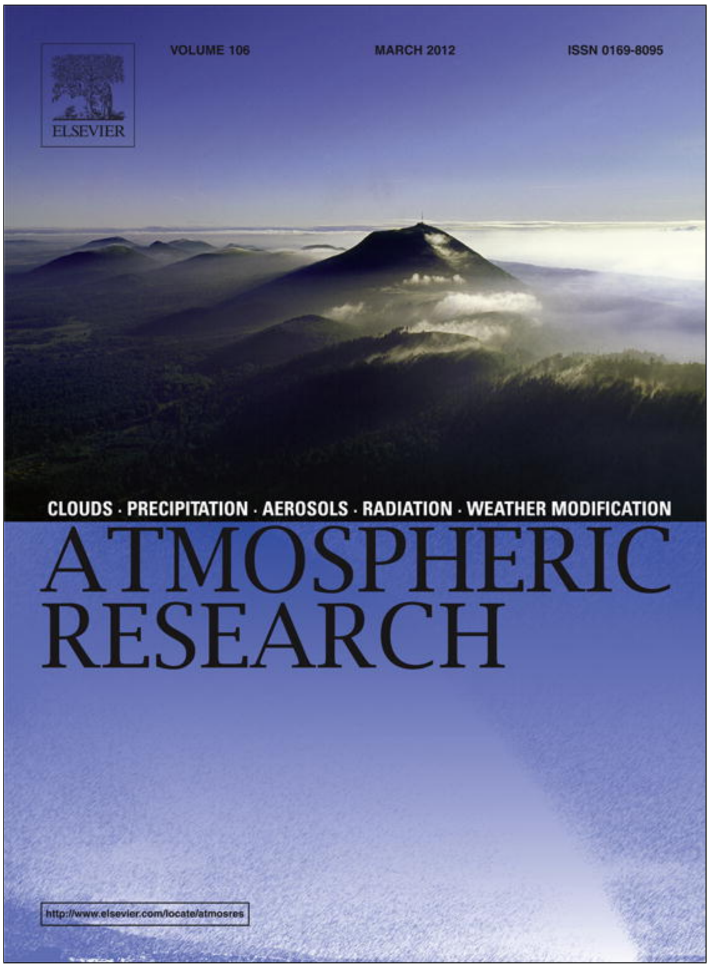
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Observed and simulated variability of extreme temperature events over South America

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ABSTRACT

This invited review paper tends to summarise the results based on the variability of occurrence of temperature extremes in South America. The first thing to note is that there is a geographical imbalance with respect to the number of published studies on temperature extremes. Most of the results come from the southern part of South America, east of the Andes, and a few from the northern part of the continent and for the Altiplano. The workshop organised by the ETCCDMI in Brazil was the first time to have the opportunity to collect information in a regional way and present trends in extreme daily temperatures. A better geographical picture enhanced with more data show significant geographical trends in warm (positive) and cold (negative) nights over Southern South America and over the northern South America coast. All other studies based on smaller regions also agree in finding the most significant trends in the evolution of the minimum temperature, with positive trends in almost all studies on the occurrence of warm nights (or hot extremes of minimum temperature) and negative trend in the cold extremes of the minimum. On the other hand, there is little agreement on the variability of maximum temperature. Generally the maximum temperature in southern South America has decreased, in opposition to the case of northern South America where it has increased. Strong decadal and interannual variability have been found in the occurrence of cold extremes. Reanalysis and climate models underestimate the intensity of extremes, mainly near the Andes. The studies trying to understand the dynamics of the circulation that leads to the occurrence of these extremes are analysed from its occurrence in almost all scales from the synoptic, intraseasonal, seasonal, annual, and multi-year linear trend with different methodologies, also, indentifying the local and remote forcing. A gap was found in studies that relate some specific local forcing (like changes in land use) and compare it with the remote ones. Different aspects of the occurrence of the temperature extremes are still missing in some regions of the continent.

Contents

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1. Introduction

The impact of climate change or variability in the environment and on the economic activities is dependent on changes in the frequency of occurrence of extreme events because they will stress or exceed our present day adaptations to climate variability. There is broad consensus that the most hazardous effects of climate change are related to a potential increase (in frequency and/or intensity) of extreme weather and climate events.

Cold outbreaks during wintertime in Central Argentina cause important damage to the regional agriculture and sometimes affect the energy supply. In particular, the consumption of natural gas is strongly dependent on significant temperature descents. The overarching goal of studying extremes is, therefore, to understand and then manage the risks of extreme events and related disasters to advance strategies for efficient climate change adaptation (Sura, 2011).

In this review paper a general perspective of extreme events in weather and climate is presented and discusses the theoretical framework, observational evidence, and related developments in stochastic modelling of extreme events in weather and climate. The main results on the observed and modelled variability of temperature extremes published over South America are summarised.

Although temperature extremes are generally less studied than the extremes of precipitation, there is an increasing interest in assessing their variability. This is based on the availability of better and more extensive series of daily data, and the interest of the community to understand the effects of climate change in their occurrence. Many studies have focused on understanding the physical causes of the occurrence of extremes, especially on cold waves and frost, so harmful to agriculture, as this is one of the main economic activities in southern South America. In general, there are more studies based on the extra-tropical region of South America; one reason could be because its highest variability but for sure because there were less long term data availability over the Amazonia region.

The results are presented based on large studied topics: the observed long term variability (including trends) for both seasonal and/or monthly aggregated and daily extremes; the ENSO influence on the variability and probability of occurrence of both extremes — cold and warm — with different persistence and intensity thresholds; the studies focused on frosts and cold surges; the studies focused on warm spells and heat waves and finally the studies that compares the modelled and observed extremes, including reanalysis. Finally, there is a discussion about gaps and generalised results.

2. Observed long term variability and trends

2.1. Seasonal and annual extremes

The first works on the variability of daily temperature extreme events, are focused on Argentina stations, mainly because of the availability of long term and quality controlled series of daily data. The first consideration about extremes is related to the variables maximum (MxT) and minimum (MnT) Temperature themselves. Based on daily minimum and maximum temperatures over Argentina, trend analysis were done on seasonal means, standard deviation, skewness, kurtosis and extremes (5% and 95%) over the 1959/1998 period (Rusticucci and Barrucand, 2004). Time evolution of distribution parameters were analysed for summer (DJF) and winter (JJA). Trend analysis results show the strongest changes over time in summer MnT. Mean seasonal MnT presented a great number of locations with positive trends in summer and also in winter.

As an example, locations with significant (95%) positive (red) and negative (blue) trend slopes are shown. Fig. 1 represents the summer mean MnT analysis and in Fig. 2, the summer MnT standard deviation trends. So, the mean seasonal MnT were increasing, but with less interdiurnal variability. Mean MxT mostly decrease over time in summer over northern Argentina, but they increase in Patagonia (southern Argentina).

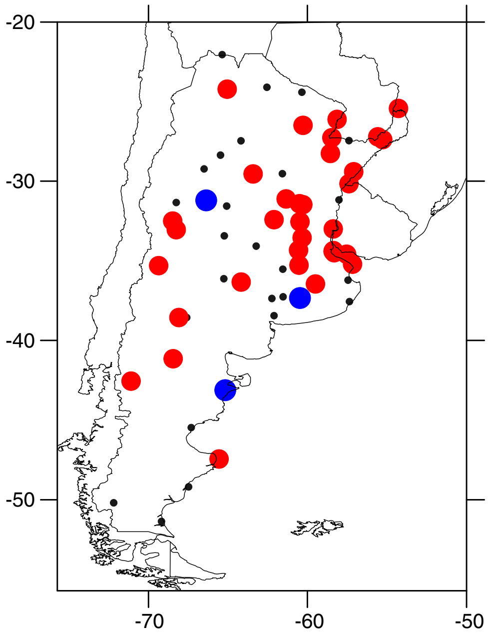

Fig. 1. This figure represents the summer mean minimum temperature trend (red, positive; blue, negative) for the 1959/1998 period.
Adapted from Rusticucci and Barrucand, 2004.

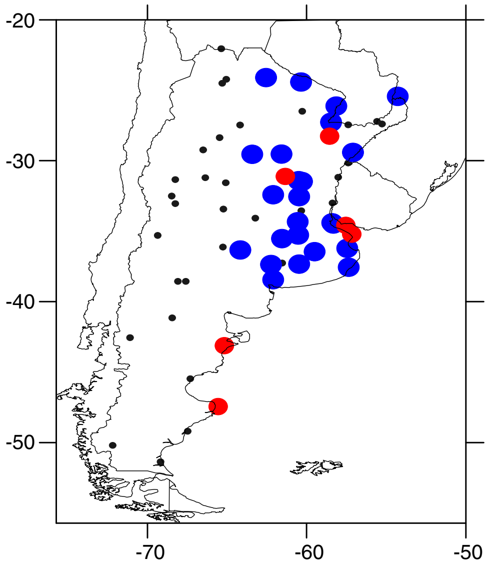

Fig. 2. The summer minimum temperature standard deviation trends (red, positive; blue, negative), 1959/1998.
Adapted from Rusticucci and Barrucand, 2004.

The largest changes were observed for all variables during summer.

The question, "What is the relationship between mean temperature values and daily extremes?" could be answered as follows, through the regressions between the mean seasonal value and the number of extreme days in the season

a) In summer, there was a stronger relationship between an increase in mean temperature and an increase in the occurrence of warm days and nights than between the increase in mean seasonal temperature and a decrease of cold nights and days. Many stations in the north of the country showed no significant correlation between the two variables.
b) In winter, the relationships between variables showed little significance; the largest correlations between mean and extreme values were found in Patagonia. In the central region, where the largest agricultural and cattle production occurs, it cannot be inferred that an increase in maximum temperature would be related to an increased number of warm days in winter.

