QUANTITATIVE HIGH-RESOLUTION RECONSTRUCTION OF UPWELLING FAVORABLE WINDS ALONG COASTAL ATACAMA DESERT (23ºS) FROM AEOLIAN LITHIC PARTICLES IN MARINE SEDIMENTS.

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RESUMEN

Este trabajo presenta los resultados de una reconstrucción cuantitativa de alta resolución de la intensidad de los vientos del sur favorables a la surgencia en la costa del desierto de Atacama durante los últimos ca. 250 años (1754-1998 AD) a partir de partículas eólicas gruesas (>35 y >100 μm) presentes en sedimentos marinos extraídos de la bahía de Mejillones (23ºS). El aumento en la intensidad y variabilidad del flujo de partículas líticas desde la segunda mitad del S. XIX confirman un fortalecimiento general de los vientos sur en la región. Análisis espectrales a la serie de tiempo anual de flujos líticos indican que la variabilidad en la frecuencia de depositación es producto de una combinación de oscilaciones interanuales (ENOS) a decadales (ENOS-like), con un aumento de la influencia decadal hacia el fin de la serie. De acuerdo al contenido de partículas mayores que 35/100 μm se determinó que la proporción de vientos bajos (< 6 m/s) e intermedios (6-8 m/s) disminuye hacia el presente, mientras que los vientos fuertes (> 12 m/s) aumentan de un 14% a un 29% desde mediados del S. XVIII. Paralelamente, durante este periodo se observa un aumento del 22% en los valores medios del carbón orgánico, evidenciando la fuerte relación entre la tasa de productividad exportada/preservada y los vientos del sur. Desde 1950 AD (año desde el cual se encuentra disponible el Índice Oceánico de El Niño (ION)) los años de vientos fuertes coinciden con altos valores del ION, sugiriendo que el refuerzo de los vientos a lo largo de la costa del norte de Chile puede ser explicado por la interferencia constructiva producida por la interacción entre fenómenos interanuales y decadales.

ABSTRACT

This work presents the results of a high-resolution quantitative reconstruction of the upwelling-favourable southerly winds intensity in the coast of Atacama Desert in the last ca. 250 years (1754-1998 AD) from the coarse (>35 y >100 μm) aeolian lithic particles found in marine sediments extracted from Mejillones Bay (23ºS). The increase in the intensity and variability of the lithic particles flux since the second half of the 19^{th} century confirm the general strengthening of the southerly winds in the region. Spectral analysis on the yearly lithic flux series indicates that the variability of the frequency of deposition is due to a combination of interannual (ENSO) to decadal (ENSO-like) oscillations, with increased influence of the decadal mode towards the end of the record. Based on the amount of

particles larger than 35/100 μm the proportion of slow (<6 m/s) and intermediate (6-8 m/s) winds decreases towards the present, while the strong (> 12 m/s) winds increase from 14% to 29% since mid-18th century. Parallel, during this period an increase of 22% in the mean organic carbon is observed, evidencing the strong relation between the export/preservation productivity rate and the southerly winds. From 1950 AD (for which the Oceanic Niño Index (ONI) data is available) strong wind years coincide with high values of ONI, suggesting that the reinforcement of the winds along the North Chile coast night be explained by constructive interference produced by the interaction between interannual and decadal phenomena.

Key words: wind reconstruction, marine laminated sediments, wind intensity variability.

1. INTRODUCTION

Marine laminated sediments are among the few geological records that provide a continuous high-resolution information about past climate variability. However, their ocurrence is not common because their formation and preservation require very particular environmental conditions. When possible, they have been used to analyze variations in the Earth climate system including changes in precipitation, atmospheric temperature, oceanic circulation and variability of paleowinds. On this latter point, the few existing studies are focused in the wind reconstruction only from a qualitative point of view (e.g., Stuut et al., 2002; Chahuan et al., 2010).

