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The unusual Buenos Aires snowfall of July 2007

Alexandre Bernardes Pezza,[1]* Ian Simmonds[1] and Caio A. S. Coelho[2]
[1] *School of Earth Sciences, The University of Melbourne, Victoria 3010, Australia*
[2] *Centro de Previsao de Tempo e Estudos Climaticos, Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, Brazil*

*Correspondence to:
Alexandre Bernardes Pezza,
School of Earth Sciences, The
University of Melbourne, Victoria
3010, Australia.
E-mail: apezza@unimelb.edu.au*

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Abstract

Buenos Aires lies near the east coast of South America at about 34 °S where snow is extremely rare. The only events measured in the city had occurred before 1930. The high latitude causes of the widespread snowstorm of 9th July 2007 are discussed, making it an extraordinary case in light of the historical record. Here, we show that this event can be linked to unprecedented seasonal circulation anomalies in the sub-Antarctic, featuring a dipole around the Antarctic Peninsula that drives the cold advection toward mid-latitudes. Our index suggests that conditions have become more favorable for cold surges over mid-latitudes with a repetition of widespread snow over mid-latitudes in 2009. Copyright © 2010 Royal Meteorological Society

Keywords: cold surges; anticyclones; automatic tracking schemes; Buenos Aires snowfall

1. Introduction

Cold surges (CSs) with severe frost and occasional heavy snow are a very important feature of the South American climate. On average, the continent experiences a few events per year where an incursion of cold air is channeled to very low latitudes facilitated by the ageostrophic flow resulting from the north–south orientation of the Andes (Fortune and Kousky, 1983; Marengo *et al.*, 1997; Garreaud and Wallace, 1998; Garreaud, 2000; Vera and Vigliarolo, 2000; Pezza and Ambrizzi, 2005). As a result of the interaction with the Andes the baroclinic wave trains are amplified, acquiring an elongated shape which is only seen in parts of North America and Asia where the topography is sufficiently pronounced (Müller and Berri, 2007).

CSs can have a devastating impact on the economy in many countries of South America (SA), with Brazil's multi-million dollar Arabic coffee market being traditionally (in the past) one of the most severely affected. Another aspect related to CSs is the occurrence of extremely cold conditions in the far south. Often those cases are associated with severe snow storms that can partially or completely paralyze the activities in a vast area of Patagonia (Pezza and Simmonds, 2008). One of the most important sources of energy in Argentina is derived from natural gas, and significant shortages can be experienced during severe winters primarily because of increases in demand (Escobar and Bischoff, 1999).

Argentina's capital, Buenos Aires, is located at about 34 °S near the coast, having a strong maritime influence year-round. Snow storms do occur in the vicinities of Buenos Aires but seldom in town, where they had been observed only twice since the start of the meteorological observations in 1906. Snow had previously occurred only in June 1918 (sleet event according to some records) and July 1928. The meteorological station of Buenos Aires is one of the oldest and most reliable in SA, being one of the only sites in Argentina that allows for a continuous comparison of snow occurrence from the beginning of the twentieth century.

On the 9th of July 2007 a widespread snow storm covered Buenos Aires, more than 79 years after the phenomenon was last observed. The CS that accompanied that storm was particularly severe over mid-latitudes, with several days of widespread frosts in the central parts of Argentina. The cold wave caused unusual snow in the coastal areas of the province of Buenos Aires as well as in the west and central areas of the country. Areas outside of the province also reported snow for the first time in at least 50 years of reliable data (available online from www.smn.gov.ar). Here, we show that the July 2007 event was associated with unprecedented anomalies during the satellite era in anticyclone strength ('depth') in the sub-Antarctic, with a dipole structure around the Peninsula acting in concert to maximize the CS. In Section 2 a brief description of the automatic tracking software used in our investigation is presented. In Section 3.1 we discuss the exceptional trajectories of the anticyclone identified in the total pressure field as well as the anomalous anticyclone (a measurement of the wave train). In Section 3.2 we put the winter 2007 in a climate perspective, showing that the anomalies in the Antarctic were unprecedented during the satellite era. This is followed by final discussions on the significance of our findings.

