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Oceanic influence on southernmost South American precipitation

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RESUMEN

En este trabajo se analiza la posible influencia oceánica en la variabilidad de la precipitación sobre el extremo sur de Sudamérica desde 1930. El objetivo es definir características oceánicas que pueden producir condiciones de más o menos lluvia en diferentes escalas de tiempo en la mencionada región. Los resultados sugieren importantes relaciones entre los océanos y la precipitación en oscilaciones decadales e interdecadales. El este y centro del índico subtropical, el oeste del Pacífico tropical y el oeste y centro del Pacífico subtropical podrían estar influenciando la precipitación en escala decadal. Por otra parte, la región este tropical y oeste subtropical del índico, y el oeste y centro del Pacífico subtropical podrían influenciar la variabilidad de la precipitación en escala interdecadal. Si bien el estudio se enfocó en la variabilidad de la precipitación, relaciones entre diferentes regiones de los océanos Índico y Pacífico en escalas decadal e interdecadal han sido también detectadas. Por lo tanto, los resultados aquí presentados pueden también ser útiles para describir nuevos aspectos de la influencia remota de ambos océanos en el clima regional.

ABSTRACT

The potential oceanic influence on southernmost South American precipitation since 1930 is analyzed in this study. The aim is to define oceanic characteristics that can produce wetter or drier conditions over the mentioned region on different time scales. Results suggest important precipitation-oceanic links in decadal and interdecadal oscillations. The eastern and central subtropical Indian, western tropical Pacific and western and central subtropical Pacific could be forcing the precipitation on decadal time scale. Moreover, the eastern tropical and western subtropical Indian and western and central subtropical Pacific could be forcing the variability of precipitation on interdecadal time scale. Although the research was focused in forcing of precipitation, relations among different regions of the Indian and Pacific oceans on decadal and interdecadal time scales have also been detected. Therefore, results presented here can be useful in describing new aspects of the remote influence of both oceans on regional climate.

Keywords: Patagonia, precipitation variability, decadal and interdecadal oscillations, precipitation-oceanic links, wavelet analysis.

1. Introduction

The influence of the sea surface temperature (SST) of the Indian and Pacific Oceans on the variability of precipitation over the South American area to the east of the Andes and south of 20º S, hereafter referred as Southern South America (SSA), has been analyzed by several authors using different methodologies. The widely documented El Niño-Southern Oscillation (ENSO) signal on precipitation over SSA (e.g., Ropelewski and Halpert, 1987; Aceituno, 1988; Montecinos *et al*., 2000) has been explained not only in terms of the Rossby waves excitation in the tropical Pacific (e.g., van Loon and Shea, 1987; Karoly, 1989), but also in terms of the role that the variability of the SST in the subtropical Pacific has in favoring or obstructing the propagation of such waves to remote regions (Barros and Silvestri, 2002; Vera *et al*., 2004).

Linkages between rainfall variability over South America and SST anomalies were examined by Nogués-Paegle and Mo (2002) showing evidence of the tropical Pacific influence on the austral summer precipitation over an area covering most of northern SSA. Such influence is established via the Pacific South American 1 (PSA1) Rossby wave train (Karoly, 1989) which has been associated with the ENSO variability by different authors (e.g., Karoly, 1989; Karoly *et al*., 1996; Mo, 2000).

The analysis performed by Peterson and White (1999) describes slow teleconnections linking the western subtropical South Pacific with Southern Hemisphere SST, sea level pressure and precipitable water. This study describes SST anomalies propagating around the southern oceans in tandem with atmospheric circulation and precipitation anomalies. In particular, the coupled ocean-atmosphere system suggests links between the western subtropical Pacific and the precipitation over SSA.

Whether or not the Indian Ocean Dipole (IOD) (e.g., Saji *et al*., 1999) can be considered as an oscillatory mode of internal atmosphere-ocean dynamics in the tropical Indian Ocean is still under debate (e.g., Baquero-Bernal *et al*., 2002; Dommenget and Latif, 2002). However, evidence about the influence of the IOD on the South American precipitation during austral spring was presented by Chan *et al*. (2008). They describe a Rossby wave train generated by the IOD divergence/ convergence anomalies over the tropical Indian Ocean and propagating to the subtropical South Atlantic. The equivalent barotropic structure influences the local surface circulation affecting the precipitation over the eastern subtropical South American continent. Influence of different areas of tropical and subtropical Indian Ocean on austral spring precipitation over subtropical SSA was also shown by Barros and Silvestri (2002).

The analysis performed by Silvestri (2004) suggests an influence of both tropical-subtropical Indian and tropical Pacific in the variability of the austral summer precipitation over subtropical areas of SSA. Specifically, Rossby waves propagating from each oceanic region generate dynamical conditions that affect the development of rainfall over the eastern subtropical part of SSA. The influence of austral summer low-frequency SST variability of the Indian and western Pacific on the interannual variability of the South American precipitation via Rossby wave trains was also described by Drumond and Ambrizzi (2008). More recently, the influence of both tropical Indian and Pacific oceans in the austral winter precipitation over areas of western SSA near the Andes Cordillera was found by González *et al*. (2010) and González and Vera (2010). They show that the oceanic conditions in both tropical basins excite Rossby wave trains which extend towards South America affecting the atmospheric circulation in the western SSA region. As a result of these local atmospheric anomalies, the precipitation in the area is also affected.

Studies mentioned in the previous paragraphs present evidence of the influence of different regions of the Indian and Pacific oceans on the variability of precipitation over SSA. The physical processes involved in these relations are described in terms of Rossby waves propagation from specific oceanic regions to the surroundings of South America. Such atmospheric teleconnections in the Southern Hemisphere can be better understood taking into account additional descriptions provided by Karoly *et al*. (1989), Berbery *et al*. (1992), Pisciottano *et al*. (1994) and Grimm and Ambrizzi (2009), among others.

There is a lack in the analysis of the oceanic influence on the precipitation over southernmost SSA because the existing studies for the region have been focused on the influence of the tropical Pacific by the action of ENSO events (e.g., Aceituno, 1988; Schneider and Gies, 2004; Aravena and Luckman, 2009) without going into a description of the possible impact of other oceanic regions. To describe in detail the influence of different oceanic forcing in the climatic variability of southernmost areas of SSA is very important not only in order to know the forcings of the present climate, but also for inferences about the causes of the notable changes in the past, detected by paleoclimatic proxy data related with precipitation changes in the region.

