), i.e., a baroclinic conceptual model where a coupled cyclone/anticyclone at the surface (guided by the circulation aloft) is responsible for the cold advection at the early stage and the radiational cooling in the mature phase, generating the cold front. Once we knew the exact location of one single point in each case, it was easy to identify the corresponding tracks using the MS automatic scheme, and then finally to plot the trajectories case by case.

A detailed manual check of the obtained trajectories was also performed in order to assure the physical authenticity of the analyses, and the tests showed that the performance of the algorithm was excellent for all cold surge cases. The only thing to consider is that, although the MS scheme is totally automatic, due to the Andes elevated topography in some cases a correction might be desirable in order to properly link two centers, i.e., before and after crossing the mountain. This was necessary only for the anticyclone associated with the June 1994 cold surge, because in that case the high pressure center crossed the Andes over considerably lower latitude where the elevation is more pronounced.

3. RESULTS AND DISCUSSION

3.1 Historical Backgrounds

Table 1 shows significant cold events in SA from 1898 to 2003 according to several sources, including official information provided by the Brazilian and Argentine National Weather Services and previous works found in the literature, as Mattos (1925), Cabral (1997), Souza (1998a, b, 2002), Celemín (1984), Myers (1964), Nimer (1979), Monteiro (1969), Scian (1970), Hamilton and Tarifa (1978), Rusticucci and Vargas (1995), Parmenter (1976), Girardi (1983), Fortune and Kousky (1983), Camargo (1997), Marengo *et al* (1997), Dapozzo and Silva Dias (1994), Pezza and Ambrizzi (1999), Satyamurty *et al* (2001) and others.

Non-conventional sources such as newspaper information and data from private meteorological stations are also used, but only to check the validity of the information in order to assure that all cases shown here are authentic and significant, i.e., showing the occurrence of frost and snow with widespread social problems. This cross-checking analysis is important considering the poor data coverage in SA, especially during the beginning of the last century. The compilation presented in table 1 does not address all extreme cold cases occurred in Brazil and Argentina, but it is an effort to bring a historical background as complete as possible, putting together the official and the non-conventional information.

Year	Cold Event	Sources
1898 (August)	Minimum temperature of -2.5ºC in São Paulo downtown area (República) and of -4.0ºC in the outskirts (Horto Florestal), with severe frost and black frost	Cabral (1997) Mattos (1925)
1902 (August)	Minimum temperature of –2.0ºC and severe frost in São Paulo downtown area (Paulista Avenue)	IAG/USP Cabral (1997)
1910 (September)	Heavy snowfall in São Joaquim (Santa Catarina State, southern Brazil), with an accumulation of 150 cm in 24 h	Climaterra Souza (1998 b)
1918 (June)	Heavy snowfall in Buenos Aires (Argentina) Severe frost in São Paulo downtown area (Paulista Avenue), with a minimum temperature of -1.2ºC	Celemin (1984) IAG/USP Cabral (1997)
1918 (July)	Record minimum temperature of –5.4ºC in Buenos Aires	Celemin (1984)
1928 (July)	Heavy snow (more than 100 cm accumulated) in São Joaquim and in Curitiba (Parana State, southern Brazil). Snowfall occurrence in Campos do Jordão (São Paulo State)	Souza (1998 b) Souza (2002) Climaterra Myers (1964)
1942 (July)	Minimum temperature of -1.2ºC in São Paulo (IAG)	IAG/USP
1945 (June)	Official record of minimum temperature in Brazil, with –11.6ºC in Xanxerê (Santa Catarina State)	Nimer (1979)
1947 (June)	Snowfall occurrence in Campos do Jordão	Souza (1998 b)
1952 (June)	Official record of minimum temperature in Brazil, with –14ºC in Caçador (Santa Catarina State)	Souza (1998 b) Climaterra
1955 (August)	Minimum temperature of –1.2º C in São Paulo (IAG)	IAG/USP
1957 (July)	Heavy snowfall in São Joaquim (up to 130 cm accumulated in rural areas)	Souza (1998 b) Climaterra Monteiro (1969) Myers (1964)
1965 (August)	Heavy snowfall in Palmas (Parana State, southern Brazil), with almost 100 cm accumulated. Generalized snow occurrence in southern Brazil	Souza (2002) Climaterra
1967 (June)	Record minimum temperature of -5.3ºC in Buenos Aires	Celemín (1984) Scian (1970)
1972 (July)	Strong "friagem" in South America, with generalized frosts damaging the coffee growing areas of south and southeast Brazil	Hamilton and Tarifa (1978)
1973 (July)	Snowfall in Uruguay and in the outskirts of Buenos Aires. Significant anticyclone of 1045 hPa in Patagonia region	Souza (1998 b) Rusticucci and Vargas (1995) Celemín (1984)
1975 (July)	Minimum temperature of -1.1ºC in São Paulo, with severe frost. Strong "friagem" in South America, with snowfall occurrence in Southern Brazil and generalized frosts in the subtropical belt. Agriculture and economies badly damaged	Parmenter (1976) Girardi (1983) Souza (1998 b) Souza (2002)
1976 (September)	Record anticyclone of 1041 hPa associated with heavy snow in central Argentina	Celemín (1984)

