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Climatology of extratropical cyclones over the South American–southern oceans sector

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Abstract A climatology of extratropical cyclones is presented. Extratropical cyclones, their main characteristics and their predominant tracks, as well as their interannual variability, affect weather in South America. For that purpose, a storm track database has been compiled by applying a cyclone tracking scheme to six-hourly sea level pressure fields, available from the National Center for Environmental Prediction–National Center for Atmospheric Research reanalyses II for the 1979–2003 period. The spatial distribution of the cyclogenesis frequency shows two main centers: one around Northern Argentina, Uruguay, and Southern Brazil in all seasons and the other near to the North Antarctic Peninsula. The lifetime of extratropical cyclones in the South American sector exhibits small seasonality, being typically of the order of 3.0 days during most of the year and slightly higher (3.5 days) in austral summer. The distance travelled by the cyclones formed in the South American sector tends to be smaller than the total paths found in other areas of the Southern Hemisphere. A *k*-mean clustering technique is used to summarize the analysis of the 25-year climatology of cyclone tracks. Three clusters were found: one storm-track cluster in Northeast Argentina; a second one west of the Andes Cordillera; and a third cluster located to the north of the Antarctic Peninsula (around the Weddell Sea). The influence of the Antarctic Oscillation (AAO) in the variability of extratropical cyclones is explored, and some signals of the impacts of the variability of the AAO can be observed in the position of the extratropical cyclones around 40°S, while the impacts on the intensity is detected around 55°S.

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1 Introduction

The conventional Lagrangian approach used to define storm track involves tracking the displacement of predefined features usually in near surface charts, such as minima (maxima) in sea level pressure (SLP), geopotential height, or vorticity fields. There are several studies on climatology of storms over the Northern Hemisphere (NH), based on the visual inspection of sea level pressure charts, from the earlier work by Petterssen (1950) to the most recent studies relying on automatic methods to detecting and tracking storms over gridded-reanalysis data (e.g., Blender et al. 1997; Trigo et al. 1999; Gulev et al. 2001).

Among the studies dedicated to storm track over the southern oceans, the first one based on an automatic scheme was developed and applied to the Southern Hemisphere (SH) by Murray and Simmonds (1991a,b). In monitoring cyclone and anticyclone tracks, it is important to notice that, in the past, this process used to demand a lot of work time because of its manual nature. Nowadays, however, the situation is completely different due to recent developments on automatic tracking schemes such as those described in Murray and Simmonds (1991a,b) and Sinclair (1994). Murray and Simmonds (1991a,b) developed an automatic procedure to find and track surface pressure systems. Jones and

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Simmonds (1993a) 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. In recent years, a relatively large number of studies using cyclone/anticyclone tracking schemes have shown this tool's reliability (e.g., Sinclair 1994; Sinclair et al. 1997; Simmonds and Keay 2000a,b; and Pezza and Ambrizzi 2003).

Sinclair (1994), using vorticity fields derived from the European Centre for Medium-Range Weather Forecasts data for the 1980–1986 period, found fairly uniformly distributed storm tracks, but with a maximum in the 45°S–55°S band. Part of this equatorward displacement of cyclone activity may be attributed to vorticity maxima, associated with orographic effects (Kidson and Sinclair 1995). More recently, Simmonds and Keay (2000a), using an updated version of the Melbourne University cyclone finding and tracking scheme (Simmonds et al. 1999) found that the annual mean number of extratropical cyclones in the Southern Hemisphere (SH), as those analyzed for the 1958–1997 period, are characterized by a year-round frequency maximum in the circumpolar trough between 50°S and 70°S.

Despite the overall symmetry of southern storm tracks, it is possible to identify regions of enhanced cyclonic activity, such as the maximum off East Antarctica, a region where the well-known katabatic outflows occur, and the secondary maximum located to the east of New Zealand during the winter-spring time, associated with the subtropical westerly jet stream near 40°S (Sinclair 1997).

Gan and Rao (1991) developed one of the first studies of cyclogenesis over the South American sector (SA). They detected and tracked cyclonic systems by visual inspection of surface pressure charts, available four times per day for the 1979–1988 period. The method used by Gan and Rao (1991) for identifying extratropical cyclones required that at least one closed isobar around a low pressure center should be found for an analysis of 2-mb intervals. Gan and Rao (1991) found that the extratropical cyclones over the South America sector (SA) are more frequent in winter than in any other season.

Previously, Satyamurty et al. (1990) did a similar analyses based on satellite imagery for the 1980–1986 period, covering South America and a wider area over the Southern Atlantic. They found that the highest cyclogenesis frequency was obtained for the summer season.

The abovementioned studies using different horizontal domains show conflicting results. Nevertheless, both studies agreed on one of the most active cyclogenetic areas, namely the Gulf of San Mathias (42.5°S, 62°W) during summer and over Uruguay (around 31°S, 55°W) during winter (Table 1).

In the mid-to-high latitudes of the Southern Hemisphere (SH), the Antarctic Oscillation (AAO) is the leading mode of atmospheric variability, corresponding to the transfer of atmospheric mass between higher and lower latitudes (Thompson and Wallace 2000). The phase of the AAO at upper levels is strongly associated with the location and intensity of the polar jet stream and, thus, directly influencing the developing regions and the steering of extratropical lows.

Recently, Pezza et al. (2007) suggested a robust link of these trends of number of extratropical cyclones with the Pacific Decadal Oscillation, especially with the last major climate shift in the Pacific Basin by the middle-late seventies. This view goes beyond the traditional study of large-scale influences related to interannual variability linked to El Niño-Southern Oscillation (ENSO).

Therefore, the objectives of the present work are to analyze the spatial distribution of cyclogenesis and cyclone tracks in the Southern American sector (SA), and also to characterize storm events, taking into account measures of intensity (minimum central pressure and the pressure deepening rate), lifetime, and total distance travelled by cyclones. The inter-annual variability of cyclone activity in the South America sector (SA) is also analyzed, with particular emphasis on possible links with the main mode of low frequency variability in the Southern Hemisphere (SH), the Antarctic Oscillation (AAO).

2 Data and methodology

This work is based on the analysis of a 25-year (1979–2003) database of cyclone tracks derived for the whole Southern Hemisphere (SH), for latitudes south of 20°S. The dataset was built by applying an automated scheme to detecting and tracking lows in sea level pressure (SLP) fields, available from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis II (2.5°×2.5° horizontal and six-hourly temporal resolution; Kistler et al. 2001; Kanamitsu et al. 2002). The year 1979 is a turning point in the sense of increasing the data coverage.

Table 1 Summary of applications of extratropical study over the South American sector

Authors	Period	Number of season		Data
		Winter	Summer	
Satyamurty et al. (1990)	1980–1986	~20	~32	Satellite
Gan and Rao (1991)	1979–1988	~31	~21	Surface data
Mendes et al. (2007)	1949–2003	~35	~28	NCEP/NCAR reanalysis

That was the year of the First Global Atmospheric Research Program (GARP) Global Experiment, and it is also the start of the "modern" satellite era.

Although the storm track database covers most of the Southern Hemisphere (SH), the analysis carried out here focuses on the area from 70°S to 20° and from 120°W to 0°, encompassing most of South America and surrounding regions (Fig. 1). Hereafter, this area will be referred to as the South American sector (SA).

