VARIABILITY OF SOUTHERN HEMISPHERE CYCLONE AND ANTICYCLONE BEHAVIOR: FURTHER ANALYSIS

Alexandre Bernardes Pezza and Tércio Ambrizzi

Department of Atmospheric Sciences
Institute of Astronomy, Geophysics and Atmospheric Sciences
University of São Paulo – São Paulo (Brazil)

In press in the Journal of Climate

Revised in September/2002.

Corresponding authors address:

Rua do Matão, 1226. CEP 05508-900. São Paulo, SP, Brazil
Phone: (+55)(11)(96867162)
Fax: (+55)(11)(61699240)

e-mail: alepezza@model.iag.usp.br, ambrizzi@model.iag.usp.br

ABSTRACT

This paper presents some additional results on the use of an automatic scheme for tracking surface cyclones and anticyclones. The Southern Hemisphere (SH) total amount of synoptic tracks (every 12 hours) was analyzed for the 1973 –1996 period using sea level pressure from the National Center for Environmental Prediction (NCEP) Reanalysis. Composites for seven El Niño (EN) and La Niña (LN) years were constructed in order to analyze the association between the hemispheric cyclone and anticyclone propagation and the phase of the El Niño – Southern Oscillation phenomenon (ENSO).

A climatological view of cyclone and anticyclone tracks and orphan centers superposed on the same map is presented and analyzed. A large area with overlapped cyclone and anticyclone tracks is seen between 30^o and 60^o S which is approximately the climatological position of the SH transient activity. To the north of 30^o S, the Subtropical South Atlantic High is embedded in a region with just a few cyclone tracks. This feature is not evident for the Pacific and the Indian's High. The subtropical cyclones dominate most of the west Pacific and north of Australia. Orographic and heat lows are well spread over the tropical regions of South America and Africa. Finally, the storm tracks region appeared as a very marked feature around the Antarctic continent.

In accordance with some previous studies, the total number of the SH cyclones and anticyclones during the austral winter season has shown an overall decline, particularly at the end of the 1970s. Nevertheless, a more complex behavior shows up when the weak systems are eliminated and the intense end of the spectrum is analyzed. For the anticyclone tracks above 1020 hPa, there is still some tendency to an overall decline, but it is small and not statistically significant. For the stronger

anticyclones this tendency rapidly disappears. On the other hand, the cyclone tracks presented a different behavior, since the decreasing trend turned into a significant increase for those stronger than 980 hPa. Our results also emphasize how sensitive the tracking scheme is to capturing low and high pressure centers, and it presents another perspective for the interpretation of cyclone and anticyclone trends.

The ENSO composites indicated a higher anticyclone concentration near the Subtropical South Atlantic High during EN years, while in the Subtropical South Pacific High it occurs during LN years. On the other hand, the cyclone tracks showed a higher variability, with an excess of lows over the subtropical Pacific, west of South America and southern Argentina during EN years and a more pronounced activity over the subtropical Atlantic and southeastern Australia during LN years. Nevertheless, the trends and the average of the total hemispheric number of cyclones and anticyclones are not significantly affected by the ENSO phase.

1. INTRODUCTION

Over the decades, operational meteorologists have been drawing synoptic charts with a particular concern for the precise location of cyclones and anticyclones near the surface. It is well known by experienced meteorologists (e.g. Taljaard 1967) that these systems and their movement associated with high level troughs and ridges are one of the main causes of weather changes all over the subtropics and polar regions.

In the past, the process of monitoring low and high pressure tracks on a climatic basis 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 like the ones described in Murray and Simmonds (1991) and Sinclair (1994).

Automatic procedures can be applied for finding and tracking highs and lows from operational numerical analyses. The most important advantages are the possibility of handling a large amount of information in a shorter time frame and generating results that can be easily compared between them, because most outputs obtained from any automatic scheme are reproducible. Furthermore, what constitutes a low or high pressure center is precisely specified.

Murray and Simmonds (1991) developed one of the first automatic procedures available nowadays to find and track surface pressure systems. Jones and Simmonds (1993 and 1994) analyzed the performance of such tracking scheme with 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, a large number of studies have applied automatic schemes on tracking cyclones and anticyclones and confirmed their reliability, adding a new global perspective for the signature of transient (e.g. Sinclair 1994, 1995, 1996; Sinclair et al 1997; Simmonds and Keay 2000a and b and references therein) and even tropical systems (Sinclair 2002). Indeed, in a recent work Sinclair (2002) showed the reliability of his automatic scheme in capturing the transition of tropical cyclones into mid-latitude systems over the southwest Pacific. This is just an example of how developed and physically consistent (and hence useful) the automatic schemes can be nowadays.

In this work, a wintertime SH climatology of cyclone and anticyclone tracks using the NCEP Reanalysis data applied to the Murray and Simmonds (MS henceforth) automatic scheme is presented for the 1973 – 1996 period. A climatological map with the total synoptic tracks superposed was produced in order to have a precise hemispheric signature for these systems. The total amount of tracks and orphan systems were counted in order to analyze possible climatic trends.

Another perspective for the climatic trend showed by Simmonds and Keay (2000a), particularly with relation to their figure 6a will be discussed. Finally, some composites of SST anomalies and cyclone and anticyclone track maps overlapping all synoptic trajectories were made for seven El Niño (EN) and La Niña (LN) years. Possible changes on the hemispheric high and low pressure belts associated with the ENSO phase are discussed.

2. DATA AND METHODOLOGY

The MS automatic scheme was used to find and track high and low pressure centers near the surface. Mean sea level pressure data from the NCEP Reanalysis (Kalnay et al 1996) was used every 12 hours from 1973 to 1996. Although some studies suggest that the automatic schemes performance would increase for data set every 6 hours, our tests did not show any significant improvement in this case. Therefore, the 12 hour analyses seem to be suitable for climatological applications. The area of study is the Southern Hemisphere, and track analyses have been carried out during the wintertime, i.e., June, July and August (JJA).

Some authors have shown that there are artificial pressure trends in the NCEP/NCAR reanalysis over the Southern Hemisphere (Hines et al 2000 and Simmonds and Keay 2000b). In fact, the SH has experienced a substantial increase in data coverage over the last decades, which has affected the quality of the reanalysis data (Eugene Kalnay, personal communication). From our own compilations, it was observed that the period after 1975 experienced a reduction in the extratropical sea level pressure up to 6 hPa in the border of the Antarctic continent, in comparison to the period between 1950 and 1975. Bearing this in mind, only the last available period was used, in which the coverage is much better than what it was before.