1979 (May/June)	Snowfall occurrence in Monte Verde (Minas Gerais State, Brazil), with an accumulation of 20 cm. Minimum temperature of –0.2º C in São Paulo (IAG)	Souza (1998 b) IAG/USP Fortune and Kousky (1983)
1981 (July)	Black frost occurrence in the eastern part of São Paulo State (Campinas and São Paulo)	Camargo (1997) Marengo *et al* (1997B)
1983 (May)	Record anticyclone of 1042 hPa in southern Argentina Heavy snow with up to 30 cm accumulated in Mendoza (Argentina)	Celemín (1984)
1984 (winter)	Exceptionally snowy winter in southern and western Argentina (frequency and intensity), with minimum temperatures reaching –24ºC in Chubut province. Many losses on cattle	SMN (Argentina) Souza (1998 b)
1985 (June)	Heavy snow in Itatiaia National Park (Mantiqueira mountains, southeastern Brazil), with several centimeters accumulated on the ground. Heavy snow occurrence in São Joaquim (up to 30 cm accumulated)	Souza (1998 b) Souza (2002)
1986 (July)	Snowfall occurrence in Campos do Jordao	Souza (1998 b)
1988 (winter)	Heavy snow in São Joaquim (30 cm accumulated) and snowfall occurrence in Mantiqueira mountains. Record minimum temperature of –12º C in Bahía Blanca (Buenos Aires province, Argentina)	Climaterra Souza (1998 b) Celemín (1984) Dapozzo and S. Dias (1994)
1990 (winter)	Record high frequency of snowfall occurrence in southern Brazil, with heavy snow (up to 50 cm accumulated) in São Joaquim. Minimum temperature of –0.4º C in São Paulo (IAG)	Climaterra Souza (1998 b) IAG/USP
1991 (July/August)	Snowfall occurrence in Uruguay and in the outskirts of Buenos Aires. Record minimum temperature of –35.3ºC in Maquinchao, southern Argentina (41ºS, 69ºW, 888 m). Record minimum temperature of -10.0ºC in São Joaquim	Souza (1998 b) SMN (Argentina) INMET
1992 (July)	Record minimum temperature of –12ºC in northwestern Argentina, in association with a 1042 hPa anticyclone over Cordoba (central Argentina)	SMN (Argentina)
1994 (winter)	Strong polar air masses affect subtropical South America, with severe frosts badly damaging coffee and other vegetables	Marengo *et al* (1997 B and C)
1995 (winter)	Heavy snow storms in southern Argentina, with a record minimum temperature of -19.4ºC in Bariloche, and many social problems (closed roads, isolated villages, many losses on cattle, etc)	Pezza and Ambrizzi (1999)
1996 (June)	Heavy snow in São Joaquim (21 cm accumulated in 7 hours)	Climaterra INMET Souza (1998 b)

1999 (April to October)	Record anticyclone of 1046 hPa in northwestern Argentina, associated with snow storms near Buenos Aires and southern Brazil, including Mantiqueira mountains. Unprecedented early and late snowfall occurrence in São Joaquim during the months of April and October	SMN (Argentina) INMET Satyamurty *et al* (2001)
2000 (July)	Record anticyclone of 1049 hPa in southern Patagonia, associated with minimum temperatures of -23ºC in the southern tip of the continent and -0.2ºC in São Paulo (IAG), with a record persistence of low temperatures and frost frequency in southern Brazil	SMN (Argentina) INMET IAG/USP
2000 (September)	Record snow storms in Patagonia, with minimum temperatures up to –19ºC and more than 19 million cattle were killed	SMN (Argentina) Newspaper "La Nacion" (Buenos Aires)
2001 (July)	Heavy snow storms in Patagonia, with record minimum temperatures ranging between –15 and –27ºC for about 15 consecutive days in some areas. Unprecedented partial freezing of the Chubut river (southern Argentina), with millions of cattle being killed	SMN (Argentina) Newspaper "La Nacion" (Buenos Aires)
2002 (June)	Record anticyclone of 1044 hPa in southern Chile, with a minimum temperature of -27ºC in Balmaceda (46ºS, 72º W, 520 m)	Meteochile SMN (Argentina)

Table 1: Intense cold events in South America (Brazil, Chile and Argentina) for the period of 1898 – 2003 (from April to October). See text for further details.

Observing the major snowfall accumulations in southern Brazil (a total layer of at least 100 cm on the ground), the cases of September 1910 (150 cm), July 1928 (100 cm), July 1957 (130 cm) and August 1965 (100 cm) appeared as the most important ones. From 1965 to the present no extreme case (over 100 cm of snow) has been measured at any point in Brazil, what is in accordance with the positive average temperature trends seen in many meteorological stations in southern Brazil during the winter, according to the INMET. However, it is interesting to notice that Gonçalves *et al* (2002) argued that in São Paulo the extreme minimum temperatures presented little frequency change, despite the warmer average temperatures. But the minimum temperatures in São Paulo are strongly controlled by local radiative aspects, differently from the processes leading to snow. In the last case, the advection is more important and, as a result, it is expected that an increase on the mean temperature will effectively reduce the snow accumulation.

Relatively recent years with significant snow accumulation in southern Brazil were 1988 (30 cm) and 1990 (50 cm), the last one being the snowiest year of the last two decades. On the other hand, the Mantiqueira Mountain Range in São Paulo, Minas Gerais and Rio de Janeiro States border presented significant snow occurrence during 1928, 1947, 1979, 1985 and 1988 (up to 20 cm in some areas), where the elevation is over 1500 m.

