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Temperature extremes in the south of South America in relation to Atlantic Ocean surface temperature and Southern Hemisphere circulation

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[1] The objective of this research is to study the main variability modes of the frequency of extreme temperatures in the south of South America, their relation to sea surface temperatures (SSTs), and some indices of atmospheric circulation in the Southern Hemisphere. Observational data and reanalysis data were used for this purpose over the 1964–2003 period. An initial analysis showed that between the months of March and June, the frequency of warm events (especially warm nights) is highly associated with the SST in coastal zones. A wavelet analysis showed that the main variability mode found at a seasonal scale was an 8-year wave signal present in spring that remains active until the 1990s; it was noticeable in the analysis of cold nights, Atlantic SSTs, Pacific SSTs, and the Southern Annular Mode (SAM). A cross-wavelet analysis among them reflected this signal as a common variability mode, with the positive phase of the SAM congruent with the warmest conditions in the coastal zones of the Atlantic Ocean and lower cases with cold nights at the reference meteorological stations analyzed. Although longer series are desirable for low-frequency variability analysis, the results agree with previous studies that take into account an 8-year periodicity of the baroclinic waves at the Southern Hemisphere, supporting the relevance of the 8-year signal.

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1. Introduction

[2] In the last years experts have become especially interested in studying and understanding the extreme events within the climate system. This entails that they have to face specific difficulties different from those encountered when studying average values, whether because of issues related to the values to be analyzed (the problem of the outliers becomes crucial since special care must be taken when accepting a certain value or not) or because of the distribution related to the variable to be studied, which requires special statistical tools in order to be dealt with since it differs from a normal distribution in many cases. When studying the extreme values in the Southern Hemisphere, in South America, to be more precise, there is an additional difficulty: the availability of information, which is much more restricted than in the Northern Hemisphere.

[3] A few years ago, due to the joint effort made by the scientific community from different countries, several workshops were held to collect climatological information on a daily basis; the objective was to carry out a strict quality control and to generate indices that could be used to analyze extreme events. These meetings were coordinated by the Team on Climate Change Detection, Monitoring and Indices (ETCCDMI), a group established by the World Meteorological Organization that developed a comprehensive list of indices meaningful over continental to global regions [*Karl et al.*, 1999; *Peterson et al.*, 2001]. One of the meetings dealt with the analysis of trends to extreme temperatures in South America [*Vincent et al.*, 2005]. According to this analysis, the indices of minimum temperature showed the highest variation in the 1960–2000 period, with an increase in the percentage of warm nights and a decrease in the percentage of cold nights in many of the stations studied.

[4] This study deals with the indices of extreme temperatures analyzing different variability scales of the series and trying to see where they are related to other climate indices. Special attention is paid to the South Atlantic Ocean (SAO) and to the Southern Annular Mode (SAM).

[5] Among the first reference on the SAO variability, mention should be made to *Venegas et al.* [1996, 1997, 1998] that find interdecadal fluctuations within the ocean-atmosphere system. They suggest that the dominant physical processes involve the horizontal heat advection by ocean currents and changes in the flows of ocean-atmosphere heat through local air-sea interactions. *Moron et al.* [1998] studied the interdecadal and interannual trends and oscillations of the surface sea temperature around the world

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using multichannel singular-spectrum analysis techniques. In this research special attention is given to the Atlantic Ocean, in which it is possible to find different significant signals. In the case of the SAO in particular, it has been possible to find a quasi-decadal oscillation (important but less intense than that found in North Atlantic Ocean), quasi-biennial and interannual low-frequency oscillations with peaks in 63–65 months, 39–43 months and 44 months (obtained with different windows). Another signal they stressed, although considered to be weaker, is centered at the 28–30 month band and is consistent with an internal ENSO-like oscillation in the equatorial Atlantic found by *Latif et al.* [1996] and *Latif and Grötzner* [2000]. This oscillation has a quasi-biennial timescale and is strongly influenced by the Pacific ENSO with the equatorial Atlantic SST lagging by about six month. *Latif and Grötzner* [2000] argue that this lag can be explained by the dynamical adjustment time of the equatorial Atlantic to low-frequency wind stress variations and the seasonally varying background state, which favors strongest growth of perturbations in summer.

[6] More recently, *Sterl and Hazeleger* [2003] published a study on air-sea variability and interaction in SAO. They use NCEP/NCAR reanalysis data (period 1949–2000) and empirical orthogonal functions (EOF) and singular value decomposition (SVD). They find out that the principal air-sea variability mode consists of a SST dipole that resembles a plane inclined from the northeast toward the southwest and a pattern of sea level pressure affecting the predominant winds from the west at 35°S approximately. They do not find any relation between the SAO and North Atlantic Oscillation (NAO) and they state that the relation with the ENSO is very weak. They also add that the main mechanism to generate SST anomalies at large scale could be associated with the atmospheric variability.

[7] Other authors suggest that the Atlantic variability (and SAO in particular) is related to the variability in other regions. This is the case of *Xie and Tanimoto* [1998] and *Tanimoto and Xie* [2002], who suggest that the decadal variability modes of the subtropical and South Atlantic are part of a coherent Pan-Atlantic Decadal Oscillation (PADO). This oscillation is characterized by zonal bands of SST and wind anomalies stacked in the meridional direction with alternate polarities from the South Atlantic all the way to Greenland [*Xie and Tanimoto*, 1998]. *Robertson et al.* [2000], by means of simulations, found significant correlations between anomalies from the tropical and subtropical Atlantic with the NAO.

[8] *Barreiro et al.* [2002] studied the relation between the South Atlantic SSTs and the SACZ through general circulation atmospheric models, and they found out that the SSTs affect the SACZ intensity and position, so positive anomalies would increase its intensity. Anyway, the processes are still not completely clear. Research by *Chaves and Nobre* [2004] shows that in a case of intense SACZ, the increase in cloudiness would decrease the incoming solar radiation and it suggests that the negative SST's anomalies would be the result rather than the cause of the SACZ intensification. Other aspects related to the SACZ and the South American climate are discussed by *Liebmann et al.* [1999], *Carvalho et al.* [2004], and *Nobre et al.* [2006], among others.

[9] Regarding the studies on surface temperature variability in the south of South America and its relation with the atmospheric circulation, reference should be made to *Minetti and Vargas* [1983], who analyze the characteristics of the 1950s, an unusually cold decade, and relate them to a north displacement of the Pacific anticyclone regarding its climatological position. Other studies analyze the influence of the ENSO event on the temperatures of the region. *Halpert and Ropelewski* [1992] find positive anomalies between May and April during El Niño years over the south of Brazil, Paraguay, east of Bolivia and north of Argentina and negative anomalies associated with La Niña over a similar region, but which is extended a little further to the south. *Barros et al.* [2002] also analyze the ENSO phases in relation to the temperatures. They find positive anomalies over the center and north of Argentina during El Niño years which they associate with an increase in the warm advection at low levels. The authors describe an opposite situation for La Niña years, although with a spatial extension reaching higher latitudes. They also analyze the influence of the intensity and displacement of the subtropical jet, finding out that the intensification (reduction) of the west component of the wind in the upper troposphere over South American subtropical latitudes and the north (south) displacement of the wind maximum tend to be associated with cold (warm) surface anomalies practically all year-round in Southern South America.