These results tend to clarify the response of extremes to a change in mean. Therefore, under the supposition of a warming climate, the response of the extreme values of the climatic system can be very diverse. These results reinforced the idea that the analysis of the changes in the mean is not enough to estimate the potential changes in extreme variables in a scenario of warming climate.

For Southern Brazil, long-term variations of monthly average MxT and MnT were presented for the 1913–2006 period in Sansigolo and Kayano (2010). Fig. 3 (MnT) and Fig. 4 (MxT) show the time series for the region. These variations were carefully analysed for seasonal and annual indices, taken as regional averages. For this purpose, the serial correlation and trend of the indices were investigated using the run and Mann–Kendall tests. The annual and seasonal MnT indices showed significant warming trends with magnitudes (1.7 °C per 100 years for annual index) comparable to those reported by the Intergovernmental Panel on Climate Change in its 4th Assessment Report, but lower than those found for the southern Brazil in another previous work. The indices showed significant trends only for summer, being a cooling trend of 0.6 °C per 100 years for the MxT. Concerning the analysis made by decades, the 1920s present the lowest annual, autumn, and spring MnT and the 1990s, the highest ones. The 1970s is the decade with the lowest summer MxT, and the 1940s the decade with the highest one.

Hoffmann et al. (1997) presented the first paper with long term monthly mean extreme temperatures. The problem regarding a possible warming in Argentina and in the adjacent sub-Antarctic region has been studied within the framework of the global warming issue and taking into account the evolution of the global mean surface temperature since 1880. For this reason, the decadal averages of the annual means of the maximum, minimum and daily mean temperature, the vapour pressure and the precipitation corresponding to the periods of 1941–1950 and 1981–1990 have been compared for representative meteorological stations. They found a significant warming in southern Patagonia and South Orkney Islands since 1940 or earlier. North of about 42° S, however, no warming has been observed. Here, mean extreme temperatures vary in opposite directions: the mean MxT decreases, while the mean MnT increases. This behaviour is consistent with that of the vapour pressure and the precipitation behaviour They argued that as to the sub-Antarctic region in particular, the augmentation of the precipitation observed in South Orkney Islands, which proved to be significant at the confidence level of 1%, may be partially associated with the general warming in that region.

In Zazulie et al. (2010) a new set of daily maximum and minimum temperature data in Orcadas was analysed. The climate observations at Orcadas represent the only southern high latitude site where data spans more than a century. Although limited to a single station, the observed warming trends were among the largest found anywhere on earth, facilitating study of changes in extreme temperatures as well as averages. Statistically significant trends were also obtained for the 20th century in both the 5% and 10% warmest and coolest portions of the temperature distributions over much of the year, with the exception of the coolest temperatures in spring (SON). The winter warming was particularly pronounced in the cold extremes, while the summer season changes represented a shift rather than a change in shape of the distribution, underscoring differences in the character of the climatic changes with season.

2.2. Daily extremes — indices of temperature extremes

For South America, there have been few published results on daily temperature changes and extremes that are available internationally.

For Argentina, the analysis of the trends in temperature extremes has also indicated a strong warming of the nighttime temperature with fewer cold nights and more warm nights (Fig. 5 from Rusticucci and Barrucand, 2004). Extreme temperatures were defined by the number of 'cold nights' ('days') and 'warm nights' ('days') per season, by comparing values to the 5th and 95th MnT (MxT) percentiles limits. In summer, mainly in the centre of the country, the cold days tended to increase and the warm days tended to diminish.

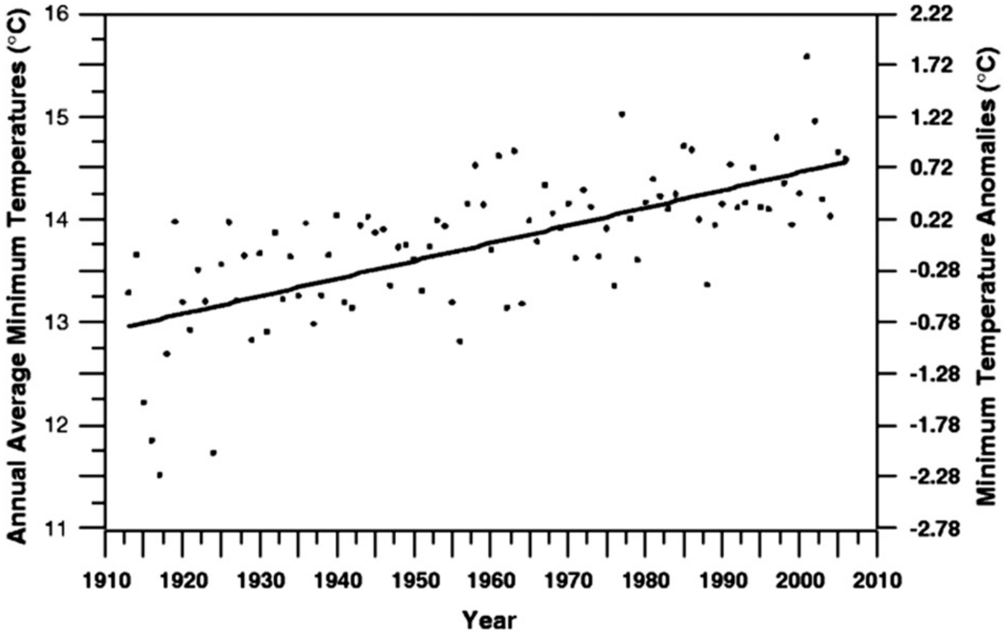

Fig. 3. Annual average minimum temperatures (dots) and the straight-line fit (continuous line) for the 1913–2006 period. From Sansigolo and Kayano, 2010.

The stations in Patagonia show the opposite pattern. In winter all stations in Patagonia had an increasing number (significant in some cases) of warm days and nights.

Daily temperature extremes trends were also analysed in other regions of South America. Warming was identified in various parts of Brazil and it was sometime attributed to the changes in land use, including the development of large cities such as São Paulo and Rio de Janeiro (Marengo, 2001, 2003; Sansigolo et al., 1992). In Colombia and Venezuela, night-time temperature has increased steadily during the last 30–40 years but maximum temperature present different behaviour between both regions (Quintana-Gomez, 1999 see Fig. 6). For the Amazon region, a warming of 0.56 °C/100 years until 1997 was detected, while Marengo (2003) has updated the trend to 0.85 °C (100 years)$^{-1}$ until 2002.

Frich et al. (2002) presented the analysis of the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) suggested indices, but without South American results. Their results indicated that there were large regions of the world where no digital daily data were readily available for analysis. ETCCDMI was established to develop a comprehensive list of indices meaningful over global regions and to coordinate a series of workshops for the preparation of climate change indices in the regions lacking daily climate observations.

The ETCCDMI South American workshop held in Maceió, Brazil, allowed the first regional papers on extremes for South

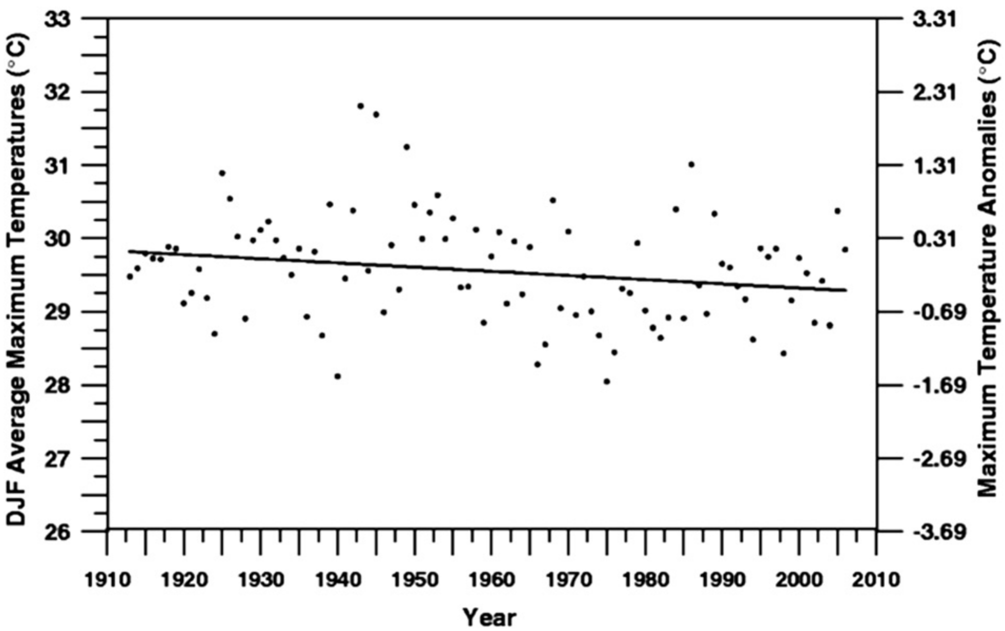

Fig. 4. December to February average maximum temperatures (dots) for the 1913–2006 period. From Sansigolo and Kayano, 2010.