In respect to extreme minimum temperatures, the Brazilian official record was -14.0ºC in Caçador (Santa Catarina State) during June 1952. However, several records near -10ºC can be found throughout the last century. In São Paulo, the coldest official temperature ever measured was -4.0ºC at Horto Florestal station, a green area at the northern tip of the city, and -2.5ºC in downtown area, in August 1898. Other significant low values in São Paulo were: -2.0ºC in August 1902, -1.2ºC in July 1918, July 1942 and August 1955 and -1.1ºC in July 1975.

For Buenos Aires, in Argentina, the records of minimum temperatures were -5.4ºC in 1918, with significant snow accumulation in the same winter, and -5.3ºC in 1967. The strongest anticyclones were measured in July 1973 (1045 hPa), July 1975 (1040 to 1045 hPa), August 1999 (1046 hPa) and July 2000 (1049 hPa) considering the whole country, generally associated with minimum temperatures between -20 and -35ºC in central – south Patagonia.

It is curious that despite the warming trend revealed by the average temperature in many stations in Brazil and Argentina (INMET and SMN, personal communication 2003), the most intense anticyclones ever measured have occurred very recently, in 2000 and 1999. This result could be partially due to recent data coverage improvements, rather than a possible bias towards more intense anticyclones during the last decades. Furthermore their positioning can show significant inter-annual variation, e.g., in 1975 the anticyclone center was found in northern Argentina and in 2000 the high pressure center developed in the extreme southern Patagonia.

Table 2 shows the climatology of daily cold events with extreme minimum temperatures below or equal to 2.5ºC between São Paulo city and Campinas, for the period of 1888 – 2003. The occurrences of frost, dew, fog and other significant weather conditions are indicated in the case of São Paulo (when available), as well as severe widespread coffee damage according to Marengo *et al* (1997). In São Paulo city, the following meteorological stations are used: Luz (1888 – 1894), República Square (1895 – 1901) and Paulista Avenue (1902 – 1933) in downtown area and IAG/USP at Água Funda Park (1934 – 2003). In Campinas, data from IAC (Campinas Agronomic Institute) are used. According to IAC, the 2.5°C threshold is a good frost indicator in tropical and subtropical areas (Camargo 1977).

Year	**Date or Period**	**Minimum temperature at 1.5 m in Campinas (IAC) and São Paulo (LUZ, REP, PAV and IAG)**	**Surface conditions in São Paulo (LUZ, REP, PAV and IAG)**	**Widespread severe coffee damage (Marengo *et al* 1997)**
1889	June	0.9 (LUZ)	NA	__
1889	August	2.0 (LUZ)	NA	__
1889	September	0.7 (LUZ)	NA	__
1890	August	0.7 (LUZ)	NA	__
1891	May	2.4 (LUZ)	NA	__
1892	July 14	0.2 (IAC); 0.7 (LUZ)	Frost	YES
1893	June	1.0 (LUZ)	NA	__
1894	June	2.4 (LUZ)	NA	__
1894	July 14	1.0 (IAC); 1.5 (LUZ)	Frost	YES
1895	June 25	1.0 (IAC); 0.0 (REP)	Frost	YES
1898	May	1.5 (REP)	NA	__
1898	July 05	2.4 (IAC); 0.9 (REP)	Frost	YES
1898	**August 24**	**-2.5 (REP)**	**Black Frost**	**__**
1899	June 18	1.6 (IAC); 2.8 (REP)	Frost	YES
1901	June	2.4 (REP)	NA	__
1902	August 18	0.5 (PAV)	NA	__
1902	**August 19**	**0.2 (IAC); -2.0 (PAV)**	**Severe Frost**	**YES**
1904	June	1.3 (PAV)	NA	__
1904	12 August	1.5 (IAC); 4.0 (PAV)	Frost	YES
1904	13 August	1.5 (PAV)	Frost	__
1905	July	-0.2 (PAV)	NA	__
1905	August	0.5 (PAV)	NA	__
1910	18 July	2.1 (IAC); 3.5 (PAV)	Frost	YES
1910	19 July	-0.2 (PAV)	Frost	__
1911	23 June	2.2 (IAC); 3.2 (PAV)	__	YES
1911	24 June	0.0 (PAV)	Frost	__
1912	03 September	1.8 (IAC); 4.4 (PAV)	__	YES
1912	04 September	1.5 (PAV)	Frost	__
1917	August	2.0 (PAV)	NA	__
1918	**25 June**	**-1.5 (IAC); -1.2 (PAV)**	**Severe Frost**	**YES**
1918	26 June	-1.2 (PAV)	Frost	__
1918	July	1.2 (PAV)	NA	__
1919	August	2.0 (PAV)	NA	__
1920	June	-0.4 (PAV)	NA	__
1920	September	2.2 (PAV)	NA	__
1921	June	0.2 (PAV)	NA	__
1921	July	-0.3 (PAV)	NA	__

