12A.5 A 12-YEAR CLIMATOLOGY OF SEVERE WEATHER PARAMETERS AND ASSOCIATED SYNOPTIC PATTERNS FOR SUBTROPICAL SOUTH AMERICA.

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1. INTRODUCTION

The subtropical sector of South America, east of the Andes mountain range, is among the regions in the world where the development of severe deep convection is most frequent (e.g., Brooks et al. 2003; Zipser et al. 2006). Nevertheless, the number of studies addressing the synoptic and climatological aspects of severe thunderstorms and tornadoes in that region is still scarce (Sánchez et al. 2008).

Based on atmospheric profiles obtained from the local rawinsonde network, the main goal of this study is to describe, for subtropical South America (SSA), the results of a 12-year climatology (1998-2009) of meteorological parameters typically employed to assess severe weather environments in the mid-latitudes. In addition to the climatological investigation of convective parameters, the synoptic-scale patterns associated with conditions that lead to significant values of such parameters are also discussed.

2. DATA AND METHODOLGY

One of the main difficulties in establishing the climatology of severe thunderstorms and tornadoes in South America is the lack of a long term and standardized dataset of ground-level reports of severe weather episodes for that continent (Nascimento and Doswell 2006). Despite some recent improvements in the documentation of South American severe convection, such documentation is still limited.

Hence, in this study we chose not to perform a climatological analysis of severe thunderstorms *per se*, but to assess the climatology of atmospheric parameters that are considered useful to describe the mid-latitude severe weather environment (e.g., Rasmussen and Blanchard 1998, Craven and Brooks 2004), namely: CAPE (surface-based and 100hPa mean layer); the lifted index; height of the LCL; height of the LFC; 700-500hPa lapse-rate; convective inhibition; 0-6km bulk shear; 0-1km bulk shear; bulk Richardson number shear; 0-3km storm-relative helicity; the energy-helicity index. Detailed description of such parameters are found in Rasmussen and Blanchard (1998), Craven and Brooks (2004), Nascimento (2005), and Brooks (2007), and references therein.

These parameters cannot be considered true proxies for the occurrence of severe thunderstorms or tornadoes. However, the judicious analysis of such fields in combination with the study of synoptic-scale patterns, allows a reasonable characterization of the environments that can be considered ***conducive*** to severe convection, meeting the goals of this investigation.

To compute the convective parameters, 00Z and 12Z data from the upper-air observation network (rawinsondes) from SSA (east of the Andes) were employed, comprising the 12-yr period from 1 January 1998 to 31 December 2009. Figure 1 depicts the locations of the upper-air meteorological stations included in the study, which are: Foz do Iguassu/BRA (***SBFI***, 25.5^{o}S–54.6^{o}W; 180m), Curitiba/BRA (***SBCT***, 25.5^{o}S–49.2^{o}W; 908m), Florianópolis/BRA (***SBFL***, 27.6^{o}S–48.5^{o}W; 5m), Porto Alegre/BRA (***SBPA***, 30.0^{o}S–51.2^{o}W; 3m); Buenos Aires/ARG (***SAEZ***, 34.8^{o}S–58.5^{o}W; 20m); and Resistencia/ARG (***SARE***, 27.5^{o}S–59.0^{o}W; 52m).

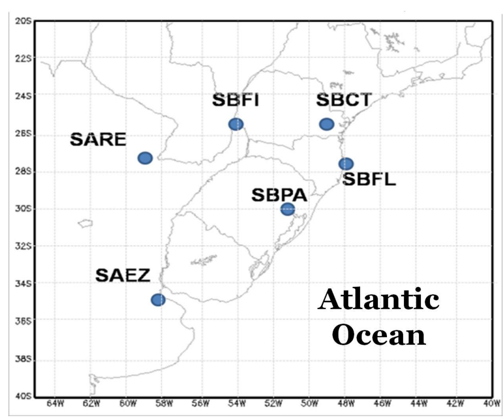

Figure 1: Geographical distribution of the upper-air sounding sites included in this study. (The corresponding local standard times for 00Z and 12Z are, respectively, 9pm and 9am).

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Two rounds of simple procedures of data quality control were performed: (1st) all soundings reporting less than ten vertical levels and/or that did not reach 300hPa were removed from the dataset before computing the convective parameters; (2nd) from the remaining soundings, those that led to suspicious values of convective parameters (e.g., CAPE above 9000 J kg^{-1}; etc…) were subjectively checked and removed if any observational inconsistency was characterized.