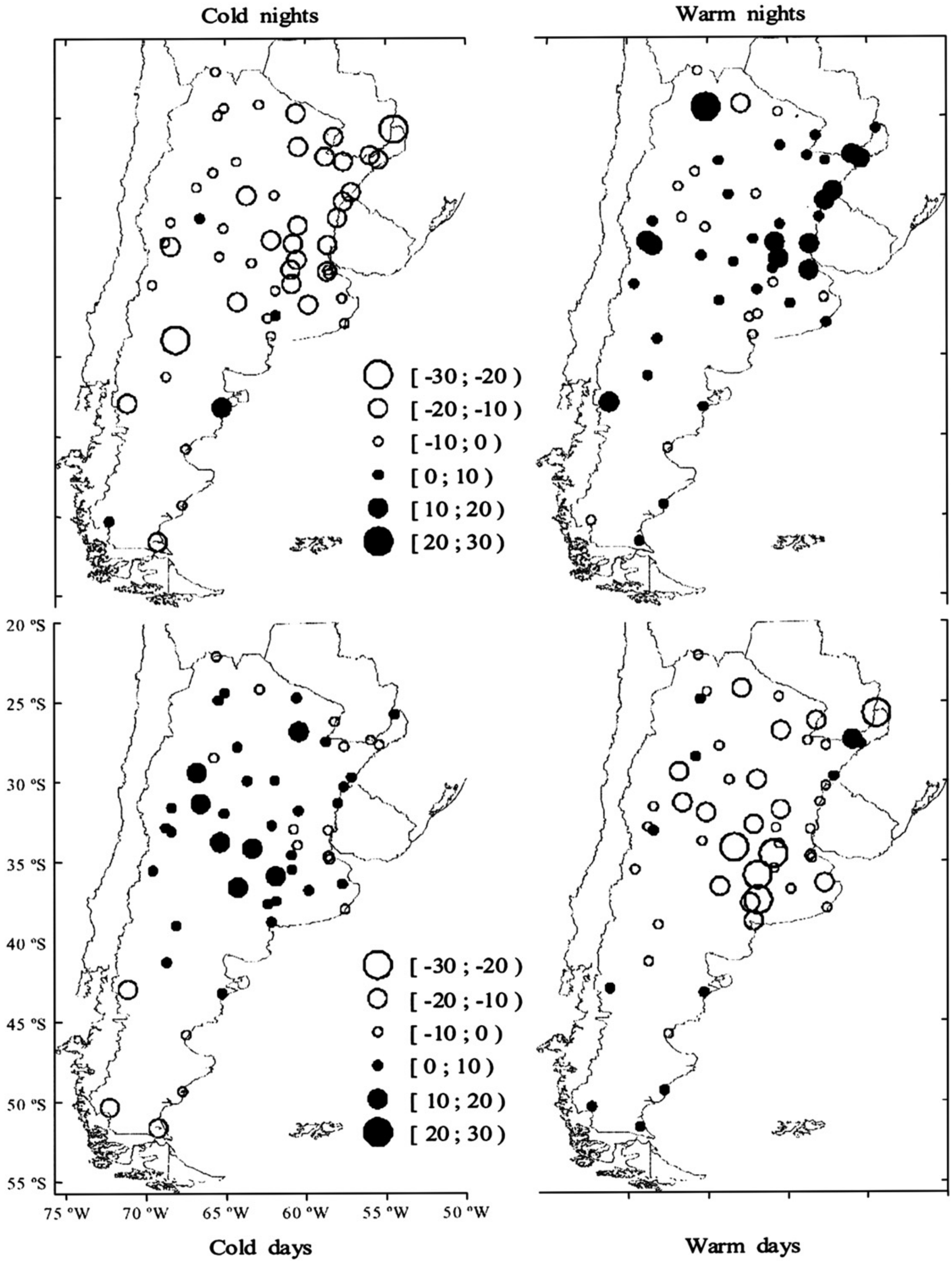

Fig. 5. Trends of percentage/100 years of (left) cold (5th percentile) and (right) warm (95th percentile) (top) nights (minimum temperature) and (bottom) days (maximum temperature) in summer. Stations with positive (negative) trends are shown with solid (open) circles. The diameter of the circles is proportional to the trend. The values of less than 10% are generally not significant at the 95% level.
From Rusticucci and Barrucand, 2004.

America with results obtained from daily temperatures and precipitation data provided by the participants from all South American countries south of the equator (temperature results in Vincent et al., 2005). This paper provided further evidence for the strong warming in the night-time temperature extremes and the weaker changes in the daytime temperature extremes for the 1960–2000 period. The findings revealed no regionally consistent changes in the indices based on daily maximum temperature, as previous local results. However, significant trends were observed in the indices based on daily minimum temperatures. The coldest night of the year is getting warmer and there are more tropical nights. The percentage of cold nights was decreasing while the percentage of warm nights has been increasing, and these changes are more pronounced during the summer (DJF) and fall (MAM). The night time warming corresponded to a significant decrease in the diurnal temperature range over the continent (Fig. 7a). After that regional workshop, more national efforts were done in this way that produced different studies and also contributed to the world-wide Alexander et al. (2006) paper (Fig. 7b) and extended the studied period to 1951–2003.

For Uruguay, a database of daily extreme temperature was created for as many stations as possible, as far back as possible (Rusticucci and Renom, 2008). This is the first attempt to gather all the different data sources together, performing a quality control and homogeneity assessment. Almost all the stations showed significant decreasing trends in the percentage of cold nights (TN10: percentage of days with MnT less than the 10th 1961–1990 percentile). The last period analysed (1961–2002) showed the most decreasing trend, around −1.2%/decade compared to the other periods studied (−0.7%/decade) indicating a strong warming of nighttime temperature, in accordance with other regional results. For indices based on daily maximum temperature they found that TX10 (cold days) presented a negative significant trend in all periods considered.

Rusticucci and Tencer (2008) found by fitting the GEV distribution to annual extremes in the period pre- and post-1976 that the 1976–1977 shift led to significant changes in

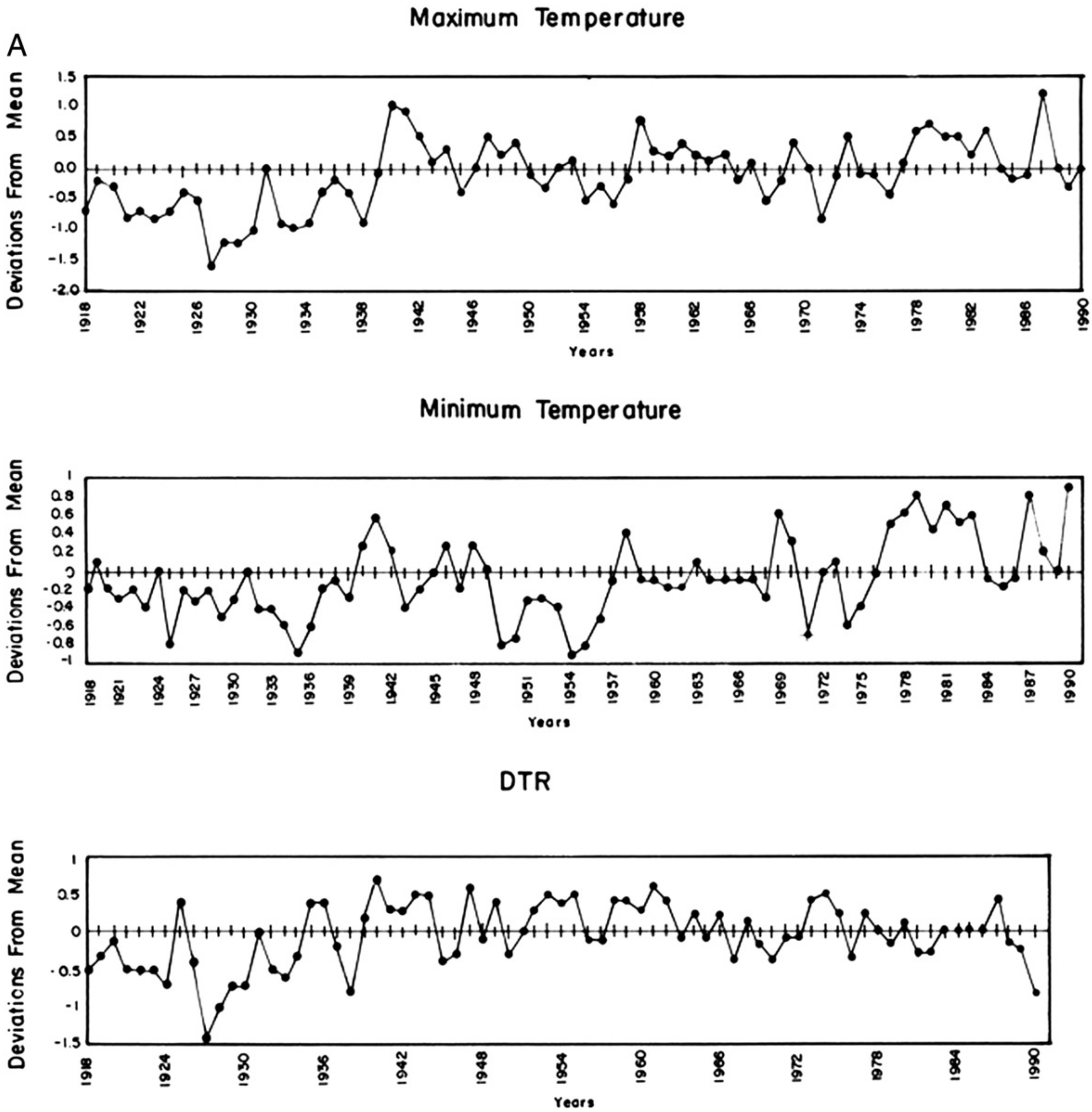

Fig. 6. a: Time series of the variations of the annual mean maximum and minimum temperature (°C) and diurnal temperature range (DTR) for the six Venezuelan climatological stations. b: Same as a, for the six Colombian climatological stations.
a and b from Quintana-Gomez, 1999.

