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Regime shifts, trends and interannual variations of water level in Mirim Lagoon, southern Brazil

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Abstract. Long-term changes of water level in Mirim Lagoon, southern Brazil, are strongly associated with the El Niño-Southern Oscillation (ENSO). However, the relationship between the water lever record and the Southern Oscillation Index changed during the last century. Two different regimes are identified. The first regime (1912-58) is drier than the second (1958-2002). Shifts in variance and wavelet analyses suggest that the extreme floods of 1941 and the subsequent drought of 1943-45 were very unusual climatic events. The following years, from 1945 to 1963, appear to be a transition towards a new climatic state characterized by more frequent El Niños. A positive trend for the entire period (> 1 m) was detected and is significant. The trend is apparently related to the higher frequency of ENSO warm events in the Pacific Ocean during the second half of the last century and references in literature report that this trend affects a wide region in subtropical South America. The record from Mirim Lagoon, spanning over 90 years, is a rare and very important indicator of long-term climatic variations and should be maintained and monitored in order to assess potential environmental changes.

Keywords: El Niño-Southern Oscillation, hydrological cycle, climate changes

Resumo. Mudanças de regime, tendências e variações interanuais de nível na Lagoa Mirim, sul do Brasil. Mudanças de longo período no nível da Lagoa Mirim, sul do Brasil, são fortemente associadas ao El Niño-Oscilação Sul. Entretanto, a relação entre nível registrado e o Índice de Oscilação Sul mudou ao longo do século passado. Dois regimes diferentes são identificados. O primeiro regime (1912-58) é mais seco que o segundo (1958-2002). Mudanças na variância e análise por ondeletas sugerem que a extrema inundação de 1941 e a seca subsequente de 1943-45 foram eventos climáticos singulares. Os anos seguintes, entre 1945-63, parecem ser uma transição para um novo estado climático, caracterizado pela maior frequência de El Niños. Uma tendência positiva maior que 1 m para todo o período foi detectada e é significante. A tendência parece relacionada à maior freqüência de El Niños no Oceano Pacífico durante a segunda metade do século passado e referências na literatura indicam que essa tendência afeta uma vasta região da América do Sul subtropical. O registro da Lagoa Mirim, cobrindo mais de 90 anos, é um raro e importante indicador de variaçõesclimáticas de longo período e deve ser monitorada com a finalidade de avaliar potenciais mudanças ambientais.

Palavras-chave: El Niño-Oscilação Sul, ciclo hidrológico, mudanças climáticas

Introduction

Mirim Lagoon (ML) catchment basin is part of Patos-Mirim hydrographic system, which comprises a portion of Rio Grande do Sul State (southern Brazil) and eastern Uruguay (Fig. 1). The Patos-Mirim system drains an approximate area of 200,000 km^2, with Patos Lagoon alone draining nearly 145,000 km^2. This hydrographic system exerts strong impacts on the adjacent costal area through the input of freshwater and nutrients (Ciotti *et al.* 1995). Its average discharge is 2,400 m^3/s. However, during El Niño (EN) years, discharge may rise above 12,000 m^3/s (Möller *et al.* 2001) inducing drastic changes in the regional ecosystem and continental shelf circulation and composition. This excessive discharge is associated with large interannual variations of rainfall over the basin. The average precipitation rate over the Patos-Mirim drainage basin is 1,200 mm/year. Above average rainfall in excess of 2,000 mm/year was observed during El Niño events and the lowest average value on record (near 800 mm/year) was observed during the 1988 La Niña (LN) (Beltrame & Tucci 1998). The mean surface area of ML is approximately 3,749 km^2 (185 km long and 20 km wide). Its catchment basin includes almost 55,000 km^2 (47% in Brazil, 53% in Uruguay) and ML is linked to the Patos Lagoon estuary through a 76-km narrow natural channel called São Gonçalo.

The term "coastal lagoon" usually refers to water bodies along the coast with one or more connections with the ocean (Bird, 2008). Therefore, although ML is traditionally known as a coastal lagoon, it resembles more closely an overflowing lake. In the past, Patos Lagoon brackish waters could reach ML through the São Gonçalo channel, damaging inundated rice crops in the region. To avoid salt penetration upstream, a subsurface dam was built across the channel in 1977 to block denser brackish waters but still allowing surface fluxes and navigation. The dam is 3.2 m high and is placed in a cross section where the mean depth is around 5 m. After the dam was built, ML waters remained fresh all the time, with an estimated mean overflow into Patos Lagoon of 700 m^3/s (Machado 2007). Changes of outlet conditions (as the subsurface dam) should only marginally influence mean overflowing lake levels (Bengtsson & Malm 1997).

In addition to rainfall-runoff relationship, the residence time of Patos-Mirim system is also influenced by synoptic scale atmospheric phenomena. With a narrow connection restricting fresh-seawater exchanges, circulation within the system is driven by the combined effect of winds and runoff.

Dynamically, the passage of a cold front and the associated strong south-southwesterly winds drive a water level set up in the northern region of both Mirim and Patos Lagoon (e.g. Möller *et al.* 2001). This could favor ML discharge, but also drives shelf waters against the coast, pushing seawater into the estuary and balancing the pressure gradient. Thus, seawater inflow and the wide flood plains along São Gonçalo channel slow down ML runoff. With the weakening of the southerly component of the winds and the establishment of northeasterlies, seawater retreats and the southward-pointing pressure gradient inside the lagoons acts to equalize the water level throughout the system, driving Patos Lagoon waters towards its estuarine area. This effect, together with the southward movement of ML waters, partially dams ML again, increasing its residence time. Northeasterly winds are predominant during the whole year with increasing importance of southwesterlies during wintertime, associated with atmospheric cold fronts propagating over the region on time scales ranging from 3 to 11 days (Stech & Lorenzetti 1992).

In general, Southeastern South America (SSA - Southern Brazil, Northeastern Argentina and Uruguay) experiences positive rainfall anomalies during EN events and negative anomalies during LN events (Grimm *et al.* 1998, 2000). This association also holds for streamflow anomalies, which present interannual cycles of 3.5 and 6.3 years, coherent with El Niño – Southern Oscillation (ENSO) cycles (Robertson & Mechoso 1998).