The southernmost area of SSA was historically a region little inhabited where the climatic information is available in only a few stations. Therefore, it is important to take into account that the longest and reliable observed precipitation data record of the region is available from the station of Río Gallegos (51º S-70º W, Fig. 1) of the Servicio Meteorológico Nacional (national meteorological service) of Argentina in the Santa Cruz Province being series without missing values during the last eighty years. Furthermore, the Laguna Potrok Aike maar lake located at roughly 90 km to the west of Río Gallegos, is potentially the only lake in SSA holding a record that spans several glacial to interglacial cycles (Zolitschka *et al*., 2006).

Haberzettl *et al*. (2005) described the hydrological characteristic of the Laguna Potrok Aike: *The catchment area (>200 km^2) reaches far south into the Chilean part of the Pali Aike Volcanic Field. However, linear runoff only occurs episodically through a few canyons and arroyos mainly after snow-melt in spring. In summer 2002 the lake level was at 113 masl and the maximum water depth was approximately 100 m. Interannual lake level fluctuations are estimated to be in the range of 0-7 m*. The water level is highly sensitive to changes in the precipitation/evaporation ratio (P/E) with a potential evaporation of 0.5-10 mm per day (Borrelli and Oliva, 2001). This dependence was validated for the period 2001 to 2005 through a modeling study of the hydrological balance incorporating meteorological instruments, stable isotope data and bathymetric information (Anselmetti *et al*., 2009). Consequently, the Laguna Potrock Aike lake level results extremely sensitive to precipitation variability.

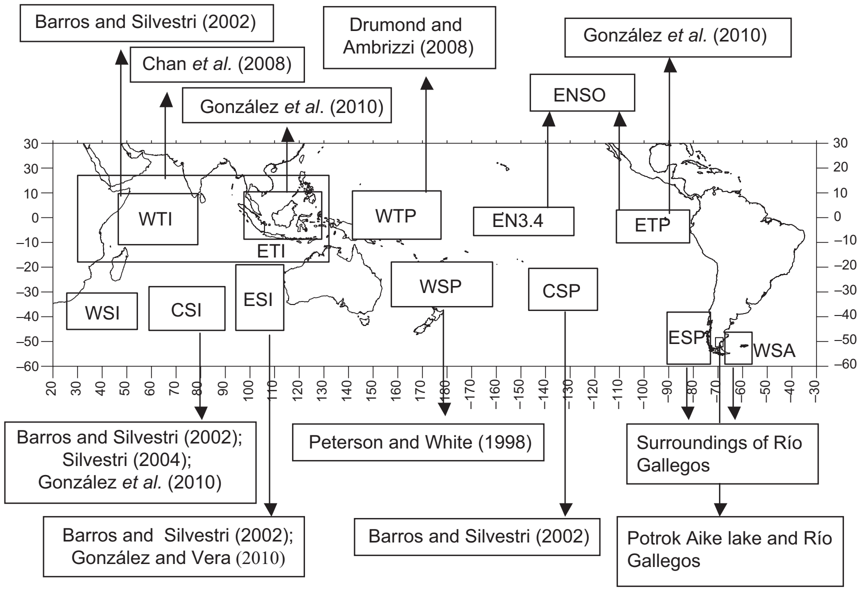


Fig. 1. Location of the Laguna Potrok Aike maar lake and the station Río Gallegos and the oceanic regions considered in the analysis. See text for the bibliography indicated in the figure.

Unfortunately, the available instrumental lake level register is reduced only at 2006, that was considered as reference level, and 2002, with 3.5 m lower (information from The Potrock Aike Maar Lake Sediment Archive Drilling Project (PASADO) public presentation; in http://www.pasado.uni-bremen.de). Due to this lack in the lake level data, we consider that the best long term information available at this moment is the inference of Haberzettl *et al*. (2005) about the qualitative variability for the last 1600 years (Fig. 2) with roughly annual or less resolution. On the other hand, accordingly to Hoffmann *et al*. (1997) the annual precipitation of Río Gallegos from 1928 to 1990 had a mean value of 250 mm/year with a non-significant long term change and the series show a period during the 1960s with less precipitation. This period with negative anomalies of precipitation is coincident with the minimum registered in the Laguna Potrok Aike level (Fig. 2). Additionally, the large suite of geophysical data collected in Laguna Potrok Aike helps to link the subsurface of the lake and the modern lake floor morphology with the subaerially exposed deposits from previous lake level highstands. The resulting past lake level evolution is thus not only a relative record of wetter and drier periods, but also provides quantitative information because it is based on a dated subaquatic and subaerial succession of shorelines (Anselmetti *et al.*, 2009). Therefore, the aim of this analysis is to study the relation in

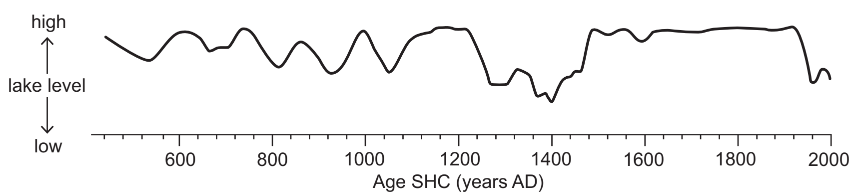


Fig. 2. Lake-level curve of Laguna Potrok Aike inferred from selected sediment parameters since AD 400 to present (Age SHC: Southern Hemisphere Calibrated radiocarbon ages) [adapted from Haberzettl *et al*., 2005].

time and frequencies between the annual precipitation in Río Gallegos and the SST in different oceanic basins that would be potentially forcings of the observed changes. It is important to answer two specific questions: 1) Which oceanic regions were linked with the precipitation in the whole space of frequency? 2) How stationary were the relations across time? Addressing these questions can aid in the understanding of the causes of the previously mentioned climatic fluctuations in southernmost areas of SSA. Since previous results indicate a good agreement between the variability of the annual precipitation in Río Gallegos and the lake level changes, the uniform rainfall distribution through the year in this subpolar region (Prohaska, 1976), and considering that the proxy data as the concomitant paleodata has annual or less resolution, this study is restricted to annual precipitation time series to analyze the variability at interannual scale or less frequency. The results will be an important contribution to the understanding of the present process of the fluctuation in the precipitation and past climate change reflected in the lake paleo-climate archives as levels alteration, that will be available for the whole Holocene or more in the future.