1923	July	-0.2 (PAV)	NA	__
1924	August	1.0 (PAV)	NA	__
1925	June	1.2 (PAV)	NA	__
1925	July	1.1 (PAV)	NA	__
1926	July	0.6 (PAV)	NA	__
1930	July	2.0 (PAV)	NA	__
1931	29 June	2.0 (IAC); 1.1 (PAV)	Frost	YES
1931	30 June	1.5 (PAV)	Frost	__
1932	June	1.9 (PAV)	NA	__
1933	June	1.9 (PAV)	NA	__
1933	14 July	1.4 (IAC); 1.2 (PAV)	Frost	YES
1935	30 July	1.6 (IAG)	Fog	__
1936	07 August	0.8 (IAG)	Frost	__
1936	10 August	2.3 (IAG)	__	__
1938	08 July	2.0 (IAG)	Dew	__
1939	24 July	1.4 (IAG)	Frost	__
1939	31 July	1.9 (IAG)	Frost/Dew	__
1939	01 August	2.1 (IAG)	Frost/Dew	__
1940	04 July	2.4 (IAG)	Frost	__
1941	04 September	2.0 (IAG)	Minim. T at night	__
1941	05 September	0.4 (IAG)	Frost	__
1942	19 June	1.1 (IAG)	__	__
1942	20 June	-0.6 (IAG)	Frost	__
1942	05 July	2.3 (IAG)	Dew at night	__
1942	06 July	-1.2 (IAG)	Frost	__
1942	11 July	1.5 (IAG)	Minim. T at night	__
1942	12 July	-0.2 (IAC); -1.2 (IAG)	Frost	YES
1943	15 September	2.0 (IAC); 0.9 (IAG)	Frost	YES
1945	11 June	2.1 (IAG)	Dew/Fog	__
1946	04 June	2.4 (IAG)	Dew	__
1946	22 July	0.4 (IAG)	Frost/Fog	__
1948	16 June	2.1 (IAG)	Dew/Fog	__
1948	09 August	1.6 (IAG)	Frost	__
1951	06 July	2.2 (IAG)	Frost	__
1953	05 July	1.2 (IAC); -0.1 (IAG)	Frost/Fog	YES
1953	11 July	0.3 (IAG)	Frost/Fog	__
1953	08 August	1.3 (IAG)	Fog	__
1955	01 August	0.9 (IAG)	Dew at night	__
1955	02 August	1.1 (IAC); -1.2 (IAG)	Frost/Fog	YES
1955	03 August	2.1 (IAG)	Fog	__
1957	21 July	1.2 (IAC); 3.3 (IAG)	__	YES
1962	07 July	2.0 (IAC); 1.8 (IAG)	Frost/Fog	YES
1963	21 June	2.8 (IAG)	Frost	__
1963	22 June	2.5 (IAC); 3.0 (IAG)	Fog	YES
1963	06 August	1.3 (IAG)	Frost	__

1964	28 July	2.4 (IAC); 2.9 (IAG)	Fog	YES
1964	04 September	1.7 (IAG)	Frost/Fog	__
1965	11 July	2.1 (IAG)	Fog at night	__
1965	12 July	1.0 (IAG)	Frost/Fog	__
1965	21 August	0.6 (IAC); 2.8 (IAG)	__	YES
1968	17 May	2.5 (IAG)	Frost/Dew/Fog	__
1969	11 July	2.4 (IAC); 0.2 (IAG)	Frost/Fog	YES
1972	09 July	1.6 (IAC); 1.4 (IAG)	Frost	YES
1975	07 July	2.2 (IAC); 2.2 (IAG)	Frost	__
1975	17 July	1.2 (IAG)	Minim. T at night	__
1975	**18 July**	**0.6 (IAC); -1.1 (IAG)**	**Severe Frost**	**YES**
1975	19 July	2.3 (IAG)	__	__
1979	31 May	0.2 (IAC); 1.4 (IAG)	Frost at night	YES
1979	01 June	1.0 (IAC); -0.2 (IAG)	Frost/Fog	__
1979	18 July	1.3 (IAG)	Frost/Fog	__
1981	20 June	2.2 (IAG)	Frost/Fog	__
1981	**21 July**	**0.2 (IAC); 3.2 (IAG)**	**Black Frost**	**YES**
1981	22 July	2.9 (IAG)	Frost	__
1984	27 August	1.6 (IAG)	__	YES
1985	08 June	1.4 (IAC); 4.4 (IAG)	__	YES
1988	05 June	1.8 (IAC); 3.8 (IAG)	__	__
1988	06 June	1.9 (IAG)	Frost/Fog	__
1990	28 July	2.4 (IAG)	Minim. T at night	__
1990	29 July	2.0 (IAC); -0.4 (IAG)	Frost/Fog	__
1990	30 July	1.7 (IAG)	Frost/Fog	__
1993	12 August	1.9 (IAG)	Frost	__
1994	26 June	0.3 (IAC); 1.2 (IAG)	Frost	YES
1994	27 June	0.6 (IAC); 0.6 (IAG)	Frost	__
1994	28 June	2.0 (IAC); 3.0 (IAG)	Frost	__
1994	09 July	2.3 (IAG)	Minim. T at night	YES
1994	10 July	2.4 (IAC); 1.5 (IAG)	Fog	__
2000	17 July	1.6 (IAC); -0.2 (IAG)	Frost	__
2000	18 July	2.2 (IAC); 2.0 (IAG)	Frost/Fog	__

Table 2: Historical background of cold events with extreme minimum temperatures (at 1.5 m) below or equal 2.5ºC between 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 – 2003. 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 2003 for IAG. In the São Paulo case, frost, fog, dew and other relevant surface conditions were indicated when present, and NA means not available. Widespread severe damage on coffee growing areas in southeastern Brazil according to Marengo *et al* (1997) was indicated, and black and extremely severe frosts are in bold.

The results show that the minimum temperatures in São Paulo and Campinas are very similar, with small fluctuations depending on the case. The most severe frost and black frost cases according to Camargo (1997) were indicated in bold, where one can see August 1898 and July 1981 with severe black frost, and August 1902, June 1918 and July 1975 with 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. The criterion used by Camargo (1997) to classify the severity of frost was rather restrictive because only the extreme cases were selected, but other important frost events shown in table 2 as the May 1979, July 1990, June 1994 and July 2000 were also very strong and damaging.