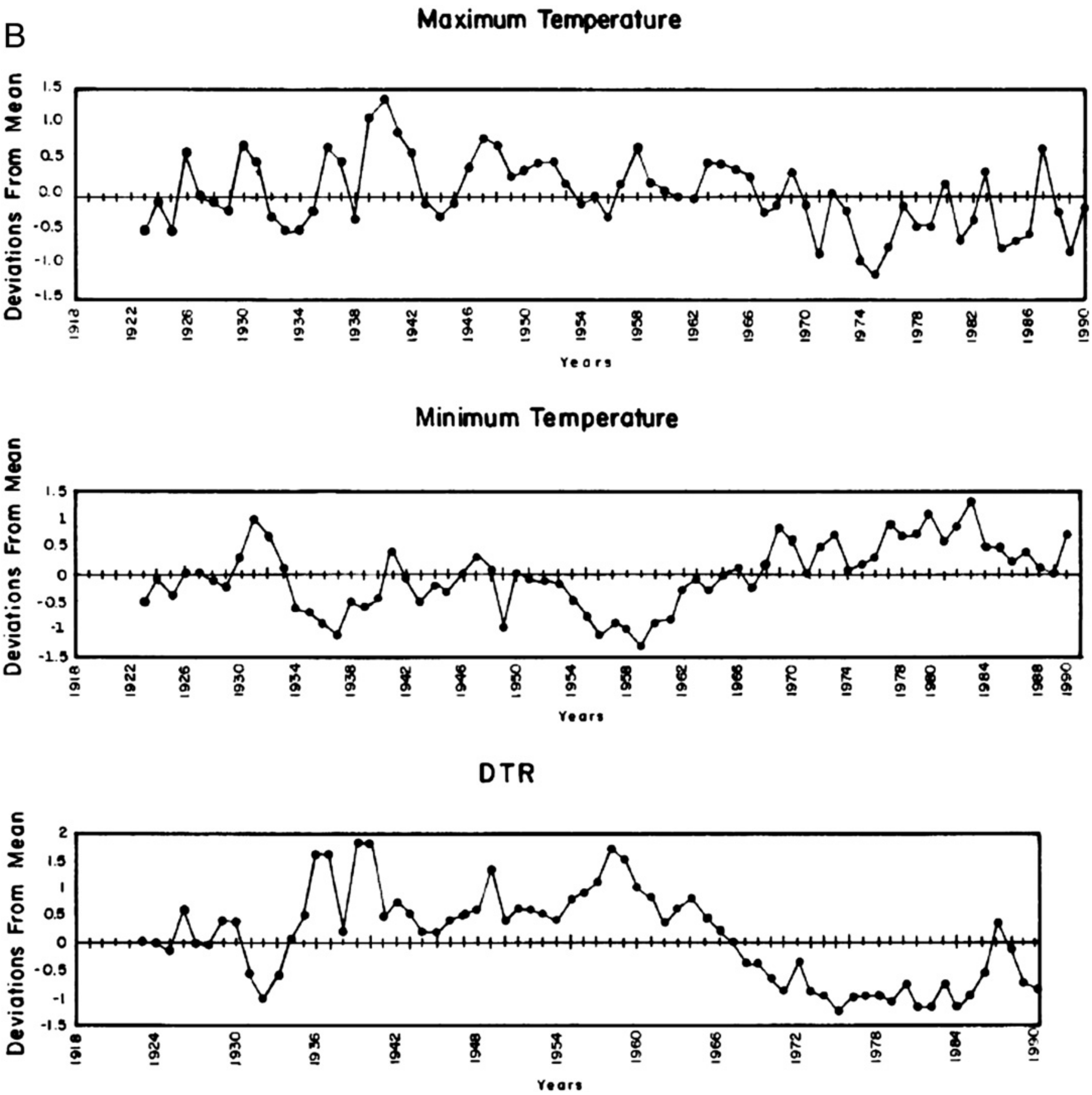

Fig. 6 (*continued*).

return values in Argentina. For example, assuming that the period post-1976 can be considered as the "present climate," at Patagonia the highest minimum temperature of the year expected once every 10 years increased from 13.7 °C in the past to 18.6 °C in the present. At Buenos Aires, where the urban heat island is more intense, an increase of 3.3 °C was found after 1976 in the lowest minimum temperature of the year that occurs every 10 years and 4.1 °C in the one that happens every 100 years.

The highest annual maximum temperature (HTx) decreased from 1956 to 2003 while the lowest annual maximum temperature (LTx) increased in central Argentina concluding in a decrease in the temperature annual range. In the central-western region trends were positive both for warm and cold extremes. It was also found that maximum temperatures greater than 32 °C are expected at least once a year all over the country, except in the Patagonia, where this value had a return period of 10 years and maximum temperatures greater than 40 °C may occur once a year or every five years in the central and northern regions, where maximum temperatures reach the highest values of the country. Minimum temperatures below 0 °C happened every 2–10 years in the northeast and once a year in the rest of country.

Another long term analysis using daily MxT and MnT were presented in Vargas and Naumann (2008). Depending on both variables, they defined four types of days: warm, cold, wet and dry. These definitions of warm or cold days differ from ETCCDMI. They concluded that the set of wet days was one of the main factors driving secular variations of maximum and minimum temperature and variations in precipitation. Also inferred that after 1920 till 1930 an increase of warm days and decrease of cold days low frequency oscillation was observed. Naumann et al. (2011) said that for MxT, which are highly dependent on the level of cloudiness, and for the minimum temperatures, which are mostly influenced by cold/warm outbreaks, changes reflected the processes that lead to the beginning or end of the cool and dry seasons. To represent persistence using these variables, it is necessary to describe in more detail the parameters that define the series during transition seasons, particularly in the fall for the maximum temperature and in the spring for the minimum temperature. A spatial analysis of the persistence in the entire region north of 36° S revealed the largest dependence for autumn and early winter. The annual changes in dependence varied between 4 and 7 days. South of this domain and in the continental region, it was observed that the temperatures were more persistent in the spring. These elements indicate that nonlinear interactions exist between the annual cycles of temperature and its anomalies.

A spectral analysis applied to Uruguayan stations (Rusticucci and Renom, 2008) showed that on inter-annual timescales, all

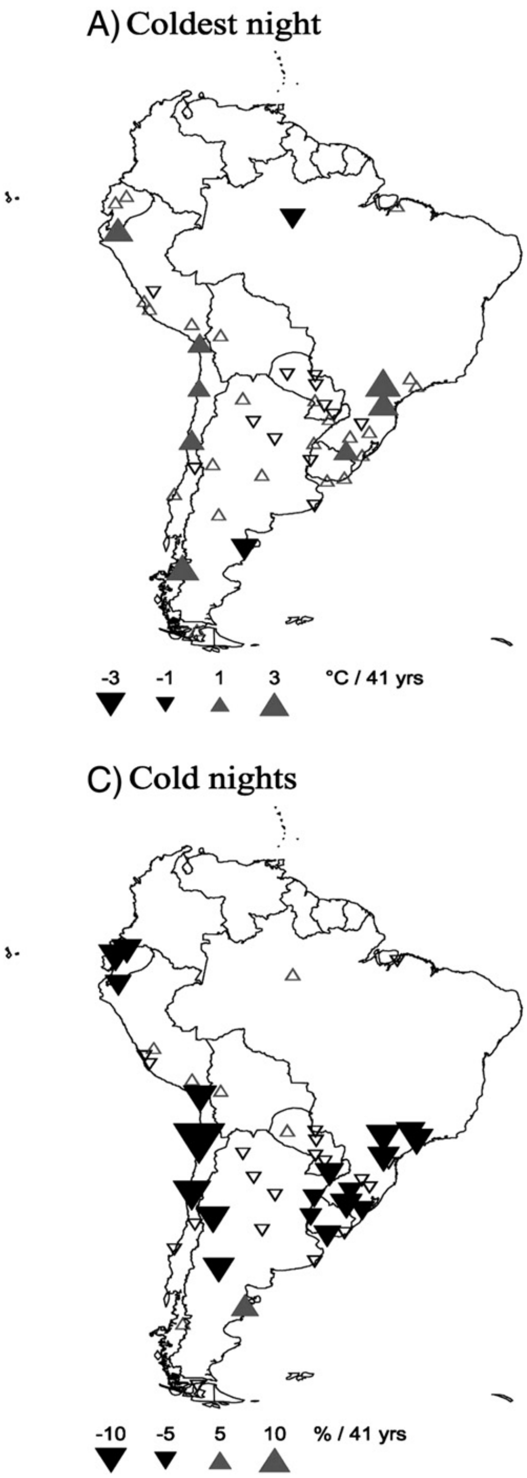

Fig. 7. a: Trends in four indices based on daily minimum temperature over 1960–2000. Upward (grey) and downward (black) pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the filled triangle is proportional to the magnitude of the trend: (a) coldest night, (b) tropical nights, (c) cold nights, and (d) warm nights. b: Trends (in days per decade) for annual series of percentile temperature indices for 1951–2003 for (a) cold nights (TN10p), (b) warm nights (TN90p), (c) cold days (TX10p), and (d) warm days (TX90p). Trends were calculated only for the grid boxes with sufficient data (at least 40 years of data during the period and the last year of the series is no earlier than 1999). Black lines enclose regions where trends are significant at the 5% level.
a: from Vincent et al., 2005; b: from Alexander et al., 2006.