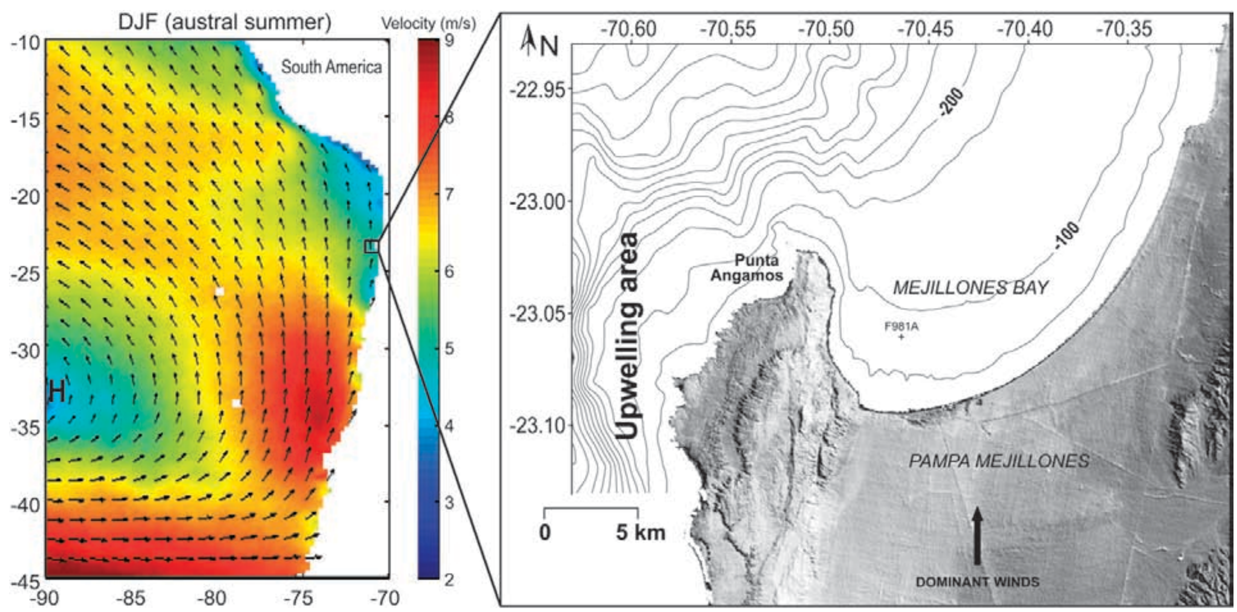

Figure 1. Study area. Left: Average (2000-2004, QSCAT) surface vector wind over the eastern South Pacific in austral summer (H=Southeastern Pacific Subtropical Anticyclone). Right: Northern side of Mejillones peninsula and marine core F981A sampling site.

In the Mejillones Bay, coast of the Atacama Desert (23ºS, Fig. 1), the conditions are particularly favourable for the accumulation and preservation of marine laminated sediments (Ortlieb et al., 2000; Valdés et al., 2004; Vargas et al., 2004) which record high-resolution (interannual to centennial) variability of the past atmospheric and oceanographic conditions (Vargas et al., 2004, 2007; Caniupán et al., 2009; Díaz-Ochoa et al., 2011). Recent studies have demonstrated that the lithic particles found in these marine sediments have an aeolian origin, and that their variability can be related to changes of the intensity of the predominant southerly winds (Flores-Aqueveque et al., 2014a). These winds are produced by the Southeast Pacific Subtropical Anticyclone (SEPSA) on which local to regional

atmospheric features superimposed (Vargas et al., 2004; 2007; Flores-Aqueveque et al., 2014b).
In this work we used this relation between the deposition flux of lithics and wind intensity for obtaining a quantitative high-resolution reconstruction of the southerly wind intensity on the last ca. 250 years.
Additionally, with the aim of assess the influence of ocean-climate changes on the exported/preserved phytoplankton-derived organic carbon fluxes from the surface towards the sea bottom we compare our results with the exported/preserved organic carbon fluxes.