[10] This study deals with the temporal variability of extreme temperatures in Argentina. Previous works analyzed trends of the variable or indices related with the frequencies of extreme temperature, but the temporal variability is quite complex. Climate series may exhibit jumps, periodic and quasiperiodic events that do not necessarily last over long periods but are present for a sequence of years and then disappear or remain as weak signals in the system. In this work these signals (at multiples scales) are analyzed in extreme temperature indices using a wavelet transform [*Torrence and Compo*, 1998]. Other climate indices such as SSTs, circulation indices and the Southern Annular Mode are examined in order to capture coherent patterns, with common variability modes physically consistent. Cross wavelets were used for this purpose [*Grinsted et al.*, 2004]. All these features are discussed in the following sections. In section 2 the data and methodology used in this study are described. The findings from the exploratory analysis on indices of extreme temperatures and the sea surface temperature are presented in section 3. Sections 4 and 5 deal with different variability scales of the indices studied at a seasonal scale for the series of frequency of extreme temperatures on surface and sea surface temperature respectively, seeking common variability modes. Further climate system characteristics are studied by means of circulation indices in section 6 in order to explain the causes of variability seen in the series studied before. Finally, the discussion and conclusions of the study are presented in section 7.

2. Data and Methodology

[11] This study considers indices representing frequencies of extreme temperatures, surface temperature of ocean zones and some atmospheric circulation characteristics. These indices are based on observed data (in the case of

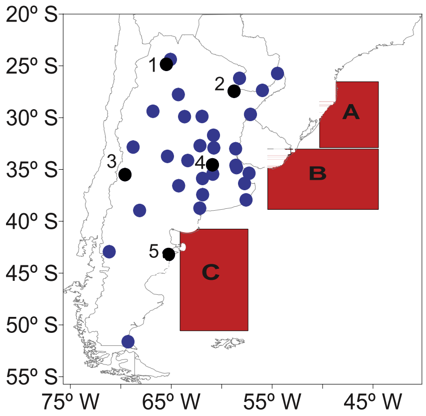


Figure 1. Stations used in the study (some reference stations are highlighted). The rectangles represent ocean zones in which the sea surface temperatures (SSTs) were averaged.

extreme temperatures and one of the circulation indices) and on NCEP/NCAR data set [*Kalnay et al.*, 1996] in the case of sea surface temperature and zonal and meridional flows at different latitudes and heights.

[12] The extreme temperatures indices were obtained by taking into consideration a database of daily maximum and minimum temperatures of 40 stations all over Argentina (Figure 1), which have been subjected to a quality control for the 1959–1998 period [*Rusticucci and Barrucand*, 2001] and then extended up to 2003. Taking this information into account, 4 indices of extreme temperatures were generated: (1) TN10 ("cold nights"): percentage of days with minimum temperatures lower than the 10th percentile, (2) TN90 ("warm nights"): percentage of days with minimum temperatures higher than the 90th percentile, (3) TX10 ("cold days"): percentage of days with maximum temperatures lower than the 10th percentile, and (4) TX90 ("warm days"): percentage of days with maximum temperatures higher than the 90th percentile.

[13] The indices, calculated for each month and each year, are defined following the ETCCDMI's recommendations, are consistent with those used in the study by *Vincent et al.* [2005] and are similar to the indices used in studies about other regions: Australia [*Collins et al.*, 2000], New Zealand [*Plummer et al.*, 1999], British Isles [*Jones et al.*, 1999], Turkey [*Sensoy et al.*, 2007], Europe [*Klein Tank and Können*, 2003], and Asia [*Klein Tank et al.*, 2006]. The same indices are given by *Alexander et al.* [2006] and *Aguilar et al.* [2005]. The percentiles used were calculated for the 1961–1990 reference period. They are defined on a daily basis, with a 5-day window centered on each calendar day.

[14] For the exploratory study using SST a monthly scale analysis was performed, only for the 1979–2003 period since it shows the most reliable data as they derive from satellite information [*Kistler et al.*, 2001]. In the subsequent analysis on the different variability scales, the period was extended to previous years (data from 1964 onward were considered) but only the seasonal averages were taken into consideration.

[15] On the basis of the results from *Rusticucci et al.* [2003] that find the Atlantic zones of highest correlation with the seasonal temperature from several stations of Argentina, three Atlantic Ocean "boxes" were considered (Figure 1), with a width between 5° and 12° longitude and 6° and 10° latitude: they are centered at approximately 30°S–48°W (SST30), 36°S–50°W (SST36) and 46°S–62°W (SST46). When choosing the boxes, the influence of the Brazil and Falklands current and the confluence between both respectively was also taken into account [*Schmitz*, 1996, and references therein]. This first approach to the relation between the occurrence of extreme temperatures and SSTs at a monthly scale was calculated for the simultaneous occurrence (lag = 0).

[16] The relations between the temperature indices and the ocean zones were evaluated through the spearman correlation coefficient in the initial stage. Then, the wavelet transform was applied to study the different variability scales of the different series and the cross-wavelet was calculated to analyze the common variability modes (adapted from *Grinsted et al.* [2004]). This methodology was applied to some stations (see Table 1) that were selected according to the homogeneity results previously found [*Barrucand et al.*, 2006] and the "quality" of the series, considering those that did not show any missing data (stations are indicated in Figure 1). At this stage of the study the indices of extremes at a seasonal scale were considered, taking into account summer (December-January-February), autumn (March-April-May), winter (June-July-August), and spring (September-October-November). The period considered was 1964–2003 since the previous years showed a higher number of missing data.

[17] Finally, some aspects of the atmospheric circulation were studied such as the zonal wind at 200 hPa, the Southern Annular Mode (SAM), the Pacific Decadal Oscillation (PDO) and subtropical south central Pacific SSTs, to explore the potential predictability of the extreme temperatures in Argentina. The zonal wind was analyzed through two local circulation indices which were defined as the zonal wind at 200 hPa averaged over 20°S to 30°S and 45°W to 65°W (u_1) and 30°S to 40°S and 45°W to 65°W (u_2). The difference $u_1 - u_2$ and the quotient u_1/u_2 were also considered in order to analyze the position and intensity of the subtropical jet.

3. Temperature Indices Versus Sea Surface Temperature (SST): An Exploratory Analysis

[18] Most of the studies dealing with the relation between surface temperatures and sea surface temperatures are mainly oriented to analyzing the influence of ENSO events.

Table 1. Selected Stations at Different Regions of the Country[a]

Station	Name	Latitude (°S)	Longitude (°W)	H (m)
87047	Salta	24°51′	65°29′	1221
87166	Corrientes	27°27′	58°46′	62
87506	Malargüe	35°30′	69°35′	1425
87548	Junín	34°33′	60°55′	87
87828	Trelew	43°12′	65°16′	43

[a] The numbers in the station column correspond to World Meteorological Organization classifications. Latitude, longitude, and height (H) are indicated.