The relationship between ENSO and river runoff in Negro and Uruguay Rivers were explored by Mechoso & Perez-Irribaren (1992). They found a tendency for below average streamflow from June through December during LN events and a slightly tendency for above average streamflow from November through February during EN years.

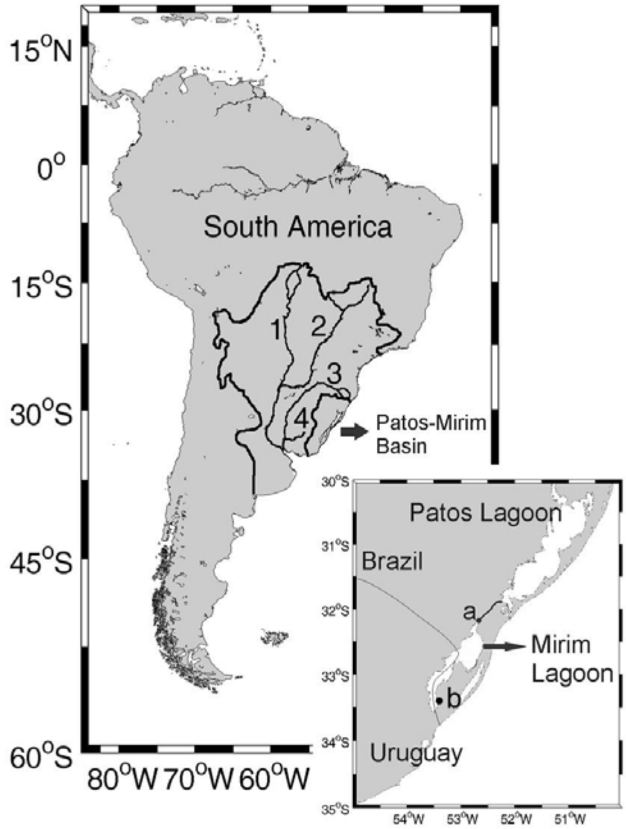

Figure 1. Map showing the La Plata River basin with (1 - Paraguay River, 2 - Paraná River, 3 - Uruguay River and 4 - Negro River) and Patos-Mirim basin. The detail shows the locations where the water level is observed (a - Santa Isabel and b - Santa Vitória do Palmar). The thick black line represents the São Gonçalo channel.

The study of Robertson & Mechoso (1998) also found a near-decadal cycle (approximately 9 years) most marked in the streamflows of Paraná and Paraguay Rivers. The authors pointed out that this cycle is associated with sea surface temperature (SST) anomalies over the tropical North Atlantic Ocean, mostly significant in austral summer. An apparent co-variability of the 9-year cycle and SST anomalies south of Greenland, also suggested a relationship of this cycle with the North Atlantic Oscillation (NAO). Negative SST anomalies would be associated with enhanced Paraná and Paraguay Rivers streamflow. They also suggested a relation to the decadal variability of the summer monsoon system and the southward moisture flux associated with the low-level jet along the eastern flank of the Andes Mountains. This impact would regulate a rainfall see-saw between the region influenced by the South Atlantic Convergence Zone and the subtropical plains of SSA. The see-saw pattern is described by Nogués-Paegle & Mo (1997). Numerical simulations presented by Robertson *et al.* (2000) showed that NAO interannual fluctuations are highly correlated with SST anomalies in the tropical and subtropical South Atlantic Ocean, accompanied by variations in the summer monsoon over South America.

Rainfall is the major source of long-term variability in the hydrological cycle over SSA once variations in evaporation seem to be less important (Berbery & Barros 2002). Positive trends of precipitation were detected over the region and related to a change to more negative Southern Oscillation Index (SOI) conditions in the tropical Pacific Ocean since the 1960's (Haylock *et al.* 2006). Genta *et al.* (1998) focused attention on the existence of long-term trends of streamflow in four major rivers in the region (Uruguay, Negro, Paraná and Paraguay). They reported a general increase in streamflow beginning in the mid-1960s consistent with a decrease in the amplitude of the seasonal cycle. In the case of the Negro River, the positive trend began almost 15 years earlier, just after the extreme drought of 1943-45. Examining SST anomalies in eastern equatorial Pacific Ocean, they suggested that an important component of the observed increase in streamflow is associated with large-scale low-frequency variability of the global climate system and the long-term trend is also possibly associated to changes in the Amazon region.

Long-term behavior of Pacific Ocean SST conditions is usually associated with interdecadal oscillations (Mantua *et al.* 1997, Zhang *et al.* 1997). Abrupt changes from one phase of this interdecadal cycle to another are commonly referred to as regime shifts. In 1977, the leading principal component of SST anomalies of the North Pacific changed from mostly negative to mostly positive values (Mantua *et al.* 1997). Since then, there is uprising ambiguity in the use of the term "regime shift" (Overland *et al.* 2008). According to these authors, confusion arises as a consequence of: (1) the shortness of climatic datasets, (2) the lack of evidence on the existence of different stable modes of the climate system (each stable mode would characterize one regime), and (3) the different usages of the term "regime" amid climate scientists. Therefore, a clear definition of the term is necessary.

Here, we follow the "displacement" viewpoint of regime shifts and use the algorithm designed by Rodionov (2004) to identify them. The displacement concept is solely based on time series analysis of relatively short records (<50 years) in which different multi-year intervals present statistically significant differences in mean relative to their variance (Overland *et al.* 2008). In other words, the mean of one time interval is significantly displaced up or down relative to a subsequent period. Regime shifts described with this definition are dependent on the length of the record, the choice of statistical parameters and may indeed constitute part of a lower frequency cycle. Hence, the regimes defined in the subsequent sections are relative to the period covered by the ML water level record only. Rodionov's algorithm was designed to be operationally used and, as new observations become available, the robustness of the regime shifts may be tested again. Consequently, we reaffirm the importance of continued monitoring and mechanistic understanding of shifts identified by this methodology on several variables (especially in the Pacific Ocean basin), as highlighted by Overland *et al.* (2008).