The paper is organized as follows. Data are described in section 2, and the methodology is detailed in section 3. Results are presented in section 4. The main conclusions are summarized in section 5.

2. Data

Monthly anomalies of SST were extracted from the Hadley Centre SST data set (HadSST2, Rayner *et al*., 2006), being anomalies with respect to the 1961-1990 means. The Servicio Meteorológico Nacional of Argentina provided the monthly precipitation at Río Gallegos (PP_{RG}) for the period 1930-2008. To be consistent with the SST dataset, monthly precipitation anomalies with respect to the 1961-1990 means were calculated. The analysis was performed for the period 1930-2008 considering annual means of monthly anomalies of both PP_{RG} and SST.

3. Methodology

3.1 Selection of oceanic regions

The precedents listed in section 1 about the influence of the SST of the Indian and Pacific oceans on SSA precipitation variability were taken into account to select specific oceanic regions in which to focus the analysis. The regions and the corresponding references are shown in Fig. 1.

Five regions were delimited in the Indian Ocean. The influence of the IOD on SSA precipitation described by Chan *et al*. (2008), the significant relation between western tropical Indian with the subtropical SSA precipitation showed by Barros and Silvestri (2002) and the relation between the eastern tropical Indian with the precipitation near the eastern slope of southern Andes showed by Gonzalez *et al*. (2010) were considered in order to select the two regions in the tropical ocean identified as Eastern Tropical Indian (ETI) and Western Tropical Indian (WTI). The Central Subtropical Indian (CSI) region was delimited in consideration of its relations with the precipitation over SSA showed by Barros and Silvestri (2002), Silvestri (2004) and González *et al*. (2010) while the results of Barros and Silvestri (2002) and Gonzalez and Vera (2010) suggest the isolation of the Eastern Subtropical Indian (ESI) region. Although there are no precedents for the possible influence of the Western Subtropical Indian (WSI) region on precipitation over SSA, it was also considered in the analysis.

In the tropical Pacific, the typical El Niño 3.4 (EN34) region was taken into account as well as the Eastern Tropical Pacific region (ETP) around the El Niño 1+2 sector for which González *et al*. (2010) show a relation with western SSA precipitation. The Western Tropical Pacific region (WTP) was considered following the conclusions of Drumond and Ambrizzi (2008). According to the results of Peterson and White (1999) the Western Subtropical Pacific region (WSP) was delimited as well as the Central Subtropical Pacific region (CSP) similar to that defined by Barros and Silvestri (2002).

Although the oceanic regions in the tropical-subtropical areas of Indian and Pacific oceans were chosen based on results of previous studies performed for seasonal means, it is clear than such regions are almost uniformly distributed over each ocean. In other words, the selected regions cover the eastern, central and western areas of tropical and subtropical Indian and Pacific oceans.

Oceanic regions in the surrounding of the SSA were also considered in the analysis. Specifically, the regions Eastern South Pacific (ESP) and Western South Atlantic (WSA) were incorporated into the study.

3.2 Relations between time series

In order to analyze relations between time series at multiple periodicities, the wavelet coherence analysis (WTC) (Torrence and Compo, 1998; Torrence and Webster, 1999; Grinsted *et al*., 2004) was applied. This methodology is especially useful in highlighting the time and frequency intervals for which two time series have strong interaction. Detailed information about calculation and interpretation of WTC results can be found in Grinsted *et al*. (2004) and Velasco and Mendoza (2008), among others. To summarize, the wavelet squared coherency is a measure of the intensity of the covariance of the two series in time-frequency space (Torrence and Webster, 1999). When the WTC = 1 it indicates that all frequency components of the output signal (reaction of the system) correspond to the input (action) meaning that there is synchronization between the output signal and the input signal. The synchronization can be in phase, frequency and/or amplitude (Velasco, 2010).

If WTC is small, then the reaction of the system is not related to action due to the presence of noise, nonlinearities and time delays in the system (Velasco, 2010). Another way to calculate the coherence of the system is through the relation signal/noise (Velasco *et al*., 2010) $WTC_{s/n}$ as:

$WTC_{s/n} = WTC \times (1\text{-}WTC)^{-1}$. This method was used in this work because it allows the minimization of the effects of noise and to find the characteristics of each relationship.

If the coherence of two series is high, arrows in the coherence spectra show the phase between the phenomena. Arrows at 0º (horizontal right) indicate that both phenomena are in phase, and arrows at 180º (horizontal left) indicate that they are in anti-phase. Arrows at other angles (vertical up and down, etcetera) indicate an out-of-phase relation which means that the two phenomena have a lagged time link. The statistical significance level of the wavelet coherence is estimated using Monte Carlo methods with red noise to determine the 95 % significance level (Torrence and Webster, 1999).

Since the wavelet transform is a band pass filter, the reconstruction of the time series or the decomposition of a signal can be obtained from the wavelet inverse (Torrence and Compo, 1998). This methodology was applied here to isolate specific oscillations in the analyzed time series. It is important to mention that the definition of wavelet coherence closely resembles the typical correlation coefficient, that can be thought of as a localized correlation coefficient in the space of time frequency (Moore *et al*., 2006).

Several precedents exist for the application of this methodology in diverse areas of science including studies on oceanic and atmospheric variability (e.g., Jevrejeva *et al*., 2004; Müller *et al.*, 2008).

4. Results and discussion

4.1 Indian Ocean

In the tropical Indian Ocean, the wavelet coherence analysis reveals poor connections between the time series of PP_{RG} and the SST in the region WTI (Fig. 3a). Significant links take place only during the 1980s-1990s in periodicities shorter than 5 yr being lagged time relations as are expressed by the non-horizontal orientation of the corresponding phase arrows.