The MS scheme was developed by Dr. Ross J. Murray and Dr. Ian Simmonds, from the University of Melbourne, Australia, in order to identify and track low and high pressure centers on a sphere. The main principle is 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 it. The dimension problem related to the grid space was partially solved through the use of bicubic splines fit. The pressure is approximated by a smoothly varying function, and the pressure Laplacian is used to find the cyclones and anticyclones.

The array is first scanned for the sites of "possible" lows (or highs) by comparing the values at neighboring grid-points. To allow for the possibility that a shallow depression (ridge) may not be detected by a local minimization (maximization) of grid-point values, a less restrictive scanning procedure has been implemented. This procedure seeks grid-points at which the Laplacian of the pressure shall be greater (or lower in the case of an anticyclone) than at any of the eight surrounding points and greater than a specific threshold. In the case of an open depression (ridge), in which no point of minimum (maximum) pressure exists, it was decided that a suitable analogue for it would be the inflexion in the pressure surface, i.e., the point of minimum (maximum) pressure gradient. Finally, the lows and highs are checked for having the character of a mid-latitude storm. The method that was found to give good discrimination is one that requires a minimum average value of the pressure Laplacian over a specified radius of the cyclone or anticyclone center.

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.

As mentioned at the introduction, previous studies have shown the reliability and efficiency of the MS scheme 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). For more information on the scheme algorithm, the reader may refer to Murray and Simmonds (1991).

In order to evaluate the MS scheme performance, many different parameters were tested, such as the latitudinal and longitudinal projection, the projection radius, the horizontal smooth parameter, the minimum values and radius used for the pressure laplacian, and some others related to the statistical process. To help other tracking scheme users, table 1 in the appendix summarizes the best values that were found for each parameter. Parameters in bold refer to cases in which cyclones and anticyclones have different values. This set of optimal parameters was determined after some tests comparing specific automatic and manual trajectories of highs and lows were applied in two case studies, which proved the scheme robustness and reliability for the transient extratropical propagation (figure not shown).

Although the optimal parameters in table 1 produced very accurate extratropical tracks, a large amount of tropical heat and orographic lows was still observed which is similar to the ones obtained by Sinclair (1994). Furthermore, there is an increase in the MS model uncertainty for pressure values ranging between 1010 and 1020 hPa, where in some cases the model was unable to distinguish between high and low pressure centers. Since the main interest in this paper is the significant extratropical transient activity, which means central pressures outside of the 1010 – 1020 hPa range (Schwerdtfeger, 1976), this problem was partially solved applying a pressure selection, forcing the scheme to capture mainly mid and high latitude systems. Therefore, only anticyclones with central pressure above 1020 hPa and cyclones with central pressure below 1015 or 1010 hPa, depending on the type of analysis, were considered. The strong end of the spectrum was also analyzed selecting anticyclones above 1035 hPa and cyclones below 980 hPa.

Murray and Simmonds (1991) have pointed out that any pressure criterion may be considered too subjective and might induce a location bias. Sinclair (1994) has also discussed the weakness of any automatic scheme based on sea level pressure, not only because the use of pressure minima can induce bias but because some cyclonic systems without a closed pressure minimum would be missing as well. In his work, Sinclair pointed out some advantages and disadvantages of using vorticity rather then pressure. He showed that while vorticity avoids bias and can adequately capture most of the transient cyclonic activity, it has also some disadvantages as a high sensitiveness to analysis errors (which could be a major concern in the SH) and a tendency to include elongated geostrophic shear or curvature zones not generally thought of as cyclones. Taking into consideration the proven robustness of the MS scheme for extratropical systems and considering that the analyses presented here aim to give a synoptic perspective through the classical definition of cyclones and anticyclones, sea level pressure was used. The possible weaknesses of this kind of scheme should be considered when interpreting the results though, specially those expressed in figure 1.

In order to study the tracking process variability and its relation with ENSO events, some El Niño and La Niña years were chosen within the data period used here: 1976, 1982, 1983, 1987, 1991, 1992 and 1993 for EN and 1973, 1984, 1985, 1988, 1989, 1995 and 1996 for LN. The criterion used to select the events was based on the NCEP seasonal list definition from 1950 to 2000, available at its website (www.cpc.ncep.noaa.gov). The NCEP criterion presented on its site classifies years into neutral, El Niño or La Niña. After the selection of the years, the SST anomalies for the wintertime period were checked, only keeping the cases in which consistent anomalies were present. The SST data set used was obtained from COADS (Woodruff et al 1998) with a resolution of 1.0^o x 1.0^o latitude-longitude grid. All the cases selected here are included in the Trenberth (1997) list.

The total amount of synoptic cyclone and anticyclone trajectories was superposed on the same map. This procedure created a “climatic cloud” containing many different signatures and a variety of paths from individual synoptic propagation systems. As a result, an easy general recognition of the hemispheric patterns was possible.

In order to distinguish between the geographical regions dominated only by cyclones or by anticyclones and the regions overlapped by both systems, a graphical treatment based on colors was used. The same procedure was applied to distinguish the paths that only occurred in LN and EN years from the others. For each feature of interest it was attributed a different color in such a way that all the trajectories could be visualized in the same map. Different colors were used to determine the intersection regions where common areas were removed in order to emphasize other characteristics. This methodology was applied to figures 3a, 3b and 3c. Further details are given in section 3b.

3. RESULTS

a) Time series of Cyclone and Anticyclone counts and climatic trends

Figure 1 shows the Southern Hemisphere winter (JJA) total number of cyclone and anticyclone tracks with no restriction to pressure ranges (figure 1a), for cyclones below 1010 hPa and anticyclones above 1020 hPa (figure 1b), and for cyclones below 980 hPa and anticyclones above 1035 hPa (figure 1c) according to the MS automatic scheme using data every 12 hours for the 1973 – 1996 period. The linear regression lines and the square linear correlation coefficients according to the least square method (Wilks, 1995) are shown in each case. The confidence level according to the T-Student Test (Wilks, 1995) is above 99% for the regressions in figures 1a and 1c, excluding the anticyclones in figure 1c which presented no tendency with a near zero square linear correlation coefficient, and slightly above 95% for figure 1b. Tracks with one point, i.e., those that disappeared in the following analysis (defined here as orphan systems) were included as well.

It is known that any pressure criterion may be rather subjective and might induce a location bias (e.g. Sinclair 1994) but, as discussed in section 2, the MS scheme accuracy is significantly higher for stronger transient systems. From a synoptic point of view figure 1b expresses the most important transient activity, where the spurious and weak systems were partially eliminated, and figure 1c only shows the systems located in the most intense end of the spectrum. As commented before, the MS scheme uncertainty may be high when one considers the whole spectrum as in figure 1a but its accuracy improves considerably for the selections in figures 1b and 1c.