The aim of the present study is to use the ML water level record to assess the impact of global climatic patterns (ENSO and NAO) over the region, and to verify the existence and temporal structure of long-term trends and regimes of mean water level and variance in the local hydrological cycle. In the next section we describe the data and statistical methods used in this investigation, with special attention to Rodionov's algorithm. Regime shifts, a positive trend and main periodicities are then described and discussed.

Material and methods

The ML monthly water level time series from January 1912 to December 2002 (Fig. 2a) is available at the Mirim Lagoon Development Agency of the Federal University of Pelotas (Rio Grande do Sul, Brazil). The monthly mean is calculated from daily records measured at two locations (Santa Vitória do Palmar and Santa Isabel, see Fig. 1 for reference). The long-term mean was removed before the application of any statistical procedure and from now on we will refer to the ML water level anomalies simply as water level unless otherwise stated.

Statistical analyses described below were carried out in 3 steps. First, the monthly time series was transformed into a mean annual water level series in order to reduce the effects of serial correlation prior to the regime shift analysis. Second, the monthly time series was used to test the existence and significance of a long-term trend. Last, the monthly values were used again to explore the temporal variability of the record through wavelet analysis.

High serial correlation impacts the rejection rate of the null hypothesis of no regime shift. Thus, monthly means were used to construct a series of mean annual water level. This procedure reduced the lag-1 serial correlation from more than 0.9 to nearly 0.30 (Fig. 3). Then, a prewhitening procedure was performed using a lag-1 autoregressive approach (von Storch 1995) corrected by the Inverse Proportionality with 4 corrections (IP4) method (Rodionov 2006). Rodionov (2006) demonstrated that this method keeps the rejection rate of the null hypothesis close to the target significance level (0.1) for series with autocorrelations as high as 0.6 prior to prewhitening. The author considers the analysis with a prewhitening procedure a more conservative method because it increases the chance of missing a true regime shift but, if a shift is detected, its significance can be accurately estimated.

The existence of regime shifts of mean and variance were tested using a sequential data processing technique based on the Student's t test (Rodionov 2004). From the number of independent observations, the Student's test determines the difference in mean necessary for a significant shift of regimes to occur. Considering a time series, for each new observation, the algorithm tests the null hypothesis of the existence of a regime shift using the cumulative sum of normalized anomalies. The parameters of the analysis were the same as those used by Rodionov (2006) in his analysis of the annual Pacific Decadal Oscillation index (cutoff length = 15, Huber weight parameter = 1 and target significance level = 0.1). The test for a shift in variance was applied over the difference between the original mean annual time series and the prewhitened time series using the same cutoff length and significance level.

The algorithm is very sensitive to the choice of these parameters. The cutoff length determines the minimum length of a possible regime. As we are dealing with annual averages, a cutoff length of 15 indicates that a regime, if identified, will have 15 or more years. The choice of 15 years was made in order to avoid the selection of near-decadal cycles as regimes. The Huber weight parameter is a way of reducing the impact of outliers, allowing an even more conservative analysis. The value of Huber's parameter indicates the value above which an observation is considered an outlier (number of standard deviations). Then, any outlier is weighted inversely proportional to their distance from the mean of the regime.

In overflowing lakes as ML, water level observations only allow the conclusion that the climate has been excessively humid (if it is the case) and even drastic climatic changes have minor influences on lake levels and small amplitude interannual variations (Bengtsson & Malm 1997). Still, the circulation and dynamics of the Patos-Mirim system, as discussed in the introduction, induces a higher autocorrelation value with longer lags. This means that ML water level behavior may not resemble that of a pure overflowing lake and may show a clearer impact of climatic forcings. Therefore, our choice of cutoff length and Huber's parameter intend to select regimes longer than 15 years and avoid an excessive flattening of extreme events due to the possible smallness of long period differences in the record.

The trend and its significance were tested using monthly mean values. A linear regression in a least-squares sense was used to estimate the trend and its significance was assessed by a Monte Carlo technique to manage the impact of serial correlation (Livezey & Chen 1983).

Periodicities were explored using wavelet analysis (Torrence & Compo 1998). Wavelet analysis was carried out using a Morlet wavelet (wavenumber 6) with an initial scale of 6 months. The Morlet wavelet was chosen because it is nonorthogonal (better suited for time series analysis with expected continuous variations in wavelet amplitude) and complex (better adapted to capture oscillatory behavior). Moreover, arbitrary choices of different nonorthogonal and complex wavelets do not qualitatively change the results (Torrence & Compo 1998). The variation rate of scales was set to 0.25 corresponding to approximately 271 scales. The maximum scale is 22 years and the series were zero padded before convolutions.

The ML water level time series was then

compared with monthly times series of the SOI and the NAO station based index through cross and coherence wavelet analysis (Grinsted *et al.* 2003). Relative phase relationship in the plots is shown by arrows, where in-phase behavior (no lag co-variation) is denoted by arrows pointing to the right and anti-phase relationship, by arrows pointing to the left. When ML water level leads by 90º, the arrows point straight down. The time lag between the two signals can be estimated by the phase relationship:

$$\text{time lag} = [\,(\Phi \times \pi/180) \times \lambda] / 2;$$

Where Φ is the angle of the arrow and λ is the wavelength (in this case, the period correspondent to a given frequency band).

The SOI time series used here is the standardized sea level pressure difference between Darwin (Australia) and Tahiti. It was obtained online from the Australian Bureau of Meteorology (BOM) Internet site (http://migre.me/3wXkX). The monthly NAO station based index is provided by Jim Hurrell's webpage (http://migre.me/3wXtE) at the Climate Analysis Section of the National Center for Atmospheric Research (CAS, NCAR). The index is the difference of normalized sea level pressures between Ponta Delgada (Azores, Portugal) and Stykkisholmur/Reykjavik (Iceland). The probability density function of the NAO index time series is highly bimodal (two discrete peaks) and, as suggested by Grinsted *et al.* (2003), it was transformed to percentiles in order to enhance the results of the analysis.