The algorithm implemented for detecting cyclones in the SA sector follows quite closely that described by Blender et al. (1997) and Trigo et al. (1999) and later adapted to the Southern Hemisphere (SH) by Mendes et al. (2007).

A cyclone candidate is identified as a local sea level pressure (SLP) minimum over a 3°×3° grid point area, which has to fulfill the following conditions to be considered as a cyclone:

1. the central sea level pressure cannot be higher than 1,010 hPa; and
2. the mean pressure gradient, estimated for an area of 9°lat× 11°lon (approximately 1,000 km×1,000 km) around the minimum pressure, has to be of at least 0.55 hPa/250 km.

The cyclone tracking algorithm is based on a nearest-neighbor search procedure (e.g., Blender et al. 1997; Serreze et al. 1997; Mendes et al. 2007): a cyclone's trajectory is determined by computing the distance to cyclones detected in the previous chart and assuming the cyclone has taken the path of minimum distance. If the nearest neighbor in the previous chart is not within an area determined by imposing a maximum cyclone velocity of 33 km/h in the westward direction and of 90 km/h in any other, then cyclogenesis is assumed to have occurred. We stress that these thresholds were determined empirically by observing cyclone behavior in sea level pressure (SLP) charts.

3 Cyclones in South America

3.1 Cyclogenesis

Figure 2 shows the average amount of cyclogenesis events, estimated for 3°×3° grid boxes. During winter (Fig. 2a), two main regions of maximum quantity of cyclogenesis are found. This is in good agreement with previous studies by Satyamurty et al. (1990), Gan and Rao (1991), and Simmonds and Keay (2000). The first cyclogenetic area is located over the coastal region of Argentina, Uruguay, and South Brazil, reaching average values of about 18 events per winter, whereas the second and wider area is located next to the Antarctic Peninsula over the Weddell Sea. For the remaining seasons, the geographical position of the most active regions remains fairly constant, although cyclogenesis events off the Argentinean coast tend to concentrate closer to the continent and slightly further south (particularly during the summer). Spring (Fig. 2b) and autumn (Fig. 2d) exhibit the lowest cyclogenesis activity, with average values within the most active area lesser than 15 events per season. In particular, the Weddell Sea area, which remains fairly active throughout the whole year, presents a pronounced minimum during autumn. In contrast with spring and autumn, summer (Fig. 2c) is very active in terms of cyclogenesis. Although the average values

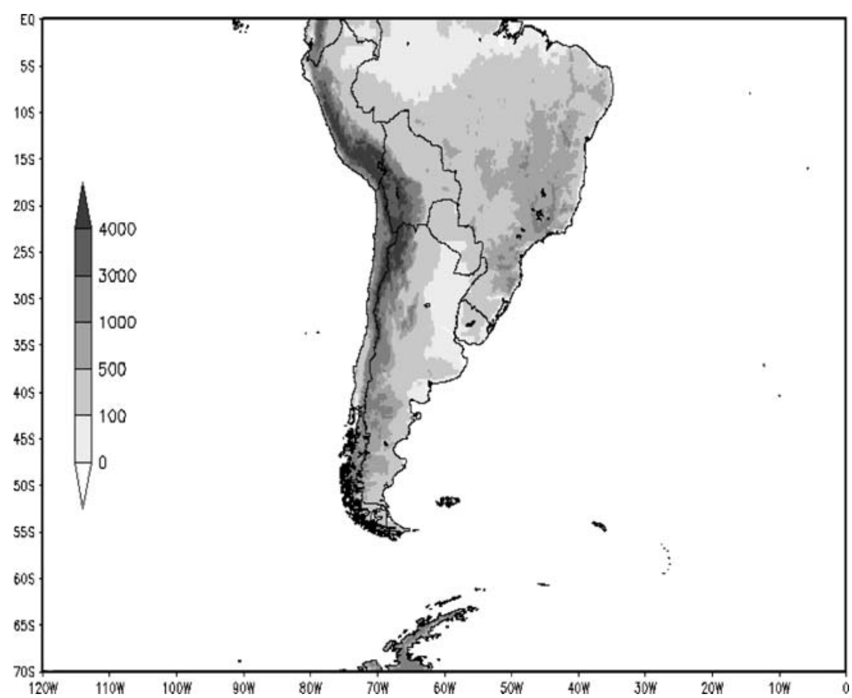

Fig. 1 Domain of study, limited between 70° and 0° and between 120° and 0°

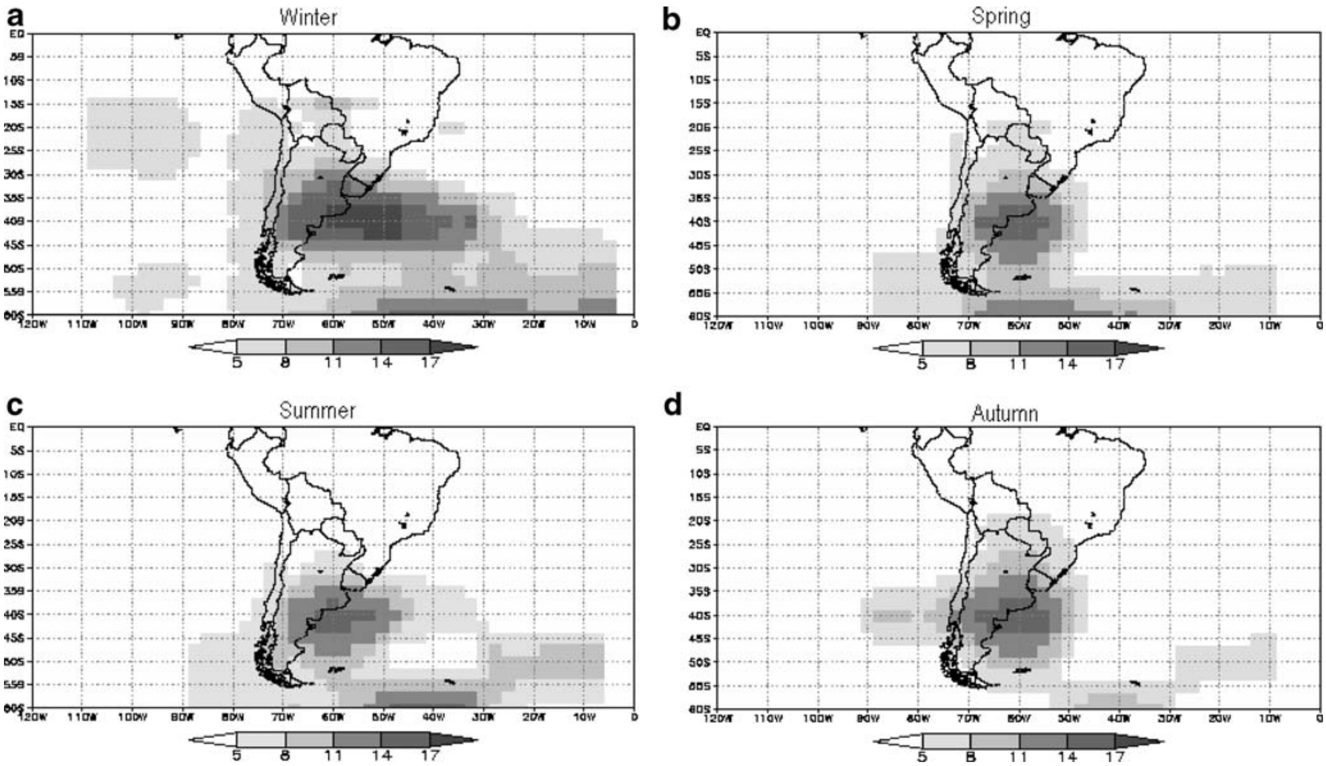

Fig. 2 Number of cyclogenesis events detected per 3°×3° cell, for each season for the whole 25-year period

per grid cell are in most cases similar to those observed during winter, the summer season is characterized by a high concentration of events over relatively smaller areas.