According to figure 1a, when no pressure restriction is applied the number of anticyclones is higher than the number of cyclones, showing 583 tracks of highs and 529 tracks of lows on average. On the other hand, figure 1b, that considers anticyclones with central pressure above 1020 hPa and cyclones with central pressure below 1010 hPa, shows an average of 340 anticyclone tracks and 358 cyclone tracks, which indicates a cyclone count slightly higher. In percentage, it means a reduction of about 42% and 32% for the anticyclones and cyclones, respectively, when the "synoptic" pressure restriction was considered. It is worthy noting that these reductions mostly assured not only the elimination of weak extratropical systems but some that might have also been falsely identified by the automatic scheme because of the weak pressure gradients associated. The fact that the reduction was more effective for the anticyclones probably suggests that they were more susceptible to be misidentified in a weak-gradient environment.

Figure 1c is showing the cyclones below 980 hPa and the anticyclones above 1035 hPa, which corresponds to the most intense 25% and 10% of tracks, respectively, in relation to the total count. These last pressure ranges only show the systems at the intense end of the spectrum, and a significant additional reduction is observed. Anticyclones above 1035 hPa are usually seen over the continent in association with strong polar air masses, and cyclones below 980 hPa only occur in mid and high latitudes and are usually associated with strong winds and precipitation. These strong cyclones are frequently seen in association with polar air masses when passing over the southern tip of South America (Ambrizzi and Pezza, 1999).

From figure 1a, the regression indicates a significant overall decline of cyclones and anticyclones. Nevertheless, the percentage of the total variance explained by the fit, which is given by the square correlation coefficients, is about

55% for the anticyclones and 44% for the cyclones, indicating a high variability. The trends are less noticed in figure 1b, where the variability is much higher (only 17% and 19% of the total variance are explained by the linear fit for the anticyclones and cyclones respectively). Finally, figure 1c shows a different pattern, with an overall increase of cyclones below 980 hPa which indicates an opposite behavior at the intense end of the spectrum. About 46% of the total variance is explained by the linear regression in this case, as shown by the square linear regression coefficient. Nevertheless, no tendency has been observed for the intense anticyclones above 1035 hPa, with a near zero coefficient.

Figure 1a bears some resemblance to figure 6a from Simmonds and Keay (2000a), who suggested a negative trend in the number of transient systems on the Southern Hemisphere. Their figure showed the time series of the total annual number of cyclone tracks and only included cyclones that lasted at least 24 hours. In our case, we are limited to just one season (JJA) and the anticyclone series and "orphan" systems were included as well. Furthermore, from Figure 5 of Simmonds and Keay's work, which shows the time series of seasonal averages of the number of cyclones per analysis for the SH, a marked decline of cyclones during the austral winter is also noticed.

From figure 1b, it is clear that when the pressure selection was applied, the difference between the total number of cyclones and anticyclones, as well as the trends, almost disappeared. Based on this result, one may wonder if the previous trend is related to how the automatic scheme is adjusted in a weak pressure gradient environment rather than to possible climate changes. Nevertheless, Simmonds and Keay (2000a) also documented an increase on the radius and depth of the systems. This would suggest fewer but more intense systems, and hence, if one progressively eliminates the weaker systems, an apparent downward trend could even turn into an increase.

Figure 1c confirms the hypothesis above, i.e., the intense cyclonic systems are becoming more frequent. Some tests considering further variations in the pressure range used to select the intense systems in figure 1c were made, but no significant change of pattern was obtained. Considering only the cyclones between 1000 and 1010 hPa, an overall decline similar to the one showed in figure 1a is also verified (figure not shown). Furthermore, these observations agree and confirm the suggestions of Simmonds and Keay (2000a) that there would be fewer but more intense cyclones.

Other studies have also pointed out a reduction in the overall cyclonic activity in different regions of the Southern Hemisphere (Leighton and Deslandes 1991, Leighton 1997, Leighton et al 1997, Simmonds et al 1998 and Key and Chan 1999), however, Sinclair et al (1997) showed an increase for cyclone number over the southern ocean during the 1980s, using the ECMWF (European Centre for Medium-Range Weather Forecasts) analyses applied to a different automatic scheme.

These considerations raise the question about how tracking schemes are sensitive to capturing low and high pressure centers when different restrictive pressure criteria are applied. Different data sets, different automatic procedures and how the cyclones are exactly defined, i.e., via vorticity or sea level pressure, are factors that may also play an important role on the final results (see also discussions on Carnell et al 1996 and Sickmoller et al 2000). The possibility of a pressure bias, as discussed in section 2, is also one point to be considered when comparing figures 1a, 1b and 1c. Any physical mechanism that would reasonably explain an environment with fewer but more frequent intense cyclones and a static number of intense anticyclones is rather complex and difficult to address. This issue needs further analyses in light of the possible climate changes occurred in the SH.

b) Cyclone and Anticyclone tracks climatology and ENSO related tracks

Figure 2 shows the sea surface temperature anomalies associated with the EN (fig.2a) and LN (fig.2b) composites during the SH wintertime. This figure provides an overall view of the hemispheric forcing that may have impacted the cyclone and anticyclone propagation during the composed years. From figure 2a, a large positive anomaly area is observed from the date line to the west coast of South and Central America, with values above +1.2°C around the Equator and eastern of 120°W. For the LN composite (figure 2b), anomalies extending from the date line to the west coast of South America with amplitudes up to –1°C are observed. Although the anomalies magnitude is not very intense, the anomalies are significant because they represent a composite of 21 wintertime months for each ENSO phase.

Figure 3 shows: (a) a superposition of systems indicating the geographical track regions of anticyclones (tracks and "orphan systems") with central pressure above 1020 hPa (violet) and cyclones (tracks and "orphan systems") with central pressure below 1015 hPa (pink color), and the regions overlapped by both systems (yellow), according to the automatic MS scheme for the 1973 – 1996 JJA period; (b) the same for anticyclones and (c) for cyclones that occurred during the El Niño (in red) and La Niña (in blue) composites alone. "Orphan" tracks are indicated by crosses. For clarity, those tracks inside of common areas, i.e., those that occurred during both ENSO phases, were removed from figures 3b and 3c, according to the methodology discussed in section 2. One should note that the cyclone definition considered in this case (below 1015 hPa) differs from the selection used in figure 1b.

The idea in this section is to present a general climatic view which allows the occurrence of weaker systems.

The most significant Southern Hemisphere climatic features related to cyclone and anticyclone activity are plotted in Figure 3a. The purple color on the subtropical belt indicates a high anticyclone concentration over the oceans corresponding to the well known pressure centers of action (Hastenrath 1985; Machel et al 1998 and Kapala et al 1998), particularly in the Subtropical Atlantic High. The Subtropical Pacific High and the Subtropical Indian High are not too evident because they are embedded in regions of high cyclone activity (transient region showed in yellow color). A high concentration of orographic anticyclones, especially over the Andes and over the Antarctic plateau is also observed.