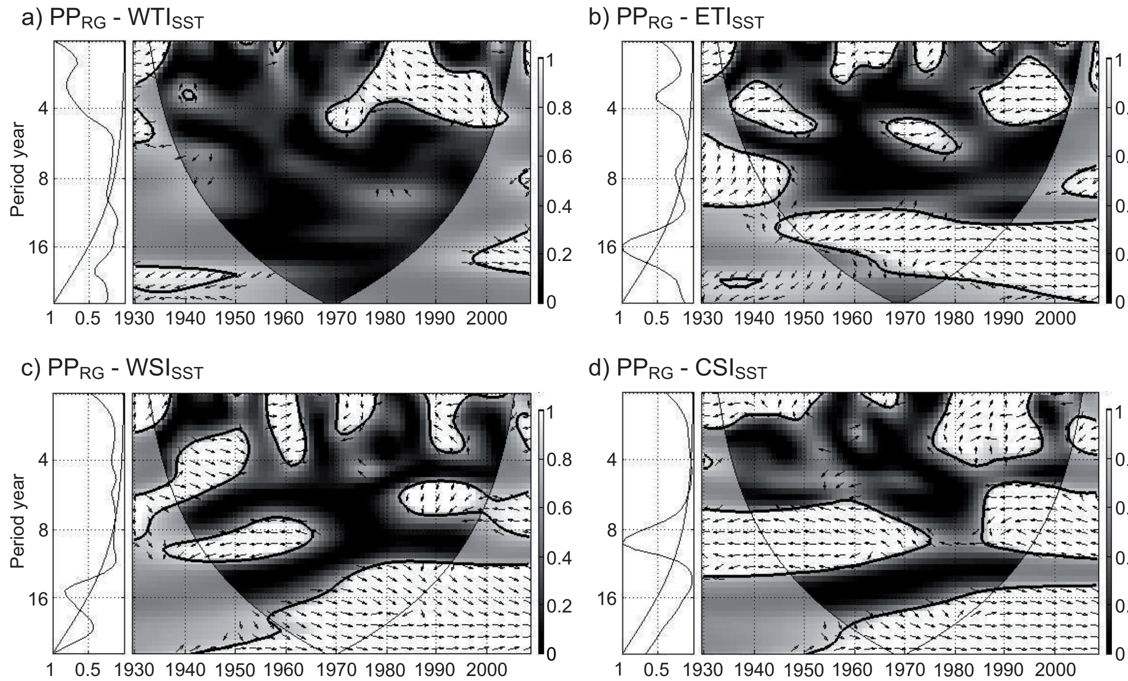
The relation between PP_{RG} and SST in the tropical region ETI is mainly characterized by a stationary in-phase relation in interdecadal time scales (bands around 15 yr) after the 1950s describing a connection of type warm (cold) ocean-more (less) precipitation in this specific periodicity (Fig. 3b). Together with these in-phase links, there are relations in anti-phase in waves shorter than 2 yr around 1960, in waves of around 5 yr in the 1970s and in waves of around 4 yr in the 1990s. In phase relations in periodicities around 4 yr during the 1940s and lagged connections in bands around 8 yr during 1930s-1940s are also detected. These results show a relation between PP_{RG} and ETI_{SST} in which over the stationary in-phase relation in the interdecadal band overlap other relations in phase, anti-phase or time lagged during some specific decades in the shortest waves. This suggests that the eastern tropical Indian Ocean could have acted as a forcing of the PP_{RG} in different ways depending on the band of frequency and the timeframe in question.

In the subtropical areas, the most prominent feature in the wavelet coherence analysis between PP_{RG} and the SST in the region WSI is the in-phase or quasi-in-phase connections in the interdecadal band after the 1960s suggesting a relation of the type a warm (cold) ocean-more (less) precipitation (Fig. 3c). Significant time lagged relations are also observed in the shortest periodicities during specific years.

The link between PP_{RG} and SST in the region CSI is mainly characterized by a significant anti-phase relation in the decadal time scale (oscillations around 8 yrs) (Fig. 3d). The suggested connection is the type warm (cold) ocean-less (more) precipitation for this band of variability but there is a clear interruption around 1980 coinciding with the 1976-77 climate shift (e.g., Nitta and Yamada, 1989; Trenberth, 1990). The analysis also reveals significant time lagged relations in oscillations shorter than 4 yr 1930s-1940s and 1980s-1990s. Although they are not significant in the global wavelet coherence spectrum, in-phase relations in the largest periodicities seem to be important after the 1960s.

The SST in the region ESI has significant in-phase or quasi-in-phase relations with PP_{RG} in the shortest oscillations before the 1960s occurring simultaneously with quasi-anti-phase links in oscillations of the decadal time scale (Fig. 3e).

For the shortest oscillations, results here reported describe significant relations between the time variability of PP_{RG} and the SST of the Indian Ocean, being in-phase, anti-phase or time lagged relations, only during specific years. Although it could be possible that atmospheric



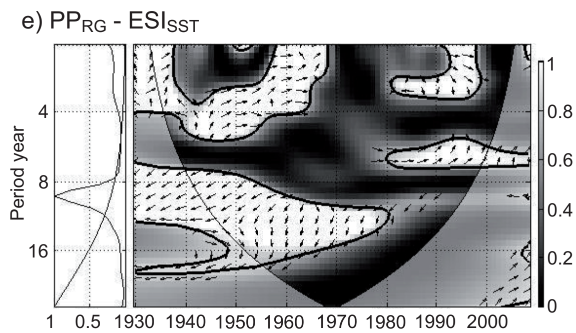


Fig. 3. Wavelet coherence analysis of the PP$_{RG}$ and Indian Ocean SST series. Wavelet coherence (right) and significance level of the global spectrum (left) are shown for each case. The 95% significance level against red noise is marking with the black curve in the global spectrum. Areas statistically significant at the 95 % level against red noise are limited with the black curve in the wavelet coherence and arrows indicate the relative phase relationship (see text for details).

perturbations have been temporarily excited in these oceanic regions establishing relations with the precipitation, the non-stationary character of such relations make it difficult to associate physical explanations for them. In contrast, the stationary or almost stationary character of the relation of the PP$_{RG}$ with three specific oceanic regions suggests the existence of dynamic mechanisms establishing a real physical connection between these variables. Such special cases are the relation of PP$_{RG}$ with the SST in CSI region in the decadal time scale and the links of PP$_{RG}$ with the SST in regions ETI and WSI in interdecadal oscillations. Mechanisms associated to Rossby wave propagation (see section 1) could explain these connections. The band pass filtered series was applied to confirm all mentioned significant relations. As an example, the relation between PP$_{RG}$ and SST in the region ETI in the interdecadal time scale is shown in Figure 4. The similarity of both interdecadal time scale components after the 1950s is clear as well as the disconnection in 1930s-1940s.