Table 1 indicates the effective number of soundings left after applying this simple data quality control. The number of thermodynamic profiles (T,q) differ from the number of kinematic profiles (u,v) because soundings that reported temperature and moisture but lacked the wind profile were kept in the dataset. [Note: if both 00Z and 12Z soundings were available for every single day during the 12-yr period for the six sites the total number would add up to 52596 soundings].

Table 1: Sample sizes of soundings (00Z + 12Z) for each upper-air station after the application of data quality control procedures.

Sounding site	Thermodynamic profiles	Kinematic profiles
SBFI	4755	4087
SBCT	6097	5130
SBFL	3758	3122
SBPA	6576	5924
SAEZ	4542	3799
SARE	2903	2355
Total:	**28631**	**24417**

Next, for each sounding site, basic statistics were computed for all convective parameters, which include the median and the 10%, 25%, 75% and 90% percentiles. This computation was carried out in a monthly and annual basis (i.e., for the set of 12 months of January, set of 12 months of February, and so on). The purpose of the statistics was twofold: (a) to describe the magnitude and to examine the seasonal distribution of the parameters; (b) to provide (and to test) objective criteria to identify, within the full sample of soundings (Table 1), those that are indicative of severe weather conditions and of tornadic environments.

Soundings were labeled as "severe weather" (SEV1) when the surface-based CAPE ***and*** 700-500hPa lapse rates ***and*** 0-6km bulk shear were equal to or greater than their respective 75% percentiles. Soundings were labeled as "tornadic" (TOR1) when, in addition to meeting the SEV1 criteria, also displayed 0-1km bulk shear equal to or greater than the corresponding 75% percentile ***and*** height of LCL equal to or less than the respective 25% percentile.

The results using these criteria were also compared to those employing a distinct set of thresholds, based on the well documented severe weather environments of North America. This second approach follows, approximately, the study by Brooks et al. (2003), by choosing the following thresholds for identifying the "severe weather" soundings (SEV2): surface-based CAPE ≥ 100 J/kg, 700-500hPa lapse-rate ≥ 6.5°C/km, and 0-6km bulk shear ≥ 20 m/s. For the "tornadic" soundings (TOR2) the set of additional criteria are: 0-1km bulk shear ≥ 10 m/s and height of the LCL ≤ 1500m. Naturally, these criteria are arbitrary. Nevertheless, they are used here to assess, *vis-à-vis* the first set of criteria, the effectiveness of using such method to characterize severe weather environments in SSA. This is preliminarily evaluated by checking the observed atmospheric conditions in those days when soundings were flagged as SEV1(SEV2) and TOR1(TOR2). This scrutiny includes the direct examination of the thermodynamic diagrams and satellite imagery, and the analysis of the large-scale atmospheric patterns prevailing in those occasions. To that end, data from the NCEP/NCAR Reanalysis were utilized to produce surface, 850hPa, 500hPa and 250hPa fields that are relevant to describe the synoptic conditions.

Finally, because the 00Z and 12Z soundings (00Z = 9PM and 12Z = 9AM, standard local time for southern Brazil and Argentina) are not representative of the mid-afternoon conditions — typically considered the best timing for the examination of pre-convective set-up associated with the strongest surface heating — profiles valid at 18Z (3PM standard local time) extracted from the NCEP/NCAR Reanalysis data were also studied.

3. RESULTS

3.1. Monthly and annual distribution

Figure 2 shows box-and-whiskers plots (BWP) for the monthly and annual distribution of surface-based CAPE (SBCAPE) at 12Z for SBFI, SBPA and SAEZ — for the sake of brevity we focus our analysis in these three sites. Overall, SBCAPE displays a strong annual cycle, with higher values on summer and lower magnitudes during the winter months (austral seasons). Same general behavior is observed for the 00Z soundings and the 100hPa mean layer CAPE (MLCAPE), not shown. The comparison of the