Some migratory extratropical anticyclones appear in the center of Australia and southeastern South America, but most of the transient hemispheric activity between 30^{o} and 60^{o}S is characterized by the passage of both cyclones and anticyclones represented by the yellow color in the map. The pink color shows a marked cyclone concentration around the Antarctic continent which is approximately the position of the SH storm tracks (Wallace et al 1988 and Trenberth 1991). Several heat and orographic lows (and highs) can be observed over the continents as well.

Figures 3b and 3c show the total amount of tracks and orphan systems that occurred in the EN (red) and LN (blue) years. Comparing figure 3a with figures 3b and 3c one can see that, depending on the ENSO phase, there are differences on the tracks concentration. Furthermore, the cyclone and anticyclone gap areas between the subtropics and the subpolar belt shown in figures 3b and 3c correspond to a baroclinic region where the transients are active at all seasons. Indeed Simmonds and Keay (2000b) in their study of the SH extratropical cyclone behavior have already shown that a large number of cyclonic systems is found between 50^o – 70^oS during all seasons. The idea of showing those tracks and points that only appeared during EN or LN years (figures 3b and 3c), eliminating the overlapping areas, contributes to emphasize the main features associated with the ENSO and the differences between its phases.

Two pronounced bands of anticyclone tracks are seen from Figure 3b. The first one is about 20^oS and the second is located around 50^oS. For the EN composites, the subtropical band shows a higher anticyclone concentration over the Atlantic Ocean. It indicates that during warm ENSO events the Atlantic Subtropical High is enhanced. This pattern is in agreement with some works which showed that during the EN austral winters there is a tendency for above normal blocked frontal systems over southern Brazil in association with a stronger than normal Subtropical high level Jet over the region (see Kousky et al, 1984; Nobre et al, 1986; and Ambrizzi, 1994).

A higher anticyclone concentration during EN years is also seen over the South Atlantic Ocean, to the South of the Australian continent and to the west of the Antarctic Peninsula. On the other hand, the subtropical eastern Pacific seems to favor the anticyclone concentration during LN years which is also true for the Antarctic Peninsula and its eastern part.

The cyclone tracks found in the EN and LN years composites are concentrated around 30^oS in a broader band (Figure 3c). During LN years, there are more tracks over the subtropical Atlantic and southeastern Australia. The cyclone tracks during the EN years are more pronounced over the subtropical Pacific, southern Argentina, west coast of South America and over the Indian ocean.

The ENSO phase is well known for its important social and economic impacts, specially with regard to precipitation anomalies all over the globe. The differences in the cyclone and anticyclone tracks obtained here are reflecting possible changes in the upper level wave patterns, since surface pressure is linked with the circulation above. The high cyclone concentration in Southern Argentina (figure 3c) and the enhanced Subtropical Atlantic High (figure 3b), for instance, are physically consistent with the observed Subtropical high level Jet enhancement over southern Brazil during austral EN winters, as discussed before. This pattern is related to heavy rains over southern Brazil, Uruguay and northeast Argentina (e.g. Grimm et al 2000 and references therein).

One important point related to the geographical regions showed in figures 3b and 3c is that the observed accumulated systems are not given by chance. Since the tracks have been analyzed every 12 hours during a 14 years period (7 EN and 7 LN years), there are enough systems to assure that the ENSO signal is higher than the sample noise. Another aspect to be considered is that there may be an inbuilt bias to position as a result of the problems addressing automatic schemes based on sea level pressure, but it seems that the most relevant weather-producer systems and their position according to the ENSO phase were correctly captured.

Some of the above results are also in good agreement with those shown by Sinclair et al (1997) who found a coherent cyclone response to ENSO using an automatic scheme based on vorticity. Furthermore, they argued that the LN cyclone patterns are almost exactly the reverse of the EN ones, suggesting a predominantly linear response. This feature was somewhat observed in our results, though it showed a high variability. For instance, over the subtropical Atlantic the high anticyclone concentration during EN years is replaced by a high cyclone concentration during LN years, and over much of the subtropical Pacific, the high concentration of anticyclones during LN is replaced by cyclones during EN.

One may wonder if ENSO events would interfere in the total hemispheric number of surface cyclones and anticyclones and the trends as well. If a plot similar to figure 1 is prepared considering the EN and LN years alone (figure not shown), the same patterns discussed before are present, i.e., the trends and the average total hemispheric count are very similar to those previously discussed. This indicates that the trends are not associated with the ENSO phase.

Furthermore, the fact that the average of the total hemispheric count is not significantly affected by the ENSO is physically reasonable and it is in agreement with figures 3b and 3c, because one would expect that the regions where there is an increase would compensate the regions of systems decrease, resulting in an approximate equal number on a hemispheric basis. The work of Sinclair et al (1997), for instance, showed a very similar pattern. In their figures 11c and 11d, which shows the winter track density anomaly composite for a Southern Oscillation Index (SOI) below minus 1.5 (c) and above 0.5 (d), one can see that on a hemispheric basis the areas of negative correlation can approximately compensate the areas of positive correlation, suggesting the possibility of a hemispheric equilibrium.

4. CONCLUSIONS

This study presents further analyses of the variability of Southern Hemisphere cyclone and anticyclone behavior based on the University of Melbourne automatic scheme. The NCEP Reanalysis data were used for the austral wintertime period of 1973 – 1996. We have also discussed some of the results found by Simmonds and Keay (2000a) who showed a possible climatic trend related to the total annual number of cyclone tracks over the Southern Hemisphere using the same automatic scheme and data source, but with a slightly different methodology.

Our results suggest another perspective for the downward trends in the cyclone numbers proposed by Simmonds and Keay (2000a). It is shown that when a "synoptic" selection is applied to the central pressure in order to prevent the inclusion of weak systems, the trends considerably change. The synoptic pressure criterion used here was an attempted to eliminate most of the weak and tropical systems, focusing on the mid-latitude and extratropical weather ones, since the MS automatic scheme skill is significantly improved for relatively stronger pressure gradients. However, analyses at both ends of the spectrum show a lower total number of cyclones with a decrease in the number of weak systems and an increase in the number of intense systems, particularly for those with central pressure below 980 hPa. For the anticyclones, there is also an overall decrease in their number due to a decrease in the number of weak systems, but the strong ones are not undergoing any change. These results are complementary to the Simmons and Keay's, indicating how sensitive the tracking scheme is to capturing low and high pressure centers, where the observed differences may depend on the pressure selection used .