The in-phase or quasi-in-phase common relations between PP$_{RG}$, ETI$_{SST}$ and WSI$_{SST}$ in interdecadal scales suggest at least two options: The atmospheric perturbations reaching SSA in

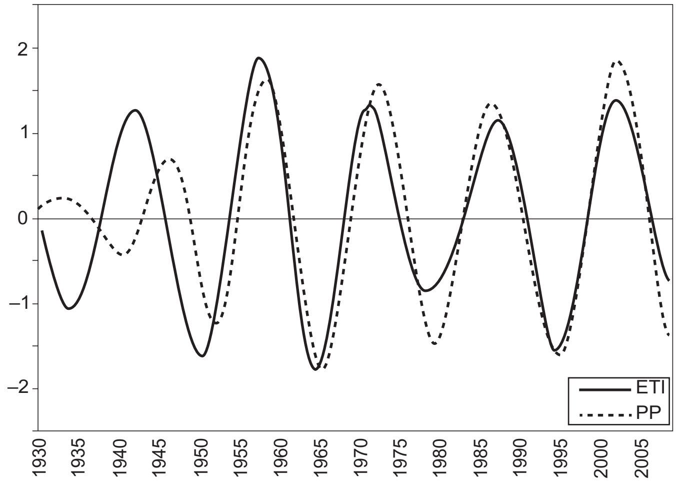


Fig. 4. Standardized band pass filtered series of PP_{RG} and ETISST for the interdecadal time scale.

such time scales are excited in both areas of the Indian Ocean or such perturbations originate in one of these regions and have a spurious connection with the other one. The statistical analysis here presented does not allow a distinction to be made between these options. Focusing the attention on the relations among different oceanic regions, the significant links of PP_{RG} with both ETI_{SST} and WSI_{SST} in interdecadal oscillations suggest a close connection between the two SST series in this specific band of variability. In fact, significant links are observed between ETI_{SST} and WSI_{SST} in the shortest oscillations during some years but the most prominent feature of their relation is the stationary in-phase or quasi-in-phase link in interdecadal periodicities (Fig. 5a). Stationary connections only in the interdecadal time scale are also observed between both series and CSI_{SST} (Figs. 5b-c) and between the WTI_{SST} and CSI_{SST}, except around 1980 (Fig. 5d). The regions CSI and ESI have sporadic links in the shortest oscillations and stationary time lagged relations in the decadal band (figure not shown).

4.2 Pacific ocean

In the tropical Pacific, the PP_{RG} has a significant lagged time relation with the SST in the region WTP in the decadal time scale from the 1930s to 1980s (Fig. 6a). In-phase or quasi-in-phase links in oscillations of the 4-8 yrs (into the ENSO time scale) during the 1990s-2000s are the most prominent feature revealed by the wavelet coherence analysis for the relations of PP_{RG} with the SST in the regions EN34 and ETP (Fig. 6b-c). These results clearly demonstrate that the variability of precipitation over southernmost South America does not have an important connection with the central and eastern areas of the tropical Pacific.

In the subtropical areas, time lagged links in decadal oscillations exist between PP_{RG} and the SST in the regions WSP and CSP before the 1980s (Fig. 6d-e). In both cases, the wavelet coherence analysis also reveals significant in-phase links in the interdecadal time scale since the 1950s describing a connection of the type warm (cold) ocean-more (less) precipitation over southernmost South America.

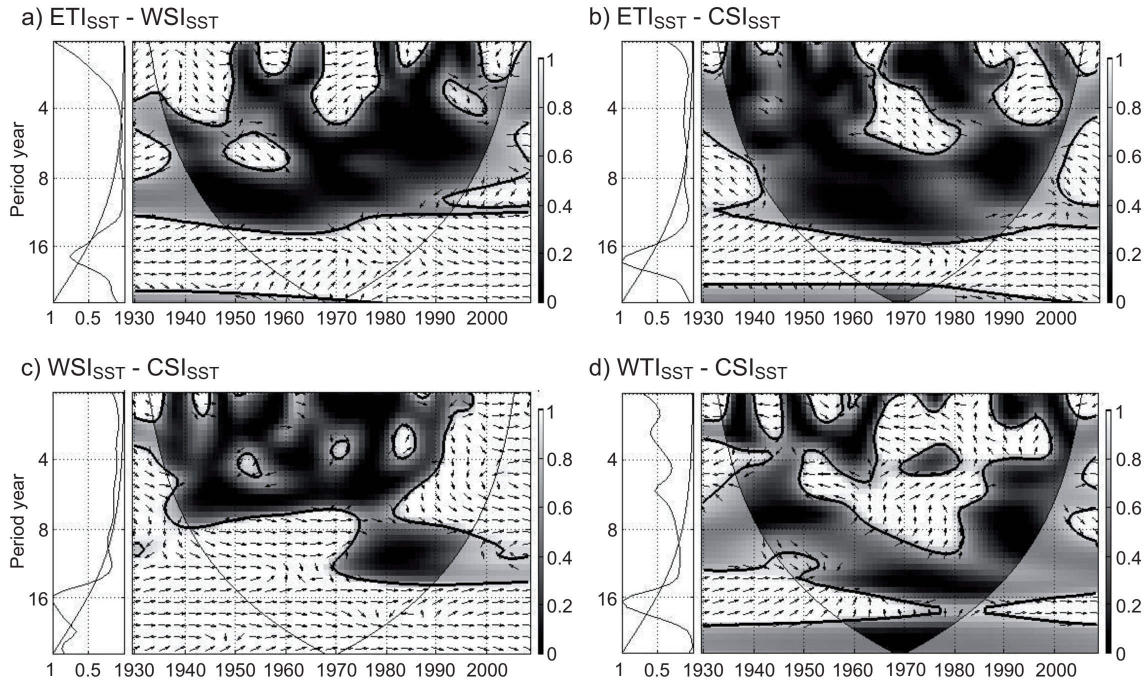


Fig. 5. As Fig. 3 but for relations among Indian Ocean SST series.

A complex pattern in the space of frequencies is described by the relations between PP_{RG} and the SST in the region ESP (Fig. 6f). Significant links occur in oscillations shorter than 15 yr in different periods of time but have, in general, an anti-phase character.