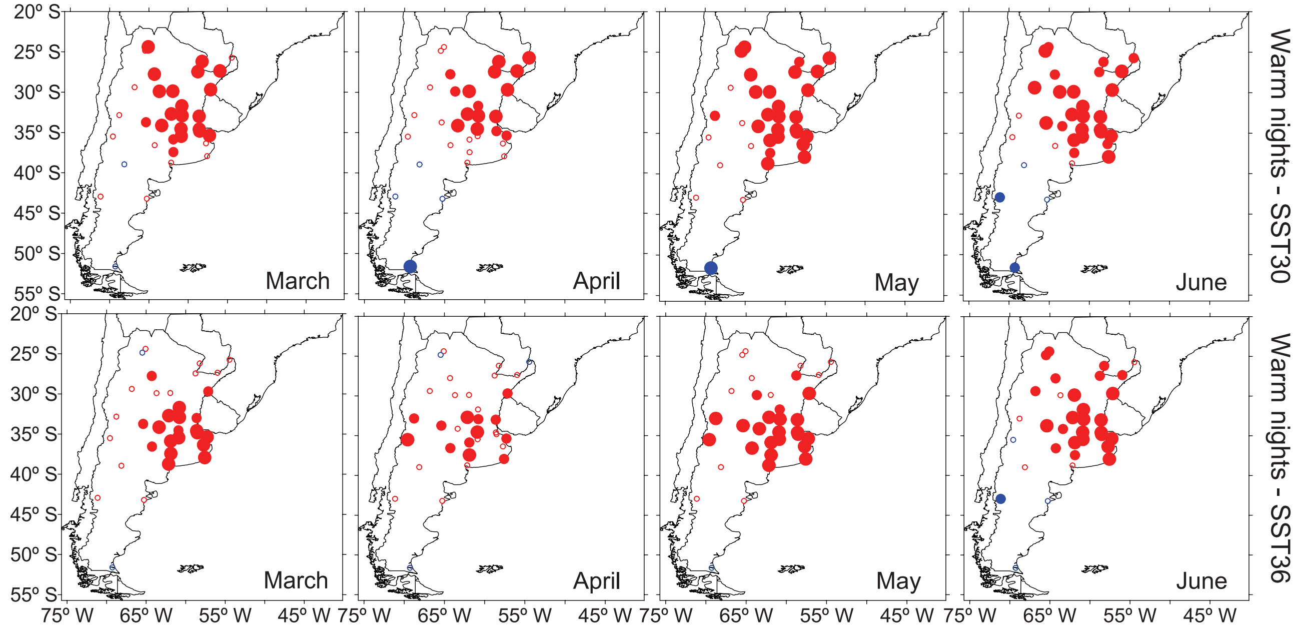


Figure 2. Correlations between warm nights and (top) SST30 and (bottom) SST36. Positive (negative) correlation values are indicated in red (blue). Full large (medium) circles correspond to significant values at 5% (10%). Small circles correspond to not significant values.

As mentioned before, *Barros et al.* [2002] showed that the temperature of the center and north of Argentina is correlated with the El Niño and La Niña events from June to August. However, they fail to find any significant correlations for the rest of the months. *Rusticucci and Vargas* [2002] study the probability of occurrence of a temperature extreme event given the ENSO phases. This study finds out that among the different occurrences of El Niño, the response is less homogeneous than among the different occurrences of La Niña. In this last case, months with extremely cold temperatures are more frequent. However, in a later study [*Rusticucci et al.*, 2003] it is possible to see that, except for spring, the ENSO signal is not the main variability mode of temperature extremes in Argentina, but the Atlantic Ocean. This reflects the importance of the orographic barrier of the Andes Mountains in driving the regional atmospheric circulation. On the basis of the results mentioned above, the relation between the Atlantic SSTs and the extreme temperature indices was analyzed but at a monthly scale, considering the ocean zones where previous studies had shown the highest degree of association. With this analysis, two aspects were investigated: (1) Can a monthly analysis improve significantly the results of the seasonal analysis? Is the seasonal relationship due to a specific month? and (2) Which extreme is more sensitive to SST variability? Four indices are analyzed in this paper, considering warm and cold nights and days instead of mean conditions of warm and cold cases as *Rusticucci et al.* [2003].

[19] Each of the ocean series was correlated with the series of extreme temperature indices of all meteorological stations. Although it was expected to see coincidences in the degree of association between the series of extreme frequencies and SST30 and SST36 (SSTs series are correlated), it was possible to observe some significant differences in the results.

[20] In general terms, the strongest relation between SSTs and the extreme temperatures was observed at warm night's frequency. It is particularly noticeable in the Humid Pampa (center to east of Argentina) and in the Argentine northeast. From March to June it is possible to see the highest number of stations with significant positive correlations (Figure 2). There is a meridional displacement of the significant correlation zone following the latitude of the ocean zone considered. It is possible to find Argentine north and northeast stations correlated with SST30 (Figure 2 (top)) while those correlated with SST36 are located further south (Figure 2 (bottom)). A similar relation was found for warm days, but the number of significant stations in this case turned out to be much lower.

[21] The southern SST box (SST46) exhibit a direct association with warm nights of Patagonian stations (south of Argentina) all year-round, although this association is not always significant.

[22] The association between SSTs and the frequency of cold events turned out to be lower than that found for warm events. It is possible to see inverse relations between SST30 cold nights and SST36 cold nights at some isolated months of the extended warm season (September to March), especially at center east and northeast zones. The relation with the frequency of cold days turned out to be even less significant. Regarding the association with the southern ocean zone (SST46), it is possible to see significant inverse relations with cold nights and days in stations close to the coast during the extended warm season.

[23] Correlations with lag between 1 and 3 months made it possible to explore some SST characteristics as temperature extreme predictors. This analysis showed a higher

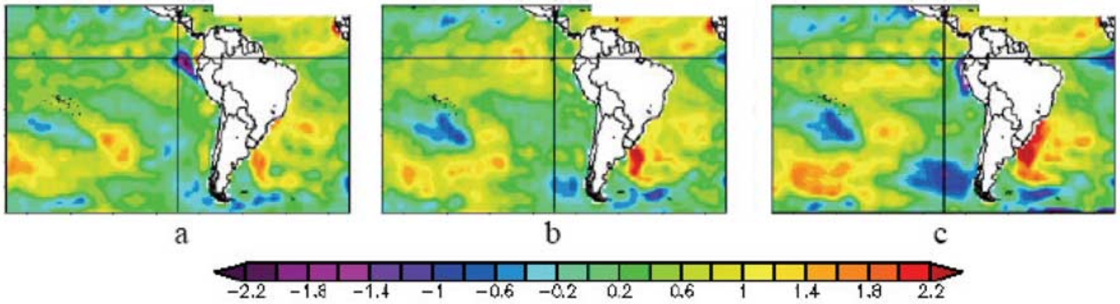


Figure 3. Example of an anomalous warm autumn. SST anomalies for (a) April, (b) May, and (c) June. Year is 2005.

variability of significant results depending on the variable, month and zone of the Atlantic analyzed. The most relevant results correspond to a positive association between warm nights of the Humid Pampa region and the SST36 for May and June, with a 1- and 2-month lag, respectively (not shown). This means that the April SST36 could be a relevant predictor of the frequency of warm extremes in this zone for the two subsequent months.