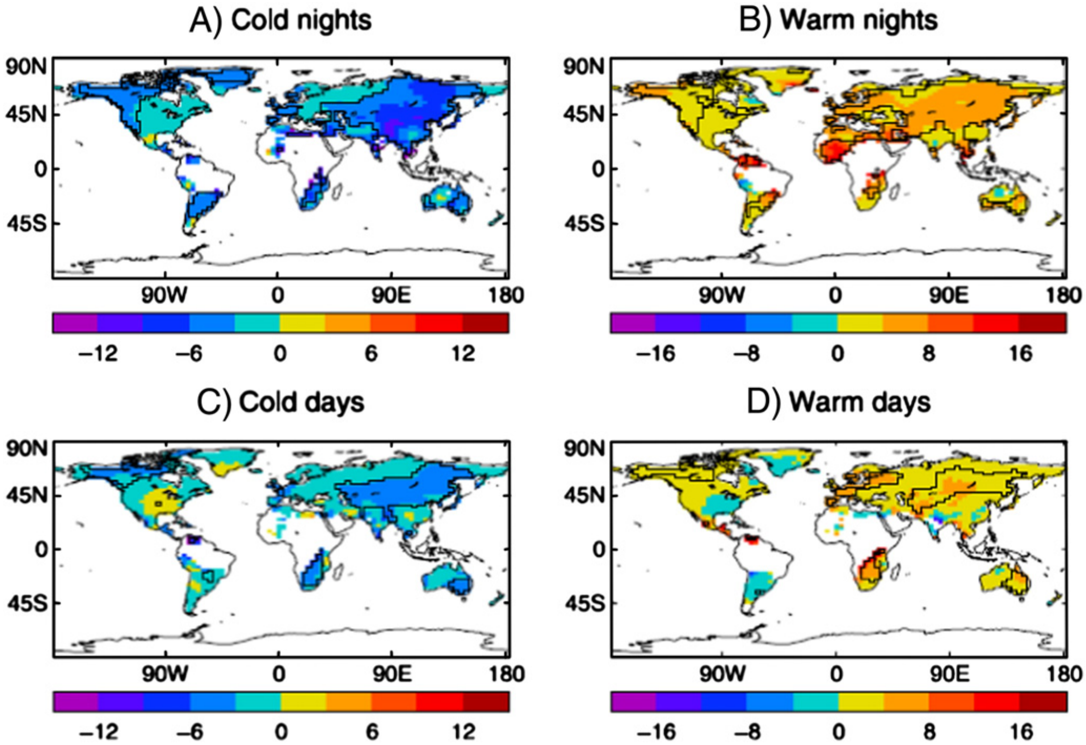

Fig. 7 (*continued*).

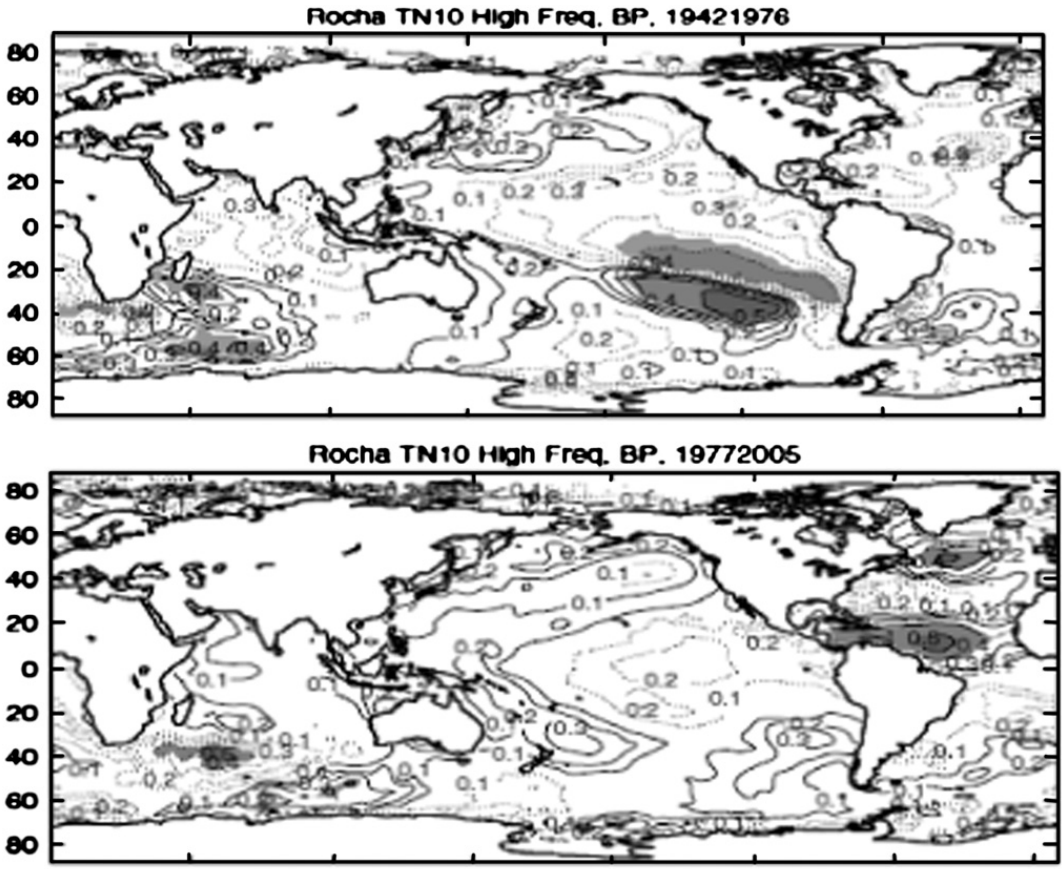

Fig. 8. Correlations between TN10 index from Rocha station and SSTs annual anomalies, with a band pass filter of 3–6 years for the periods 1942–1976 and 1977–2005. Significant correlations at the 5% level are shaded.
From Rusticucci and Renom, 2008.

extremes analysed (both MnT and MxT 10th and 90th percentiles) the most significant range of frequencies is from 2 to 2.5 years and from 3 to 6 years . Low frequencies of variability were detected when the MTM (multitapper method) was applied to de-trended smoothed annual time-series, around the range of frequencies of 15–25 years for almost all the indices analysed. The indices showed largest correlations with SST anomalies in the Pacific Ocean. They also analysed the impact of the 1976/1977 climate shift and detected changes in the response of the TN10 index for Rocha station when the series was split up into two different periods (1942–1976 and 1977–2005) as can be seen in Fig. 8. A large weakening of correlation with the Pacific Ocean, losing its significance, as well as an increase in positive correlation with tropical and northern Atlantic, was detected during the last period compared with the first one for TN10 index in Rocha station. For TN90 (percentage of days with MnT over than the 90th 1961–90 percentile), they found for the last period a change in sign for correlation with the western Pacific, while there was, at the same time, a strengthening of negative correlation along the South Pacific Convergence Zone (SPCZ) through the south-eastern Pacific.

The differences in the correlations structure with TN10 and TN90 indices, during the two analysed periods, could be due to the change in phase of the Pacific Decadal Oscillation (PDO), which modulates the ENSO events. Many studies show differences in the circulation response over the Southern Hemisphere during ENSO, influenced by the inter-decadal variability. Changes in the Pacific Ocean affect particularly minimum temperature, and this could account for the strong warming detected in the trend analysis during the last period.

Rusticucci et al. (2003) have explored the first mode patterns of a joint Singular Value Decomposition (SVD) analysis between the number of days classified as warm/cold events in Argentina (WD/CD) and the South Atlantic and South Pacific Sea Surface Temperature SST. The atmospheric circulation patterns associated with them have also been analysed by computing Sea Level Pressure correlation maps. Meridional atmospheric circulations over the continent, bringing warm air from the tropics or cold air from the subpolar regions into the country were the responsible. Such atmospheric circulation patterns result in turn from displacements and intensity changes of the subtropical anticyclones over the oceans and of the continental low-pressure centre in north-western Argentina. The warm and cold events were also closely related to the warming and cooling of the coastal waters in the South Atlantic and South Pacific. The large percentage of the covariance explained by the first SVD mode revealed a high degree of predictability of the warm and cold events in Argentina based on the Atlantic and Pacific SST in all seasons. This is especially true in winter, (Fig. 9) in which the first mode accounted for up to 70% of the covariance between the SST and the temperature events. For all seasons, the occurrence of temperature events in Argentina showed higher correlation with the Atlantic than with the Pacific. Based on these results, Barrucand et al. (2008) studied the main variability modes of the frequency of extreme temperatures in the south of South America and their relation to SST, mainly over the South Atlantic and atmospheric circulation in the Southern Hemisphere. The most important association were in the frequency of warm events (especially warm nights) in the centre east and northeast of Argentina, with a direct association with the ocean zones centred at 30ºS and 36ºS from March to June, up to a 2-month lag. In general terms, significant variability modes were concentrated on a 2- to 4-year band and on another band close to 8 years, with differences according by the analysed variable and time of the year. The shortest signals appeared 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 SST linked with a decrease of cold events. Also the Southern Annular Mode (SAM) index and the SST over southern South Pacific present this 8-year signal, showing that it is a strong feature in southern climate. This 8-year wave signal was not detected at PDO, neither at other local indices related to subtropical areas, but it was clearly found in the SAM index.

3. El Niño-southern oscillation influence on temperature extremes

Because of the relevance of the ENSO mode, most studies focused on this relationship, not only in South America. There are significant indications that ENSO events are an important source of interannual/interdecadal variability. Rusticucci and Vargas (2001) have analysed with different indices the influence of temperatures of the equatorial Pacific on the occurrence of extreme cold and warm spells, in particular for the north of Argentina, a region for which, a priori, the strongest ENSO signal is expected. Müller et al. (2000) studied the number of freezing events that occurred within the Argentine region known as Pampa Húmeda and its relationship with the ENSO. Both studies agreed on the fact that warm spells are more intense and persistent in the winter season during the El Niño phase, and a number of freezing events lower than the climatological value. Consistently, Barros and Scasso (1994) pointed out that the northwest low is intensified during the negative phase of the SOI, advecting more warm air to the region from the North.