Results

Before removing the mean of the series, it is possible to observe that the maximum water level of 4.8 meters occurred near the end of the record while the minimum value is reached by the beginning of 1943 (anomalies in Fig. 2a). The 1943-45 period, recognized as the worst drought of the last century in SSA by Genta *et al.* (1998), is also evident in the ML water level time series.

The hydraulic behavior of ML induced by its morphology and dynamics is apparent in the time series. Figure 3 shows lagged autocorrelations for the water level time series with and without the seasonal cycle. The high values and slow decay of the autocorrelation coefficient toward higher lags indicate that the ML water level has strong dependence from month to month. This character-ristic supports the idea that the synoptic scale dynamics that was suppose to drive water exchange between ML and Patos Lagoon estuary is not capable to overcome the long memory of the time series variability.

Rodionov (2004)'s sequential method to detect regime shifts in the annual mean water level series revealed only one shift, in 1958. Before 1958, the annual mean water level was approximately -0.28 m (-0.34 m considering Huber's weighted mean). After the shift, the mean water level jumped to 0.27 m (weighted mean of 0.20 m). The confidence level (CF) of the difference between the means before and after the shift (tested by a Student's two-tailed test with unequal variance) is 6.54×10^{-4}. This very small value indicates that it is very unlikely that this shift had occurred by chance or as a result of red noise. The existence of two different regimes agrees with the hypothesis of Genta *et al.* (1998) for their streamflow series, in the sense that the later period has a higher mean water level than the first one. No signal of shift was detected around 1977, when the subsurface dam was built in the São Gonçalo channel.

The test for a shift in variance resulted in 5 different regimes. The first and last shifts in variance (1919 and 2001) are too close to the record ends, being smaller than the cutoff frequency of 15 years, and should be viewed with caution. From 1912 to 1918 the estimated variance was 0.84. The shift of 1919 has a CF of 5.55×10^{-4}, suggesting that it had not occurred by chance. The following period, from 1919 to 1946, had a smaller variance of 0.10 and, in 1947, a second regime shift was detected (CF = 5.33×10^{-5}). The variance jumped to 1.10 for 15 years. In 1963, the variance decreased to 0.51 (CF = 6.29×10^{-4}) and remained in this level for 38 years, until 2001, when the last shift is detected (CF = 0.57).

The CF in the last shift is poor and the regime is much shorter than the cutoff length. This shift should be taken as "on test" and may be confirmed by new observations. Figure 2b highlights the regime shifts described above. The variance regimes will be later compared with the wavelet analysis results.

After the statistical detection of two regimes with significantly different mean annual water level, the monthly time series is used to detect a difference in the annual cycle between the two periods. Estimating the annual cycle from the mean values for each month of the year results in a shift to higher water levels during the entire year, accompanied by a longer season with positive values (Fig. 4). In this case, the amplitude of the annual cycle is smaller for the second period (1.30 m from 1912 to 1957 against 1.21 m from 1958 to 2002), consistent with the results of Genta *et al.* (1998), who used the same method to present differences in the cycle. If the