Despite using different methodology and/or different data, the results presented here generally agree with those obtained by Gan and Rao (1991) and Simmonds and Keay (2000a,b). Moreover, the spatial distribution and inter-seasonal variability of cyclogenesis are consistent with the main mechanisms associated with cyclone development frequently suggested for this area, namely baroclinic instability of the westerlies and orographic-induced cyclone development in the lee side of the Andes Cordillera (Gan and Rao 1991; Gan and Rao 1994; Sinclair 1995; Bonatti and Rao 1987). Recently, Mendes et al. (2007) showed that cyclone formation over the Southern American sector (SA) is characterized by some remarkable features: (1) this large number of events originates in a rather localized area; (2) the cyclogenesis process is preceded by an anomalous flow over the continent, associated with the transport of warm and moist air into the cyclogenesis region; and (3) cyclogenesis occurs in all seasons with similar mean anomalies but with somewhat different statistics.

3.2 Cyclones lifetime and total travelled distance

The strong zonal behavior (orientation) of storm tracks in the Southern Hemisphere (SH), associated with the lack of orographic barriers over large portions of the southern middle and high latitudes, leads to relatively longer-lasting systems traveling over larger distances, in comparison with the corresponding synoptic disturbances in the Northern Hemisphere (NH), which have modal lifetimes between 2 and 3 days (Gulev et al. 2001).

Figures 3 and 4 show, respectively, histograms of cyclone's lifetime and total distance travelled for systems originated within the South American sector (SA) (light bars) and for systems detected in the whole Southern Hemisphere (SH) (dark bars).

The highest frequency of cyclone lifetime is found with 2–3 days total duration, for both the South America sector and for the whole Southern Hemisphere (SH). The latter, however, tends to have lower relative frequencies associated with those modal values and larger upper tails. This is particularly the case of the winter and the spring distributions (Fig. 3a, b), where the fraction of lows lasting 8 days or more is about 76% to 70%, compared with 85% to 80% in the vicinity of South Hemisphere (SH). Many of these long-lasting systems occur over the circumpolar ocean, where they can also travel for long distances (Simmonds and Keay 2000a,b).

Accordingly, the distribution of cyclone total-traveled paths for the whole Southern Hemisphere (Fig. 4) presents longer left tails, with secondary maxima between 2,600 and 3,000 km, while the corresponding histograms for the Southern American sector (SA) exhibit considerably less skewness. Indeed, the extratropical cyclones generated over

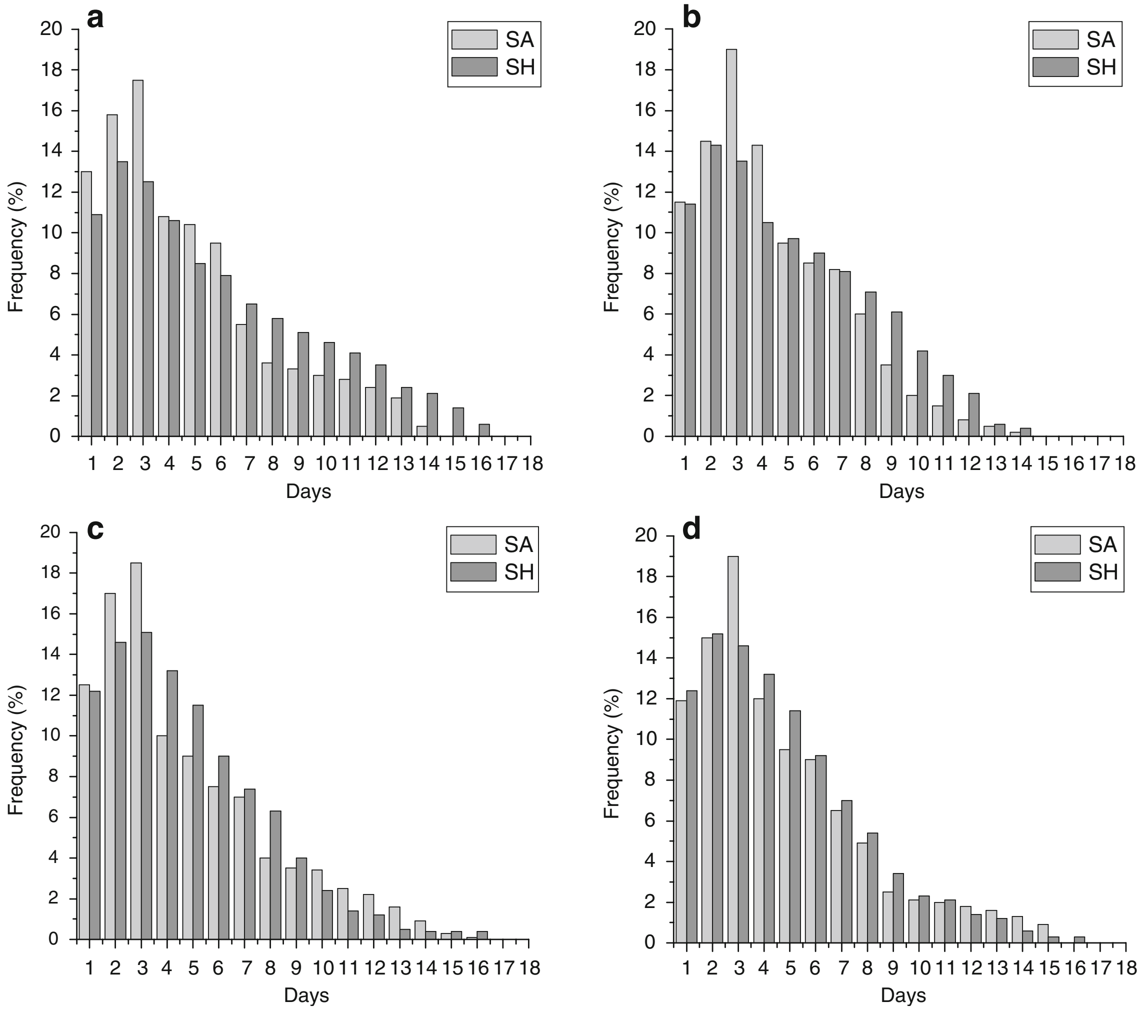

Fig. 3 Lifetime distribution of cyclones, obtained for all set of detected cyclones with a minimum life cycle of 24 h, for **a** winter, **b** spring, **c** summer, and **d** autumn. *Dark bars* represent the distribution of lifetime in the Southern Hemisphere and *light bars* represent the distribution in the South America sector

the east coast of Argentina (in the South American sector—SA) are seen to be transported downstream by the westerlies (Simmonds and Keay 2000a,b). The peak around 400 km for the summer and autumn distributions for the South American sector (SA) (light bars in Fig. 4c and d) corresponds to the occurrence of (quasi-)stationary lows over the relatively warm continent. These thermal lows tend to persist during several days. This explains, therefore, the longer right tails of lifetime distributions for these seasons, when compared with the whole Southern Hemisphere (SH) (Fig. 3c, d). About 10% of all such systems travel less than 500 km and approximately 40% travel between 500 and 1,000 km. Figure 4a–d shows a steady decay in frequency at the longer travel distance, but a significant proportion of the systems travel in excess of 3,000 km. As might have been expected, the longest mean track length occurs in winter (1,553 km), while the shortest is found in spring (1,228 km).