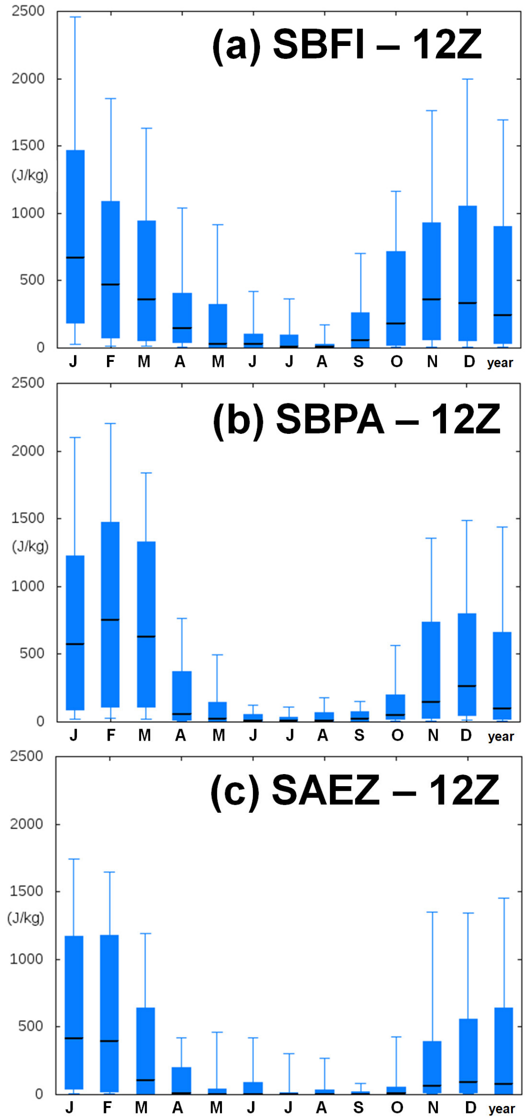

Figure 2: Box-and-whiskers plots (10%, 25%, 50%, 75%, and 90% percentiles) for the annual distribution of SBCAPE [J kg^{-1}] at 12Z for three different sites. [Note: only soundings with non-zero SBCAPE were sampled.]

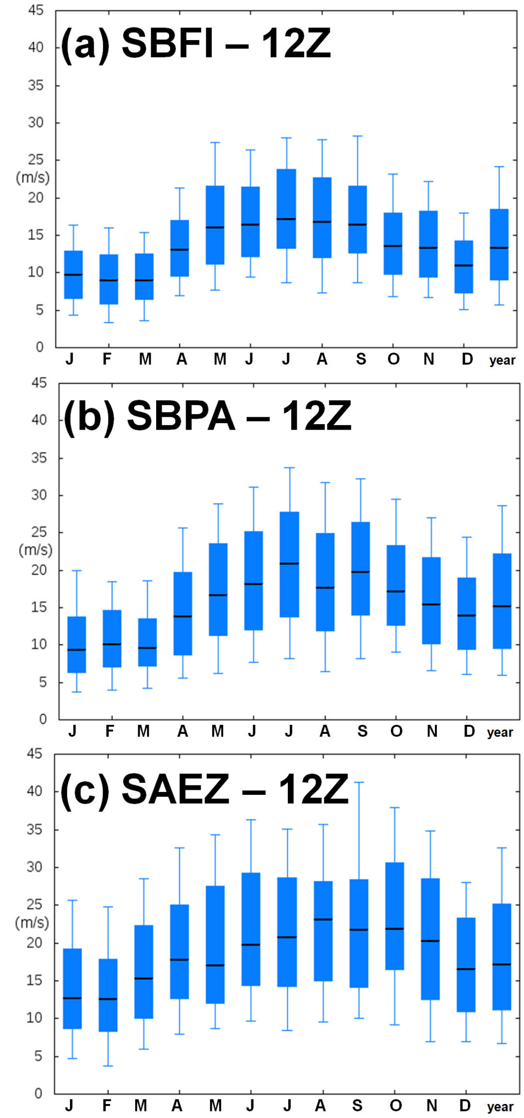

Figure 3: As in Fig. 2, but for 0-6km bulk shear [m s^{-1}].

annual SBCAPE distribution among the three sites suggests the existence of a latitudinal dependence, with lower values of SBCAPE as latitude is increased (SBFI ⇒ SBPA ⇒ SAEZ). This is consistent with the fact that SBFI is nearly 10° of latitude closer to the main source of moisture — the Amazon Basin, to the north — than SAEZ. It stands out that 10% of the non-zero SBCAPE soundings at SBFI displayed SBCAPE ≥ 1700 J kg^{-1} (last BWP in panel (a)).

The distribution of 0-6km bulk shear (DLS) is indicated in Figure 3. The annual cycle for DLS is less significant than that found for SBCAPE, but it is fairly distinguishable.