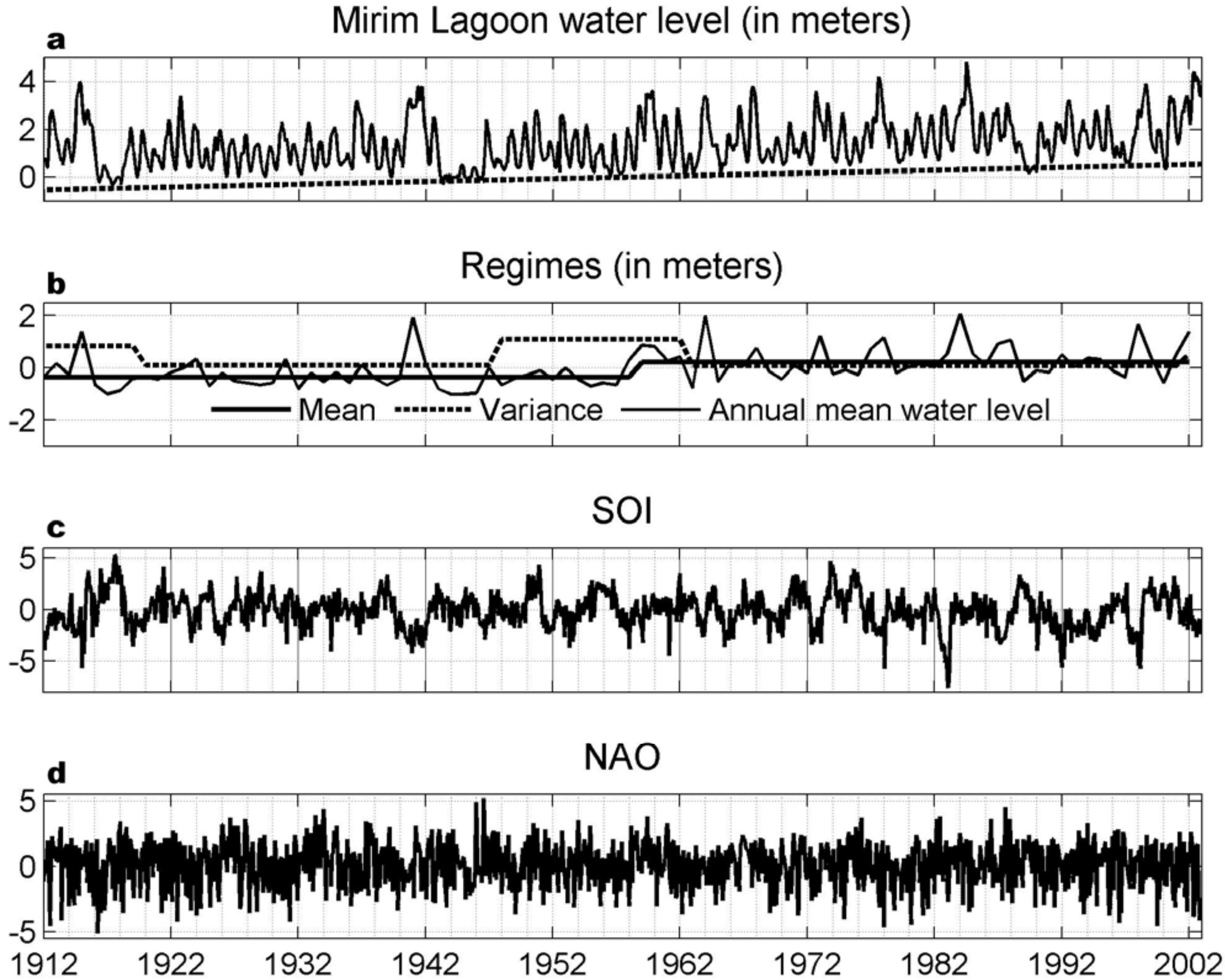

Figure 2. a) Mirim Lagoon monthly water level time series and the linear trend of anomalies (1.06 m from 1912 to 2002, significant at 99% - thick dashed line). b) The average annual water level anomalies and regimes of mean and variance identified by Rodionov's sequential method. c) The Southern Oscillation Index (SOI) time series. d) The North Atlantic Oscillation station index (NAO).

annual cycle is estimated by calculating its amplitude for all years and averaging the respective values, the scenario changes. The amplitude of the annual cycle during the first period becomes smaller than that of the second regime (1.67 m, with a 95% confidence interval between 1.46 and 1.88 m, against 1.88 m with a confidence interval between 1.70 and 2.07 m). A Mann-Whitney U-test indicates that this change in amplitude is not significant at 0.05 significance level, although the same test applied to the two regimes identified by Rodionov's algorithm reveals that their probability distribution function has changed signi-fycantly with the shift in 1957-58. Thus, it is still not clear if the water level annual cycle has changed over the years.

The estimation of a linear trend using the water level anomalies resulted in a positive increase of 11.9 mm/year (1.0669 m from 1912 to 2002), significant at 99% (Fig. 2a). This linear increase was not corrected to take into account vertical motions of the terrain and might be affected by isostatic adjustment or tectonic subsidence. The closest tide gauge station with a near-centennial record (83 years) is in Buenos Aires (Argentina). Raicich (2008) estimated the sea level rise recorded in Buenos Aires from 1905 to 1987 to be around 1.57 mm/year with peaks associated with high freshwater discharges of the La Plata River during EN events. The author also indicated that the United States Geological Survey consider the area between Buenos Aires and Southern Brazil as a region of low seismicity. Jelgersma (1996) argued that subsidence in coastal sedimentary lowlands is slow (a few centimeters/century) and consists of basement subsidence enhanced by subsidence due to isostatic loading. Therefore, even if the increase in ML water level is influenced by both sea level rise and land subsidence, their magnitude would be at least one order smaller than the observed trend.

Using wavelet analysis, it is possible to verify that main periodicities are concentrated in two frequency bands (Fig. 5). There is a broad band centered at 4 years, in agreement with the ENSO periodic band ranging from 2-7 years and commonly found in environmental records worldwide (e.g. Allan, 2000). These periods are also related to large scale atmospheric circulation anomalies that reach South America during ENSO events as described by Grimm *et al.* (1998). This relationship is confirmed by cross wavelet between the water level record and the SOI time series (Fig. 6a). Grinsted *et al.* (2003) pointed out that cross wavelet analysis shows regions in the time-frequency domain where two time series present high spectrum power. If two series are physically related, it is expected a consistent or a slowly varying phase lag. The arrows inside the significant area of Figure 6a suggest an anti-phase relationship in a frequency band ranging from 4 to 5 years (48 to 60 months) and localized in time from the late 1930s to the early 1980s. The anti-phase relationship indicates that when ML water level is positive (negative), SOI is negative (positive). This is expected since negative values of SOI are indicative of El Niño events. The wavelet coherence presented in Figure 6b indicates that both series co-vary in a frequency band ranging from nearly 3 to 6 years around 1940 and after 1990, predominantly showing the same anti-phase behavior inside the 0.05 significance regions.

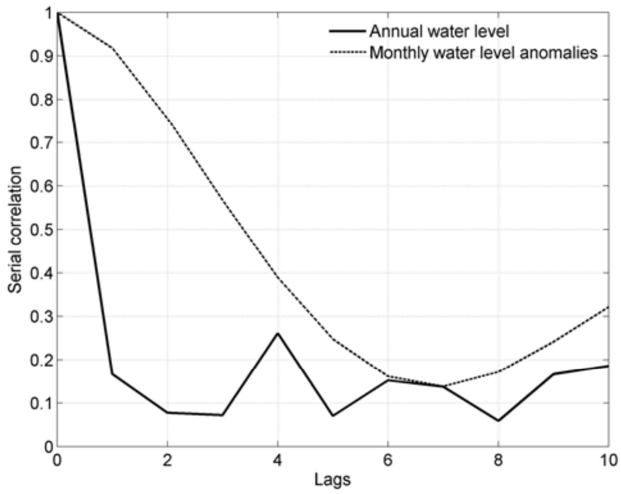

Figure 3. Serial correlations coefficients for Mirim Lagoon water level anomalies (demeaned), for the anomalies with the annual cycle removed (deseasoned) and for the annual mean water level anomaly.

Figure 4. Annual cycles for the two regimes with significant different annual mean water level. Vertical bar indicate the standard deviation for each month.

A near-decadal cycle even more energetic than the ENSO-associated cycles was detected in the analysis. This periodicity was already identified by Robertson & Mechoso (1998) for streamflow series in SSA and was most marked in Paraná and Paraguay rivers. Cross wavelet analysis between SOI and ML water level do not show significant peaks near the 10-year frequency band, but the wavelet coherence presents a wide significant region near the 6-year band. As arrows inside the 0.05 significance level region at this frequency band indicate that SOI leads ML water level by approximately 2 years.

Robertson & Mechoso (1998) suggested an association between SSA streamflow variability and the NAO. Hurrel *et al.* (2003) reported that the NAO has a signal with a period around 8-10 years. When ML water level time series is compared with the transformed NAO index time series, there is a small region in the time-frequency domain, near the 6-year band and localized in time around 1960, where cross wavelet indicates common energy concentration (Fig. 6c). Approximately the same significant region is detected in wavelet coherence presented in Figure 6d, with both time series varying in phase during this period.