Table 2 shows a high frost incidence in São Paulo for temperatures below 2.5ºC, usually taking place with fog or shallow fog. However, it is interesting to notice that some significant cold cases are not associated with frost, generally because of wet conditions as measured in July 1994, with 1.5ºC and fog. With regard to the coffee growing areas in southeastern Brazil, it was seen at least more than thirty cases of widespread damage all over the period. This is a complex parameter because it depends on the techniques used and the general improvements in agriculture, and similar weather situations can produce different degrees of damage.

From the table it is also clear that there is a concentration of severe coffee damage cases during the beginning of the last century, what is possibly a result of the poorer techniques used against the cold weather at that time. In the 90s 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.

Date (A)	**Min Temp (ºC)**	**Anticyc. Press. (hPa)**	**Position (Lat/Lon)**	**Average Pressure (hpa)**	**Maximum Pressure (hPa)**	**Position (Lat/Lon)**	**Length (days)**
07/18/75	-1.1	1031.8	28S/56W	1029.4	1039.5	42S/72W	16.5
06/01/79	-0.2	1025.2	25S/52W	1024.6	1030.8	49S/77W	09.0
07/29/90	-0.4	1034.5	37S/66W	1030.9	1035.4	36S/56W	07.5
06/27/94	0.6	1024.4	24S/51W	1026.8	1033.2	36S/81W	30.0
07/17/00	-0.2	1022.1	26S/53W	1025.0	1030.0	26S/66W	04.0
Average	**-0.3**	**1027.6**	**28S/56W**	**1027.3**	**1033.8**	**38S/70W**	**13.4**

Date (B)	**Min Temp (ºC)**	**Cyclone Press. (hPa)**	**Position (Lat/Lon)**	**Average Pressure (hpa)**	**Minimum Pressure (hPa)**	**Position (Lat/Lon)**	**Length (days)**
07/18/75	-1.1	Indef.	Indef.	994.9	989.9	49S/63W	05.0
06/01/79	-0.2	974.2	54S/21W	978.7	961.2	63S/33E	21.0
07/29/90	-0.4	994.3	48S/14W	998.2	994.3	48S/14W	02.5
06/27/94	0.6	972.8	48S/44W	979.4	969.8	65S/18E	11.0
07/17/00	-0.2	992.7	40S/37W	976.9	943.9	63S/23E	16.0
Average	**-0.3**	**983.5**	**48S/29W**	**985.6**	**971.8**	**58S/01W**	**11.1**

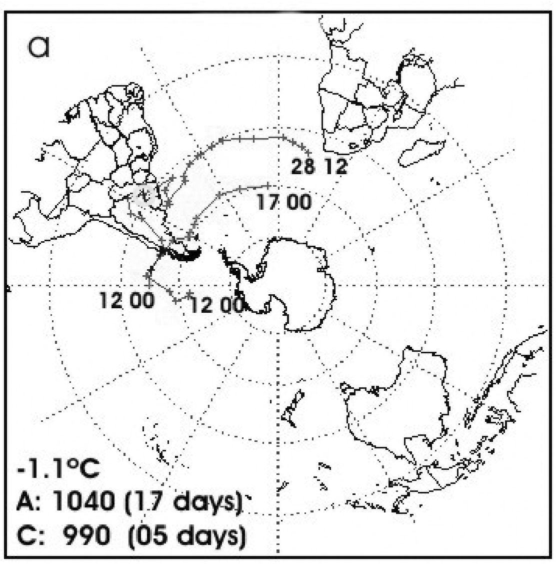
Table 3: Mean and extreme characteristics of the (A) anticyclones and (B) cyclone tracks associated with case studies of minimum temperatures below 1.0ºC with frost in São Paulo, from 1973 to 2003.

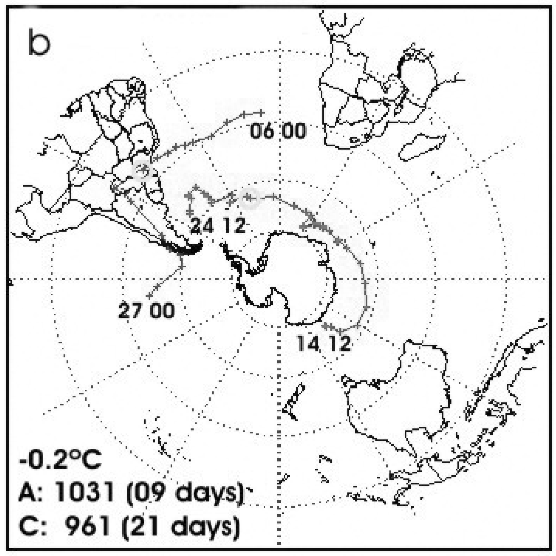
3.2. Cyclone and Anticyclone Tracks Associated