There is a general tendency to weaker DLS during the austral summer months, and enhanced DLS from autumn to spring — the same being observed for 00Z and also SBCT, SBFL and SARE, not shown. Similar result was discussed in Craven and Brooks (2004) for North America. During summer, a tropical-like atmospheric regime tends to prevail over the region, reducing the baroclinicity and, consequently, DLS. There is an indication of a latitudinal dependence for DLS as well, since SAEZ soundings reported stronger values of DLS, especially as compared to SBFI. In addition, the inter-quartile range for SAEZ was also considerably wider, characterizing an enhanced variability.

In terms of mid-level lapse rates (MLLR) (Figure 4), the seasonal dependence is the weakest of the three variables analyzed so far, especially because of the rather narrow range within which MLLR typically varies. There is, though, a hint that MLLR is stronger on the winter months — more frequent passage of extratropical cyclones over the region.

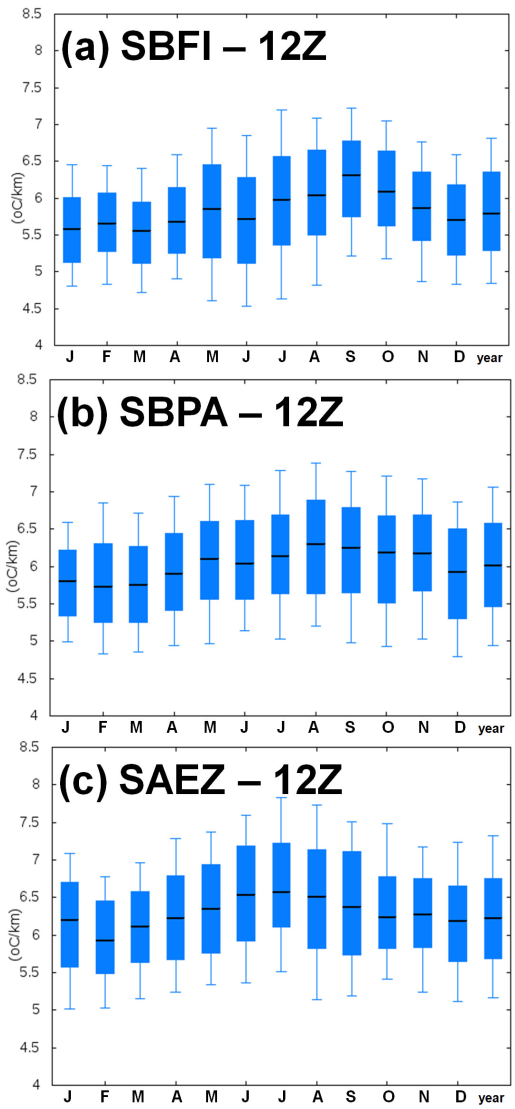

Figure 4: As in Fig. 2, but for 700-500hPa lapse rates [°C km^{-1}].

It is clear that MLLR reported in SAEZ are the highest among the three sites for almost every single month. This is not a surprise given the higher latitude of Buenos Aires.

Because the parameter space consisting of deep-layer shear and conditional instability provides, as a zeroth order approximation, a qualitative picture of the severe weather environment, we examine the scatterplots of DLS versus SBCAPE for SBPA at 12Z for distinct seasons (Fig. 5). Overall, the analysis of the four panels highlights a seasonal migration between two extremes: from the high CAPE and low DLS summer environment (Fig. 5a) to the low CAPE and high DLS winter conditions (Fig. 5c). This is also found for the remaining five sites (and at 00Z as well), not shown.

Note, for example, that during winter at SBPA (Fig. 5c) none of the sampled 12Z soundings “visited” the upper right portion of the parameter space where SBCAPE ***and*** DLS are above their respective 75% percentiles (represented by the straight lines), mainly because of the relatively low values of SBCAPE. [However, the sample size (307) amounts for less than 30% of the total number of days that comprises the set of 12 winters: 1104]. During summer (Fig. 5a), on the other hand, a considerable number of soundings displayed SBCAPE above the 75% percentile. Among these, roughly 35 also displayed DLS above its 75% percentile. [Note: these are the 75% percentiles computed from the full set of data for the six sounding sites].

As expected, during the transition seasons (autumn and spring; Figs. 5b and 5d), moderate to high values of SBCAPE and DLS were found, with the data points spreading more evenly in both DLS and SBCAPE ranges.