[24] It should be highlighted that in all the cases in which significant relations between the SSTs and extreme temperatures were found, it was possible to see a special area of influence: Humid Pampa and northeast, a zone that sometimes extended toward the center and north of Argentina (never to the south). The monthly analysis did not improve significantly previous results with one exception. June, previously classified as winter month, has an ''autumn-like'' association pattern. Autumn months appear to be linked to frequencies of warm events at northeast and center east of Argentina up to 2-month lag. Figure 3 shows such one example of an anomalous ''warm June'' out of the studied period having this characteristic association. This month and the two previous ones exhibit positive anomalies over South Atlantic. It is interesting to observe that a negative anomaly at the subtropical south central Pacific (SSCP) prevails in the three months. This zone was studied by *Barros and Silvestri* [2002] in relation to the atmospheric circulation and rainfall variability over Southeastern South America (SSA). They showed that SSTs in the equatorial regions do not modulate rainfall variability among different El Niño years or among different La Niña years. In contrast, among El Niño events, SSTs in SSCP modulate the seasonal rainfall over most of SSA. In the next sections, these results will be taken into account when different climate indices were studied in relation to extreme temperatures variability modes.

4. Different Variability Modes of Extreme Temperature Frequencies

[25] The study of the linear trend of the maximum temperature series and the frequency of extreme events [*Rusticucci and Barrucand*, 2004] made it possible to make a first approach to study the variability in low frequency of those series. In the present research, other variability modes are studied. In order to detect them, the wavelet transform was applied to the 5 reference series mentioned in section 2. This study presents the results at a seasonal scale, considering separately the four seasons of the year for the 1964–2003 period. Having one datum per year, the data series is reduced in size and the border effect is enhanced. It is, however, possible to see several clear dominant signals.

4.1. Signals at the Frequency of Cold Extremes

[26] Summer was the most affected season concerning the decrease of ''cold nights,'' especially in the 1964–1979 period. This characteristic was clearly shown in the wavelet results together with the 4-year signal at many stations (not shown). Significant signals in the 2- to 4-year band are present in many stations in autumn, mainly in the first years. Trelew station is the exception. This signal is observed in the last years, together with an increase in the number of cold days in that station. A quasi-decadal significant signal (near 8 years) is present at center east stations too. During winter, the only significant signal that can be mentioned is a 4-year signal in many stations in the center and north of Argentina, especially during the 1980s (not shown). Finally, the spring season appeared with a marked 8-year signal at all stations (Figure 4). A near-4-year signal is present too as a secondary variability mode. This season will be especially analyzed later.

[27] Regarding the frequency of cold days, two signals can be observed at all the stations studied with no preferred occurrence period. They are centered at 10 years and 2–4 years. The last one is clearly observed during summer. In autumn this signal is present at the northern stations while the center stations are affected by temporal waves longer than 4 years. The other seasons (winter and spring) are principally affected by a decadal signal.

4.2. Signals at the Frequency of Warm Extremes

[28] The 2- to 4-year signals are present at all the stations studied for the warm nights index. The center and north ones were affected by a positive trend during the last years. On the other hand, Trelew had a negative trend. No pattern can be found in the summer and autumn series. A 2- to 4-year signal is present in winter and spring was affected by signals of 4–8 years. The last one is not as strong as the 8-year signal found at TN10 series, but it is present at many stations (e.g., Corrientes Aero; Figure 5).

[29] The series of warm days are mainly characterized by two signals: one in the 2- to 4-year band, and the other around 8 years. Summer, autumn and spring reflect a similar