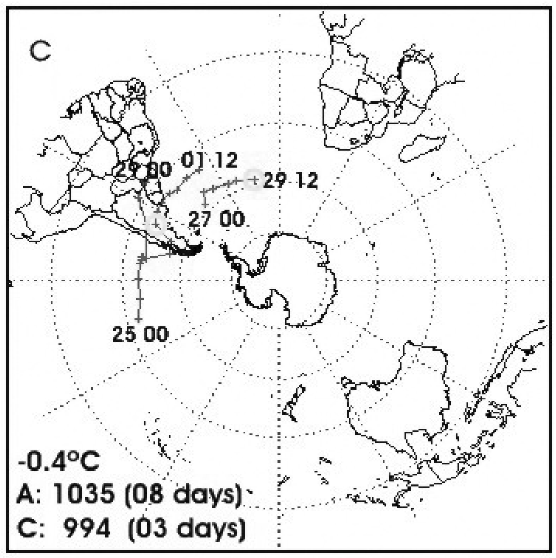
Table 3 shows the average and extreme characteristics of all (a) anticyclone and (b) cyclone tracks associated with cold surges leading to frost and minimum temperatures below 1.0ºC in São Paulo. The anticyclone (cyclone) central pressure and the corresponding coordinates were obtained at 12UTC of the coldest day, and the average, maximum (minimum) pressure and length in days correspond to the whole trajectory. Overall it is seen five days with temperatures below 1.0ºC in São Paulo from 1973 to 2003, being very strong cases since they represent more than one and a half standard deviation with regard to the minimum temperature climatology. In addition, a strong large scale pattern can be seen for composed atmospheric fields such as pressure, geopotential and wind (figure not shown). From table 3a, the minimum temperatures range from -1.1ºC in July 18th 1975 to 0.6ºC in June 27th 1994, with an average of -0.3ºC. The anticyclone strength at 12 UTC of the coldest day ranges from 1022.1 hPa for the 2000 event to 1034.5 hPa for the 1990 cold surge, averaging 1027.6 hPa and therefore indicating a high variability. However, one has to consider that such variability was associated with a strong positioning shift, since the latitudes range between 24 and 37ºS with significant longitude variations too. Usually the stronger anticyclones are found further south, what is reasonable to expect because the high pressure tends to weaken considerably when moving to subtropical latitudes, as a result of the increasing solar radiation and the mixture occurring with warm and less dense air.

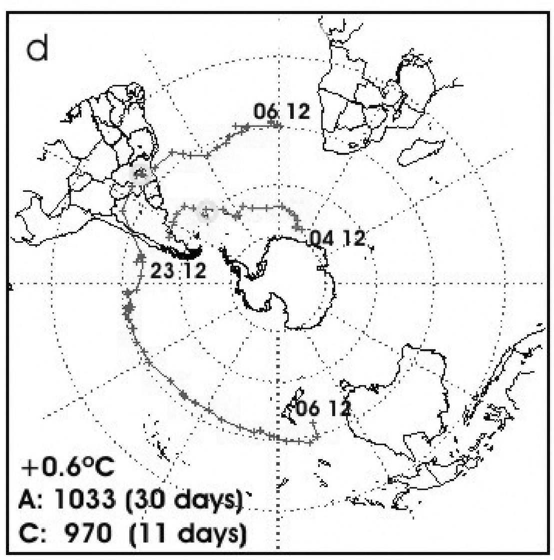
The average pressure for all tracks is 1027.3 hPa, with a minimum of 1024.6 and a maximum of 1030.9 hPa, and the maximum pressure oscillating between 1030.0 and 1039.5 hPa. It is interesting to notice that the extreme maximum pressure corresponds to the coldest event (-1ºC in July 1975). The positioning of the maximum points also presented a high variability, ranging from 49 to 26ºS. Finally, the trajectories length show an intense variability going from only four days in the 2000 case to thirty days during 1994, and averaging 13.4 days.

Table 3b is similar to table 3a but for the cyclones. During the extreme 1975 case the cyclone at 12UTC of the coldest day was indefinable because the trajectory previously existent had already undergone cyclolisis (see also figure 1a). On the other hand, all values associated were very intense, ranging from 972.8 to 994.3 hPa and averaging 983.5 hPa during the coldest day, and their location was also very variable, ranging from 40 to 54ºS. This is suggesting that, despite the importance of the cyclones during the preliminary and mature phases leading to frost, those systems can be found either closer to SA or further offshore, towards the southern ocean. The average pressure oscillated between 976.9 hPa during the 2000 case and 998.2 hPa in July 1990, with an average of 985.6 hPa, and the extreme minimum pressure was 943.9 hPa









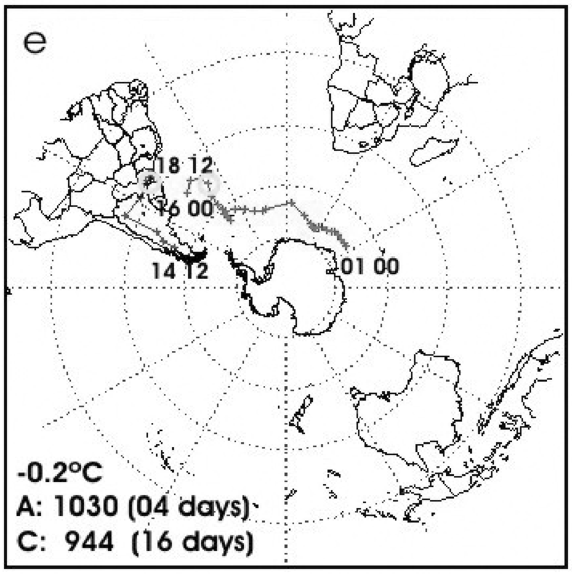


Figure 1: Cyclone (in red) and anticyclone (in blue) tracks associated with polar outbreaks leading to frost and minimum temperatures below 1.0ºC in São Paulo (1973 – 2003), for (a) July 1975, (b) May/June 1979, (c) July 1990, (d) June 1994 and (e) July (2000). The yellow circles indicate the positioning at 12 UTC for the coldest day, and the extreme minimum temperature, extreme maximum and minimum pressure and the length (in days) are indicated on the left bottom corner. See text for further details.

in the July 2000 outbreak. On average, the lowest pressure was 971.8 hPa, and usually the cyclone centers were found further south (around 60ºS) during the maximum strength. Finally, their length oscillated between 2.5 and 21 days, indicating a high variability as seen in the anticyclone case.