The general behavior described above is in agreement with the well known intra-annual atmospheric variability in SSA regarding low-level moisture availability (stronger during the tropical-like summer months) and activity of baroclinic systems (more frequent during the mid-latitude-like winter months) (Marengo et al. 2004; Cavalcanti and Kousky 2009).

The SBCAPE vs. DLS analysis above has some theoretical implications to the climatology of severe thunderstorm activity in SSA: while high CAPE *and* high shear environments can occur during summer, it is during the transition seasons (spring and autumn) that stronger chances for simultaneous occurrence of moderate values of CAPE *and* shear exist. Is there any observational evidence that severe thunderstorms are more frequent during spring and/or autumn over SSA? Results from recent studies based on media and Civil Defense reports of hail and damaging winds indicate the trimester from September to November (late winter to mid-spring) as the period

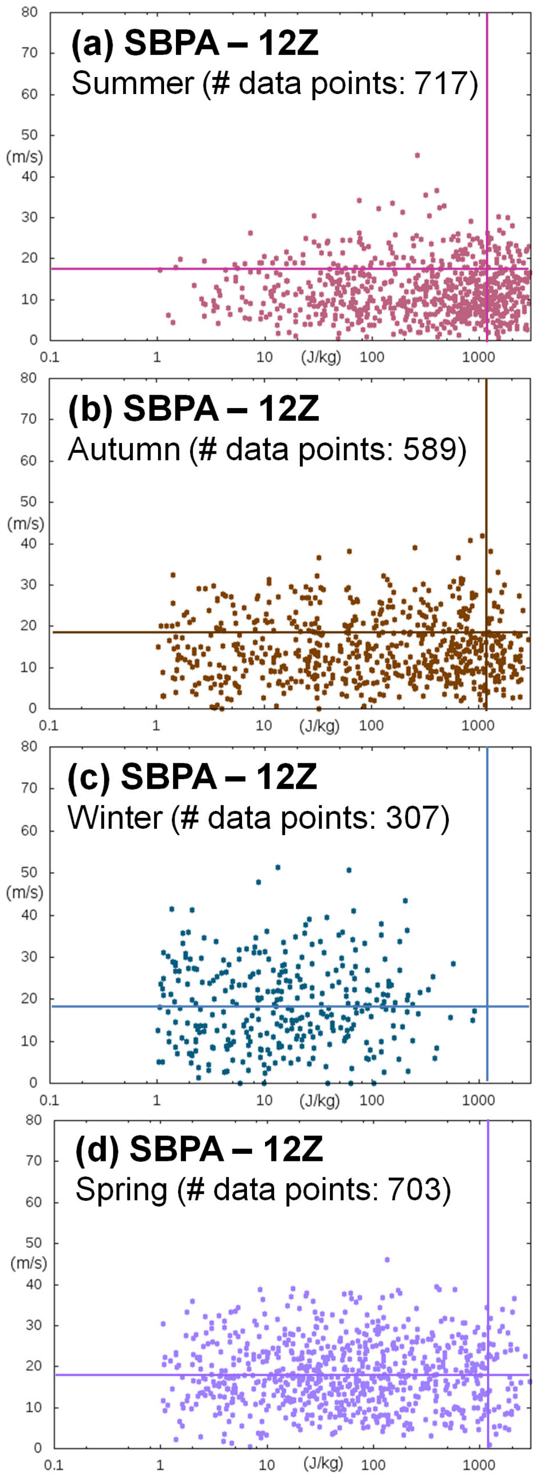

Figure 5: Scatterplots for 0-6km bulk shear [m s^{-1}] vs. SBCAPE [J kg^{-1}] for SBPA in distinct seasons. Vertical [Horizontal] straight lines indicate the 75% percentile for SBCAPE [DLS] as determined from the full sample of six sounding sites. (Only soundings with non-zero SBCAPE are included in the scatterplots).

with most frequent occurrence of large hail and damaging winds in southern Brazil (Reckziegel 2007). Sanchez et al. (2008) found, for central Argentina just east of the Andes, that severe thunderstorms (as defined by the ones with radar reflectivity above 55dBz) are most frequent during summer. However that region is far upstream from the geographical domain studied here (Fig. 1). Further north in the domain, over São Paulo state (just north of SBCT in Fig. 1), tornadoes have been reported during autumn (Nascimento and Marcelino, 2006; Antonio et al. 2005), but an improved documentation of the climatology of severe thunderstorms is still necessary to draw a better picture of autumn storms in that part of the world. Finally, it should be mentioned that during winter months a few tornadic events occurred under strong shear and low CAPE environments in the highlands of Rio Grande do Sul state (extreme southern Brazil). Further investigation on those environments is currently being carried out.

