# 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 6-hourly sea level pressure fields, available from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalyses II, for the 1979-2003 period. The spatial distribution of the cyclogenesis frequency shows two main centres, 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 Southern Hemisphere. A K-mean clustering technique is used to summarize the analysis of the 25-yr climatology of cyclones 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 Antarctic Peninsula (around Weddell Sea). The influence of the 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.

Key words: Cyclones, South America, storm-tracks, ENSO, AAO

### 1. Introduction

The conventional lagrangian approach used to define storm track involves tracking the displacement of pre-defined features usually in near surface charts, such as minima (maxima) in sea level pressure, geopotential height or vorticity fields. There are several studies on climatology of storms over the Northern Hemisphere, 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 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 (ECMWF) data for the 1980-86 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 SH, as those analyzed for the 1958-97 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. They detected and tracked cyclonic systems by visual inspection of surface pressure charts, available four times per day for the 1979-88 period. The method used by Gan and Rao (1991) to 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 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 above-mentioned studies used 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 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 extratropical cyclones with the Pacific Decadal Oscillation (PDO), 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 analyse the spatial distribution of cyclogenesis and cyclone tracks in the Southern American sector, 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 is also analysed, with particular emphasis on the possible links with the main mode of low frequency variability in SH, the AAO.

### 2. Data and methodology

This work is based on the analysis of a 25-year (1979-2003) database of cyclones tracks derived for the whole Southern Hemisphere, 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 NCEP/NCAR reanalysis II (2.5° x 2.5° horizontal and 6-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. That was the year of the First Global Atmospheric Research Program (GARP) Global Experiment, and it is also the starting of the "modern" satellite era.

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

The algorithm implemented to 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 SH by Mendes et al. (2007).

A cyclone candidate is identified as a local SLP minimum over a 3°x3° grid point area, which has to fulfil the following conditions to be considered as a cyclone:

- (i) the central sea level pressure cannot be higher than 1010 hPa; and
- (ii) The mean pressure gradient, estimated for an area of 9°lat x 11°lon (approximately 1000km x 1000km) around the minimum pressure, has to be of at least 0.55hPa/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 SLP charts.

### 3. Cyclones in South America

### 3.1 Cyclogenesis

Figure 2 shows the average amount of cyclogenesis events, estimated for 3°x3° 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 (Figure 2b) and autumn (Figure 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 (Figure 2c) is very active in terms of cyclogenesis. Although the average values 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 Key (2000). 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, 1997). Recently, Mendes et al. (2007) showed that cyclone formation over SA is characterized by some remarkable features: (i) this large number of events originates in a rather localized area; (ii) 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 (iii) 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 behaviour (orientation) of storm-tracks in SH, associated with the lack of orographic barriers over large portions of the southern middle and high latitudes, leads to relatively longer-lasting systems travelling over larger distances, in comparison with the corresponding synoptic disturbances in the Northern Hemisphere, 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 SA (light bars) and for systems detected in the whole 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. 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 (Figures 3a and 3b), 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. Many of these long-lasting systems occur over the circumpolar ocean, where they can also travel for long distances (Simmonds and Keay, 2000).

Accordingly the distribution of cyclone total-travelled paths for the whole Southern Hemisphere (Figure 4) presents longer left tails, with secondary maxima between 2600 and 3000 km, while the corresponding histograms for the Southern American sector exhibit considerably less skewness. Indeed, the extratropical cyclones generated over the east coast of Argentina (in SA) are seen to be transported downstream by the westerlies (Simmonds and Keay, 2000). The peak around 400 km for the summer and autumn distributions for SA (light bars in Figures 4c and 4d) 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 SH (Figures 3c and 3d). About 10% of all such systems travel less than 500 km and approximately 40% travel between 500 and 1000 km. Figures 4a-d show a steady decay in frequency at the longer travel distance, but a significant proportion of the systems travel in excess of 3000 km. As it might have been expected the longest mean track length occurs in winter (1553 km), while the shortest is found in spring (1228 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 SH) are the two most commonly 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 Figure 5 for the SA and for SH. This reference latitude used for the geostrophic adjustment, which allows the use of deepening rates for the comparison of cyclones 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-America sector. It should 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 analyse 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 SA cases and the whole cyclone population in SH. Spring presents the distribution with the longest left-tail (Figure 5b), although the most extreme cases of very rapidly developing systems, or explosive cyclones, tend to occur in winter. When compared with Northern Hemisphere, deepening rates are generally smoother in Southern Hemisphere, 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 SA, the storm tracks within the South America 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 standardised vectors containing the 6-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 formation of cyclones, as discussed previously. Compared to the other two regions, the contribution of the centersouth Pacific region is small.

In Figure 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 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 Antarctic Oscillation (AAO) in the variability of the extratropical cyclones over Southern Hemisphere.

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

In relation to a possible influence of 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 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)<sup>-2</sup> for winter and summer (Figure 7). These latter characteristics are also observed in winter (two phases, see Figure 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 (Figures 7c-d) the sub-polar region of Atlantic and Indian Oceans show a higher density of extratropical cyclones [more than 5 x  $10^{-3}$  (deg lat)<sup>-2</sup>], mainly about 60°S. The phase difference for summer (Figure 8b) shows a pattern similar to the winter conditions (Figure 8a). In lower latitudes an interesting feature is some thermal lows over Australia and New Zealand. These lows last about 20 hours (Simmonds and Keay, 2000).

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 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 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 Figure 9a-b.

Table 2 shows the mean lifetime of the extratropical cyclones of SH and SA for each season. The lifetime, both in SH and SA, is about 3 days. The seasonal variation is very small, irrespective whether the AAO phase is negative or positive. The extratropical cyclones whose cyclogenesis occurs between 45°-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 Southern Hemisphere, few studies have focused on the characteristics and frequencies, as well as possible variability of cyclones in ENSO

years (Sinclair, 1994; Simmonds and Keay, 2000; 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 travelled using the 1979-2003 NCEP/NCAR reanalyses II. We also verified the space variability through clusters for seasons with negative and positive 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 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 Satymurty et al. (1990) and Gan and Rao (1991), as well as those obtained by Simmonds and Keay (2000) from their 40-year climatology of cyclones for SH.

In relation to lifetime (life cycle), there is a striking similarity between the extratropical cyclones formed in the region of SA and the cyclones in the entire 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 SA, but also for the 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 travelled 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 fall the cyclones rarely travel distances larger than 3000 km. These results compared well with those of Simmonds and Keay (2000). 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 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 x  $10^{-3}$  extratropical cyclones (deg lat)<sup>-2</sup> over Indian and Pacific oceans. This is more remarkable in winter of the positive 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 AAO phase.

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# TABLES

## Table 1

Authors	Period	Nur	nber of eason	Data	
		Winter	Summer		
Satyamurty et al. (1990)	1980-86	~ 20	~32	Satellite	
Gan and Rao, (1991)	1979-88	~ 31	~21	Surface data	
Mendes (2006)	1949-2003	~ 35	~28	NCEP/NCAR Rean.	

## Table 2

	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°-	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°S												
45°-	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°S												
75°-	2.19	2.18	2.19	2.66	2.65	2.66	2.55	2.50	2.54	2.31	2.31	2.35
90°S												

# FIGURES







Figure 3









8.



Total Distance (km)



Figure 5









10-

5-

dp/dt (hPa/6h)













Figure 9