2. Data and methodology

The cyclone and anticyclone trajectories and statistical parameters associated with the 2007 CS were obtained through the Melbourne University tracking algorithm [e.g. Simmonds *et al.* (2003)]. From the statistical component of the software we use Depth (DP), which is a robust indicator of anticyclone strength defined as $DP = 0.25\ R^2 \times \nabla^2(P)$, where R is the radius of the cyclone and P is the pressure (Lim and Simmonds, 2007). In addition to its value of a synoptic indicator, this measure has the advantage of being relatively insensitive to artificial trends in the mean sea level pressure (MSLP) (Simmonds *et al.*, 2003).

Six hourly data from the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996) were used for the large-scale atmospheric circulation for the satellite era using the most updated data (1979–2009). The snow data was measured in Buenos Aires city meteorological station (Villa Ortuzar observatory), and all the analyses of station records and statistics were based on the official surface network data provided by Servicio Meteorologico Nacional (www.smn.gov.ar). The analysis of trends was performed based on the least square methods (Wilks, 1995).

We here define two areas of interest representing the polar and subtropical Pacific and the polar Atlantic, viz., the PB (Pacific Box: 70 to 15 °S, 140 to 90 °W) and the AB (Atlantic Box: 75 to 50 °S, 70 to 30 °W). Those areas are important for the preliminary phase leading to cold air advection over South America when the anticyclone can form a very elongated pattern contributing toward cold advection. The anticyclone DP was averaged for each box generating indices that convey a potential for cold advection (see Section 3 for more details). There are also other aspects involving the formation of CS in South America, particularly the interaction with the upper level jet stream and local interactions with topography and shortwave development (e.g. Müller and Berri, 2007). We here concentrate on the large-scale connections in polar latitudes, offering a new view on one of the potential amplification mechanisms.

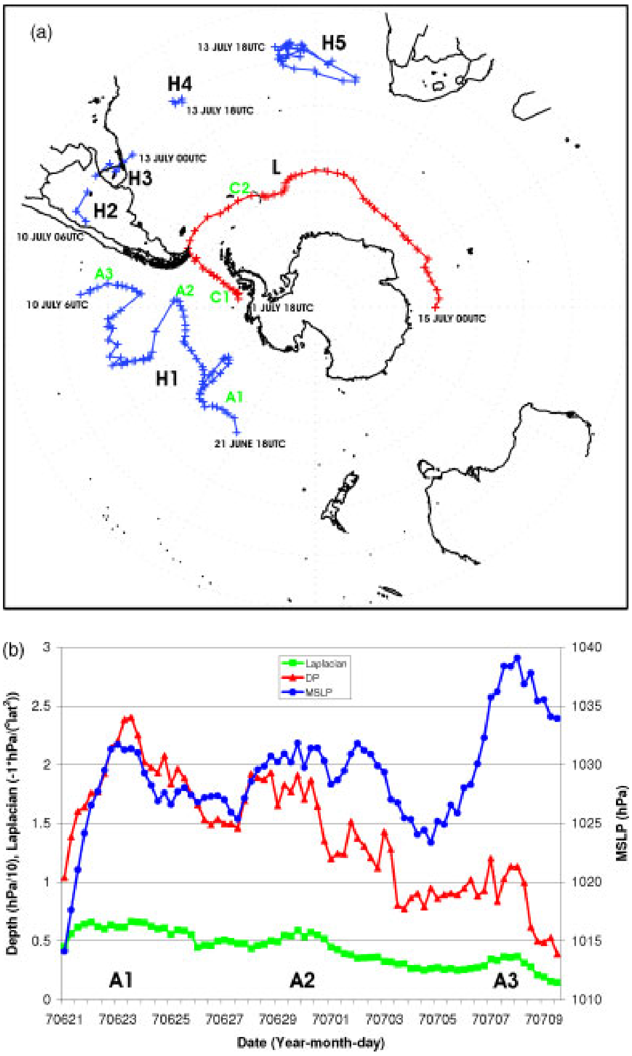

Figure 1. (a) Tracking-scheme derived trajectories of the anticyclone (H, in blue) and cyclone (L, in red) associated with the snow storm of 9 July 2007 in Buenos Aires. The different phases of the anticyclone track are marked as H1 to H5. Key dates are also indicated, and regional maxima in combined intensity (Depth, MSLP and laplacian) are marked next to the main H and L trajectories as A1, A2 and A3 (anticyclone maxima) and C1 and C2 (cyclone maxima). (b) Time series of strength (MSLP, in blue; DP, in red and Laplacian, in green) associated with the trajectory H1. The three maxima of H1 (A1 to A3) are marked near the horizontal axis. See text for further details.