As a consequence of the preceding analysis of statistical relations between the time series of PP_{RG} and the SST in different areas of the Pacific Ocean, links among some oceanic regions are clearly detected. Specifically, the western tropical, western subtropical and central subtropical areas of the Pacific have a common relation with PP_{RG} in decadal time scale before the 1980s suggesting that these three oceanic regions are interlinked in this band of variability. This characteristic comes to light with the wavelet coherence analysis performed for the mentioned SST, being easy to see the significant in-phase or quasi-in-phase relations in the decadal band (Fig. 7a-c). The common association of the western and central regions of the subtropical Pacific with the PP_{RG} in the interdecadal band suggests that both oceanic areas also have significant co-variability in that periodicity. It is confirmed by the wavelet coherence analysis performed for the corresponding time series of SST (Fig. 7c). The band pass filtered series isolating the interdecadal periodicities clearly shows the mentioned similarity between the variability of PP_{RG} and the western subtropical and central subtropical Pacific after the 1960s as well as the in-phase relation between both oceanic regions since 1930 (Fig. 8).

4.3 Indian-Pacific oceans

To detect real or spurious precipitation-SST links in decadal and interdecadal time scales is a very complex problem because regions of the Indian and Pacific oceans have the same relations with the southernmost South America precipitation, but they also have relations between themselves.

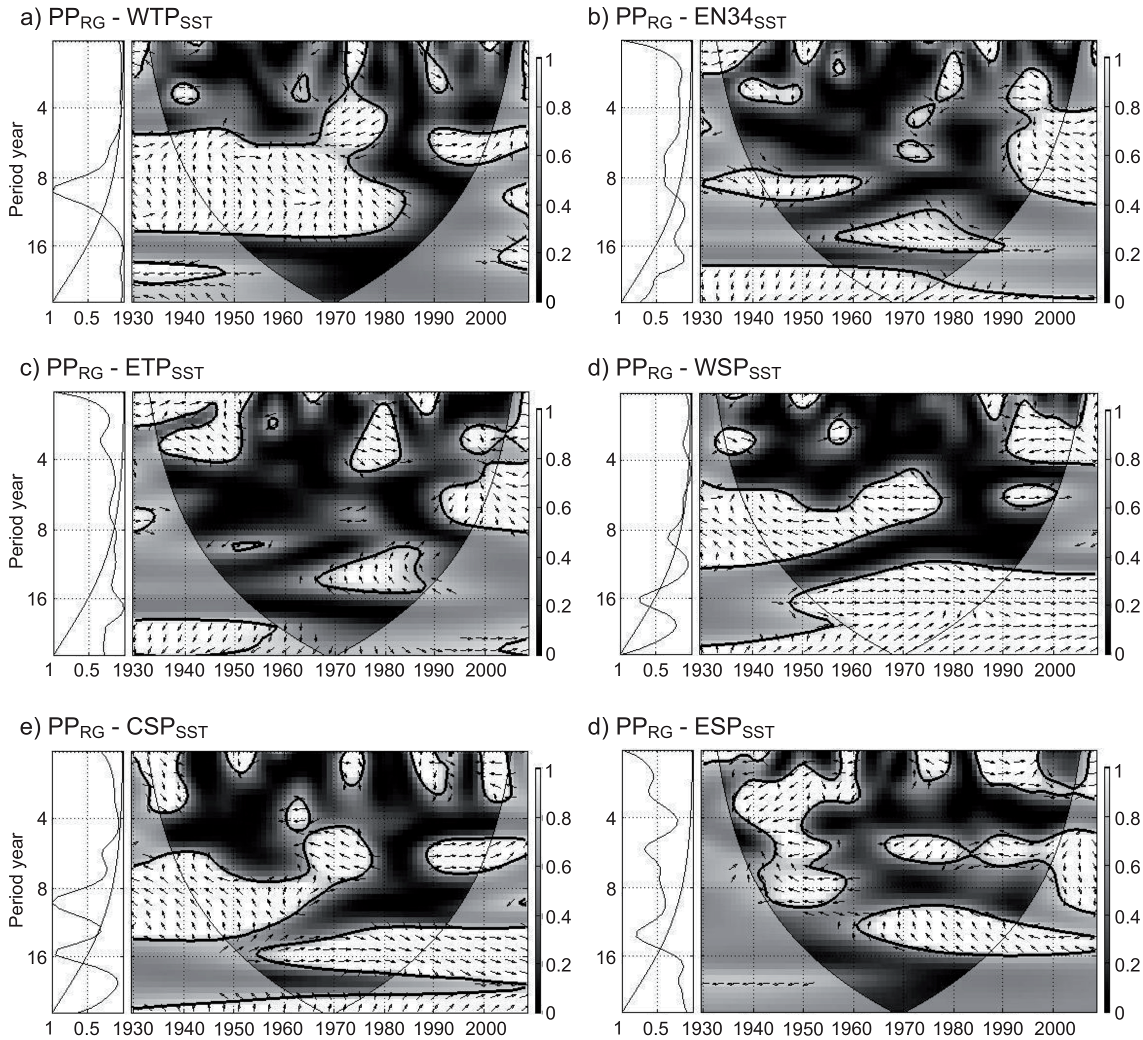


Fig. 6. As Fig. 3 but for relations of PP_{RG} with the Pacific Ocean SST series.

In fact, the regions ESI and CSI in the Indian Ocean and WTP, WSP and CSP in the Pacific have a common relation with PP_{RG} in the decadal time scale (Figs. 3 and 6), but they also have significant links between them in this band of variability (see Fig. 7 for regions in the Pacific; the other figures are not shown). In the interdecadal time scale, the regions ETI and WSI in the Indian Ocean and WSP and CSP in the Pacific have in-phase links with PP_{RG} (Figs. 3 and 6), but they are also linked between themselves in each basin (Figs. 5a and 7c) and with the regions of the other ocean (Fig. 9). It is important to point out that the interdecadal band is the only one in which the mentioned regions of the Indian Ocean are stationary linked with the regions of the Pacific Ocean.