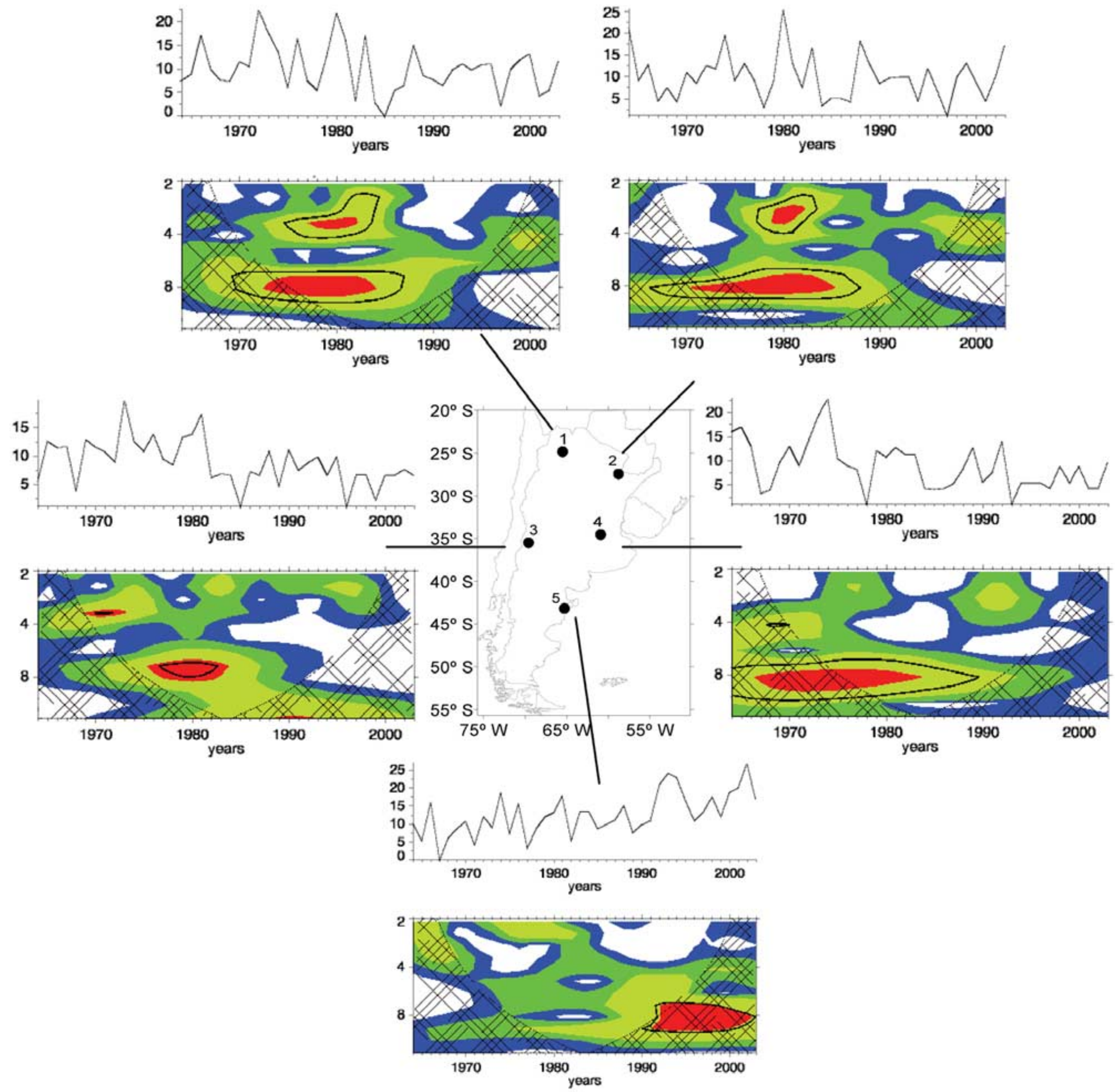


Figure 4. Cold nights (spring) time series used for the wavelet analysis (% cold nights versus time (years)) and the local wavelet power spectrum (period (years) versus time (years)) for the selected stations. Contour levels are chosen so that wavelet power is above the 25th percentile (blue), 50th percentile (green), 75th percentile (light green), and 95th percentile (red). Black contour is the 10% significance level, using a white-noise background spectrum. The cross-hatched region indicates the "cone of influence," where edge effects became important.

pattern. During winter, the 8-year signal is the most important feature during the second half of the series.

5. Different Variability Modes of the South Atlantic SST Series

[30] The wavelet analysis was performed to the seasonal South Atlantic SSTs series (Figure 6). In general, waves between 2 and 4 years are predominant for zones centered at 30°S and 36°S during summer, autumn and weaker in winter, but during spring the wavelet power spectrum shows an important feature: a strong and prolonged 8-year signal stands out in the SST series of both zones. The remarkably strong 8-year signal is especially interesting, taking into account that the analysis on the extreme indices (especially in cold nights) showed an 8-year wave signal also during spring. Both cases come from independent databases, what strengthen the hypothesis that there actually is a real coupled variability.

[31] In order to make a consistent study on the variability scales between the mentioned series, the cross-wavelet spectrum was calculated (Figure 7). It shows a common

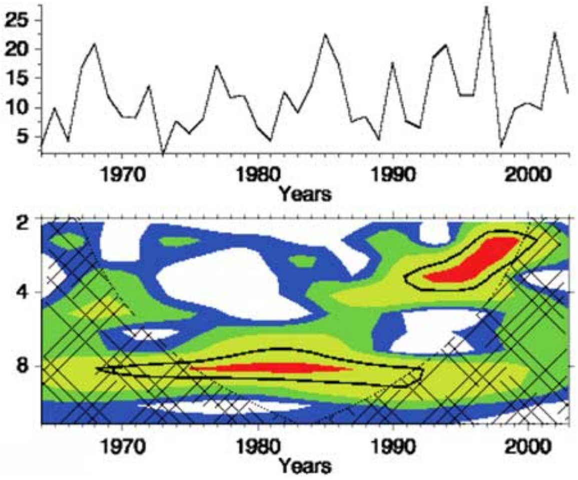


Figure 5. Same as Figure 4, but for wavelet power spectrum of the warm nights spring series. Station Corrientes Aero.

8-year signal between SST30 and cold nights. The results for SST36 are similar. As can be seen, the series are in antiphase, so that the temperature increase in the ocean regions is associated with a decrease in the cold events in spring. However, as evidenced by the wavelet analysis of each of the series, there is no such a relation in the late 1980s, which could imply a change in the relations within the system, or simply that the mode became inactive then.

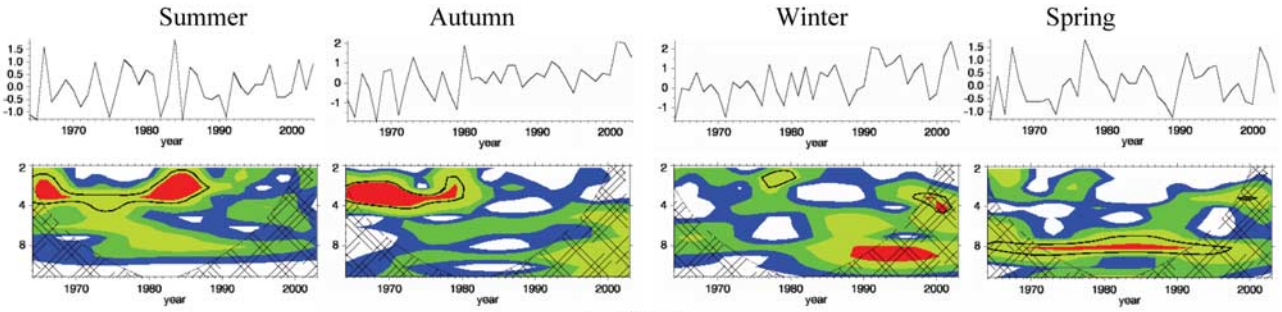
[32] The 8-year wave modulation that was so clearly seen at the four reference stations at central and north of Argentina does not appear in the Patagonian stations, except for a signal in the cross-wavelet with SST30, in phase, that appears after 1990. Although this signal is mostly outside the cone of influence, it also indicates that there may be a change in the climate system at the beginning of the 1990s. This possible change or potential jump in the climate system was early mentioned by *Zhang et al.* [1997] and is being observed by different studies and meteorological variables. Some examples can be found in the work of *Huth and Canziani* [2003], who find changes in the Antarctic polar vortex, and in the work of *Malanca et al.* [2005], who find a change in the ozone fields at middle latitudes, both observed at the beginning of the 1990s.

[33] The association with the southern ocean region (SST46) turned out to be different from the one corresponding to SST30 and SST36. The 8-year wave appears in the cross-wavelet with the Patagonian station, in antiphase, from the 1990s onward.

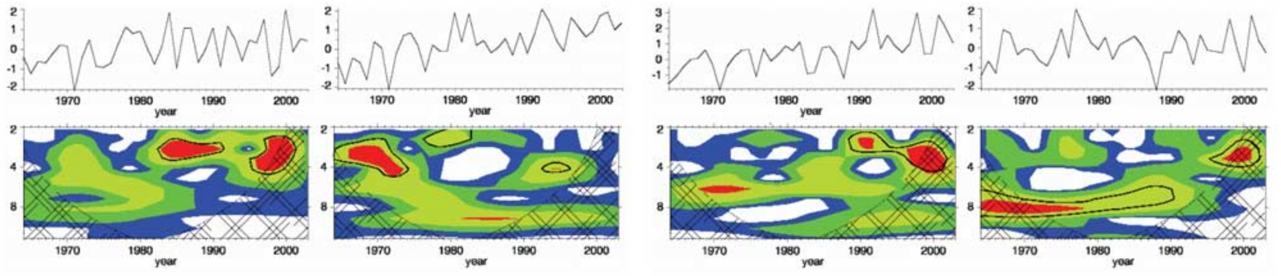
[34] The analysis was performed for the other three extreme indices. The 8-year wave signal is also reflected on many cases, but with a changing phase, so the physical relation becomes more complex.