Discussion

Statistical analysis of the ML water level time series allowed the detection of two different regimes of mean water level and a significant positive trend. The first regime, with negative mean relative to the record, ranges from 1912 to 1957 and the second, positive relative to the record, spans from 1958 to 2002. The study of Genta *et al.* (1998) showed a significant probability of larger median streamflow for Negro and Uruguay Rivers between 1970 and 1995 than the median before 1940. They also detected a consistent decrease in the annual cycle in the later period for the Uruguay River streamflow. The 30-year running mean for Negro River streamflow (a basin located just next to ML basin) increased monotonically since the late 1940's. The same increasing trend was detected by the author for another neighbor basin, the Uruguay River, but only after the mid 1960's.

In ML, the first regime (1912-1957) embraces two major droughts (1917 and 1943-45). Both events were also observed by Mechoso & Perez-Irribaren (1992), while Genta *et al.* (1998) described the 1943-45 drought period as "extraordinarily strong anomalous climate events". The one in 1917 coincides with a LN year and it is possible to observe that both the ML water level wavelet transform (Fig. 5) and the cross wavelet between the water level series and SOI (Fig. 6a) show significant energy around the 4-year band at that time. The later drought is considered the longest dry event of the last century and was not related to a LN event. However, Figure 5 indicates that there is significant power concentrated in a wide frequency band (corresponding to periods between 4 and 12 years). Cross wavelets from Figures 6a and 6c suggest a significant relationship between ML water level and both SOI and NAO, but on shorter timescales (3 to 8 years). Therefore we conclude that neither ENSO nor NAO are able to completely explain those extreme drier conditions over SSA. However, global-scale tropospheric and stratospheric circulation anomalies during the early 1940's may be a result of a particular state of the climate system associated with the strong 1941-42 EN (Brönnimann 2005) and the long-lasting drought may be related to pre-existent conditions set up by that unusually extreme warm ENSO event.

The existence of two regimes with significantly different means agrees with Genta *et al.* (1998) although a change in the water level annual cycle is not clear. The regime shift in mean is apparently associated to a shift of the ENSO-SSA teleconnection towards higher spectrum frequencies. From 1912 to 1957, when the mean regime was negative, both cross wavelet and wavelet coherence between ML water level and SOI exhibit a high common energy and co-variation in a frequency band centered between 3 and 8 years. During the second regime, when the mean anomaly jumped to a positive value, this frequency band of significant association is concentrated between 1 and 5 years. This supports the idea of Haylock *et al.* (2006) that wetter conditions in SSA are associated with a higher frequency of ENSO warm events. Figure 6c also suggests that even the weak association between ML water level and NAO observed during the first regime is not observed in the second period.

The shift in the ML mean water level is hard to be addressed, but large-scale conditions of the climate system may help to assess its causes. Long-term changes in ENSO are partly described as an interdecadal oscillation of SST anomalies over the Pacific Ocean, with a well expressed El Niño-like regime prevailing from mid-1920s to 1942-43 and again since 1976-77 (Zhang *et al.* 1997). This interdecadal oscillation is also connected to the most powerful principal component analysis mode of streamflow variability calculated using North and

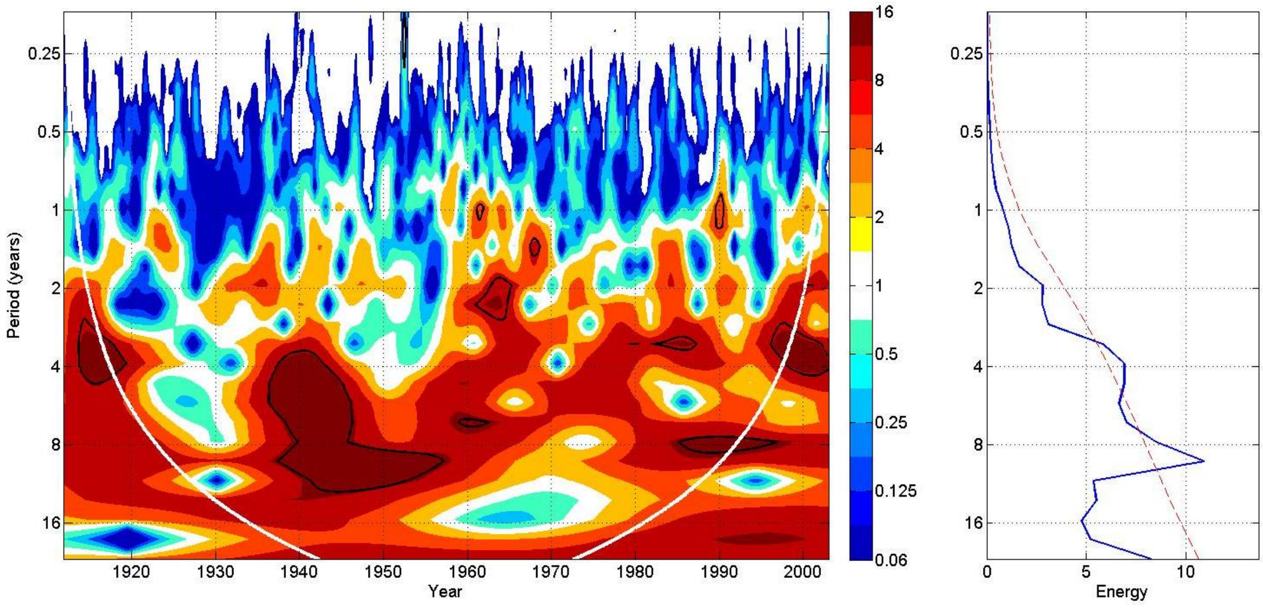

Figure 5. Wavelet transform (left) and global wavelet spectrum (right) of ML water level record. The white line in the wavelet transform plot represents the cone-of-influence and black contours represent the 5% significance level against red noise. The red dashed line in the global spectrum represents a 95% confidence level.