3. Results

3.1. Combined polar trajectories, exceptional wind fetch and subtropical cold vortex

Figure 1a shows the trajectories of the surface anticyclone and cyclone associated with the July 2007 snow event. The relevant dates are indicated, and the different phases of the anticyclone are marked as H1 to H5 (H1 Pacific intensification; H2 crossing the Andes; H3 migrating to the Atlantic; H4 demise of transient signal; H5 subtropical high). Regions of local maximum intensities are marked as A1 to A3 for the Pacific anticyclone and C1, C2 for the cyclone (in green). As noted by Pezza and Ambrizzi (2005) the break up of anticyclone trajectories frequently arises over the Andes during CS events as the high splits into two, with parts of the original signal remaining trapped over the Pacific and parts continuing toward the Atlantic. As observed only in extreme CS events (Pezza and Ambrizzi, 2005) the anticyclone crossed the Andes over relatively low latitudes (H2), implying that the available potential energy was strong enough to allow the high-cell to cross the Andes where the average elevation is high, considerably blocking the flow. The cell weakened and moved rapidly toward the Atlantic (H4) to join and reinforce the subtropical high (H5). The couplet formed between H1 and L is central to the structure and development of the CS because of the strong southerly wind anomalies that result from them (Garreaud, 2000; Ashcroft *et al.* 2009).

The most relevant feature associated with the anticyclone is seen during the preliminary phase when the high was over the Pacific (H1). Two pronounced

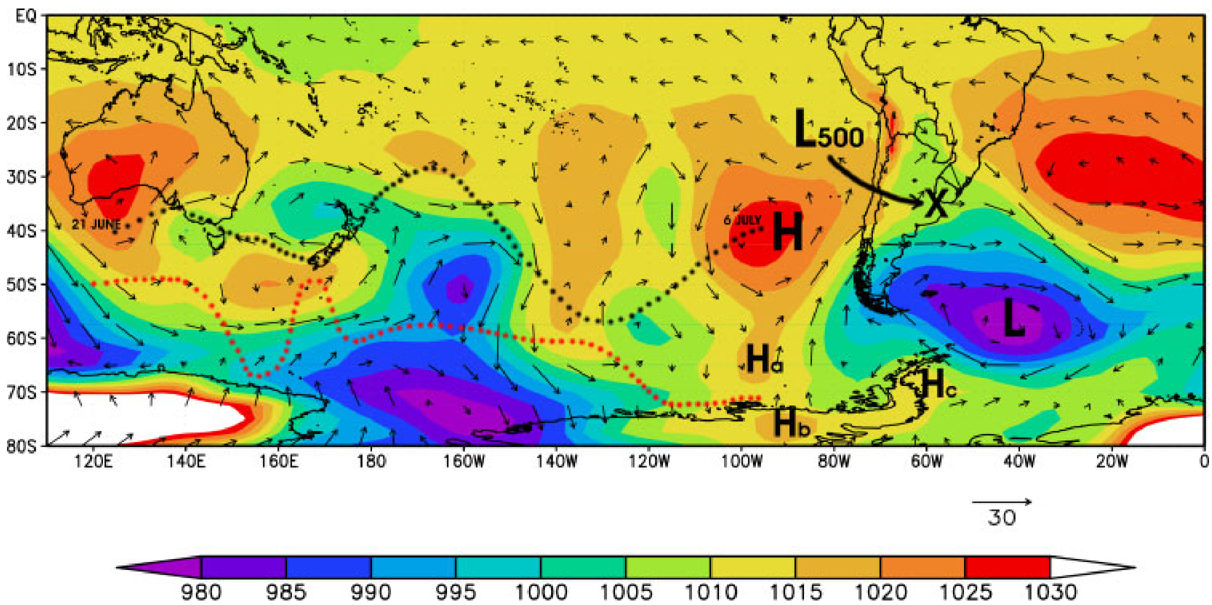

Figure 2. MSLP and 925 hPa mean wind averaged for 6th July 2007. The elongated anticyclone (H) extending toward polar latitudes is indicated by sub-cells marked as Ha to Hc, and the main cyclone is given by L. The trajectory of the upper level cold vortex (L500) is indicated by the arrow (X marks the location of Buenos Aires). The red (black) dots show the trajectory of the 500 hPa geopotential (MSLP) anomaly from the first time of appearance (21 June). See text for further details.