6. Spring 8-Year Signal in Other Climate Indices

[35] The important signal detected both in the surface temperature indices and in the Atlantic's SST encouraged further research in order to seek possible forcing mechanisms that could modulate the observed variability. The fact that the 8-year signal was more strongly shown in the series of cold events frequency, encouraged the analysis of some index representative of middle and high latitudes. In this context, the SAM turns out to be an appropriate index for evaluating potential patterns modulating the variability observed. Other local circulation indices, the PDO and South Pacific SSTs were also analyzed in order to provide a more robust analysis.



a. (SST30)



b. (SST36)

Figure 6. Same as Figure 4, but for standardized SST series and wavelet power spectrum discriminated by season: (a) SST30 and (b) SST36.

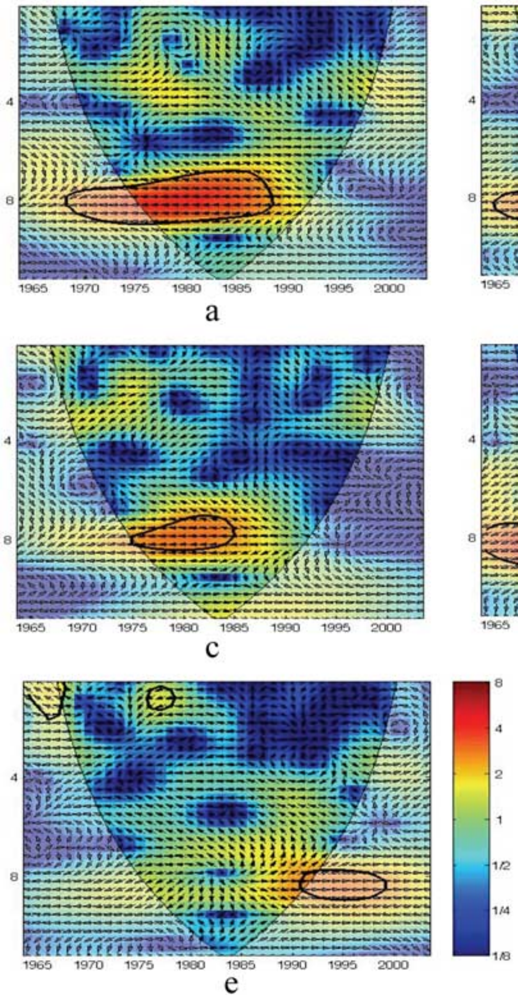


Figure 7. Cross-wavelet transform between some reference cold nights series and the standardized series SST30 (spring). The arrows indicate the phase relation between the series analyzed as a thick contour (with in phase pointing right, antiphase pointing left, and SST leading cold nights by 90° pointing straight down). The thick contours enclose regions of greater than 95% confidence (red noise assumption). There are similar results for SST36: (a) Salta, (b) Corrientes, (c) Malargüe, (d) Junín, and (e) Trelew.

6.1. Southern Annular Mode

[36] The main variability mode in the Southern Hemisphere atmospheric circulation that is dominant in the extratropical regions and the high latitudes has a symmetric or "annular" zonal structure, with anomalies of opposite signs between the Antarctica and middle latitudes. It can be observed in several atmospheric fields, such as surface pressure, geopotential height, surface temperature and zonal wind [*Thompson and Wallace*, 2000]. Previous studies have found that SAM is significantly associated to the climate variability of high frequency [*Baldwin*, 2001], low frequency [*Kidson*, 1999], and to the variability observed in the southern Oceans [*Hall and Visbeck*, 2002].

[37] Many of the studies that have discussed this variability mode found an important positive trend of the index. While the NCEP data indicates a more significant trend during winter, *Marshall* [2003] using the observational data, shows that the highest trend occurs in summer, and no trend is observed in spring.

[38] In this work the SAM index is defined as by *Marshall* [2003], who considers a zonal average of sea level pressure at 40°S and 65°S based on six stations close to each of the latitudes. A wavelet analysis showed that the 8-year signal is clear in the spring SAM index (Figure 8). It is possible to see that in the late 1980s to beginning of the 1990s, there appears another significant signal of a higher frequency.

[39] A cross-wavelet analysis between SAM, Atlantic SSTs and the cold nights index reaffirmed this signal as a common variability mode. It appears consistently for the SST30 (Figure 9a) and SST36 (Figure 9b) zone and in phase (higher values of the SAM index associated with higher ocean temperatures). On the contrary, the SST46 zone does not show consistency with the SAM (not shown).

[40] The 8-year signal appears consistently for the cross-wavelet between SAM and cold nights (Figure 10), with and antiphase relationship. It should be noted that in the cases of the positive SAM index, there is a higher relative pressure on the south of South America with respect to the one seen

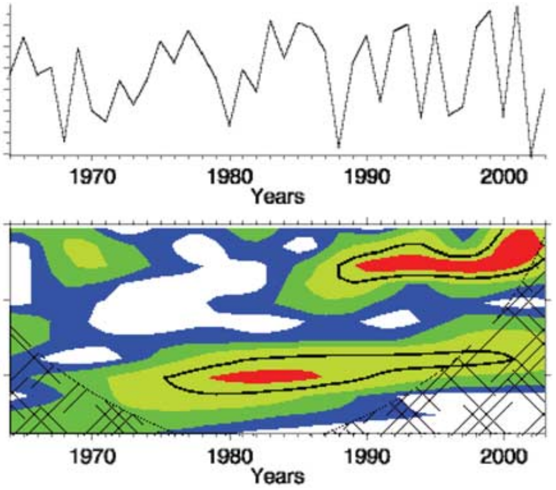


Figure 8. Same as Figure 4, but for wavelet power spectrum of the Southern Annular Mode (SAM) (spring).

for cases with negative SAM (Figure 11), which would be associated with a lower number of cyclones for the first case, lower number of cold events and consequently, warmer conditions. These results agree with *Gillett et al.* [2006], who analyzed regional impacts of the Southern Annular Mode over the whole of the Southern Hemisphere. They found a positive association between the positive phase of the SAM and the temperature anomalies of the Southern South America, although not significant for stations located at subtropical latitudes.

6.2. Local Circulation, Pacific Decadal Oscillation, and Subtropical South Central Pacific SSTs

[41] As it was mentioned in section 2, indices related to the intensity (u_1, u_2) and position ($u_1 - u_2$, u_1/u_2) of the zonal wind at 200 hPa were analyzed. *Barros et al.* [2002] analyzed them and they found that the intensification (reduction) of the west component of the wind at this level and the displacement toward the north (south) of the wind maximum was likely to be associated with cold (warm) anomalies on the surface over almost all year-round. The database used took into account the 1963–1990 period. The results raise some questions: Is the relation maintained after 1990? Is there any dominant low-frequency variability mode of the position and intensity of the subtropical jet that could be modulating the variability observed in the frequency of extreme temperatures and SSTs?