2. METHODOLOGY

Basically, the method consists in inverting the relationship between the current wind variability and the sedimentological characteristics (size distribution and abundance) of the aeolian lithic particles present in the laminated sediment cores extracted from the Mejillones bay (Alfaro et al., 2011; Flores-Aqueveque et al., 2012). To do that, we used a simple model designed to account for the uptake, transport, and deposition within the bay of the particles initially set into motion by the wind on the pampa's surface (Alfaro et al., 2011). This model was designed based on the link between the aeolian lithic particles present in marine sediments and southerly wind intensity as result of two field campaing (EOLOS 2006 (Flores-Aqueveque et al., 2010) and EOLOS 2008 (Flores-Aqueveque et al., 2014b). Additionally, following the results obtained by Flores-Aqueveque et al. (2012), we consider the flux of lithic particles >35 μm contained in marine sediments as an indicator of the wind erosive activity at the surface of the pampa.
Thus, the model was applied to a lithic particles time series obtained from a core (F981A) extracted in 1998 at a water depth of ca. 75 m b.s.l. in the central part of the Mejillones Bay (23º04' S – 70º27' W), in an area dominated by the hemipelagic sedimentation of biogenic rests (Fig.1). A gravity box corer of 20 cm of diameter and approximately 50 cm length was used for its extraction. Geochronological determinations from detailed ^{14}C and ^{210}Pb data were obtained by Vargas et al. (2007). The determination of the high-resolution variability of the lithic content and its grain size distribution was performed through a polarized-light microscope using an ocular lens of x10 and a magnification of x10 in four thin sections prepared according to the resin replace procedure described in Vargas et al. (2004). The quantification of lithic particles (mainly quartz, feldspar and amphibole) was completed millimetre to millimetre over an area of 1 mm^2 approximately. Because of the relation between aeolian lithic particles and the strength of the southerly winds, the counting was focused on particles with sizes >35 μm and >100 μm. If more than a value of the flux were obtained in the same year, these values were averaged.
The lithic particles time series were analyzed by means of the Fourier Transform which allow determining the the intensity of the frequency of the different temporal signals (power spectrum). In order to detect a possible evolution in the temporal structure of the signal we applied the method to the first, and to the last, hundreds years of the period covered by the core.

3. RESULTS AND DISCUSSION

3.1 Characteristics of the marine laminated sediments

Marine laminated sediments of Mejillones Bay correspond to a sequence of dark and light laminae, of millimetrics to centimetric thickness composed by diatoms, and other biogenic rests, organic matter and lithic particles, agreeing with previous observations described by Vargas et al. (2004; 2007), and Caniupán et al. (2009). Dark laminae are generally enriched in lithic particles showing maximum sizes between 35 and 250 µm approximately, biogenic rests, organic carbon-content and fish scales, suggesting increased upwelling intensity, phytoplankton production rates and oceanic productivity with respect to light layers (Vargas et al., 2004; Valdés et al., 2008; Caniupán et al., 2009).

Based on the style of lamination, two different segments can be identified (Fig. 2). The first 15 cm approximately (from the base to the top) display massive, relatively dark laminations. This segment is followed by a sequence of fine to medium-thickness dense dark and porous light layers with a dominance of dark facies towards the top. These changes could represent variations in the frequency of the upwelling events and of the associated primary productivity rate.

Geochronological determination from this sediment core (Vargas et al., 2007) suggests that from at least the mid-18th century (bottom of the core) until the second half of the 19th century (ca. AD 1878), the atmospheric and oceanographic conditions were relatively more stable than later on. These conditions were characterized by comparatively long (15 to 70 yrs) periods of relatively weak winds and moderate upwelling. This relatively steady period was followed by a phase, between AD 1878 and 1998 (top of the core), in which the conditions favoring the hemipelagic sedimentation processes became more frequent, especially towards the second half of the 20th century. The higher frequency of laminations in the first part of this segment (AD 1878 - 1900), suggests rapid (<10 yrs) changes of sedimentation conditions with a dominance of dark layers (Fig. 2).

This has been interpreted as being the result of relatively short events of deposition driven by ENSO-like conditions during this period (Vargas et al., 2007). From AD 1900 to the end of the record (Fig. 2) the layers become thicker and dark facies dominate towards the top. This suggests that from the second half of the 19th century dominated the conditions favoring an increase in primary productivity with higher fluxes of upwelling-related biogenic species, as well as relatively coarser terrestrial supply and increasing hypoxia within the bay (Vargas et al., 2004).