A climatological analysis highlighted the most important signatures associated with transient and semi – stationary activity all over the Southern Hemisphere. The superposition of cyclonic and anticyclonic paths indicated the transition regions and the areas crossed by cyclones and anticyclones alone. These results are in accordance with previous studies found in the literature, emphasizing the climatological signatures of transient (Wallace et al 1988 and Trenberth 1991) and semi permanent patterns (Hastenrath 1985).

The analysis of the EN and LN track composites showed that there are some significant differences on the extratropical propagation patterns when the ENSO phases are compared. For instance, there appears to be a higher anticyclone concentration near the Subtropical South Atlantic High during EN years, while in the Subtropical South Pacific High it occurs during LN years. On the other hand, the cyclone tracks showed a higher variability, with an excess of lows over the subtropical Pacific west of South America, southern Argentina and the Indian Ocean during EN years and a more pronounced band over the subtropical Atlantic and southeastern Australia during LN years. Nevertheless, the cyclone and anticyclone trends previously discussed do not seem to be related to the ENSO phenomenon, and on a hemispheric basis the regional differences are approximately compensated, producing similar count numbers for EN and LN years.

A complete understanding of the physics associated with cyclone and anticyclone tracks may be of great interest and very useful as a forecast tool, specially with regard to the occurrence of major storms and polar wave propagation (Ambrizzi and Pezza 1999). Furthermore, the well known global influences associated with the ENSO phases can be better understood considering their impacts on the transient activity over the hemisphere. These issues need further analyses.

ACKNOWLEDGMENTS

This research was funded by FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), under grants 99/04105-2 and 98/12976-0. TA has also received support from CNPq (301111/93-6) and the Inter-American Institute for Global Change Research (IAI) through the project IAI-CRN-055. The authors would like to thank Dr. Ian Simmonds and an anonymous reviewer for their very helpful comments in the early version of the paper. They would also like to thank Dr. Ross Murray and Dr. Ian Simmonds, from the University of Melbourne (Australia), for providing the automatic scheme.

APPENDIX

Validation of the MS automatic scheme

Parameter	Description	Chosen Value Highs	Chosen Value Lows
Ni	Longitudinal projection	73	73
Nj	Latitudinal projection	73	73
Rproj	Projection radius (2.5^o)	36	36
Rdiff	Horizontal smooth parameter	3.5	3.5
Iopmxc	Including or not the open systems (0 = not)	0	0
Nshell	Scanning points	8	8
Itmx1	Maximum grid points to be crossed	20	20
Df1t1	Minimum distance between two systems	7.5	7.5
Cmnc1	**Minimum average for pressure Laplacian**	**0.1**	**0.25**
Cvrad	Radius used for the Laplacian average	2.0	2.0
Cmncw	**Minimum for the Laplacian central value**	**0.2**	**0.7**
Refdt	Time interval, in days	0.5	0.5
Wsteer	Weight for the climatological steer on the tracks	0.6	0.6
Fsteer	Steering Velocity scale factor	2.0	2.0
Wpten	Weight for pressure tendency	0.0	0.0
Wmotn	If Wmotn =1, the climatological speed will be used for new created systems	1.0	1.0
Rcprob	Passage Radius for the probability function	12	12
Rpbell	Shape of the probability function	0.5	0.5
Qmxnew	Maximum probability for new cyclones	0.75	0.75
Irevmx	Maximum iterations allowed	18	18

Table 1: Summary of the most important parameters used within the automatic scheme of Murray and Simmonds. Different configurations applied to highs and lows are indicated in bold.

REFERENCES

Ambrizzi, T., 1994: Rossby Wave Propagation on El Niño and La Niña non-zonal basic flows. *Revista Brasileira de Meteorologia* (Available from Brazilian Meteorological Society), **8/9**, pp. 54 – 65.

Ambrizzi, T., and Pezza, A. B., 1999: Cold Waves and the Propagation of Extratropical Cyclones and Anticyclones in South America: A Synoptic-Climatological Overview. *Revista Geofísica* (Available from Pan-American Institute of Geography and History), **51**, pp. 45 – 67.

Carnell, R. E., Senior, C. A. and Mitchell, J. F. B., 1996: An assessment of measures of storminess: simulated changes in Northern Hemisphere winter due to increasing CO2. *Climate Dynamics*, **12**, pp. 467 – 476.

Grimm, A.M., Barros, V.R., and Doyle, M.E., 2000: Climate variability in Southern South America associated with El Niño and La Niña events. *J. of Climate*, **13**, 35-58.

Hastenrath, S., 1985: Climate and circulation of the tropics. *D. Reidel Publish. Co*, 455 pp.

Hines, K. M., Bromwich, D. H. and Marshall, G. J., 2000: Artificial surface pressure trends in the NCEP-NCAR reanalysis over the Southern Ocean and Antarctica. *Journal of Climate*, **13**, pp. 3940 – 3952.

Jones, D.A., and I. Simmonds, 1993: A climatology of Southern Hemisphere extratropical cyclones. *Climate Dyn*., **9**, 131 –145.

Jones, D.A., and I. Simmonds, 1994: A climatology of Southern Hemisphere anticyclones. *Climate Dyn*., **10**, 333 –348.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Celliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne and R. E Joseph, D., 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, vol.**77**, 3, 437-471.

Kapala, A., H. Machel and H. Plohn, 1998: Behavior of the centers of action above the Atlantic since 1881: Part II: Associations with regional climate anomalies. *Int. J. Climatol*., **18**, 23-36.

Key, J. R. and A. C. K. Chan, 1999: Global and regional trends in 1000 mb and 500 mb wave cyclone frequencies, 1958-1997. Preprints, 10th symp. on Global Change Studies, Dallas, TX, Amer. Meteor. Soc., 193-196.

Kousky, V.E., Kagano, M.T. and Cavalcanti, I.F.A., 1984: A review of the Southern Oscillation: Oceanic-Atmospheric Circulation Changes and Related Rainfall Anomalies. *Tellus*, **36A**, 490-504.

Leighton, R. M. and R. Deslandes, 1991: Monthly anticyclonicity and cyclonicity in the Australasian region: averages for January, April, July and October. *Aust. Meteor. Mag*., **39**, 149-154.

Leighton, R. M., 1997: Variations in annual cyclonicity across the Australasian region during the 29-year period 1965-1993. Preprints, Fifth Int. Conf. on Southern Hemisphere Meteorology and Oceanography. Pretoria, South Africa, Amer. Meteor. Soc., 362-363.

Leighton, R. M, K. Keay and I. Simmonds, 1997: Variations in annual cyclonicity across the Australasian region during the 29-year period 1965-1993 and relationships with annual Australian rainfall. Climate Prediction for Agricultural and Resource Sciences, 257-267.