In Rusticucci and Vargas (2002) warm (cold) events were defined considering the spells of positive (negative) daily anomalies of the maximum (minimum) daily temperature over Argentina. Two parameters were proposed to represent the events: the spell persistence (in days), the number of days for which the anomaly remains with the same sign, and its maximum value (°C), or intensity of the spell, which is given by the maximum anomaly during the spell. Those spells for which any of two parameters exceed the third quartile (upper 25%) of their frequency distributions are defined as 'events'. In general, great inter-monthly variability was observed. Cold events during El Niño were more intense and persistent in the south of the country in the coldest months (MJJA) but shorter and less intense in the centre and north (April to September). Polar air is confined to the south or an intense zonal circulation restricts its motion toward the north. Grimm et al. (2000) showed that during this phase, and by the end of winter, the westerly winds are stronger south of 40°S. The cold fronts are, therefore, less frequent in the north; northerly advection is thus enhanced. In December, events are more persistent than in the Neutral phase, in a region close to the Andes. During La Niña phase, the cold events are significantly more persistent and intense than during the Neutral phase in June and July in the central region of the country, and in the centre

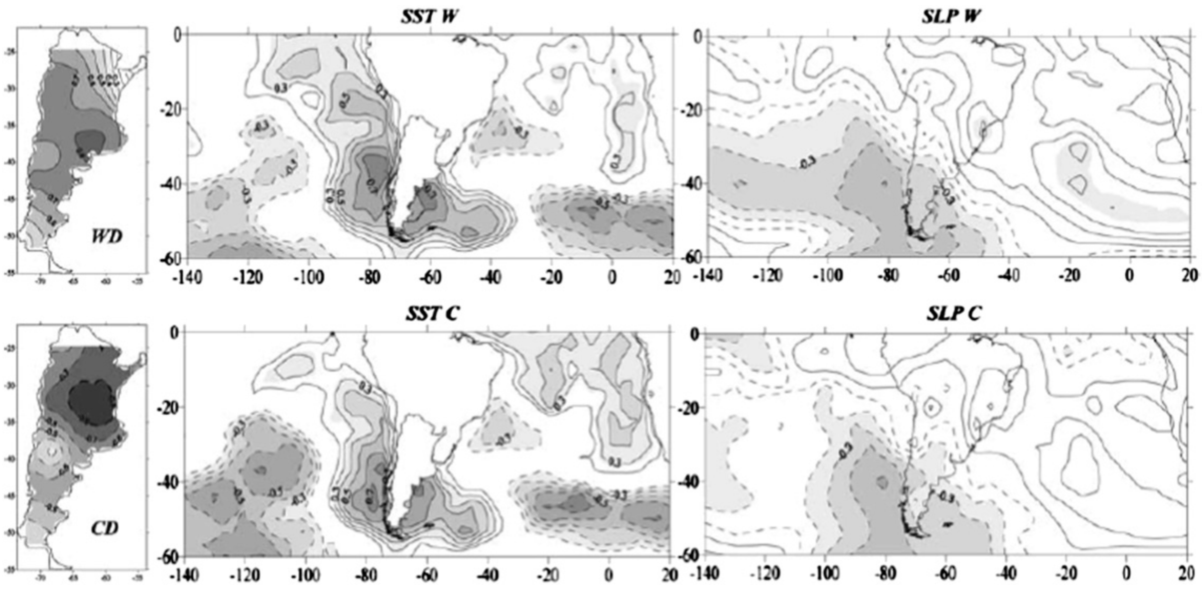

Fig. 9. Correlation map between the SVD time series of WD and the WD grid point anomalies over Argentina. Positive (negative) values show regions with more (less) WD than normal. (top middle) Correlation map between the SVD time series of SST (associated with WD) and the SST grid point anomalies in the SA and SP. (top right) Heterogeneous correlation map between the SVD time series of WD and the SLP grid point anomalies over Argentina, the SA, and SP. (bottom left) Correlation map between the SVD time series of CD and the CD grid point anomalies over Argentina. (bottom middle) Correlation map between the SVD time series of SST (associated with CD) and the SST grid point anomalies in the SA and SP. (bottom right) Heterogeneous correlation map between the SVD time series of CD and the SLP grid point anomalies over Argentina, the SA, and SP. Correlation maps show correlation coefficients between −1.0 and 1.0 and have no units. Centres with correlations higher that ±0.27 are significant at the 95% level and are shaded.
From Rusticucci et al., 2003.

and northeast during the months from October to December. This was the most significant case (cold events during La Niña). It had also an effect on the occurrence of warm events, which were significantly more intense and persistent by the end of the year; therefore, during this phase, the meridional exchanges of extreme air masses were favoured in both directions, as cold events were also more intense. The variability induced by the ENSO phases on the occurrence of events was, for most of the region, lower than 30% of the observed climatic variability.

The temporal patterns (SVD time series) of the warm and cold days (WD, CD) (Rusticucci et al., 2003) in Argentina exhibited significant interannual variability in fall, winter and spring, presenting oscillations of period around 3 to 5 years. In spring ENSO was the dominant SVD mode for warm events. Renom et al. (2011) found that during the austral summer of 1950–1975 period, negative SST anomalies (SSTa) in the tropical Indian Ocean and in small regions close to the coast of South America at about 40ºS were associated with a higher occurrence of cold nights in Uruguay. At the same time, the atmospheric configuration showed a Southern Annular Mode (SAM) in its negative phase with a low pressure anomaly centred off Uruguay that favoured the entrance of cold air from the south. On the other hand, the analysis in the present climate (1976–2005) showed no relationship at all with the SAM. Instead, cold nights are associated with a cyclonic anomaly over South Eastern South America at upper levels. There were significant positive correlations with the SSTa in the South Pacific Converge Zone region and negative correlations over the western South Atlantic and eastern South Pacific. Using an AGCM coupled to a slab ocean they showed that the cyclonic circulation that was related to TN10 was independent of ENSO and forced the SSTa off Uruguay and in the southeastern Pacific. During the winter season the large scale pattern associated with the occurrence of warm nights (TN90) showed significant interdecadal variability. While in 1948–1975 the El Niño phenomenon clearly was the dominant structure in all regression maps of TN90, internal atmospheric variability played an important role after 1976.

4. Frost and cold waves

Frosts are a threat mainly for agriculture in medium latitudes and elevated places so do the extreme cold waves. The study by Scian (1970) represented the first example of interest in extreme temperature events, and it analysed the synoptic situation associated with an episode of very cold temperatures observed during June 1967 in Argentina. Cerne and Rusticucci (1997) studied a cold event that reached tropical latitudes in February 1996, enhanced by a blocking situation that avoided the normal west–east circulation of the synoptic systems in summer. Compagnucci and Salles (1997), amongst others, inferred as one of the surface circulation patterns the pattern associated with these cold air outbreaks. In this manner, it would coincide with the results presented by Vera and Vigliarolo (2000), who gave a detailed description of extreme cold air outbreak dynamics during the winter season based on data gathered over a 6-year period, where it was inferred that the presence of a subtropical upper-level feature played a key role on the cold-surge occurrence over tropical regions of South America. Garreaud (1999) analysed an instance of a cold surge that took place in May 1993, and explained it with a three-stage evolution of the cold air incursion.

On the whole, the processes associated with the entrance of polar masses that generate important damage in the south of South America have been studied in depth. Their effects are different according to the season. In winter, these cold events produce freezing events, whereas in summer they organise deep convections (Garreaud, 2000). These intense cold air advections can reach equatorial latitudes, e.g. as shown by Ronchail (1989). Ambrizzi and Bernardez Pezza (1999) discussed a larger collection of papers that treated polar events in a synoptic–climatic manner. Lupo et al. (2001) examined the climatological, large-scale, and synoptic-scale aspects of South American cold surges using NCEP-NCAR gridded reanalyses for the 1992–1996 period. Marengo et al. (2002) pointed out that the large amplitude upper-level trough in middle latitudes, which extends into the tropics, is one of the major features of the cold situation. These waves embedded in westerly flow are an example of wintertime tropical–extratropical interactions leading to cooling in south-eastern South America.

Prela-Pantano et al. (2009) studied the Medium Paranapanema region (an agricultural area in the State of São Paulo, Brazil) where minimum air temperatures below 5 °C (Tmin5) occur during May to September, with little occurrence of frosts but could be harmful to agriculture. Therefore, data of 13 years were analysed at 7 locations of the region. They said that it was possible to determine that historical series with six years of data were enough for study of the Tmin5 based on Gaussian distribution fitting for different temperature ranges. It was observed that the highest probability for minimum air temperature was about 7% for the whole Medium Paranapanema region in July for temperatures between 0 and 5 °C.

Astolpho et al. (2005) also studied frost in São Paulo. The greater accuracy on the occurrence probability establishment for such events, based on historical data obtained from a larger agrometeorological network, appropriated probabilistic models and modern mapping technical can provides assistance for agricultural risk studies, which are very important for agricultural financing and insurance programmes. The probabilistic model “normal distribution” was used to estimate the punctual risks of yearly minimum air temperatures below 0, 1, and 2 °C for 28 localities of the State of São Paulo, Brazil. They mapped the probabilities by means of geographical information system (GIS) techniques. Multiple regression equations results show that the partial independent variables that better explained the dependent variable “probability” were, in order of importance altitude ($R^2 = 0.74–0.78$), latitude ($R^2 = 0.33–0.44$) and longitude ($R^2 = 0.15–0.20$). The equations generated through multiple regression analyses showed determination coefficients between 0.87 and 0.90. The multiple regression equations generated continuous pixel-to-pixel variations for different classes of probability of occurrence of absolute minimum air temperature. Two maps are presented showing the spatial variability of the frost risk occurrence with minimum temperatures below 1 and 2 °C in Fig. 10.

In Astolpho et al. (2004) the “extreme value distribution” model (Gumbel) was used to estimate the probabilities of monthly (May, June, July, August, September) and yearly frost occurrence for Campinas region in the State of São Paulo, Brazil. It showed good agreement between observed and estimated probabilities for all the monthly and yearly periods based on a 110 years (1891 to 2000) historical series of absolute minimum air temperature. Despite the increase of the average values of the absolute minimum air temperature since 1891 to 2000, the estimated monthly and yearly probabilities showed a great variability during the different periods of years studied. The yearly highest probability of low temperature occurrence (34.2%) was during the 1891/1910 period, while the yearly lowest probability (18.4%) was during the 1941/1970.

In Peru, as part of the study on the Mantaro river basin's (central Andes of Peru) current vulnerability to climate change, the temporal and spatial characteristics of frosts were analysed in Trasmonte et al. (2008). The critical risks were related to high altitudes on the basin (altitudes higher than 3800 m a.s.l.), while the low (or null) probability of occurring risks were found in the lower zones (less than 2500 m a.s.l.). Because of the very intense agricultural activity and the high sensitivity of the main crops (Maize, potato, artichoke) in the Mantaro valley (altitudes between 3100 and 3300 m a.s.l.), moderate to high frost risks can be expected, with a low to moderate probability of occurrence. Another significant result was a positive trend of 8 days per decade in the number of frost days during the rainy season.