[42] The indices that evaluated the mean position of the jet in spring did not show any jump in the 1990s, but they showed that the trend observed in the last years still continues; this trend accounts for a displacement of the subtropical jet toward the south (Figure 12). These results are consistent with the IPCC AR4 [*Trenberth et al.*, 2007],

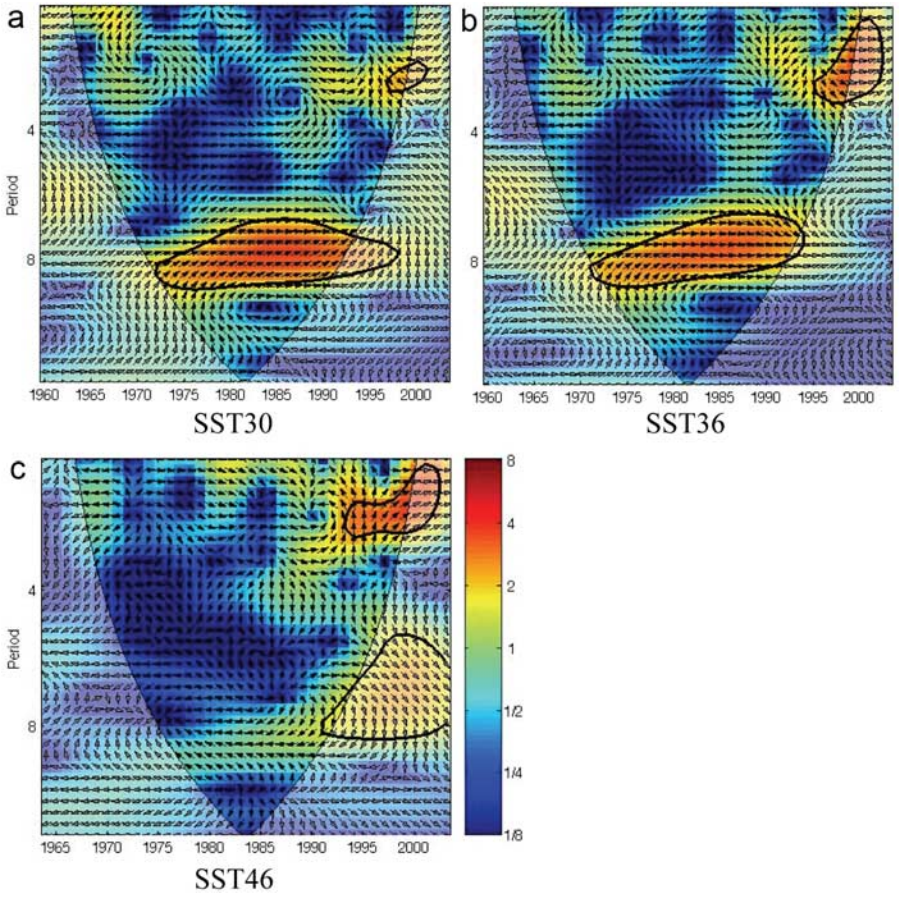


Figure 9. Cross-wavelet transform between SAM and the standardized SST (spring): (a) SST30, (b) SST36, and (c) SST46.

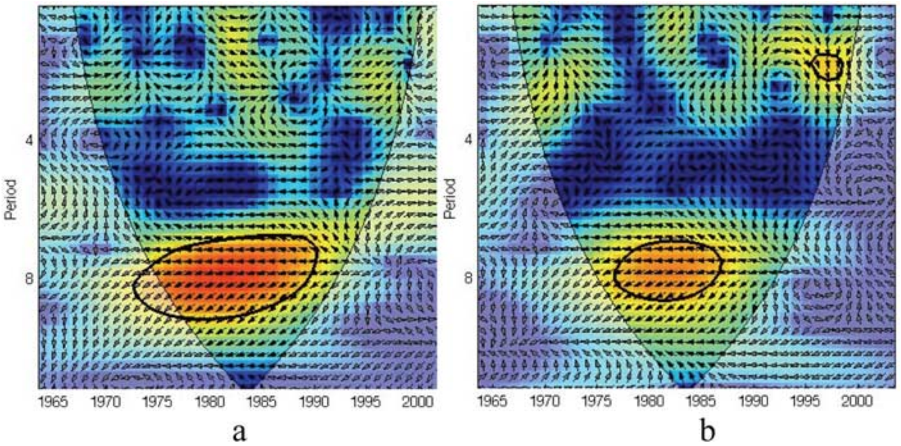


Figure 10. Cross-wavelet transform between SAM and cold nights (spring) of some reference stations: (a) Salta and (b) Malargüe.

where the poleward displacement of the Atlantic and southern polar front jet streams is mentioned. It was not possible to see any dominant 8-year wave variability, although it was seen in one of the zonal flow analysis, which disappears in the beginning of the 1990s.

[43] The PDO is a multidecadal pattern of climate variability centered across the North Pacific Ocean, defined as the leading Principal Component of monthly SST anomalies in the North Pacific Ocean, poleward of 20N [*Zhang et al.*, 1997; *Mantua et al.*, 1997]. Many studies have taken into account this teleconnection pattern, such as *Schneider* [2005] or *Pezza et al.* [2007] in their study about Southern Hemisphere cyclones and anticyclones, to mention some studies. Recently, *Rusticucci and Renom* [2008] analyzed the extreme temperature indices for some stations of Uruguay for summer and winter and they found that indices based on minimum temperature, cold nights (warm nights) have a significant negative (positive) correlation in the Pacific Ocean, with a PDO structure, in accordance with the significant peaks in the interdecadal timescale found with Multi taper methods (2–2.5 and 3–6 year bands).

[44] Specific studies at spring showed that this teleconnection pattern does not exhibit an 8-year modulation, so the PDO would not be related with that specific variability mode previously observed at Atlantic SSTs and some temperature indices.

[45] Finally, the temporal variability of South Pacific SSTs was performed for one specific region: the subtropical south central Pacific. Previous research showed that during spring it is linked to differences in the El Niño response over the Southern Hemisphere [*Barros and Silvestri*, 2002; *Vera et al.*, 2004].

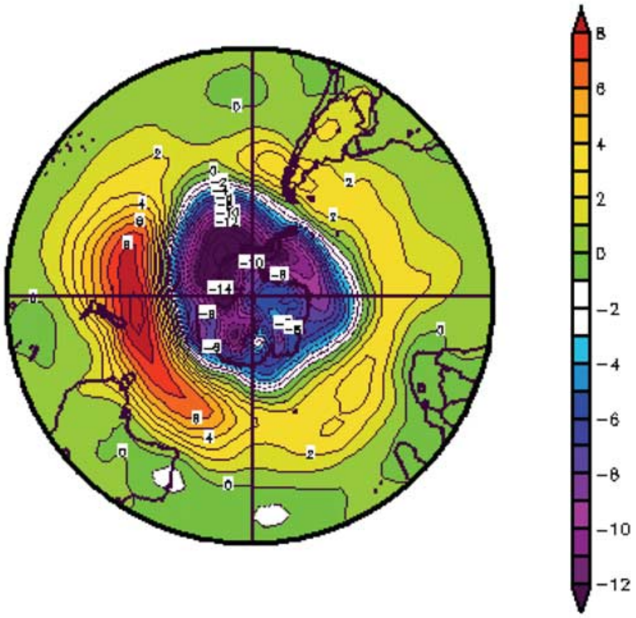


Figure 11. Composites of sea level pressure of three cases with positive minus three cases with negative SAM. Spring. Image provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/.