3.3 Intensity of the cyclones

Minimum central pressure reached during the cyclone lifetime, and maximum rate of pressure decay, which is directly linked to the generation of local vorticity minima (for the Southern Hemisphere—SH), are the two most common parameters used to access the severity of a storm. Here, special attention is given to the distribution of the maximum deepening rate, geostrophically adjusted to a "reference latitude" represented in the histograms of Fig. 5 for the South American sector (SA) and for the Southern Hemisphere (SH). This reference latitude used for the geostrophic adjustment, which allows the use of deepening rates for the comparison of cyclone intensities observed at different latitudes (e.g., Serreze et al. 1997; Trigo et al. 1999; Gulev et al. 2001), is 45°S—roughly the mid-latitude of the South American sector (SA). It should

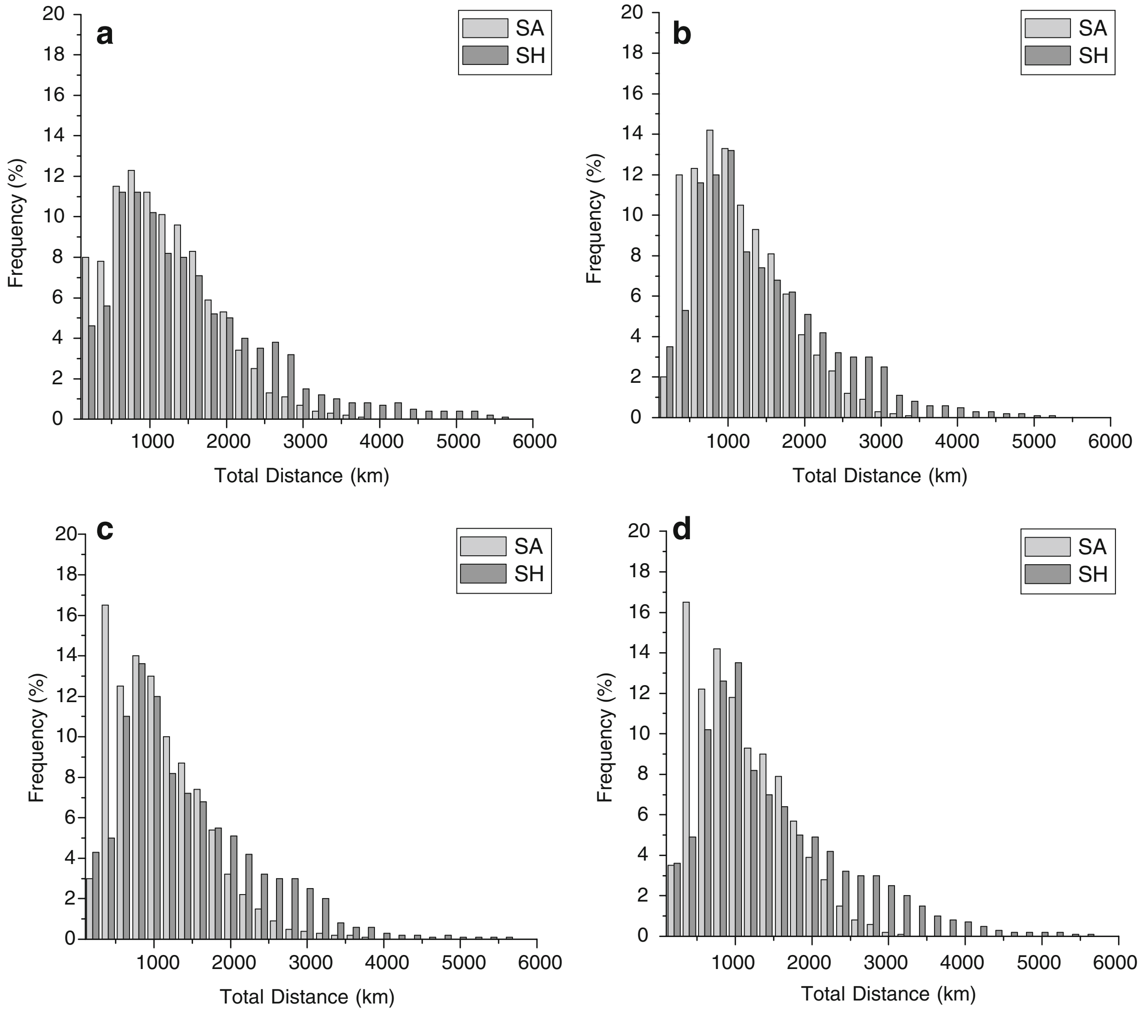

Fig. 4 Distribution of total distance travelled by cyclones during the time life, for **a** winter, **b** spring, **c** summer, and **d** autumn. *Dark bars* represent the distribution in the Southern Hemisphere and *light bars* represent the distribution in the South America sector

be pointed out that positive values correspond to events detected when their minimum central pressure has already been reached.

The storm intensity, as measured by the maximum deepening rate (hPa) (in order to analyze deepening for individual cyclones, it is more effective to consider mean and extreme deepening rates during the phase of cyclone intensification rather than the overall statistics of deepening rates) does not differ significantly between the South American sector (SA) cases and the whole cyclone population in the Southern Hemisphere (SH). Spring presents the distribution with the longest left tail (Fig. 5b), although the most extreme cases of very rapidly developing systems, or explosive cyclones, tend to occur in winter. When compared with the Northern Hemisphere (NH), deepening rates are generally smoother in the Southern Hemisphere (SH), with a lower number of explosive cyclogenesis cases (e.g., Lim and Simmonds 2002).