The atmospheric circulation associated with frosts in the central region of Argentina with the objective of improving the prediction capacity for these events were studied in Müller (2007) for the 1961–1990 period. Frosts were selected according to a spatial principle, which takes into consideration those events affecting an area above 25% of the weather stations located in the region known as Wet Pampas. Partial frosts (PF, less than 75% of the stations) and generalised frosts (GF, above 75% of the stations). At low levels, the wind prevalence was from the south in the southern section of the continent. At upper levels, this pattern is accompanied by anomalies of the prevailing westerly wind for PF + GF and PF. This means a subtropical jet over South America more (less) intense than normal is associated with a higher (lower) frequency of frost occurrence in the seasonal composites and the annual.

In a complementary paper, Müller and Berri (2007) continued the analysis. GFs were caused by an anticyclonic anomaly that enters South America, generating southerly wind anomalies and cold air advection that are strengthened by the meridional layout of a cyclonic anomaly over the South Atlantic Ocean. In the case of the more persistent events the wind anomaly growed during the previous days and becomes quasi-stationary. Also, the study identified at 250 hPa a double train of eastward-moving Rossby waves along the subtropical and subpolar latitudes, respectively, of the Southern Hemisphere. On the other hand, the propagation pattern during the less persistent GFs showed only one arc-shaped Rossby wave train that reached South America, and then propagated north-eastward. Additionally, there was a subtropical jet entrance/confluence over the western side of the continent that induced a secondary meridional circulation whose subsiding branch facilitated the equator ward displacement of the low-level anticyclone, particularly in the case of the less persistent events.

Numerical experiments confirmed that the principal wave activity takes place inside the subtropical and polar jets. In particular, for the basic state with maximum frequency of GF occurrence, the wave trains propagating inside the subtropical and polar waveguides merge just before entering the continent, as shown by the observations prior to the occurrence of GF events. This configuration favoured the development of an intense south wind anomaly with large meridional extension which results in the intensification of anticyclonic circulation

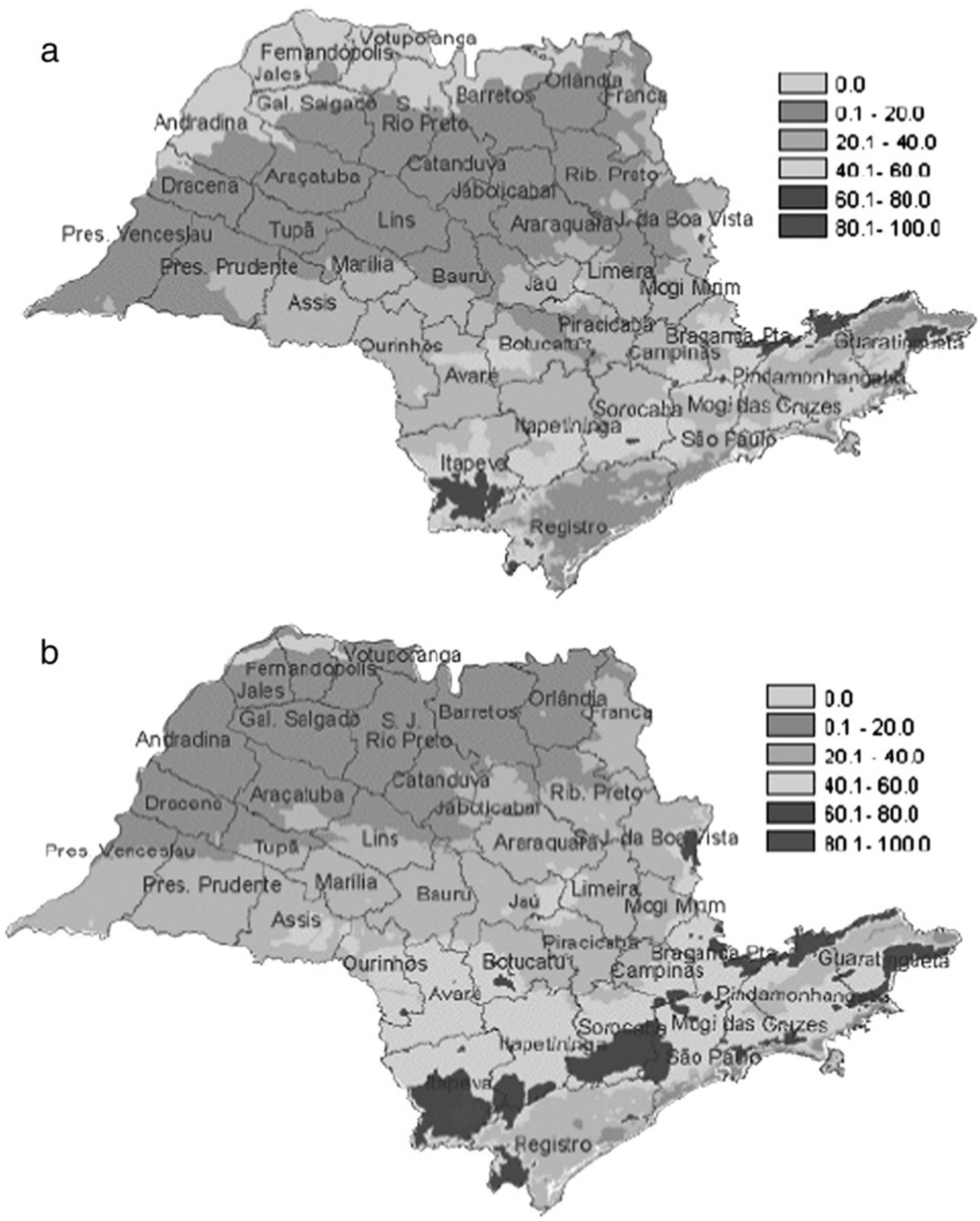

Fig. 10. Risk (%) of occurrence of minimum temperatures below 1 °C (a) and 2 °C (b) in Sao Paulo State. From Astolpho et al., 2004.

in southern South America. A conceptual model was presented to summarise all these results in Müller and Ambrizzi, 2007 (Fig. 11).

Müller (2010) paper focused on the dynamic mechanisms. The objective was to determine whether the conditions found in previous studies for the composite of winters with extreme (maximum and minimum) frequency of GF occurrence respond to typical characteristics of the austral winter or they are inherent to those particular winters. The wave trains excited by anomalous convection situated in specific regions may propagate across the Pacific Ocean and reach South America with the appropriate phase, creating the local favourable conditions for the occurrence of GF. However, the anomalous convection was, by itself, not sufficient since the response also depends on the basic state configuration.

A 1973–2000 synoptic climatology of the surface cyclone and anticyclone tracks associated with cold surges in tropical South America, complemented by the corresponding atmospheric circulation for the period of 1950–2000 was presented in Pezza and Ambrizzi, 2005. Extreme minimum temperatures and frost occurrence from the University of São Paulo meteorological station in São Paulo city (Brazil) were used to select cold events with different intensities. Through a superposition technique, climatological 'clouds' showing all tracks on the same map were produced, adding some new insights into the synoptic patterns of propagation and improving the Southern Hemisphere climatology. For all composites the mean cold front crossed the equator, and the extratropical cyclones also played an important role in favouring frost occurrence in São Paulo. The lagged composites indicated that most of the cold events may be tracked up to 9 days before their occurrence, with a persistent upper level signal in the eastern Pacific.

An objective classification of sequence patterns of 1000 hPa and 500 hPa geopotential heights associated with cold surges

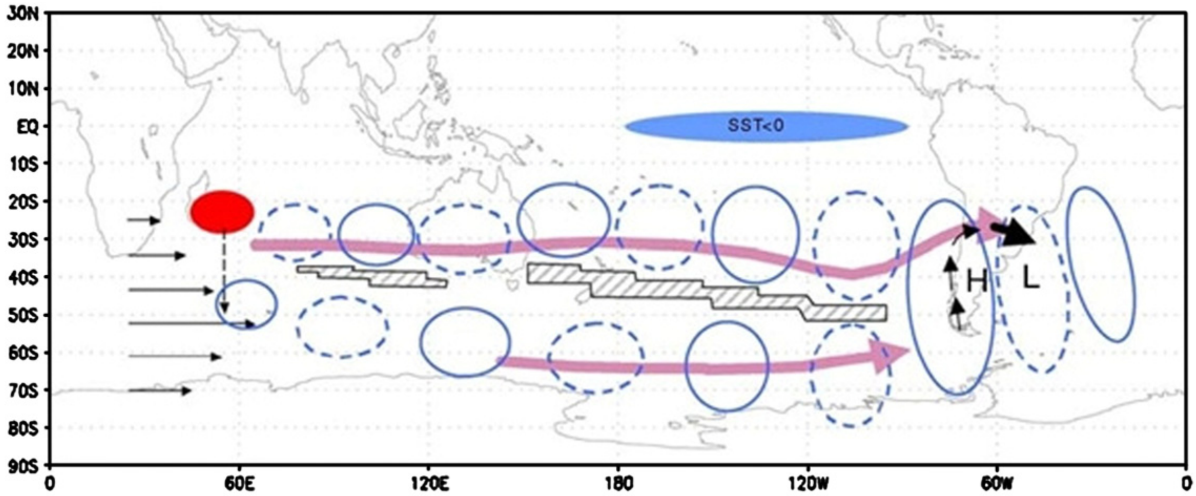

Fig. 11. Teleconnection patterns and Rossby wave propagation associated to generalised frosts over southern South America. From Müller and Ambrizzi, 2007.

over Central Argentina was carried out in Escobar et al. (2004). The rotated Principal Components Analysis was used to obtain the basic patterns of sequence of 1000 hPa and 500 hPa geopotential heights. The winter cold surges during the 1979–1993 period occur in seven patterns at 1000 hPa and three modes at 500 hPa. The combination of both levels shows three typical situations related to cold surges over Central Argentina. The most classic pattern showed an important ridge west of the Pacific coast of the continent at its upper level and a postfrontal anticyclone at its lower level producing cold air advection over Central Argentina. The other two patterns presented a long wave trough at upper levels affecting the continent, one of them with the postfrontal anticyclone moving over middle and low latitudes, and the other with the migratory anticyclone affecting lower latitudes.