Machel, H., A. Kapala and H. Flohn, 1998: Behavior of the centers of action above the Atlantic since 1881: Part I: Characteristics of seasonal and interannual variability. *Int. J. Climatol*., **18**, 1-22.

Murray, R.J., and I. Simmonds, 1991: A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme; and Part II: Application to January and July general circulation model simulations. *Aust. Metero. Mag*., **39**, 155-180.

Nobre, C.A., Oliveira, A.S. and Neves, E.K., 1986: Precipitation and Circulation Anomalies in South America and the 82/83 El Niño/Southern Oscillation Episode. Fourth Brazilian Meteorological Conference (Available from Brazilian Meteorological Society), **1**, 339-345.

Schwerdtfeger, W., 1976: "Climates of Central and South America". *World Survey of Climatology*. Elsevier, Scientific Publishing Company, **12**, 01 – 145.

Sickmoller, M., Blender, R. and Fraedrich, K., 2000: Observed winter cyclone tracks in the northern hemisphere in re-analyzed ECMWF-data. *Q. J. R. Meteorol. Soc.*, **126**, pp. 591 –620.

Simmonds, I., D. A. Jones and D. J. Walland, 1998: Multi-decadal climate variability in the Antarctic region and global change. Ann. Glaciol., special edition, 35-49.

Simmonds, I., Murray, R. J. and Leighton, R. M., 1999: A refinement of cyclone tracking methods with data from FROST. *Aust. Met. Mag*., especial edition, 35-49.

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

Simmonds, Ian and Keay, K., 2000 (b): Mean Southern Hemisphere Extratropical Cyclone Behavior in the 40-year NCEP-NCAR Reanalysis. *Journal of Climate*, **13**, 873 – 885.

Sinclair, M.R., 1994: An objective cyclone climatology for the Southern Hemisphere. *Mon. Wea. Rev*., **122**, 2239-2256.

Sinclair, M.R., 1995: A climatology of Cyclogenesis for the Southern Hemisphere. *Mon. Wea. Rev*., **123**, 1601-1619.

Sinclair, M.R., 1996: A climatology of Anticyclones and Blocking for the Southern Hemisphere. *Mon. Wea. Rev*., **124**, 245-263.

Sinclair, M.R., Renwick, J.A., and Kidson, J.W., 1997: Low-Frequency Variability of Southern Hemisphere Sea Level Pressure and Weather System Activity. *Mon. Wea. Rev*., **125**, 2531-2543.

Sinclair, M.R., 2002: Extratropical Transition of Southwest Pacific Tropical Cyclones. Part I: Climatology and Mean Structure Changes. *Mon. Wea. Rev*., **130**, 590-609.

Taljaard, J. J., 1967: Development, distribution and movement of cyclones and anticyclones in the Southern Hemisphere during the IGY. *Jour. Appl. Met*., **6,** 973-987.

Trenberth, K. E., 1991: Storm Tracks in the Southern Hemisphere. *J.A.S*., Vol.48, **19**, 2159-2178.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc*., **78**, pp. 2771 – 2777.

Wallace, John M., Gyu-Ho Lim and Blackmon, M. L., 1988: Relationship between Cyclone Tracks, Anticyclone Tracks and Baroclinic Waveguides. *J.A.S*., vol.**45**, **3**, 439-462.

Wilks, D. S., 1995: Statistical Methods in the Atmospheric Sciences. *International Geophysics Series*, **59**. Academic Press, New York, 467 pp.

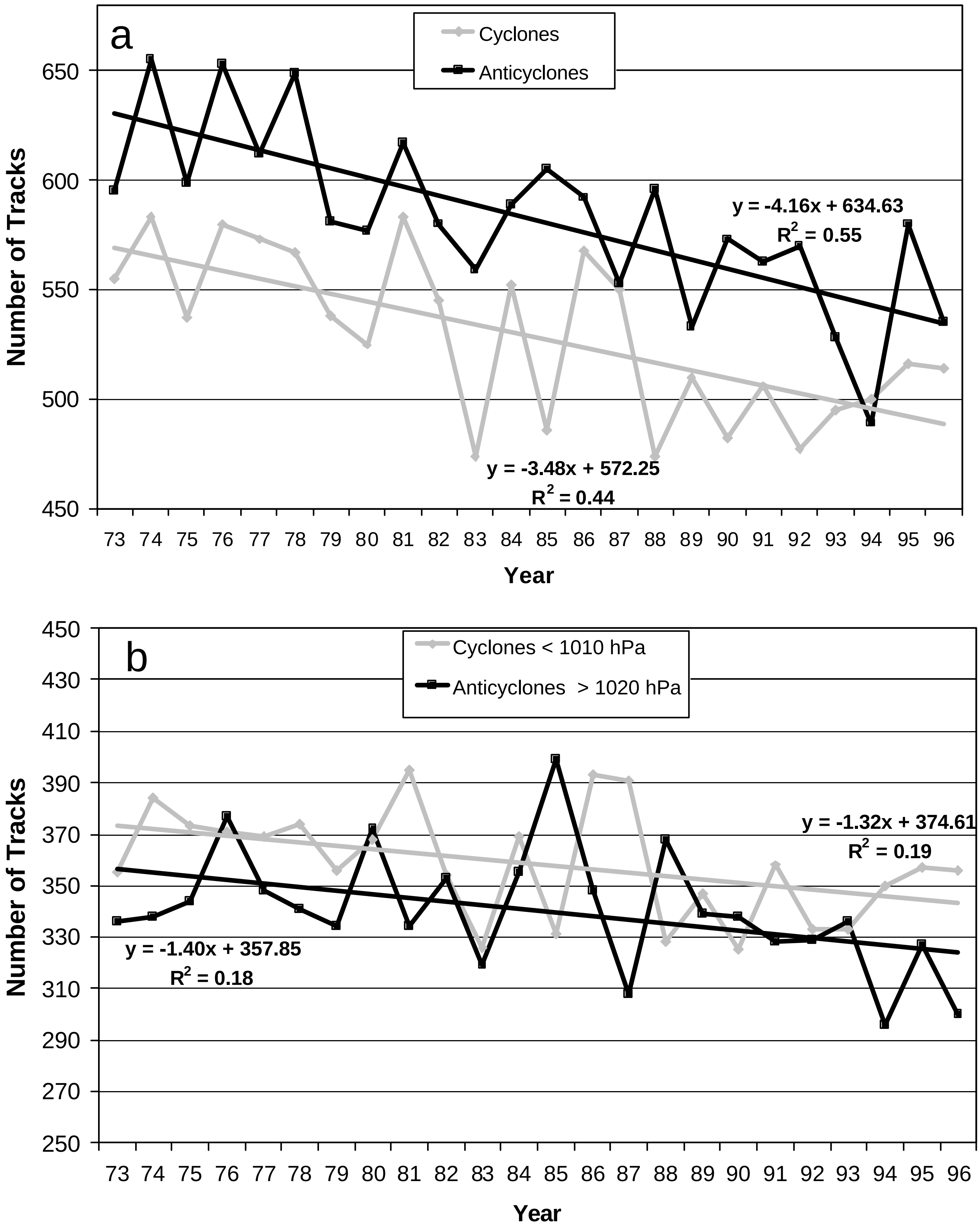
Woodruff, S. D.; Diaz, H. F.; Elms, J. D. and Worley, S. J., 1998: COADS Release 2 Data and Metadata Enhancements for Improvements of Marine Surface Flux Fields. **Phys. Chem. Earth**, Vol. 23, 5-6, pp. 517-526.