Comparing tables 3a and 3b, the presence of a strong cyclone-anticyclone couple contributes to produce an intense wind anomaly from the south, and hence generating significant cold advection towards lower latitudes. This is typical of strong polar surges in SA (Hamilton and Tarifa 1978, Fortune and Kousky 1983, Girardi 1983, Marengo *et al* 1997 and 2002, Krishnamurti *et al* 1999, Gan and Wallace 1998, Garreaud 1999 and 2000, Vera and Vigliarolo 2000, Lupo *et al* 2001, Muller *et al* 2003 and Pezza and Ambrizzi 1999 and 2005 and references therein), and the positioning of each couple is an essential ingredient for maximizing the cold and dry advection in the area of São Paulo, hence contributing for frost occurrence.

Another point is the very long length of some tracks, as occurred with the anticyclone in June 1994 and with the cyclone in June 1979. Such long tracks suggest persistent upper level conditions supporting the signal found at the surface. Finally, the anticyclones seemed to have a reasonable dependency on the temperature and on its positioning, with stronger systems associated with colder temperatures and centers located further south, while in the cyclone cases only a certain dependency with latitude was suggested, also meaning stronger cyclones when they are located further south.

Figure 1 shows the cyclone (in red) and anticyclone (in blue) tracks associated with the intense cold cases leading to minimum temperatures below 1.0ºC with frost in São Paulo, indicating an overall of five cases as discussed in table 3: (a) July 1975, (b) May/June 1979, (c) July 1990, (d) June 1994 and (e) July 2000. The yellow circles indicate the position of the cyclone and anticyclone centers at 12 UTC of the coldest day in São Paulo (see table 3). The initial and final tracking times, the minimum temperatures in São Paulo and the maximum and minimum pressures and the track lengths in days were also indicated.

The July 1975 case (figure 1a) presented both cyclone and anticyclone tracks beginning at the same time (12 at 00 UTC) over the eastern Pacific Ocean and developing a very intense pressure gradient in the southern tip of the country, with a 1040 hPa anticyclone over the Andes versus a 990 hPa cyclone off the southern Patagonian coast. While the cyclone followed a zonal path towards the open waters of the central Atlantic Ocean till the 17th (dying out during the coldest morning in São Paulo), the anticyclone showed a pronounced meridional track, following the typical "*friagem*" path to the right of the Andes and oscillating around Rio Grande do Sul area before reaching the Atlantic and finally disappearing near the African coast 17 days later.

This case was first analyzed by Parmenter (1976) and Girardi (1983), and it presented very damaging frosts in both subtropical and tropical areas of SA, being considered as one of the worst "*friagem*" ever measured. It is suggested that what made this case so strong was the combination of four principal ingredients: I) the high latitude source of the anticyclone (around 55ºS), suggesting that the air parcels arriving in SA could have a significant influence from the Antarctic continent; II) the very tight isobars to the south with the cyclone and the anticyclone tracks being almost coincident from the Pacific to the Patagonian region, leading to a very strong pressure gradient; III) the fact that the anticyclone presented a pronounced meridional track without losing its intensity, reaching northern Argentina with more than 1040 hPa which is rare (up to 1045 hPa according to Parmenter 1976); IV) the oscillation of the anticyclone occurred near southern Brazil, favoring frosty conditions in the area during several days.

The May/June 1979 case is shown in figure 1b, and it was relatively similar to the 1975 case, but with an important exception since in this case the anticyclone was originated at lower latitudes (around 40ºS) and initially acquired a southward component, crossing the Andes at the extreme southern tip of the continent. However, the overall meridional displacement was similar to the 1975 case because the anticyclone reached lower latitudes in this case (extreme northern Paraguay). This event was first studied by Fortune and Kousky (1983) who also plotted the tracks associated but were unable to capture the whole tracks over the oceans because they used conventional analyses (at that time automatic schemes were not available). The tracks over the continent, however, are similar.

Figure 1b also shows that for the 1979 case the cyclone appeared before the anticyclone and it was much more intense compared to the 1975 case (961 hPa versus 990 hPa). This situation approximately compensated the weaker anticyclone and also produced an intense "*friagem*" incursion. In addition, it is interesting to notice that the anticyclone passed closer to São Paulo during the morning of the coldest day, and the cyclone was also present on the Atlantic, describing a very long trajectory of 21 days and disappearing near the Antarctic coast.

The July 1990 case presented a different behavior (fig. 1c), with a relatively short cyclone track and an anticyclone split into two tracks over SA. The cyclone reached 994 hPa near the Patagonian coast, and the high pressure reached 1035 hPa around the Andes, characterizing a strong pressure gradient favorable to cold advection in the continent. During 12 UTC of the coldest day in São Paulo, the high pressure path further to the north was undergoing anticyclolisis, but a stronger center was seen in central Argentina (in yellow), and the cyclone was well off shore on the Atlantic. Compared with the other cases, the anticyclone was originated at lower latitudes and did not present a pronounced meridional displacement over the continent, but it is suggested that the split of the track may have contributed to increase the cold advection leading to frost in São Paulo. Furthermore it might be indicating the passage of a secondary wave reinforcing the initial cold surge.