4.4 Atlantic Ocean

The wavelet coherence analysis performed between the PP_{RG} and the SST of the surrounding Atlantic shows that these time series have significant relation only in oscillations shorter than 8 yr during

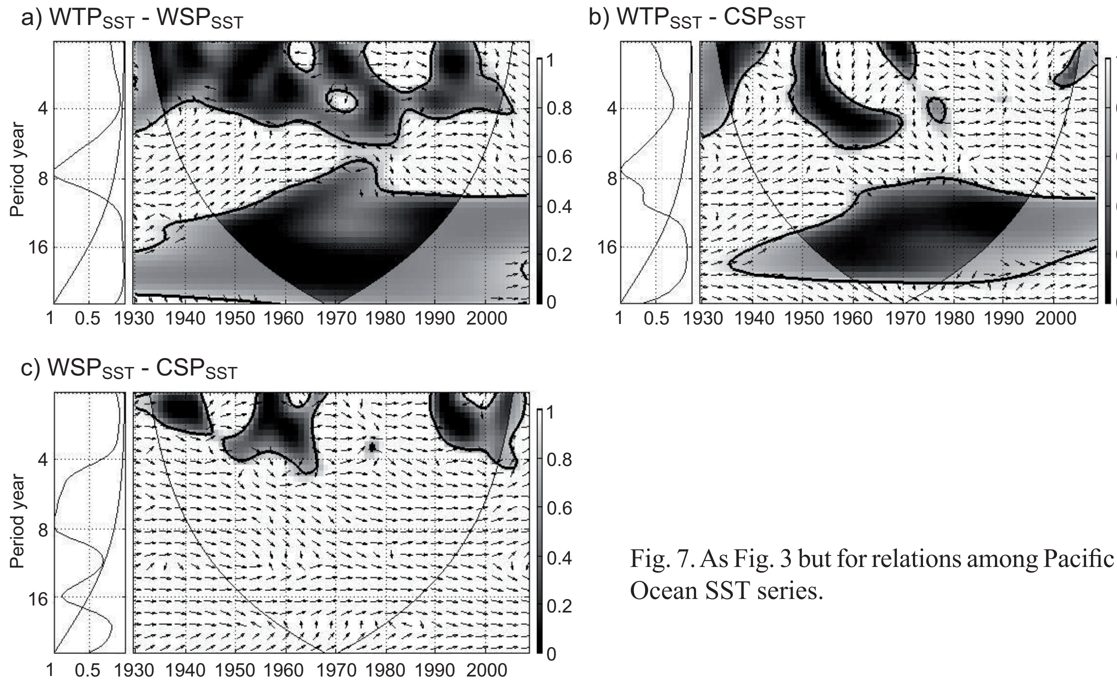


Fig. 7. As Fig. 3 but for relations among Pacific Ocean SST series.

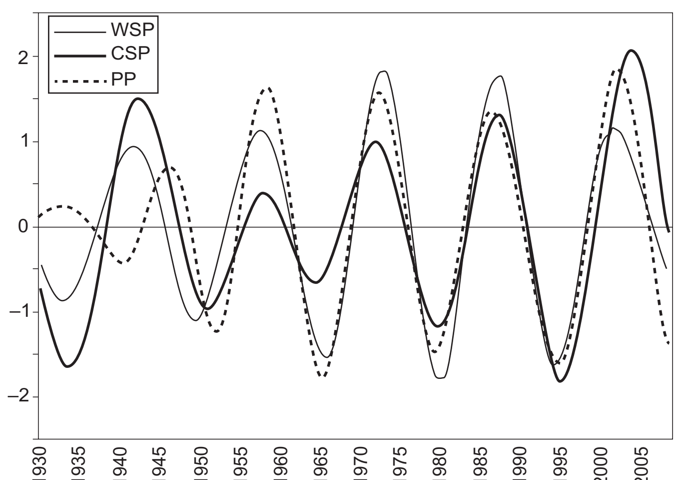


Fig. 8. Standardized band pass filtered series of PP_{RG}, WSPSST and CSPSST for the interdecadal time scale.

some specific decades (Fig. 10). In other words, the conditions leading to more or less precipitation over southernmost South America seem to be indifferent to the characteristics of the SST in the southwestern portion of the Atlantic Ocean.

5. Conclusions

Southernmost South America is a region of low population in which complete and reliable climatic information is available from only a few stations. In the area to the east of the Andes Cordillera

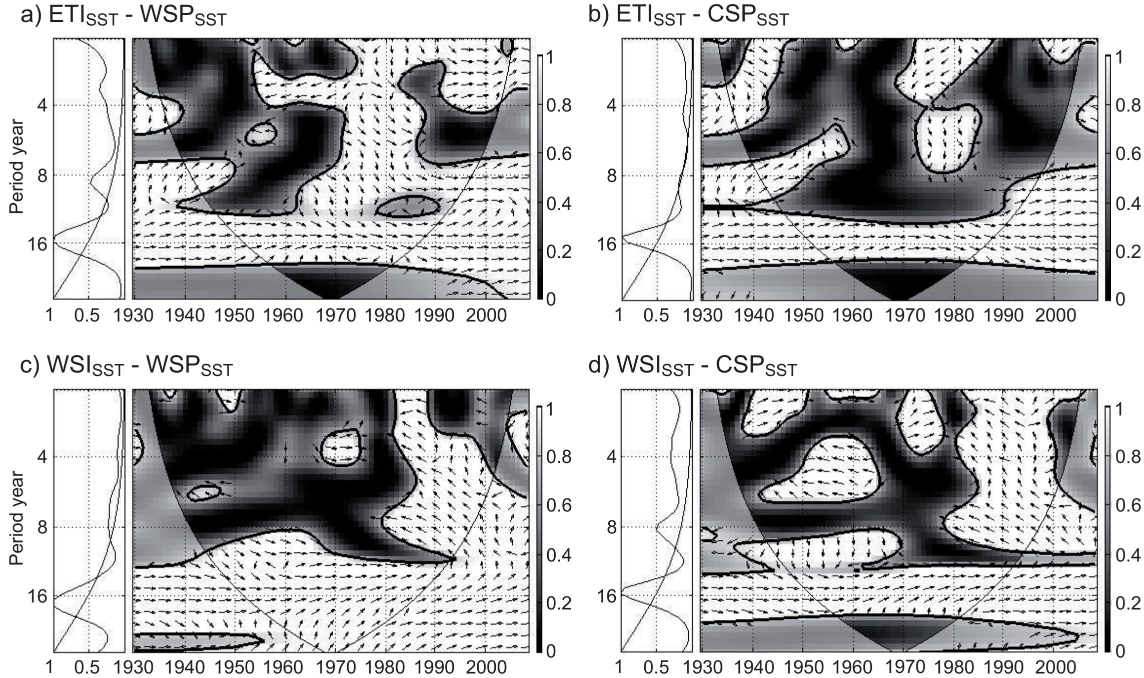


Fig. 9. As Fig. 3 but for relations among the Indian and Pacific oceans SST series.