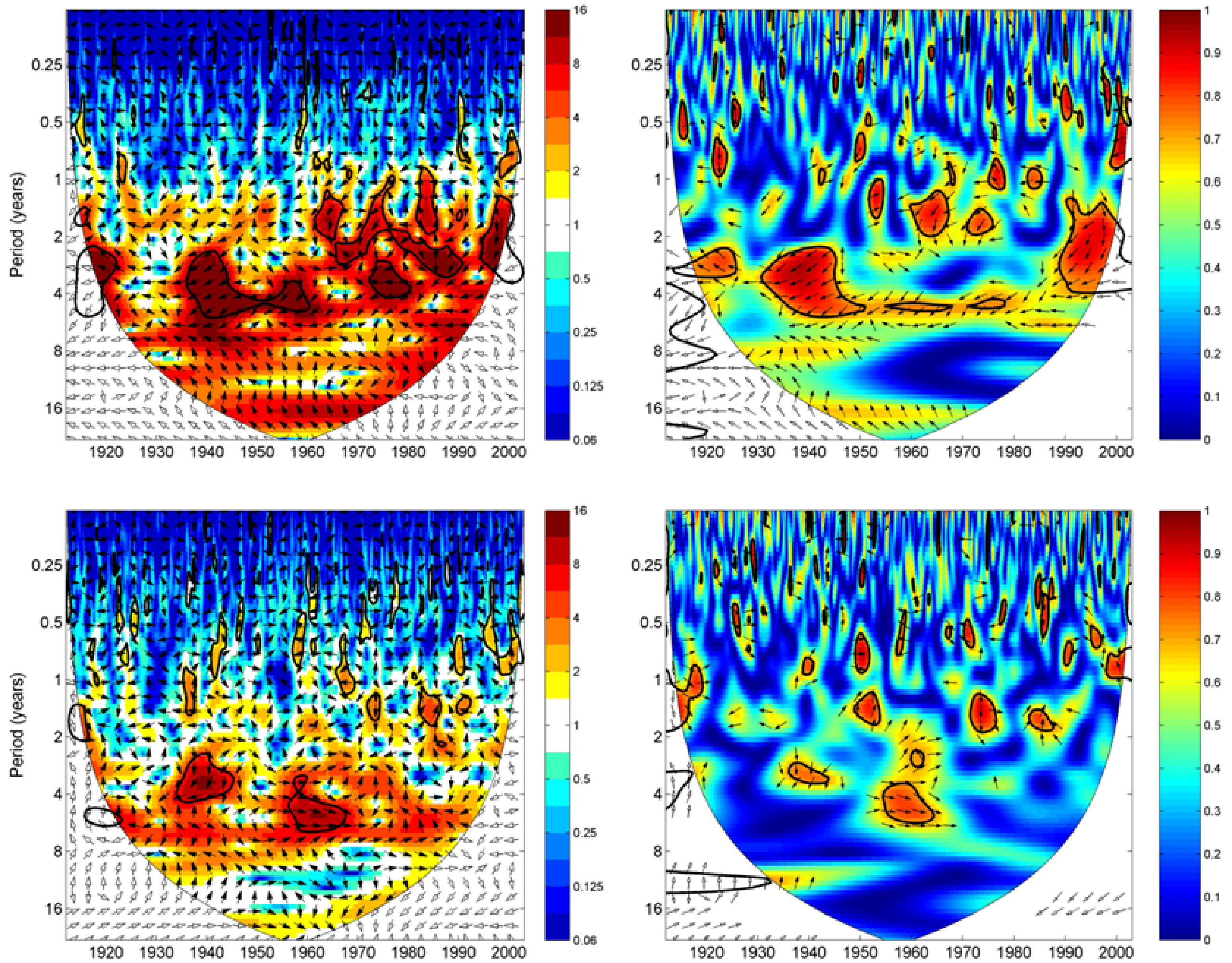

Figure 6. a) Cross wavelet analysis between ML water level and SOI time series (upper left). b) Wavelet coherence between ML water level and SOI time series (upper right). c) Cross wavelet analysis between ML water level and NAO index time series (lower left). d) Wavelet coherence between ML water level and NAO index time series (lower right). The 95% significance against red noise is shown as a thick contour. Relative phase relationship is shown by arrows (in-phase pointing right, anti-phase pointing left and ML water level leading by 90º pointing straight down).

South American rivers together (Dettinger *et al.* 2000). Zhang *et al.* (1997) also pointed out that the interdecadal pattern of the Pacific Ocean presented a change around 1957-58. According to them, this change was analogous to the one in 1976-77 but has received less attention because its subsequent warm phase was shorter. The mid-1950's shift of ML water level regime may be related to these basin-wide changes in the Pacific described by Zhang *et al.* (1997).

Shifts in variance detected in the previous section support the idea of a regime from the early 1920's until the late 1930's. The wavelet coherence in Figure 6d suggests a co-variation of the water level and SOI from the 1930's to the late 1970's. Allan (2000) reported more robust ENSO periods in the 1910's, 1950's, 1970's and 1980's and less energetic periods between 1920's and 1940's and during the 1960's. Again, shifts in variance seem to agree with this argument until the 1960's. Then, the variance decreases in the 1963 shift and remains leveled off until the end of the record. This discrepancy may also be related to the positive shift in the mean that occurred in 1958.

Zhang *et al.* (1997) argued that the interdecadal behavior of Pacific anomalies were different in 1942-43 when compared to the variations that took place in 1957-58 or 1976-77. The high-variance water level regime that began just after the great drought of 1943-45 and lasted until 1963 may reflect a transition period towards a new basic climatic state (considering the observed low variance of the two major regimes of ML water level). Although the nature of the early 1940's climate anomalies is not known, their strong signal in ML water level record and the Pacific anomalies reported by Zhang *et al.* (1997) suggest a worldwide climatic disturbance as proposed by Brönnimann (2005).