3.4 Cyclone tracks

In order to identify the main paths of the cyclones originated in the vicinity of the South American sector (SA), the storm tracks within the South American sector were subject to a *k*-mean cluster analysis. The goal of the *k*-mean algorithm is to get *k* clusters, which minimize the variability within the clusters, and maximize the variability among them (Mirkin 1996). In the present case, the *k*-mean cluster analysis is applied to the standardized vectors containing the six-hourly (latitude/longitude) positions of each cyclone. For a better definition of the acting area of the cyclones in this study, we use a value of one standard deviation to delimitate this area of storm tracks. Figure 6 shows three regions with well-defined paths: the first one includes the coast of Argentina, Uruguay, and Southern Brazil; the second one is in the region near the Antarctic Peninsula; and the third one is the South Central Pacific. The first two regions are regions of

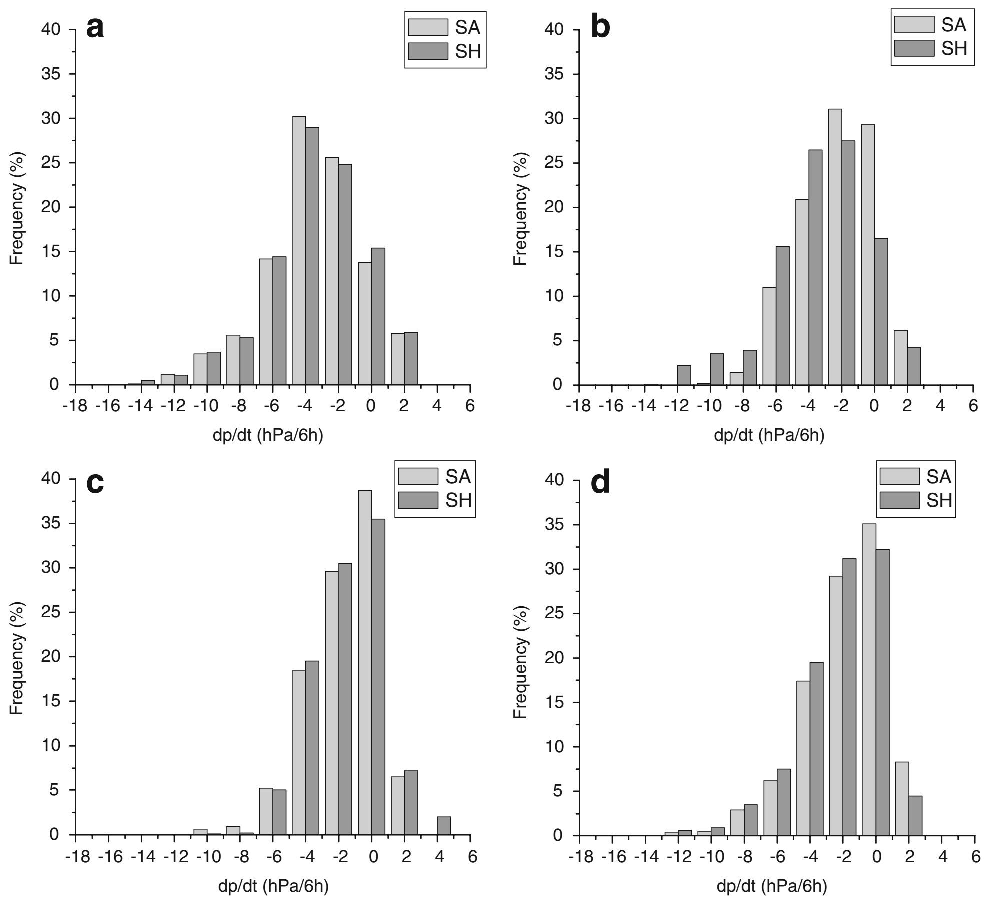

Fig. 5 Maximum deepening rate distribution, geostrophically adjusted to 45°S, for **a** winter, **b** spring, **c** summer, and **d** autumn. Negative values indicate deepening. *Dark bars* represent the distribution in the Southern Hemisphere and *light bars* represent the distribution in the South America sector

formation of cyclones, as discussed previously. Compared to the other two regions, the contribution of the center-south Pacific region is small.

In Fig. 6, one can see a small seasonal variation in the mean course of the cyclones originated in the coast of Argentina. The seasonal difference in the acting area of the cyclones is also small, though it is spreader in summer. One can also notice a break in the influence area of the cyclones formed in the vicinity of the South American sector (SA). This might be related to the presence of the high-pressure system of the South Atlantic (daily scale). In the region near the Antarctic Peninsula, both the seasonal variation of the mean course and the acting area of the cyclones are more remarkable. The center-southern Pacific region also exhibits a small seasonal variation in the course of the cyclones. Nevertheless, there is a clear northward shift from autumn to spring. The acting area is spreader in comparison to the other regions. During summer, the influence area of the cyclones is also spreader than for the other seasons. One can also verify a break in the influence area in the vicinity of the Chilean coast, due to the Andes. A factor that may contribute to the small quantity of cyclones originated in this region of the Pacific Ocean is the presence of a blocking system with origin in the southern border of the acting area of the cyclones (Marques and Rao 2000). Berbery and Nuñez (1989) argued that such blocking episodes may result from a local resonance between Rossby waves generated by the Andes Mountains. This blocking system is of paramount importance in the modulation of the weather over southern Brazil, and may have influence on the origin or even on the displacement of the cyclones within this impact region. This causes precipitation over South America to increase to north of the blocking high and diminish over southern South America (Marques and Rao 1999; Damião et al. 2005).

4 Influence of the Antarctic Oscillation (AAO) in the variability of the extratropical cyclones over the Southern Hemisphere (SH)

Since the pioneer work of Thompson and Wallace (2000) on the Arctic Oscillation (AO) in the Northern Hemisphere (NH), many AO studies have been conducted to investigate its climate influence particularly over mid-latitudes (Kerr 1999; Thompson and Wallace 2001).

Analogous to the AO, there is a large-scale swinging of SLP fields between polar and mid-latitude regions in the Southern Hemisphere (SH). This huge atmospheric mass exchange in the Southern Hemisphere (SH) is referred to as the Antarctic Oscillation (AAO) or high latitude mode (Karoly