Regarding the remaining variables (not shown), most of them displayed a seasonal variability, except for the 0-1km bulk shear for which no seasonal dependence was distinguished.

3.2. Theoretical categorization of "severe weather" and "tornadic" soundings.

Following the methodology described in Section 2, an attempt to objectively characterize the profiles as susceptive to severe weather (SEV) and tornadoes (TOR) was conducted. Table 2 indicates the 75% percentiles for the variables employed to carry out this task — for the height of the LCL it is the 25% percentile. These figures represent threshold values above which SBCAPE, DLS and MLLR are utilized to categorize the SEV1 soundings, and the lower [upper] limit for 0-1km bulk shear [height of the LCL] to categorize the TOR1 soundings. Table 1 also compares these "South American thresholds" with those used to characterize SEV2 and TOR2 soundings which are roughly based on Brooks et al. (2003) (see their Table 1).

Worth of notice are the differences between the thresholds used for SBCAPE and height of the LCL between SEV1 and SEV2 and TOR1 and TOR2, respectively. For SBCAPE the difference clearly occurs because Brooks et al. (2003) chose a minimum value of CAPE for which deep convection can still be sustained — since severe thunderstorms can also occur under low-CAPE environments. Conversely, our SEV1 criteria to sample severe weather-prone profiles follow an approach where the thresholds are based on extreme values extracted from the full dataset.

Table 2: Threshold values of convective parameters used to objectively categorize soundings from SSA. SEV1 and TOR1 are based on the 75% percentiles considering the entire 00Z *and* 12Z dataset from the six sites (25% percentile for height of the LCL).

Variable	Threshold values for SEV1, TOR1	Threshold values for SEV2, TOR2
CAPE (surface based)	≥ 1230 J Kg^{-1}	≥ 100 J Kg^{-1}
700-500hPa lapse rate	> 6.2 °C km^{-1}	> 6.5 °C km^{-1}
0-6km bulk shear	≥ 18 m s^{-1}	≥ 20 m s^{-1}
0-1km bulk shear	≥ 6 m s^{-1}	≥ 10 m s^{-1}
Height of the LCL	≤ 300 m	≤ 1500 m

The height of the LCL typically found in SSA is considerably low (its median value being 540m). We believe that this finding is, to a large extent, influenced by the local time at which the soundings are performed. During early morning (12Z) the dew point depression tend to be much less than during mid-afternoon hours (which is the most frequent pre-convective timing), leading to lower LCLs than those reported in other parts of the world at distinct local times, such as North America. Ongoing analysis is addressing the LCL topic in more detail.

From Table 1 it is also evident that high values of MLLR (say, above 7 °C km^{-1}) are less often observed in SSA than in North America (see, for example, Fig. 4). In fact, the 90% percentile of MLLR for SSA is 6.7 °C km^{-1}. Nevertheless, it will be shown later that for some locals, at 18Z, a higher 75% percentile is found for MLLR (as extracted from Reanalysis data).

A total of 121 profiles were classified as SEV1 (roughly 0.5% of the soundings), and only 5 profiles as TOR1. In contrast, using the SEV2 criteria we found a total number of 315 "severe weather" profiles (around 13% of the total number of soundings), while for TOR2 criteria this number is 27 (around 0.1%). It is clear, then, that SEV1 and TOR1 represent more stringent classes because of the very high threshold of SBCAPE and very low threshold for the LCL.

Naturally, one very relevant question to be addressed is how well the criteria summarized in Table 2 detect atmospheric profiles that effectively lead to severe thunderstorms in SSA. It is one of the main goals of the ongoing research to estimate the probability of detection and false alarm ratio associated with such approach. In this context, one has to bear in mind that the presence of conditional instability, moisture and vertical wind shear are necessary but not sufficient conditions for severe convection (e.g., Brooks 2007).

Thus far, the basic questions that have been addressed are: do the profiles flagged as SEV1 and SEV2 show any resemblance of what is typically considered a proximity sounding for severe thunderstorms? Have we extracted any "loaded-gun sounding" from the SEV1 or SEV2 criteria? What are the large-scale atmospheric patterns in SSA associated with the SEV 1 or SEV2 profiles?