The near-decadal cycle revealed by the wavelet analysis consistently lags SOI by 2 years. The study of Robertson & Mechoso (1998) cited the association of streamflow with SSTa south of Greenland, which would be a possible link to the NAO. Cross wavelet and wavelet coherence between ML water level and the transformed NAO index indicate a sharp region of possible association near the 8-year band around 1960. Hurrel *et al.* (2003) suggested that the 1960's were characterized by anomalously high surface pressures and severe winters from Greenland across northern Europe, during a negative NAO regime. Although the results described here do not reject the hypothesis of association between the NAO and SSA surface climate, the overall signal on ML basin is punctual and barely significant. This may result from the fact that NAO impacts climate mostly during northern winter (austral summer) and this is the dry season in southern Brazil. Decadal variations of the basic state during this season may not be as important as the world-wide ENSO impact on the 7 year timescales.

Whether the positive trend identified here is a consequence of natural oscillations of the climate system or a result of anthropogenic forcing is still unclear. Recently, Church *et al.* (2008) suggested that volcanic activity may be related to a global cooling of the upper ocean and the offset of the increasing rate of sea-level rise between 1963 and 1991. A combination of a robust ENSO period during the 1950's and the subsequent period of high volcanic activity might led to the regime configuration of positive mean and low variance from 1958/1963 to the end of the water level record analyzed here.

Considering human impact around ML basin, surrounding regions in Uruguay have been subjected to intensive cattle and sheep grazing since the early 1940's (García-Rodríguez *et al.* 2002). Overbeck *et al.* (2007) estimated a 25% decrease in natural grassland area in southern Brazil since the late 1970's due to the expansion of agricultural activities (mainly grazing, irrigated rice crops and more recently Eucalyptus sp. plantations). Marques *et al.* (2004) reported that nearly 89% of Uruguayan irrigated rice is cultivated on ML basin. On the other hand, Baldi & Paruelo (2008) used satellite data to demonstrate that ML region presented a small rate of change from grass to cropland when two periods in the last 30 years were compared (1985-89 and 2002-04), suggesting that major changes may have occurred before 1985. Nonetheless, Gautreau (2010) showed evidences that forest loss on the Uruguayan banks of ML could be explained by rice crop extension but improved conditions for forest growth in Uruguay during the last century could be a consequence of increased rainfall. Medeanic *et al.* (2010) used algal palynomorphs from another coastal lagoon in southern Brazil to demonstrate a tendency of increasingly humid conditions during the last century, with a marked anthropogenic impact detected after the 1970's. All these references lead to the conclusion that human impact is important. However, the increase in water level is remarkably high, especially considering that water diverted from ML to irrigated rice production negatively impacts the water balance of the lagoon.

The positive trend in ML is consistent with the trends found by Genta *et al.* (1998) for four major rivers in SSA. A positive trend in rainfall over a large region in SSA is presented by Haylock *et al.* (2006) at least between 1960 and 2000. In the Amazon basin, Marengo *et al.* (1998) found no evidences of changes in the 20th century, whereas slow increases in rainfall were found for northeastern Brazil. Collinschon *et al.* (2001) analyzed river flow and rainfall from 1900 to 1995 on the Paraguay River basin. They detected increased river flow since 1970 associated with changes in rainfall patterns (increased frequency of rainfall events) and suggested that at least part of the runoff increase should be due to deforestation. Moreover, the authors showed that, in Africa, the Congo River flow presented the exactly opposite behavior of Paraguay River throughout the last century, indicating a possible large-scale climatic connection between the continents.

A modeling study by Cook *et al.* (2004) pointed out that the West African Monsoon, in boreal summer, generates a Walker-type circulation with low-level convergence and wet conditions over Africa and divergence and drier conditions over northeastern South America and tropical Atlantic. Thus, a weakening of the African Monsoon would lead to higher precipitation over northeastern Brazil. In fact, the African Monsoon presented a reduction in precipitation during the second half of the last century and numerical modeling experiments indicate Atlantic SST variability as the main driver of the observed rainfall decline (Paeth & Hense 2004). Janicot *et al.* (1998) showed that divergent anomalies over the tropical Atlantic, associated with El Niño events, may lead to a weaker African Monsoon especially if there are positive SST anomalies over the eastern tropical Atlantic as well. Moron *et al.* (1995) showed evidences of stronger El Niño impact over the West African Monsoon after 1970. On the other hand, Diaz *et al.* (1998) demonstrated that the Atlantic Ocean may impact rainfall over southern Brazil and Uruguay and that this impact may be independent of ENSO. In their study, unusually high precipitation was observed in 1959 (a neutral ENSO year) and associated with SST anomalies in the Atlantic basin. It is also worth to note that all trends described by these studies (Genta *et al.* 1998, Marengo *et al.* 1998, Collinschon *et al.* 2001, Paeth & Hense, 2004 and Haylock *et al.* 2006) identify an increasing (decreasing) trend of precipitation or river flow in South America (Africa) starting around 1960. In summary, the tendency of more frequent warm ENSO events and a possible influence of long-term variations of the Atlantic basin may be responsible for these changes in rainfall. Last, the modeling experiments of Paeth & Hense (2004) suggested that increasing concentration of greenhouse gases may lead to warmer SST conditions in the Atlantic and a stronger African Monsoon. If the arguments presented here are correct, the strengthening of the African Monsoon would possibly lead to another shift, now towards a drier regime in South America.

Climatic variations or changes, as described here, impact a wide and important region of the South American continent, with many different ecosystems. Patos Lagoon, for instance, may suffer a strong limnification process of its estuarine area, influencing species distribution and abundance. Ecological changes on interannual timescales such as those observed in shallow-water fish assemblage (Garcia *et al.* 2001, 2004) and algal palynomorphs (Medeanic *et al.* 2010) may become permanent with the abundance of freshwater. Higher discharge of the Patos-Mirim system and the La Plata River would introduce considerable modifications of temperature, salinity and nutrient loads in this heavily fishery-explored continental shelf also affecting the ecological settings of coastal waters (Paes & Moraes 2007). Because different time series spanning such a long period of time are not common in SSA, the ML water level record may be used as an indicator for changes in the regional hydrological cycle and environmental conditions. Its maintenance and operational monitoring is vital to track regime shifts and trends in the region in order to develop environmental policies and to manage the ecosystem and the anthropogenic impact on the neighboring areas.

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