loops around the Antarctic are seen in this phase, when the simultaneous intensity metrics given by the Laplacian, DP and MSLP were all at their maximum for the entire lifecycle (marked in green as A1 and A2). From figure 12 of Pezza and Ambrizzi (2005) there were no previous CS-associated trajectories observed in the Bellingshausen Sea over a near 30-year climatology (1973–2000). Figure 1b shows the buildup of the Pacific conditions (H1) that led to the snow on the 9th of July. The MSLP (blue curve) reached its maximum of almost 1040 hPa a day before the snow (period A3), when parts of the pulse crossed the Andes (compare with Figure 1a). However, as discussed above the Laplacian and DP assumed greater values earlier, when the trajectory was in polar latitudes (periods A1 and A2). This is very revealing, showing that the source of intensification is not simply a local potential vorticity increase due to the interaction with the Andes, but rather a continuous, long-lived baroclinic wave train traveling near the Antarctic. This concept is similar to the fundamental role of the wave train driven by the polar jet discussed earlier in the literature (e.g. Vera and Vigliarolo, 2000; Müller and Berri, 2007).

The nature of the cyclone track (red in Figure 1a) was also rare with cyclogenesis occurring very close to the southwestern tip of the Antarctic Peninsula followed by a meridional path leading to strong cold advection in southern SA. The cyclone reached a pressure of about 960 hPa with a Laplacian above 3 hPa/(°lat)^2 two days before the snow (period C2 in Figure 1a). Figure 1 also shows that a first maximum in the cyclone intensity occurred to the west of the Antarctic Peninsula (C1) at the beginning of the trajectory, contributing to a stronger cold advection during the preliminary phase in synchrony with the maximum in the high pressure cell to the west (A2).

Figure 2 shows the MSLP and the 925 hPa vector wind averaged for 6 July 2007, depicting the beginning of the third and last intensification phase of H1 (corresponding to period A3 in Figure 1). This date is chosen to illustrate the polar connection observed about 72 h before the snow. There is a long wind fetch over SA, with direct southerlies from 75 °S reaching the mid-latitudes. The marked pressure gradient arises from the main couplet (H and L), but the key signal building up in the polar region is characterized by the components Ha, Hb and Hc as annotated in Figure 2. The meridional elongation of H is a key feature of the whole CS, reflecting that the main baroclinic wave train propagated through polar latitudes. This is shown by the red dots, which depict the translation of the 500 hPa geopotential anomaly track associated with H. The signal can be traced all the way back to the Southern Ocean off Australia on 21 June. This component remains at latitudes greater than 50 °S during the whole path. On the 6th of July the signal joins the elongated surface pressure cell (H), forming Ha, Hb and Hc. With anticyclonic conditions, the radiational cooling over polar latitudes is extremely pronounced, contributing to the further build of Hb and Hc inland. Aloft, in the days previous to 9 July, a double wave train can be seen, moving with the polar and subtropical jets of the southern hemisphere, which meet to form a single pattern which gives place to the elongated anticyclone (H). This is in agreement with one of the conceptual models described by Müller and Berri (2007).

The progression of the MSLP wave train anomalies is shown by the black dots in Figure 2. Comparing it with the anticyclone trajectory shown in Figure 1a it is evident that the anomalous trajectory is longer lasting, starting considerably further west. The surface anomalies remain to the north of the 500 hPa anomalies implying (isentropic) descent of upper level (high latitude) cold air. This vertical tilt fits well with the typical structure of baroclinic cyclones found in high latitudes over the Pacific Ocean (figure 6 of Lim and Simmonds (2007)). The L500 denotes the initial position of an upper level cold vortex formed on the 6th of July (where the signature of a surface trough is apparent in the surface wind field shown), and the arrow gives the trajectory described by this small vortex toward Buenos Aires between the 6th and 9th of July (i.e. the day of the snow). This development formed a blocking-like structure near 90 °W with tropical/extratropical wave interaction (of different scales) as described by Vera and Vigliarolo (2000). As the cold vortex moved toward Buenos Aires it joined and reinforced the upper level polar trough, reducing the static stability and increasing the upper level moisture, facilitating the snow storm. We also note that the CS was preceded by very unstable conditions, with a stationary front in northeastern Argentina and Uruguay and a low-level jet transporting moisture toward eastern Argentina so that the static stability was already low when the event was triggered.