Figure 6 shows skew-t diagrams for two examples of (springtime) profiles that fall in both SEV1 ***and*** SEV2 categories.

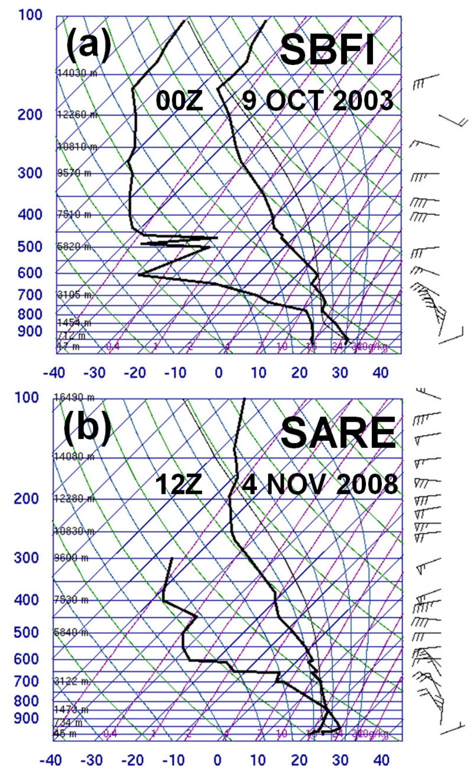

Figure 6: Skew-T diagrams for two soundings flagged as both SEV1 and SEV2. (Diagrams extracted from www.weather.uwyo.edu/upperair/sounding.html).

Interestingly, the first sounding, from Foz do Iguassu, is the same one studied in Nascimento (2004) (see his Fig. 8), for which there is radar and ground confirmation of severe thunderstorms occurring hours later. The second one, from Resistencia, is a morning sounding; one can notice an inversion close to the surface. In both soundings the MLLR is intense, particularly for SBFI, and the vertical wind profiles are clearly indicative of an environment that favors severe thunderstorms (intense DLS with the vertical wind shear vector strongly changing direction with height) — see, for example, Nascimento (2004) for the plot of the hodograph for this SBFI sounding.

Naturally, the two profiles in Figure 6 do display some clear-cut characteristics of severe weather soundings. However, not all soundings classified as SEV1 or SEV2 were “well-behaved” like that, indicating potential shortcomings in the approach tested here, which will be explored more deeply as this investigation continues (and to be discussed at the Conference).

3.3. Synoptic-scale patterns: a first look.

To *assess* the prevailing large-scale atmospheric pattern associated with the SEV soundings, composite (averaged) fields for several atmospheric variables at distinct levels were elaborated utilizing data from NCAR-NCEP Reanalysis. A moving domain of fixed size was set in such a way that the sounding sites were positioned at its center. The atmospheric fields extracted from the SEV2 (and SEV1) samples for each site where then averaged for this domain; hence, the composite fields obtained refer to a reference frame in which the sounding sites are located at the center. For sake of brevity, Figure 7 shows only the results obtained from the SEV1 sample for surface and 850hPa fields.

The surface composite field for SEV1 (Fig. 7a) displays a col-type pattern in the MSLP, with the col center roughly 8° of latitude south of the sounding site. The sounding location is placed, in average, just east of an inverted trough with winds blowing from the northeast; i.e., veered surface winds, as expected for a severe-weather prone environment in the Southern Hemisphere. The inverted trough in the averaged MSLP field in fact represents the low pressure system which is commonly observed over northern-northeastern Argentina or Paraguay (Seluchi et al. 2006) and often present in the South American severe weather scenario (e.g., Foss and Nascimento, 2010). The second trough forming the col pattern is located further south and is typically associated with a migratory extratropical system responsible for the main synoptic forcing.