On the intraseasonal scale, the relation of extremes and Madden–Julian oscillation (MJO) were explored in Naumann and Vargas (2010). It was found that the different phases of the MJO show a consistent signal on winter temperature variability in south-eastern South America

5. Heat waves

Conversely, the mechanisms associated with tropical air incursions into higher latitudes have been studied in less detail, which can be explained by the fact that cold air incursions are the most relevant mode in the circulation variability (Kousky and Cavalcanti, 1997) or because the heat waves are less common and intense compared to Northern Hemisphere ones. Meridional transport of air masses between the tropics and midlatitudes in South America are the most intense in the entire Southern Hemisphere, mainly due to the presence of the Andes. The incursions of tropical air into midlatitudes occur on the eastern side of the Andes in two preferred regions. The first is located in the tropical latitudes, close to the mountains between 20° and 30°S, and the second is a function of the position of the South Atlantic Convergence Zone (SACZ) (Petrone and Rouse, 2000).

However, it is clear that both temperature extremes are important during every season, as their effects can be beneficial or harmful for a wide range of human activities, such as agriculture, human comfort or energy consumption. The harmful health effects associated with extreme warm events can be mentioned as an example, especially when they occur outside the months of highest temperatures that affect daily activities as was presented in Campetella and Rusticucci, 1998. In this paper, they studied the factors conducting to the occurrence of a strong and long heat wave occurring in March 1980, when school classes had to be cancelled. It was a result of two important factors. One was the persistence of a long-wave ridge over all troposphere in conjunction with the persistence of north-westerly winds which brought warm air with high humidity content from the tropical Atlantic and Amazon Basin. These factors were helped by an intense incoming solar radiation product of the clear days.

Rusticucci and Vargas (1995) studied the surface circulation related to extreme warm and cold temperature situations from the climatic–synoptic point of view, determining the circulation patterns favourable for their occurrence. The extreme summer and winter warm spells occurred because of a general northerly circulation. In winter they were associated with a warm front. The influence of the intraseasonal variability on heat wave development over subtropical South America during austral summer was analysed in Cerne and Vera (2010) that can explain on average at least 32% of summer temperature variance. Moreover, 73% of the heat waves in subtropical South America develop in association with an active South Atlantic Convergence Zone (SACZ). The analysis of pentad maps showed that warm conditions in the region under study developed in association with the strengthening of an anticyclonic anomaly, which was discernible over the subtropical regions at least 15 days before temperature peak occurrence. In addition, the development of the anticyclonic circulation over subtropical South America appeared to be strengthened by the subsidence conditions promoted by the active SACZ, which result in temperature rise in the subtropical region under relatively dry conditions. On the other hand, during the last 2 days of evolution, SACZ activity weakened and the progressive temperature rise in the region was dominated by warmer and moister air being anomalously advected from the north.

The physical process associated with the occurrence of a heat wave over central Argentina during the austral summer of 2002/2003 was carried out in Cerne et al. (2007). It was found that not only the activity of synoptic-scale waves, but also the intraseasonal oscillation variability, had a strong impact on the temperature evolution during this summer. An extratropical anticyclone that evolved along southern South America further intensified subsidence conditions, while horizontal temperature advection began to dominate over central Argentina due to the intensification of the South American low-level jet. The temperature anomalies were at least two standard deviations larger than the climatological mean values and the highest temperature recorded over the last 35 years at several stations of the region.

6. Observations vs. reanalysis and models

A comparison study of station temperature observations with National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis datasets has shown the ability of reanalysis data to reproduce extreme warm and cold events (Rusticucci and Kousky, 2002). There were good agreement between the station data and the Reanalysis grid-point data for low-elevation regions in central and eastern Argentina. The poorest correspondence was in the vicinity of the Andes and, in general, at all low latitudes during summer. The poor correspondence over the Andes was probably due to the differences between model topography and real topography. The poor results during summer (daily values in the Reanalysis were colder than the station data) over northern Argentina imply that there may be differences between model predicted cloudiness, possibly resulting from convection, and observed cloudiness. The analysis of extreme duration events revealed that the Reanalysis data underestimated the intensity of extreme warm events over Northern and Southern Argentina and overestimated winter extreme cold events over central Argentina. These results indicated a negative temperature bias in the Reanalysis data for extreme events. Otherwise there were no differences in extreme events intensity, with the exception of southernmost and higher elevation locations. The NCEP/NCAR Reanalysis data correctly indicated the sign of the 24-h temperature changes in about 60% of the cases, with results being best over eastern and north-eastern Argentina. However, when a comparison was made for cases having the largest negative and positive changes there was less than 40% agreement, and in some cases less than 20% agreement. Thus, the NCEP/NCAR Reanalysis data have to be used with caution for studies of the magnitude of day-to-day temperature changes. The use of anomalies tends to improve the amount of agreement between the Reanalysis data and station observations.

The performance of eight of the global coupled climate models used in the WCRP CMIP3 Multimodel Dataset in simulating annual indices of extreme temperature and precipitation climate events in South America were analysed in Rusticucci et al. (2010). Over southeast South America, a low land region which has more dense information, frost days (FD) average values were well simulated for the period 1961–2000. But over tropical regions, were there is no frost at all, some models gave a number of occurrences different from zero. The other temperature index analysed is the number of warm nights per year. In some cases, warm nights average values are well simulated. The interannual variability pattern was also in good agreement with the observed values. In comparison, the number of warm nights was better represented than the FD. Unfortunately, Amazonia was the worst represented region in South America, because there were very few stations with long records available to the climate community to do this kind of studies.

In Marengo et al. (2010) they found that warming is apparent in observations and models, even though all models (but the GFDL2.0) tend to overestimate the magnitude of the TN90 (warm nights) positive trends, both observations and simulations exhibited positive trends that reach field significance. The warming in the probability distribution of TN90, and the trend analyses documented a substantial rise in warm nighttime temperatures apparent over the 41-year period, and that was well captured by the models. The observed and simulated positive TN90 trends suggested that most of South America has warmed at a similar rate.

Thibeault, et al. (2010) examined CMIP3 multimodel, multiscenario projections of temperature extreme indices for the Altiplano and compute temperature indices for La Paz/Alto, covering 1973–2007. The observed temperature indices at La Paz, were shown to have increasing trends in warm nights and warm spells, which are consistent with increasing temperature trends identified in the tropical Andes by a number of studies The increase in observed frost days was not simulated by the models in the 20th century, and projections of warm nights, frost days, and heat waves were consistent with projected annual cycle temperature increases. However, unexpectedly, frost days and warm nights both exhibited increasing trends. An additional index calculation for cold nights also showed an increasing trend at La Paz. Though this trend was not statistically significant, it provided further evidence that the frequencies of both cold and warm nights were increasing at La Paz. Vincent et al., 2005 also identified positive trends in cold nights and warm nights at Patacamaya covering 1960–2000 that were not statistically significant.

Tencer et al. (2011) presented a south-eastern South American gridded data set of daily minimum and maximum surface temperatures for 1961–2000. They compared the gridded with station data and as expected, the 5th percentile showed an overestimation of the estimated values while the 95th percentile showed an underestimation, both in minimum and maximum temperature, except in the western part of the domain. These differences implied an underestimation of cold and warm extremes. Averaged over the whole region, these differences were positive and showed an underestimation of 1.3 °C for minimum temperature and 0.8 °C for maximum temperature. Differences were generally higher for minimum than for maximum temperature, as expected since daily data was better represented by the interpolation method for the latter. However, in the western part of the region, near the Cordillera de los Andes, differences were always negative, for all percentiles and months and for both variables. This region characterised by high and irregular topography, is also the one that presented the biggest differences of the whole domain. One possible cause could be due to the nearest grid box centre can be up to 50 km away from the station and station elevation may differ significantly from the nearest grid-box elevation station elevations tend to be lower than grid-box elevations, due to stations being located in valleys.

7. Summary

The first thing to note is that there is a geographical imbalance with respect to the number of published studies on temperature extremes. Most of the results come from the southern part of South America, east of the Andes, and a few from the northern part of the continent and for the Altiplano. The workshop organised by the ETCCDMI in Brazil was the first time to have the opportunity to collect information and obtain results in a regional way. The Alexander et al. (2006) paper was enhanced with more data to obtain a better geographical picture that show significant geographical trends in warm (positive) and cold (negative) nights over Southern South America and over the north at the Caribbean coast.

All other studies based on smaller regions also agree in finding the most significant trends in the evolution of the minimum temperature, with positive trends in almost all studies on the occurrence of warm nights (or hot extremes of minimum temperature) and negative trend in the cold extremes of the minimum. On the other hand, on the maximum temperature behaviour there is little agreement, but generally the maximum temperature in South America has decreased, but in the case of Venezuela, that has increased.

The studies that tried to understand the dynamics of the circulation that leads to the occurrence of these extremes are analysed from its occurrence in almost all scales from the synoptic, intraseasonal, seasonal, annual, and multi-year linear trend with different methodologies, also, indentifying the local and remote forcing.

A gap was found in studies that relate some specific local forcing (like changes in land use) and compare it with the remote ones. Different aspects of the occurrence of the temperature extremes are still missing in some regions of the continent, like more dense and extended databases and local studies. These studies could improve the confidence on continental scale results.

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