3.2. Unprecedented anomalies in the Antarctic

Figure 3a shows the surface anticyclone DP anomaly for JJA 2007. The areas of interest for cold air advection in SA are marked on the map as PB and AB as discussed in Section 2. The polar dynamics that favors CS occurrence is strongest when the pressure gradient is directed toward PB, which gives a southerly geostrophic flow toward the south of the continent. On the basis of this principle we introduce the notion that a combined high DP index over the Pacific with a low DP index over the Atlantic gives the ideal conditions for the development of CS cases, at least from the partial view point of polar anomalies. A dipole structure is formed when opposite anomalies are observed over each side of the Peninsula. The choice of size for the boxes was based on the configuration discussed in Figure 2, given the elongated anticyclone over the Pacific (H) and the cyclonic development in the Atlantic (L) confined to the south of 50 °S. The PB and AB had strong anomalies with opposite signs in the winter 2007, and the positive anomalies over the PB were the strongest in the Southern Hemisphere.

Figure 3b gives the variability associated with the average winter anticyclone DP calculated over the boxes (PB and AB). Our dipole index, given by PB–AB, is shown in green at the bottom of the graph. This anticyclone strength polar index is here introduced for the first time, offering an additional indicator of large-scale seasonal anomalies associated with CSs based on the dynamic concept of the pressure dipole (couplet) around the Antarctic Peninsula. The average winter DP is usually higher in the PB, suggesting that the main climatological source of cold

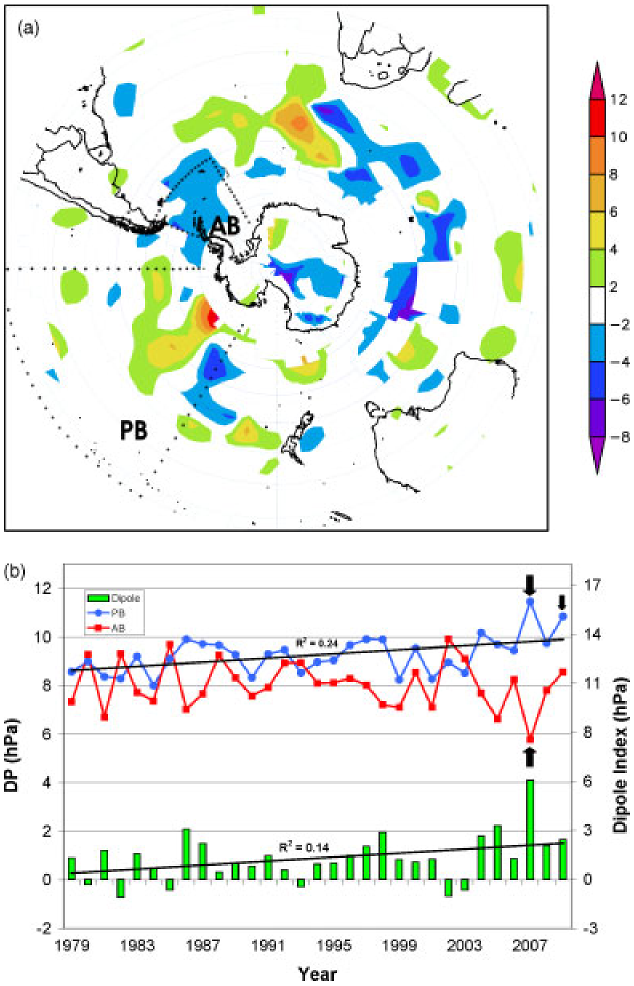

Figure 3. (a) DP anomaly for JJA 2007 showing the location of the Pacific Box (PB) and Atlantic Box (AB). (b) Time series of the DP index measured over the boxes during the satellite era, and the respective polar index. The large arrows indicate the record high (and low) measurements during the winter 2007, forming a dipole favorable for cold surge over South America as reflected by the index. The small arrow indicates the record high observed in the winter of 2009. See text for further details.

air lies in the Pacific sector. Hence, the index is often positive. The graph also shows considerable interannual variability and a positive trend (statistically significant at the 1% level) for the DP in the PB, which also reflects as a trend in the index. In contrast, no significant trend was observed for the AB. The winter 2007 presented the largest anomalies in both boxes (marked by the larger arrows). As a result, 2007 measured the highest index on record with very conducive conditions to enhance CS occurrence. The winter 2009 presented the second highest DP index on record for the PB (marked by the small arrow). This is discussed in the next section in connection to yet another unusual snowstorm over mid-latitudes.