In clear contrast with what is usually observed over the Central Plains of North America (under strong synoptic forcing), the evident severe weather environment in SSA is not established very close to the surface extratropical cyclone, but further north way inside the warm sector and next to a quasi-stationary inverted trough. Because surface cyclogenesis over the La Plata Basin (on SSA) climatologically occurs very close to or over

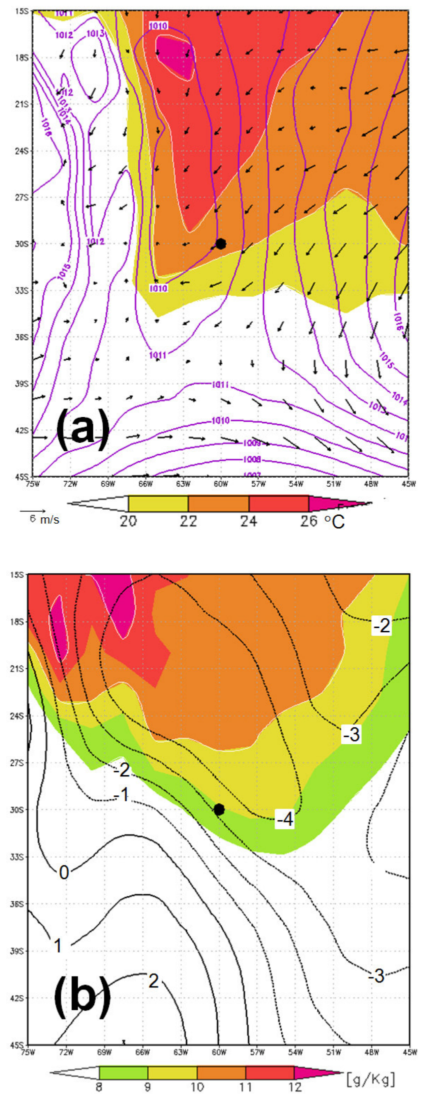

Figure 7: Composite fields for the SEV1 sample for a moving domain in which the sounding sites are located at the center (black circle). (a) mean sea-level pressure (contours; hPa), air temperature at 2m (shading; °C), and 10m-winds (vectors; m/s); (b) 850hPa mixing ratio (shading; g/kg) and meridional component of the wind (contours; m/s). NCEP-NCAR Reanalysis data were used. Latitude and longitude are indicated just to provide information about the size of the domain.

the Atlantic Ocean (see Gan and Rao 1991), a significant portion of the warm sector, as well as the accompanying warm front, are positioned over the ocean.

Nearly all severe weather episodes over SSA occur just ahead of (or along) either the surface cold front or the surface inverted trough, or on both; this is farther away from the extratropical cyclone than what is normally found over the Central Plains of North America (e.g., Johns 1993; his Fig.5) This statement is also corroborated by the composite 500hPa geopotential height fields (not shown) that depict a rather weak trough over the domain as a whole, but becoming better defined over the southern boundary of the domain, where the migratory synoptic system is effectively positioned.

In the authors´ experience analyzing a large number of (actual) severe weather episodes over SSA the col pattern is a frequent observation (e.g., Foss and Nascimento, 2010).

At 850hPa the composite meridional wind field (Fig. 7b) indicates the strong shift in the wind direction (just south of the sounding location) separating the cold and dry air mass to the south from the warm and moist sector to the north and northeast. The 850hPa height field (not shown) displays a trough along this wind shift. These features indicate the presence of low-level convergence within a fairly baroclinic region, which might represent the mechanism that will corroborate to initiate deep convection.

Results obtained from the composite fields generated from the SEV2 data sample display a synoptic pattern in very close agreement with that shown in Figure 7.

3.4. Analysis at 18Z.

One final question to be addressed is: would our results change significantly if we had available the 18Z soundings (3PM local standard time)? To assess that, again NCEP-NCAR Reanalysis data were used. Results will be shown during the presentation.

4. SUMMARY AND FINAL REMARKS

This ongoing work aims at examining the South American severe thunderstorm environment based upon a 12-yr climatology of severe weather parameters and upon the synoptic-scale patterns that prevail when these parameters reach extreme values (as determined statistically). A critical examination of the results is performed to evaluate if the statistically-based methodology employed can provide relevant information regarding severe weather conditions in SSA that is physically sound.

The discussion addresses the monthly and annual distribution of the convective parameters over SSA, and its implications to severe weather susceptibility in distinct seasons. In addition, two different approaches to objectively categorize the South American atmospheric profiles in terms of severe weather proneness are investigated. It is found that the objective criteria used to realize such categorization are capable of highlighting profiles that show classic features of severe weather environments; however, there are apparent and important shortcomings regarding high false alarm ratio in such categorization that require further investigation.

There are also strong evidences that, despite sharing several characteristics in common, the South- and North-American severe weather environment also display important distinctions regarding: (a) the magnitude of severe weather parameters; (b) the sectors, within synoptic systems, where the effective development of severe thunderstorms is favored.

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