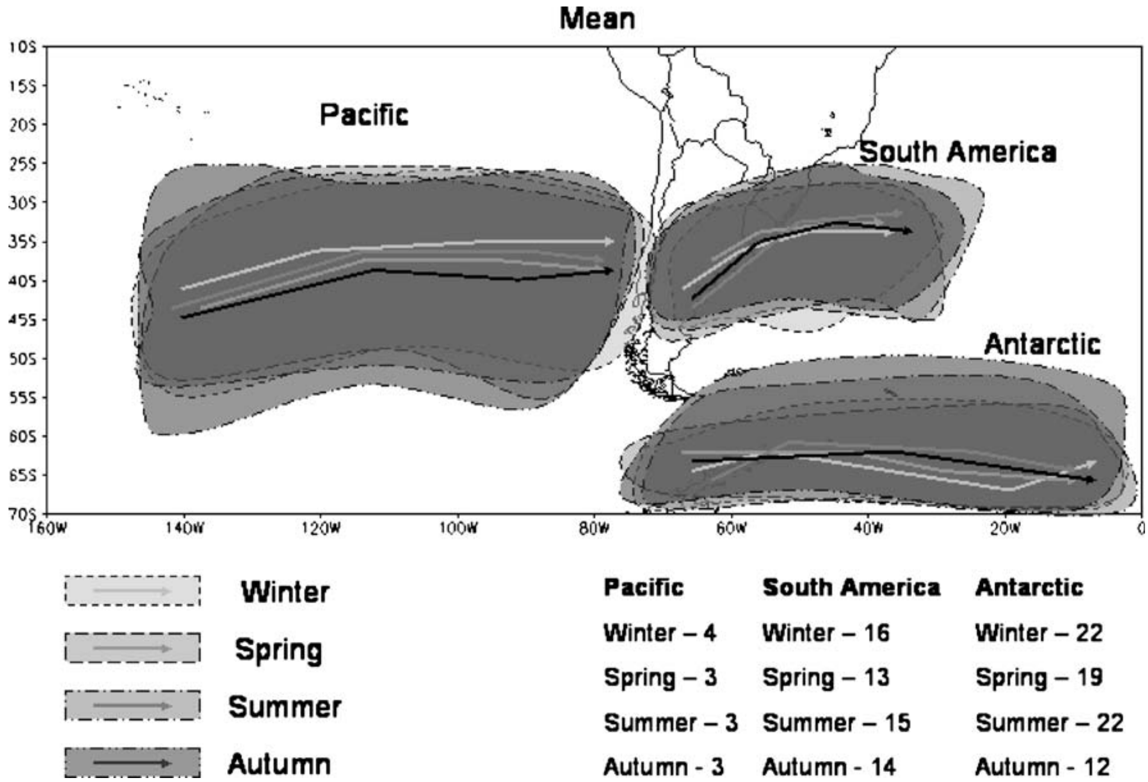

Fig. 6 Cluster's mean positions for **a** winter, **b** spring, **c** summer, and **d** autumn, and number of case. Shaded regions represent the area of influence of each cluster

1989; Thompson and Wallace 2000). The Antarctic Oscillation (AAO) index is defined as a series of leading empirical orthogonal function (EOF) mode for the sea level pressure (SLP) or the 850-hPa geopotential heights in the Southern Hemisphere (SH). It can also be obtained from the difference of the zonal mean sea level pressure (SLP) between 40°S and 65°S (Gong and Wang 1999). The Antarctic Oscillation (AAO) may be one of the main climate modulators of the Southern Hemisphere (SH), similarly to Arctic Oscillation (AO) that influences on the overall climate from the surface to the lower stratosphere in the Northern Hemisphere (NH).

In relation to a possible influence of the Antarctic Oscillation (AAO) in the variability and intensity of transient events (cyclones), Rao et al. (2003) found a correlation between the meridional wind at high levels and the Antarctic Oscillation (AAO) index. Rao et al. (2003) also verified that the negative correlation found in the subtropical storm track region is due to a reduction in the wind shear and the increase of the static stability.

The mean density of extratropical cyclones is shown through the number of events per analysis within an area of 10^3 (deg lat)$^{-2}$ for winter and summer (Fig. 7). These latter characteristics are also observed in winter (two phases, see Fig. 7a–b) when the density of extratropical cyclones in the sub-Antarctic region is somewhat reduced and the line of the higher values is displaced northward.

In summer (Fig. 7c–d), the sub-polar region of the Atlantic and Indian Oceans show a higher density of extratropical cyclones [more than 5×10^{-3} (deg lat)$^{-2}$], mainly about 60°S. The phase difference for summer (Fig. 8b) shows a pattern similar to the winter conditions (Fig. 8a). In lower latitudes, an interesting feature is some thermal lows over Australia and New Zealand. These lows last about 20 h (Simmonds and Keay 2000a,b).

The pressure depth (difference between negative and positive AAO phases) in both winter and summer is more than 7 hPa in a substantial portion of the Pacific, Atlantic, and Indian oceans (not shown). In Wilkes and in the sub-Antarctic region, about 30°E, the mean depth difference of the extratropical cyclones of the two Antarctic Oscillation (AAO) phases exceeds 11 hPa (not shown). The phase difference is a result of the excess of negative values over the sub-Antarctic region. This is reflected in small depth in positive phase both in winter and summer, as can be seen in Fig. 9a–b.

Table 2 shows the mean lifetime of the extratropical cyclones of the Southern Hemisphere (SH) and the South American sector (SA) for each season. The lifetime, both in the Southern Hemisphere (SH) and the South American sector (SA), is about 3 days. The seasonal variation is very small, irrespective whether the Antarctic Oscillation (AAO) phase is negative or positive. The extratropical cyclones

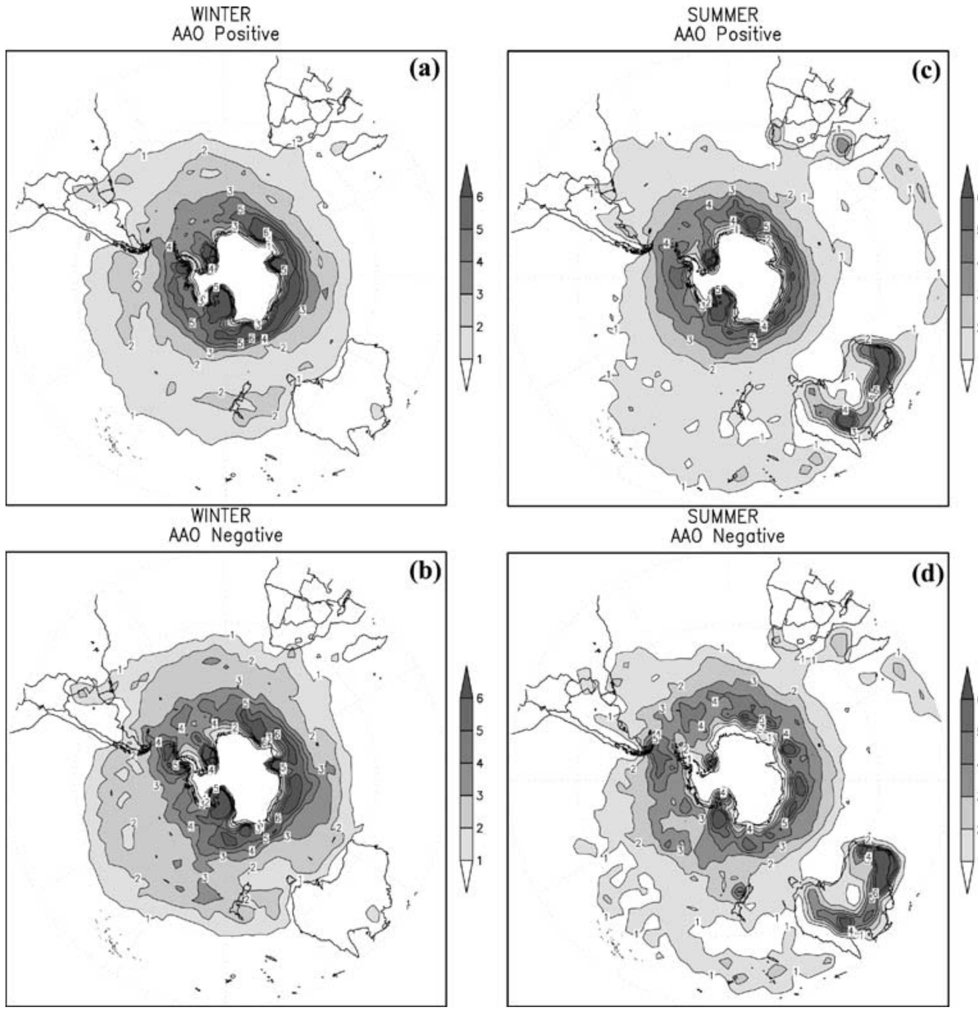

Fig. 7 Extratropical cyclones measurement means number per analysis found in a 10^3 (deg lat)^2 in **a** winter and **b** summer. Contour interval is 2×10^{-3} (deg lat)$^{-2}$ in positive and negative phase

whose cyclogenesis occurs between 45° and 75°S are more long lasting than those originated in lower latitudes. The lifetime of extratropical cyclones originated in the sub-polar region exhibits a moderate seasonality in both phases.