Figure Captions

Figure 1: Number of cyclone and anticyclone tracks every 12 hours during JJA (1973 – 1996), according to the automatic scheme of MS for the Southern Hemisphere (a) without pressure restriction, (b) for cyclones of central pressure below 1010 hPa and anticyclones of central pressure above 1020 hPa and (c) for cyclones of central pressure below 980 hPa and anticyclones of central pressure above 1035 hPa. Tracks consisting of only one point ("orphan systems") were also counted.

Figure 2: SST anomaly composites for JJA, based on 7 (a) El Niño (76, 82, 83, 87, 91, 92 and 93) and (b) La Niña (73, 84, 85, 88, 89, 95 and 96) years. Values between –0.2 and +0.2^{o}C are not shown, and negative values appear in dashed lines. Contours are plotted every 0.2^{o} C.

Figure 3: (a) Superposition of systems indicating the geographical track regions of anticyclones (tracks and "orphan systems") with central pressure above 1020 hPa (violet) and cyclones (tracks and "orphan systems") with central pressure below 1015 hPa (pink color), and the regions overlapped by both systems (yellow), according to the automatic MS scheme for the 1973 – 1996 JJA period; (b) the same for anticyclones and (c) for cyclones that occurred during the El Niño (in red) and La Niña (in blue) composites alone. "Orphan" tracks are indicated by crosses. See text for further details.



a
Cyclones
Anticyclones
Number of Tracks
Year
y = -4.16x + 634.63
R^2 = 0.55
y = -3.48x + 572.25
R^2 = 0.44
b
Cyclones < 1010 hPa
Anticyclones > 1020 hPa
Number of Tracks
Year
y = -1.32x + 374.61
R^2 = 0.19
y = -1.40x + 357.85
R^2 = 0.18