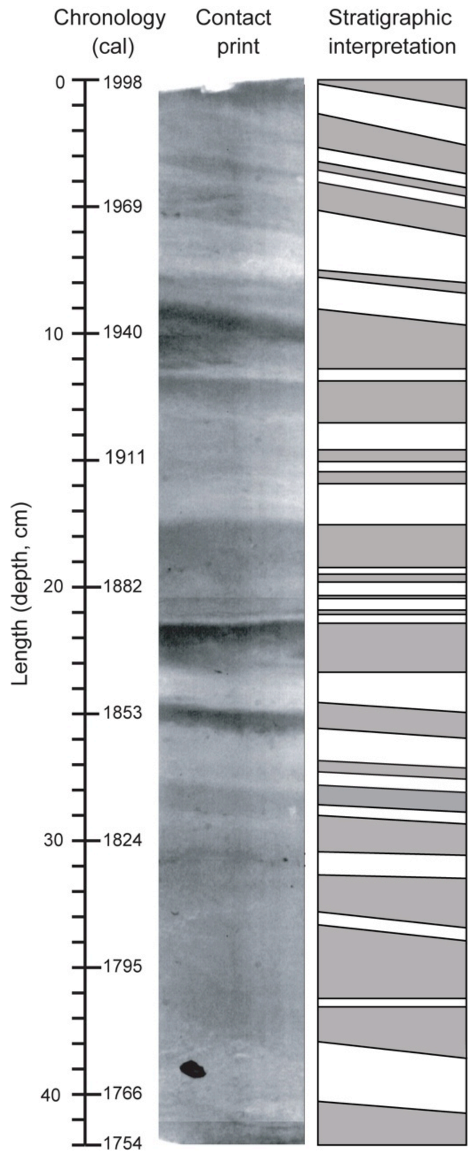

Figure 2. Chronology and stratigraphy of core F981A.

3.2 Aeolian lithic particles time series

The flux of particles >35 μm increase from the bottom to the top of the core, being the 10-years running mean of this flux less than 2 particles/mm^2/year at the base and close to 8 part/mm^2/year near the top (Fig. 3A). According to the annual values of the flux of these particles three periods can be roughly distinguished. The first period (P1), corresponding to approximately from AD 1754 to 1820, is defined by a low and relatively steady flux, characterized by a mean of < 2.05 part/mm^2/year, a mode of 2.35 part/mm^2/year, and a maximum of 4.69 part/mm^2/year (Fig. 3A). The next period (P2) ranging approximately from AD 1820 to 1878 corresponds to a transition period between P1 and P3 (AD 1878 – 1998), the most recent segment. This latter period presents the highest flux of lithics with a mean of 4.68 part/mm^2/year, a mode of 5.68 part/mm^2/year and a maximum of 10.72 part/mm^2/year (Fig. 3A).

Similar results were presented by Vargas et al. (2004) who, based on the FTIR mineral flux of two cores extracted from the centre of the Mejillones bay, defined two stages separated by an upwelling transition period running from AD 1820 to 1878.