5 Summary and concluding remarks

Cyclones are of major importance in the modulation of weather and climate in South America. In the Southern

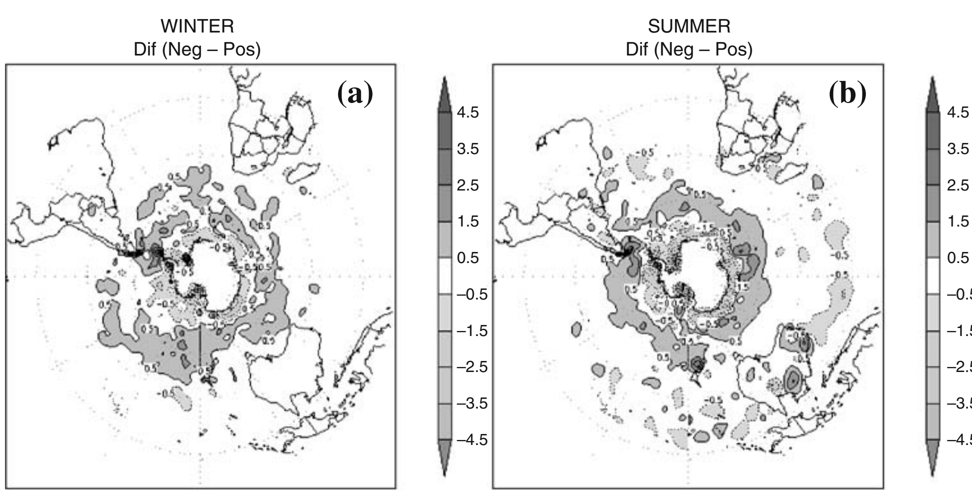

Fig. 8 Difference between extratropical cyclones density in negative and positive phase in **a** winter and **b** summer. Contour interval is 0.5×10^{-3} (deg lat)$^{-3}$day^{-1}

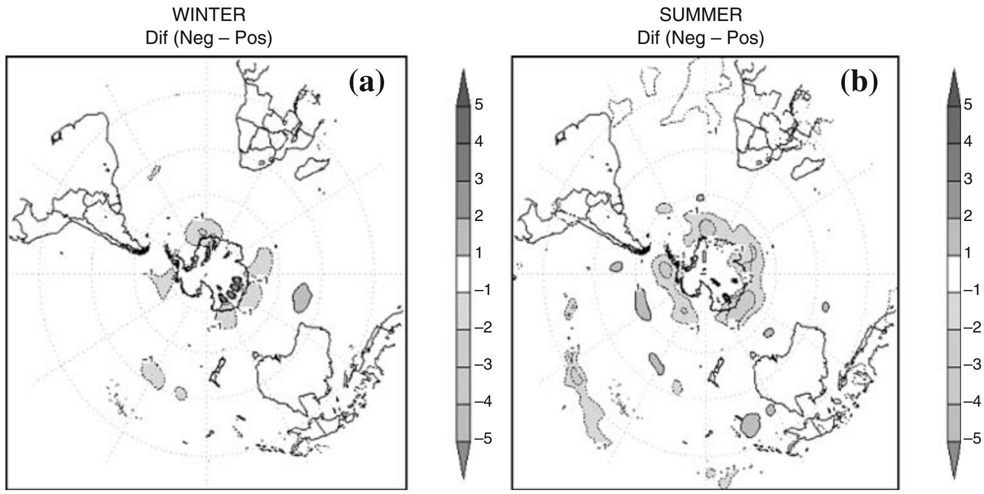

Fig. 9 Difference between extratropical cyclones depth in **a** winter and **b** summer for negative and positive phase of the Antarctic Oscillation (AAO). Contour interval is 1 hPa

Hemisphere (SH), few studies have focused on the characteristics and frequencies, as well as possible variability of cyclones in ENSO years (Sinclair 1994; Simmonds and Keay 2000a,b; Solman and Menéndez 2001; Pezza and Ambrizzi 2003). Previous studies in southern South America have used short-term data for First GARP Global Experiment (FGGE) to investigate the characteristics and variability of cyclones. Necco (1982) used 1 year of data from the FGGE. Satyamurty et al. (1990) used satellite images to diagnose cyclones for a period of 7 years. Gan and Rao (1991) developed a short-term climatology using 10 years of data of surface observations for 1979–1988. In this paper, we developed an analysis of the quantity of cyclones for the four seasons, and verified some characteristics of the cyclones, such as lifetime, maximum deepening, and overall distance traveled using the 1979–2003 NCEP/NCAR reanalyses II. We also verified the space variability through clusters for seasons with negative and positive Antarctic Oscillation (AAO) phases.

It was found a characteristic region for formation of cyclones, located near the coast of Argentina, Uruguay, and Southern Brazil. This region is characterized as a cyclogenesis one for cyclones that form in the vicinity of the South American sector (SA). Winter and summer are the seasons with the largest quantity of cyclones formed in this region. These results are in agreement with those obtained by Satyamurty et al. (1990) and Gan and Rao (1991), as well as those obtained by Simmonds and Keay (2000a,b) from their 40-year climatology of cyclones for the Southern Hemisphere (SH).

In relation to lifetime (life cycle), there is a striking similarity between the extratropical cyclones formed in the region of the South American sector (SA) and the cyclones in the entire Southern Hemisphere (SH). In the distribution of the frequency of the lifetime, we verified a small variability between seasons, not only for the cyclones formed in the region of the South American sector (SA) but also for the Southern Hemisphere (SH). In relation to the frequency of the maximum deepening, winter is the season with more different characteristics, being verified a large skewness (intensification of extratropical cyclones). For the overall distance traveled by the cyclones, as well as for the maximum deepening, the winter cyclones exhibited different characteristics in relation to those of the other seasons. In winter, the frequency of distance is better distributed, and in spring and in autumn the cyclones rarely travel distances

Table 2 Mean extratropical cyclones tracks duration (days) for at least 24 h

	Summer			Autumn			Winter			Spring		
	POS	NEG	ALL	POS	NEG	ALL	POS	NEG	ALL	POS	NEG	ALL
SH	3.06	3.04	3.04	3.11	3.08	3.10	3.15	3.11	3.14	3.05	3.01	3.02
SA	3.05	3.01	3.03	2.92	2.86	2.99	3.05	3.02	3.07	3.0	2.98	3.01
15°–45°S	2.65	2.58	2.61	2.61	2.57	2.60	2.42	2.40	2.42	2.48	2.46	2.48
45°–75°S	3.19	3.11	3.15	3.19	3.14	3.20	3.22	3.21	3.25	3.27	3.25	3.24
75°–90°S	2.19	2.18	2.19	2.66	2.65	2.66	2.55	2.50	2.54	2.31	2.31	2.35

An extratropical cyclone track is allocated to the latitude band and phase of the Antarctic Oscillation (AAO). *POS* means positive, *NEG* means negative, and *ALL* means positive, negative, and neutral phases larger than 3,000 km. These results compared well with those of Simmonds and Keay (2000a,b). To gain insight about the acting area, as well as the average course of the cyclones, we used a cluster analysis that gave three regions located on the coast of Argentina, Uruguay, and southern Brazil, near the Antarctic Peninsula and in the Southeastern Pacific, for the same period of analysis of the cyclones (25 years of data). These results show little variability in the region of influence of the cyclones for the three areas studied, and also for their mean trajectories.