4. Conclusions

Although the 2007 event had typical characteristics also observed in other extreme CS cases in South

America with widespread snow and frost across central and northern parts of Argentina, it presented the rare additional of snow in Buenos Aires where a combination of heat island (HI) and a strong linear increase in maximum and minimum temperatures would have created conditions unfavorable for such development. The event was facilitated by a combination of anomalous surface features and an upper level cold vortex that moved over the area from the subtropical Pacific, providing the necessary moisture and instability profile. Our results suggest that large-scale variability in wave amplification in the polar region, as measured by our dipole index, is the key driver of the 2007 event. The trend in winter polar anticyclone strength over the southeastern Pacific suggests that the large-scale conditions have become slightly more favorable for CS occurrence in SA during the satellite era, in spite of an observed temperature increase of up to 1 °C in the mid-latitudes of SA in the period 1970–2004 (IPCC, 2007).

The local conditions in Buenos Aires can be used as a parameter to help put the severity of the phenomenon in perspective, although the generalized nature of the cold event meant that the whole northern part of Argentina was affected. When comparing present day data to observations from early last century a significant HI developed in Buenos Aires, where the long-term rate of linear warming was calculated at 2.7 °C per century in the average winter temperature for the period 1909–2008. Bejaran and Camilloni (2003) showed that the effect of the HI in Buenos Aires is enhanced during polar air masses.

On 22 July 2009, it snowed again in the outer suburbs of Buenos Aires (e.g. Ezeiza airport) with widespread falls over mid-latitudes. Figure 3b shows that the winter 2009 presented the second maximum winter anticyclone depth over the PB (small arrow on the top-right hand corner), reinforcing the implied association of Pacific polar connections with the snow. The configuration of the anomalies in the 2009 case was remarkably similar to the one shown in Figure 2 (2007), both in terms of the Antarctic connection and the cold vortex propagating from the subtropical Pacific. This supports the dynamical association conveyed by our polar index, suggesting that manifestations of climate variability at high latitudes are setting up an environment more conducive to these extreme events regardless of background warming.

The apparent paradox of an increased CS activity with global warming is resolved when one considers that a warmer average temperature does not necessarily mean weaker extremes. In fact, the circulation changes arising in a warmer planet can be more conducive to extremes (IPCC, 2007). A warmer atmosphere can hold more humidity, and if the circulation has become more favorable for the occurrence of cold extreme events in Buenos Aires one could also expect the occurrence of snow events as the one investigated here. The fundamental driver of the couplet around the Antarctic Peninsula (stronger anticyclones to the west and stronger cyclones to the east) is intimately related with inequalities in the mass adjustment between subtropical and polar latitudes, for which the Southern Annular Mode (SAM) is one of the indicators. Our index also ties well with the Antarctic Dipole derived by Yuan and Martinson (2001), reflecting the out-of-phase relationship between the Pacific and Atlantic polar regions and the variability of sea ice extent (SIE). The winter 2007 had the second lowest SAM on record in the satellite era, contributing to the intensification of polar anticyclones. Key modes additional to the SAM (e.g. the second mode in the Empirical Orthogonal Function of the MSLP) also lie almost precisely over the southern tip of our PB box [figure 2 of Simmonds and King (2004)].

Our anticyclone index over the boxes is also relevant for the SIE around the Antarctic Peninsula. A larger index is associated with conditions more favorable for anomalous ice displacement toward the southern tip of SA. In the winter 2007, the SIE in this sector was one of the five largest on record during the satellite era, helping to reinforce the very cold air mass arriving at the southern tip of SA. Although the ice behavior is mainly tied to the general circulation, particularly the SAM (Lefebvre *et al*., 2004; Comiso and Nishio 2008), our polar index gives an additional tool to monitor the local conditions which are of more direct relevance for CS over SA, revealing the polar source of circulation anomalies associated with severe snowstorms in mid-latitudes of South America.

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