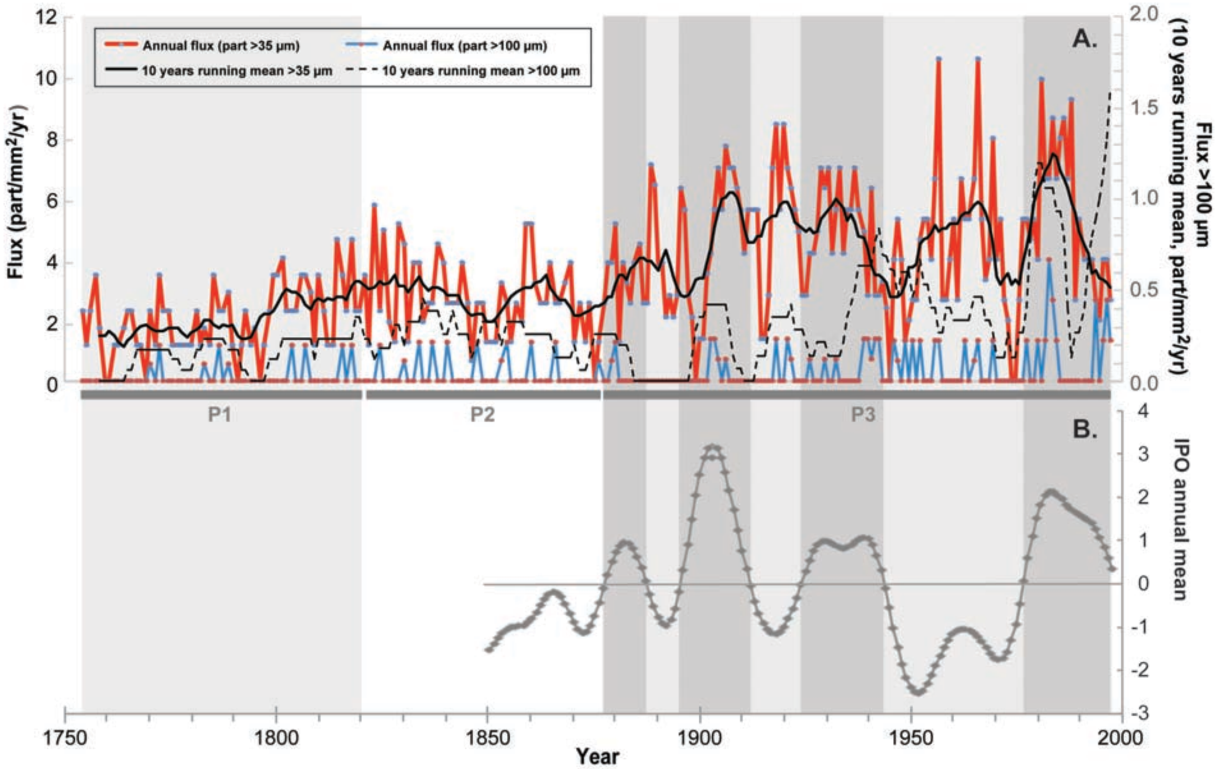

Figure 3. A. Yearly values of the deposition fluxes of lithic particles > 35 µm (red line), and > 100 µm (blue line). The 10 years running means of the two time series are also represented (note that for the sake of readability the values of the running mean for particles >100 µm are reported on the secondary vertical axis). B. IPO annual mean time series (dark grey bands highlight the cyclicity).

The time series of particles >100 µm also presents an increase in abundance towards the end of the 20th century (Fig. 3A). From the base of the core to AD 1900 approximately, the frequency and magnitude of the flux of coarse particle are very low (Fig. 3A). Coarse particles are even totally absent in the periods AD 1754 – 1770 and AD 1883 – 1903. Between AD 1903 to 1963 approximately the frequency of particles >100 µm increases, but the yearly flux itself remains relatively low, with a maximum of 1.42 part/mm^2/year. From AD 1963 to AD 1998 both the frequency and amount of coarse particles increases markedly reaching a maximum of 4.00 part/mm^2/year (Fig. 3A). Noteworthy is the fact that these values and those of the flux of particles >35 μm are within the ranges of fluxes predicted by the transport model of Alfaro et al. (2011).

A comparison of the segments defined independently based on the lithic content quantification, and stratigraphic description with those proposed by Vargas et al. (2007) highlights the good correlation existing between the direct quantification and the FTIR mineral flux analyses.

The spectral analyses applied to the whole record of the flux of particles >35 µm results in a periodogram characterized by three main peaks centered on 16, 27 and 82 years (Fig. 4A) evidencing the importance of these decadal periods in the reconstruction of the observed signal. The cause of these oscillations can probably be linked to large scale oscillations such as the Pacific Decadal Oscillation (PDO). Secondary peaks of shorter period (<10 yrs) are also observed indicating the influence of interannual oscillations of the ENSO-type.

In attempt to detect similarities between the temporal scales of the deposition of lithics and the PDO, and considering the equivalence between PDO and the Interdecadal Pacific Oscillation (IPO) (Folland et al., 2002), spectral analyses were applied to the available data (1871-2008; www.iges.org/c20c/IPO_v2.doc) of the IPO. The obtained periodogram (Fig. 4B) is characterized by the presence of major peaks centered approximately on 20-28, and on 50 years. Interannual oscillations are also present. The occurrence of similar decadal oscillations with periods between 20 - 30 years in the periodograms of the lithics and IPO time series suggest an influence of the latter on the wind regimes at the surface of Pampa Mejillones. This also can be observed in Figure 3 where a coincidence between the cycles of both series is noticeable.