Effects of variation in the Antarctic Oscillation (AAO) phase were observed in the extratropical cyclones (~40°S). The higher extratropical cyclone density is found south of 45°S in all seasons, with values exceeding 5×10^{-3} extratropical cyclones (deg lat)$^{-2}$ over the Indian and Pacific Oceans. This is more remarkable in winter of the positive Antarctic Oscillation (AAO) period. In summer, the structure is similar, but with less density for extratropical cyclones.

The largest variation of extratropical cyclone depth is found about 55°S, north of the Antarctic region that presents high density of extratropical cyclones, both in winter and summer, despite the Antarctic Oscillation (AAO) phase.

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References

Berbery EH, Núñez MN (1989) An observational and numerical study of blocking episodes near South America. J Climate 2:1352–1361

Blender R, Fraedrich K, Lunkeit F (1997) Identification of cyclone track regimes in North Atlantic. Quart J Roy Meteor Soc 123: 727–741

Bonatti JP, Rao VB (1987) Moist baroclinic instability in the development of the North Pacific and South American intermediate-scale disturbances. J Atmos Sci 44:2657–2667

Damião MCM, Trigo RM, Cavalcanti IF, DaCamara CC (2005) Bloqueios armosféricos de 1960 a 2000 sobre o Oceano Pacífico Sul: Impactos climáticos e Mecanismos Físicos Associados. Rev Bras Meteor 20(2):175–190

Gan MA, Rao VB (1991) Surface cyclogenesis over South America. Mon Wea Rev 119:1293–1302

Gan MA, Rao VB (1994) The influence of the Andes Cordillera on transient disturbances. Mon Wea Rev 122:1141–1157

Gong D, Wang S (1999) Definition of Antarctic oscillation index. Geophys Res Lett 26:459–462

Gulev SK, Zolina O, Grigoriev S (2001) Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. Climate Dyn 17:795–809

Jones DA, Simmonds I (1993) A climatology of Southern Hemisphere extratropical cyclones. Climate Dyn 9:131–145

Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo JJ, Fiorino M, Potter GL (2002) NCEP-DEO AMIP-II Reanalysis (R-2) Bull Atmos 1631–1643

Karoly DJ (1989) Southern Hemisphere circulation features associated with El Niño-Southern Oscillation events. J Climate 2:1239–1252

Kerr RA (1999) Big El Niños ride the back of slower climate change. Science 283:1108–1109

Kidson JW, Sinclair MR (1995) The influence of persistent anomalies on Southern Hemisphere storm tracks. J Climate 8:1938–1950

Lim E-P, Simmonds I (2002) Explosive cyclone development in the Southern Hemisphere and a comparison with Northern Hemisphere events. Mon Wea Rev 130:2188–2209

Marques RFC, Rao VB (2000) Inter-annual variations of blocking in the Southern Hemisphere and their energetic. J Geophys Res 105:4628–4636

Marques RFC, Rao VB (1999) A diagnosis of a long-lasting blocking event over the southeast Pacific Ocean. Mon Wea Rev 127:1761–1775

Kistler R et al (2001) The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bull Amer Meteor Soc 82:247–267

Mendes D, Souza EP, Trigo IF, Miranda PMA (2007) On precursors of South-American cyclogenesis. Tellus A 59:114–121

Mirkin, B., 1996: Mathematical classification and clustering. Kluwer, Dordrecht 428 pp.

Murray RJ, Simmonds I (1991a) A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme. Aust Meteorol Mag 39:155–166

Murray RJ, Simmonds I (1991b) A numerical scheme for tracking cyclone centres from digital data. Part II: Application to January and July general circulation model simulations. Aust Meteorol Mag 39:167–180

Necco GV (1982) Comportamiento de vortices ciclónicos en el área sudamericana durante el FGGE: ciclogénesis. Meteorológica 13 (1):7–20

Petterssen S (1950) Some aspects of the general circulation. Centen. Proc Roy Met Soc, Roy Meteor Soc 120–155

Pezza AB, Ambrizzi T (2003) Variability of Southern Hemisphere cyclone and anticyclone behavior: further analysis. J Climate 16:1075–1083

Pezza AB, Simmonds I, Renwick JA (2007) Southern Hemisphere cyclones and anticyclones: recent trends and links with decadal variability in the Pacific Ocean. Int J Climatol 27:1403–1419

Rao VB, Do Carmo AMC, Franchito SH (2003) Inter-annual variations of storm tracks in the Southern Hemisphere and their connections with the Antarctic Oscillation. Int J Climatol 23:1537–1545

Satyamurty P, Ferreira CC, Gan MA (1990) Cyclonic vortices over South America. Tellus 42A:194–201

Serreze MC, Carse F, Barry RG, Rogers JC (1997) Icelandic low cyclone activity: climatological features, linkages with the NAO, and relationships with recent changes in the Northern Hemisphere circulation. J Climate 10:453–464

Simmonds I, Keay K (2000a) Variability of Southern Hemisphere Extratropical Cyclone Behavior, 1958–1997. J Climate 13: 550–561

Simmonds I, Keay K (2000b) Mean southern extratropical cyclone behavior in the 40-year NCEP–NCAR reanalysis. J Climate 13:873–885

Simmonds I, Murray RJ, Leighton RM (1999) A refinement of cyclone tracking methods with data from FROST. Aust Meteor Mag, Special Issue, 35–49

Sinclair MR (1994) An objective cyclone climatology for the Southern Hemisphere. Mon Wea Rev 122:2239–2256

Sinclair MR (1995) A climatology of cyclogenesis for the Southern Hemisphere. Mon Wea Rev 123:1601–1619

Sinclair MR (1997) Objective identification of cyclones and their circulation intensity, and climatology. Weather Forecast 12:595–612

Sinclair MR, Renwick JA, Kidson JW (1997) Low-frequency variability of Southern pressure and weather system activity. Mon Wea Rev 127:2531–2542

Solman SA, Menéndez CG (2001) ENSO-related variability of the Southern Hemisphere winter storm tracks over the Eastern Pacific–Atlantic Sector. J Atmos Sci 59:2128–2140

Thompson DWJ, Wallace JM (2000) Annular modes in the extra-tropical circulation. Part I: Month-to-month variability. J Climate 13:1000–1016

Thompson DWJ, Wallace JM (2001) Regional climate impacts of the Northern Hemisphere annular mode. Science 293:85–89

Trigo IF, Davies TD, Bigg GR (1999) Objective climatology of cyclones in the Mediterranean region. J Climate 12:1685–1696