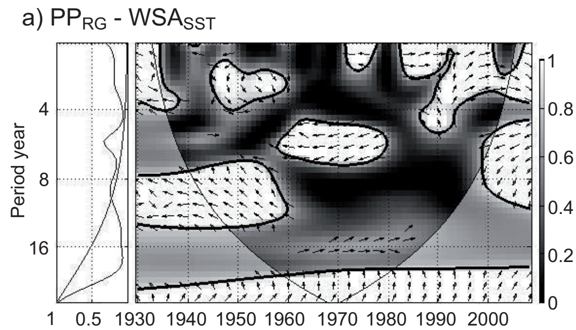


Fig. 10. As Fig. 3 but for relations of PP$_{RG}$ with the Western Subtropical Atlantic SST series.

only one meteorological station has complete and highly reliable data of precipitation for the last eighty years. Analysis of this specific information provides a unique opportunity to understand not only the characteristics of the variability of precipitation over this remote region of the world but also the oceanic forcing associated to that variability during most of the last century. It is no less important to emphasize that this particular meteorological station is located a few kilometers from the Laguna Potrok Aike lake, for which the paleoclimatic reconstructions reveal notable fluctuations of the water level across time. Therefore, the analysis of the precipitation in this region is also an important first step to understand the origin of such fluctuations.

The study was performed with the methodology of wavelet coherence analysis which allows a description of the relations between two time series simultaneously in all the space of frequencies. In this analysis, annual means of monthly anomalies of precipitation and SST have been considered.

The most notable oceanic relation with the southernmost South America precipitation can be summarized as follows: i) eastern and central subtropical Indian, western tropical Pacific, western and central subtropical Pacific could be forcing the decadal time scale variability of precipitation; ii) eastern tropical and western subtropical Indian, western and central subtropical Pacific could be modulating the interdecadal time scale variability of precipitation. These relations are schematized in Figure 11.

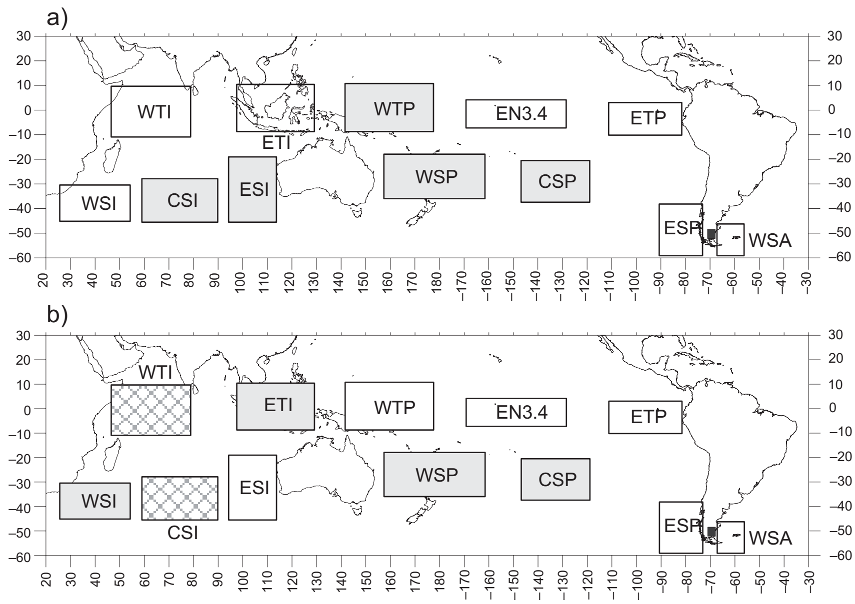


Fig. 11a). Regions of SST linked with PP_{RG} in decadal time scale are shaded; b) Regions of SST linked with PP_{RG} in interdecadal time scale are shaded (the regions WTI and CSI were also specially marked; see text for detailed comments).

The oceanic influence on southernmost South America precipitation could be the input to understand the causes of the changes in the level of the Potrok Aike lake. In particular, the paleoclimatic reconstructions of the lake's level describe a decrease of the level from the 1920s to the 1960s and an increment since the 1970s (Fig. 2). Results shown here describe an influence of areas of the Indian and Pacific oceans in decadal time scale before the 1970s, being relations in anti-phase, quasi-anti-phase or with a pronounced lag time (Figs. 3 and 6). But since the 1950s-1960s, an in-phase relation with areas of both oceans is detected in the interdecadal variability of the precipitation. This change in the characteristics of the links between the southernmost South American precipitation and the SST around the 1960s could be the key to discover the causes of the fluctuations of the lake's level across time. More investigations incorporating paleoceanography and paleoclimatic data must be done in future studies to better describe this issue.

Although the research was focused on the oceanic influence on the precipitation over southernmost South America, relations between the SST in different regions of the Indian and Pacific oceans has also been detected in the space of frequencies. In fact, the central and eastern areas of the subtropical Indian, the western tropical Pacific and the western and central subtropical Pacific (Fig. 11a) have an in-phase or quasi-in-phase relation in the decadal time scale. Moreover, the Indian Ocean (except the eastern subtropical area) and the western and central subtropical Pacific (Fig. 11b) have an in-phase or quasi-in-phase relation in the interdecadal time scale. The wavelet analysis shows that the mentioned oceanic regions are not statistically independent, but they are synchronized in frequency suggesting a coupled relation in those specific bands of variability.

The mentioned similarity in the variability of different regions of the Indian and Pacific oceans make it difficult to detect which regions have a real influence on southernmost South American precipitation. Further analysis considering methodologies based on the dynamic of the atmosphere must be done to better individualize the oceanic regions that are remote forcing of the regional climate in decadal and interdecadal time scales. Slow teleconnections like those described by Peterson and White (1999) could be the key to explain the relations here detected. However, these studies should be made considering outputs of global circulation models due to the scarce availability of meteorological information over most of the Southern Hemisphere before the 1980s. Although the reanalysis of NCEP-NCAR and ECMWF provide information for the satellital period post 1979, the previous decades have no suitable information to perform the study of the possible influence of different patterns of atmospheric circulation on the climatic variability over southernmost South America.

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