Figure 1d shows the June 1994 case first discussed by Marengo *et al* (1997). This case presented a very particular behavior, with a long anticyclone track originated near the cost of New Zealand coast and lasting an entire month on its way to the African coast. Such pattern suggests a very persistent upper level signal contributing to the maintenance of the high pressure at the surface. One may wonder what would be the meaning of such a long track since the typical synoptic time scale is around seven days. A careful synoptic analysis based on the NCEP data revealed that the cold front responsible for the frost in southeastern Brazil was formed near the continent, triggered by the strong cyclogenesis (970 hPa) occurred in Patagonia on the 23rd. However, it was the interaction with the long anticyclone track that created favorable conditions leading to the pronounced meridional air exchange occurred in this case.

Another interesting feature associated with this case is that the anticyclone track in the Pacific stayed most of the time near 30ºS, showing a small displacement to the south before crossing the Andes. As a result, the high pressure center crossed the mountains at significant low latitudes (30ºS), having a continental path at low latitudes during the 24 hours before the frost, and reaching São Paulo during the coldest day. This result suggests that the origin of the polar air mass in this case was not as characteristic of high latitudes as in the other events. This was reinforced by the Argentine National Weather Service, which indicated that no major cold event took place in central and south Argentina during that month, despite the very low temperatures measured at lower latitudes.

Some air parcel analyses done by Sanchez-Ccoyllo and Silva Dias (1996) indicated that the air parcels reaching southeastern Brazil were extremely dry and originated at high levels over the eastern Pacific ocean around 30ºS, hence suggesting a good agreement with the anticyclone track showed in figure 1d and adding further evidence that the radiative cooling was the dominant process which could explain the minimum temperatures measured in the tropical and subtropical areas. An additional point is that the anticyclone propagated from the Pacific to southeastern Brazil in less than 48 hours (as seen by the crosses which indicate the location every 12 hours), suggesting that the original parcels underwent little change during the whole path.

Figure 1e shows the recent case of July 2000 when severe frost and below zero temperatures affected subtropical areas. This case was very different from the 1994 one, presenting a significant shorter anticyclone track (4 days). However, the pronounced meridional trajectory going from the southern tip of Chile to northern Argentina in 48 hours and the presence of a very deep cyclogenesis on the Atlantic (minimum pressure of 944 hPa) gave the ingredients for a strong meridional air exchange, explaining the severity of this case. For the coldest day, the yellow circles are showing the proximity of the high and the low pressure systems, emphasizing the cold advection.

Another feature present in this case is the occurrence of a strong event before the one showed in Figure 1e which affected southern Argentina, with a record 1049 hPa anticyclone associated with temperatures as low as -23ºC in some areas (figure not shown, see table 1). Although not commonly mentioned in the literature, it is possible that the passage of a previous strong front at higher latitudes can create favorable conditions to amplify the effects for the next immediate event at low latitudes.

4. FINAL DISCUSSIONS

The historical background of cold waves in SA complements the references in the literature and adds the possibility of new case studies not only in Brazil but also in Argentina. It is interesting to notice the occurrence of cases which were very severe in southern Argentina, however without affecting the southeastern Brazil (1995, 2001 and others), and cases affecting the tropical area without being severe in southern Argentina as occurred in 1994. This is in accordance with the inverse pattern first proposed by Pezza and Ambrizzi (1999). Furthermore, either in Argentina or Brazil it is suggested that the frequency of extreme cold events is undergoing little change, as shown by recent severe snowstorm cases and record minimum temperatures in Patagonia and the occurrence of intense "*friagens*" in the Amazon River basin as well.

With regard to the trajectories, from the studied cases a simplified conceptual model for the dynamical influences of the Andes in association with the migratory cyclones and anticyclones could be summarized as follows: a) at the

Figure 2: 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. The heavy colored areas and arrows indicate regions of higher tracks density. Dashed arrows indicate other frequent paths. The crosses indicate the climatological position of the Pacific (PH) and Atlantic (AH) semi - permanent high pressure centers and the cold front line approximately shows the north boundary of significant cold advection. Typical cyclogenetic and anticyclogenetic regions, and sea level pressure values (hPa) after Pezza and Ambrizzi (2005) are also plotted.

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 significant cold advection, and hence pressure starts to increase fast over the continent; b) when pressure becomes very high at the southern tip of the continent, a significant 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 decreased, reducing the coriolis effect and generating an ageostrophic component from the south (driven by the pressure gradient), therefore advecting cold air towards lower latitudes in the eastern side of the Andes; d) the anticyclone center tends to move to the north towards the region of maximum cold advection, 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 adjust is very slow at tropical latitudes (Garreaud 1999), hence the remaining cold air is innertially advected to the western Amazon river basin, characterizing the mature phase of the *friagem* event.

Figure 2 shows a conceptual model for the cold surge problem in South America after Pezza and Ambrizzi (2005). It shows the most important cyclone and anticyclone paths superposed on a topographic map of SA and the adjacent oceans and continents, summarizing the most important physical patterns. The heavy colored areas indicate the most dense anticyclone (in blue) and cyclone (in red) tracks, dashed arrows indicate other frequent paths. The crosses indicate the climatological position of the Pacific High (PH) and the Atlantic High (AH). The most important 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 significant cold advection, as derived from previous studies found in the literature. This figure adds a new insight to the *friagem* mechanism proposed in the literature and corroborates the simplified conceptual model of the dynamical influences of the Andes discussed before.

5. ACKNOWLEDGEMENTS

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