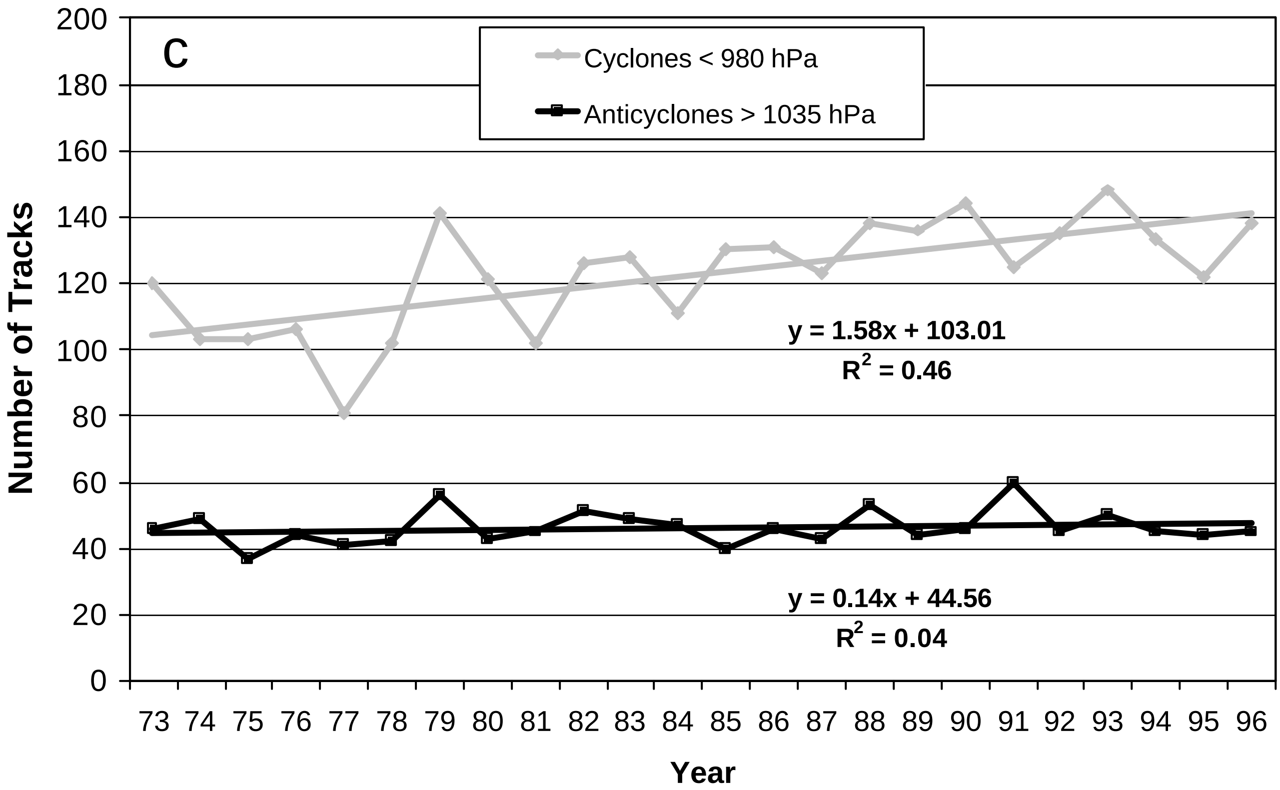


Figure1

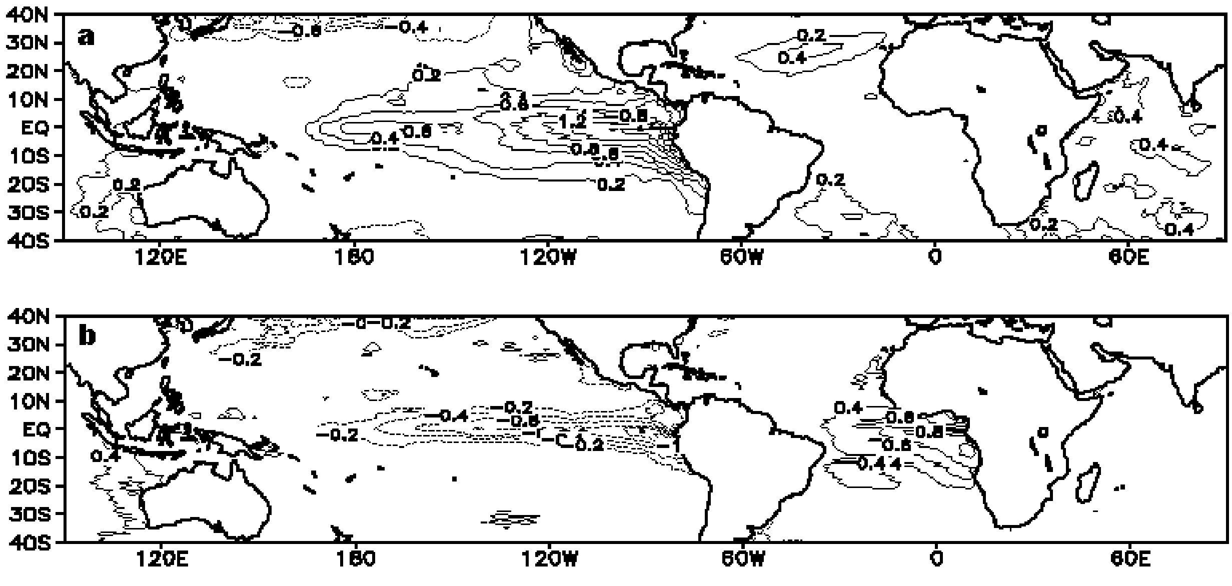
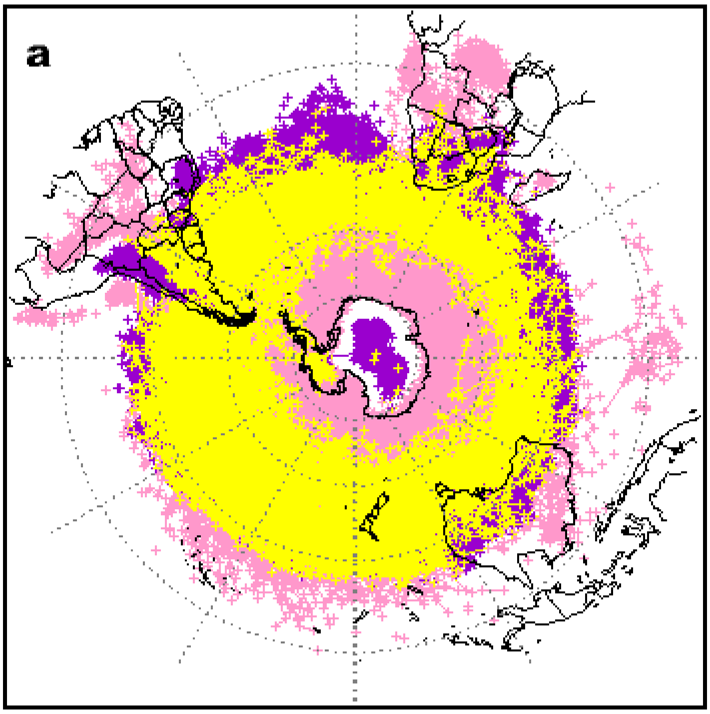
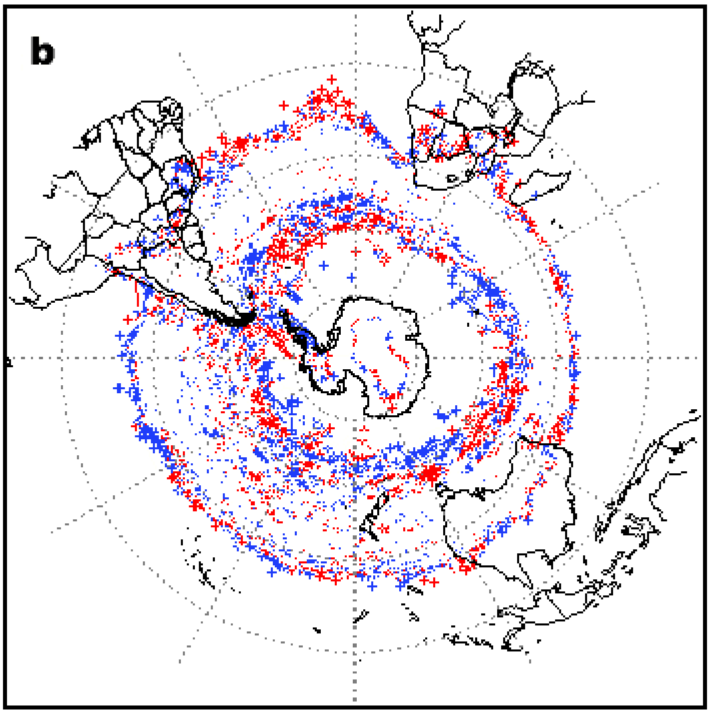


Figure 2


a


b

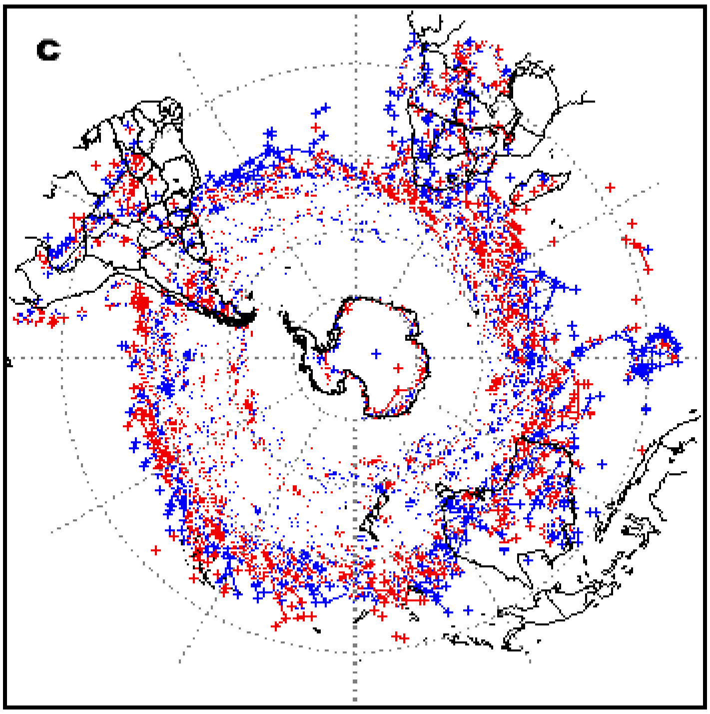


Figure 3