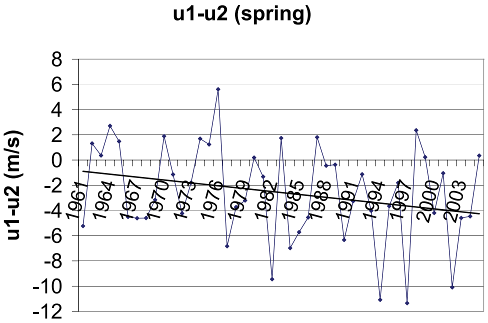


Figure 12. Differences between u_1 and u_2 for the period 1961–2005 (spring).

[46] A wavelet analysis over the SSCP SSTs showed a clear 8-year signal during spring. Either SSCP-SAM as the SSCP-Atlantic SST cross wavelets showed an opposite relation while a direct relation SSCP cold nights index emerged (Figure 13). Although for a different month/season, the inverse relation between Atlantic and SSCP SSTs was reflected in the example showed at Figure 3, representing a warm case at southeastern South America. The reason of this relation exceed the statistical approach presented in this study, but might be consider in future research.

7. Discussion and Conclusions

[47] This research analyzed different temporal variability modes of extreme temperature frequencies in Argentina (southern South America) and their relation with SSTs and some atmospheric circulation indices. On the basis of previous result that showed the importance of the South Atlantic Ocean over temperature conditions in South America, sea surface temperature in the coastal zones of the Atlantic Ocean are specially analyzed.

[48] Correlation between Atlantic SSTs and four temperature indices (warm days and nights, cold days and nights of 40 meteorological stations) showed the most important association in the frequency of warm events (especially warm nights) in the center east and northeast of Argentina, with a direct association with the ocean zones centered at 30°S (SST30) and 36°S (SST36) from March to June, up to a 2-month lag

[49] In general terms, significant variability modes are concentrated on a 2- to 4-year band and on another band close to 8 years, with differences according by the analyzed variable and time of the year. In the first case, the signals appear more or less active in different periods, but the 8-year signal stands out for its continuity at least until the 1990s in spring. A cross-wavelet analysis confirmed that it is an important common variability mode that is more significantly observed in the frequency of cold extremes, with an increase of Atlantic SSTs linked with a decrease of cold events

[50] Different circulation indices were explored which could be also modulated by an 8-year wave signal. It was not detected at PDO, neither at other local indices related to subtropical areas, but it was clearly found in the SAM index and in the SSCP SSTs. It must be mentioned that the 8-year signal that appears at cold event frequencies, Atlantic SSTs, Pacific SSTs (SSCP region) and SAM was captured from three different databases. This fact provides a stronger result. Even more, the present study is not the unique that makes a reference to such signal. *Rao et al.* [2003] studied the interannual variations of storm tracks in the Southern Hemisphere and their connections with the Antarctic Oscillation. They analyzed dominant periodicities of the baroclinic waves for the period January 1974–December 2000 and they found a dominant 8.33-year periodicity in October, something congruent with the 8-year signal that is been mentioned here. Certainly, we need longer series for a better

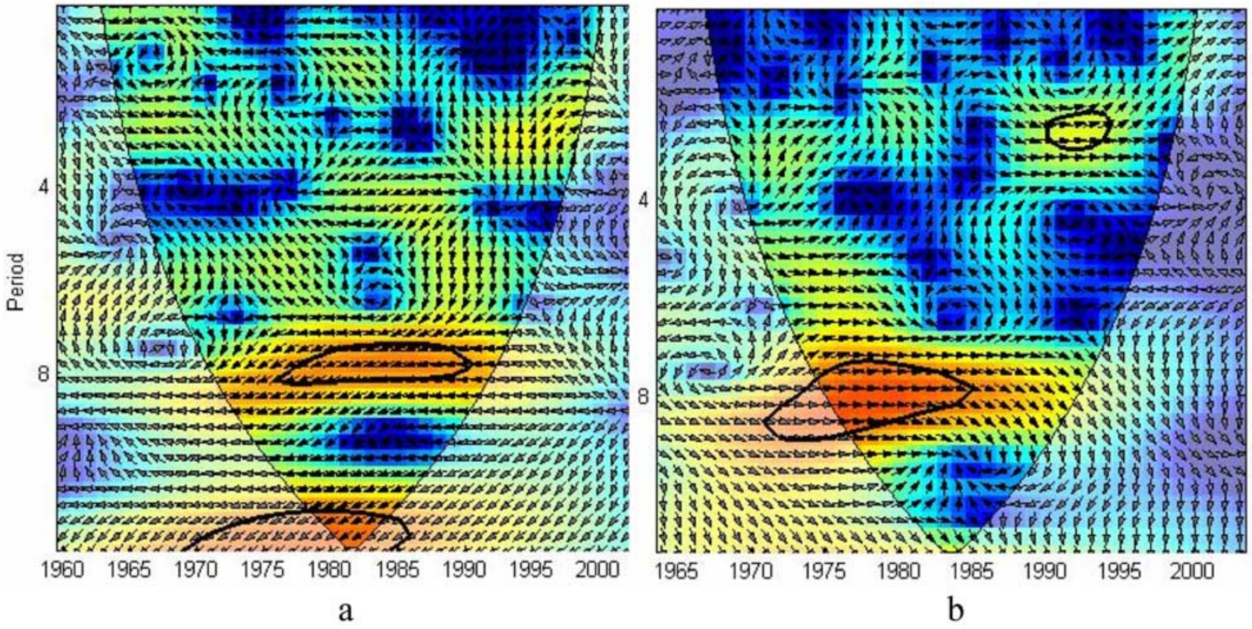


Figure 13. Cross-wavelet between subtropical south central Pacific SSTs and (a) SST30 and (b) cold nights Junín.

analysis of low-frequency variability and further analysis must be done in order to understand the propagation path of the signal, and the connection between the South Pacific and the South Atlantic. Nevertheless, the fact that the 8-year wave signal has been found in different variables coming from different sources of information and other studies as *Rao et al.* [2003], permit us to infer that it is a real part of the climate variability at the Southern Hemisphere.

[51] Although the current analysis is not intended to be directly applied to prediction, our results certainly contribute to a better understanding of the main variability modes present in the Southern Hemisphere and can be considered as a starting point in the improvement in the knowledge of interannual to interdecadal variability.

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