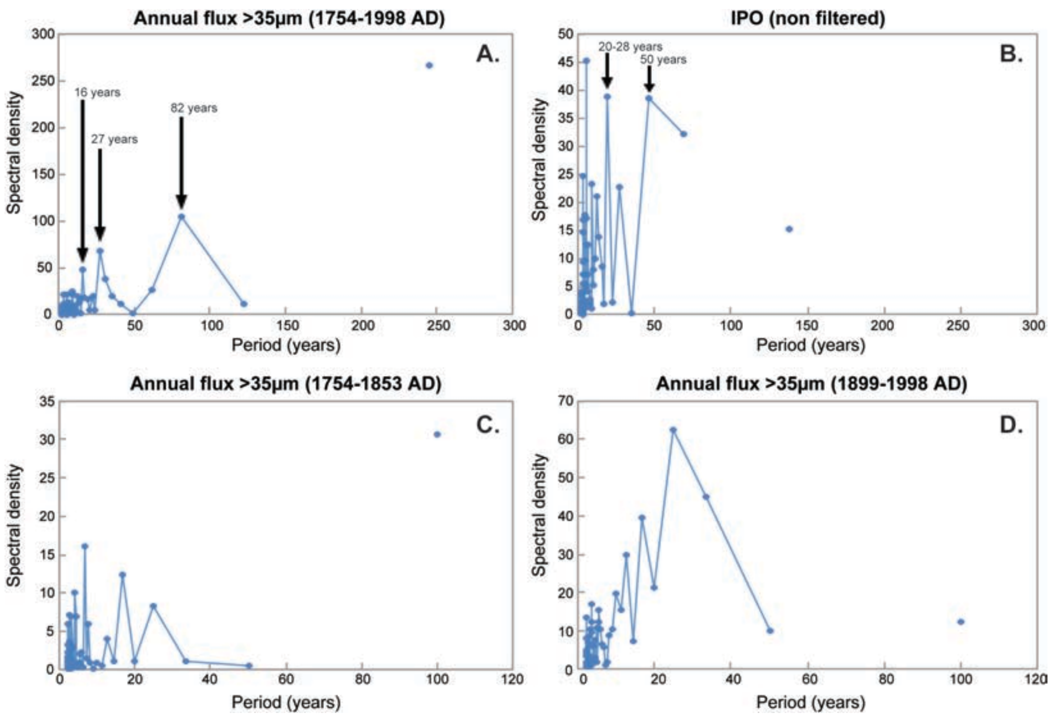

Figure 4. Spectral analyses of the lithic fluxes and IPO. A. Annual flux of particles > 35 µm for the entire core, B. Non filtered time series of the IPO index (annual values) for the period (1871-2008), C. Annual flux of particles >35 µm for the period (1754-1853 AD), D. Annual flux of particles > 35 µ m for period (1899-1998 AD).

When applied to the first (1754-1853 AD) and to the last (AD 1899-1998) hundred years of the period, the spectral analysis yields significantly different periodograms (Fig. 4C, 4D). To the last hundred years most of the variability of the lithic flux can be explained by decadal oscillations. While, in the first case the relative weights of the interannual and decadal oscillations are much more balanced. This shows that the increase in the deposition of lithics >35 μm during the 19th century was accompanied by a reinforcement of the influence of the decadal variability and the relative decreasing importance of the interannual one. Unfortunately, the lack of IPO monthly values before AD 1871 prevents checking if the change in the temporal modes of lithics deposition also affected this oscillation.

3.3 Variability of the wind stress

Based on the presence/absence of coarser particles in the sedimentary record winds were classified into three categories: Low Wind Years (LWY; < 6 m/s), Intermediate Wind Years (IWY; 6 - 8 m/s) and Strong Wind Years (SWY; 10 - >12 m/s). The first class corresponds to the years when the wind stress do not exceed the threshold of erosion over the pampa's surface, and thus, particles >35 μm are not mobilized. As can be seen in Figure 3 there are 7 such years (AD 1760, 1761, 1769, 1777, 1783, 1791, and 1797) of particularly low winds in the second half of the 18th century that compare with only 3 (AD 1813, 1847 and 1876) and 4 (AD 1900, 1916, 1946, and 1975) during the 19th and 20th centuries, respectively. This observation is consistent with the general intensification of wind erosion already commented.

The second class of intermediate winds are years during which only particles >35 μm are transported to the bay. The SWY correspond to the years when both particles >35 and >100 μm are observed. Table 1 presents the relative distribution of LWY, IWY and SWY years in the three defined intervals.

Table 1. Numbers (and proportions (%)) of LWY, IWY, and SWY detected in the three defined periods. The classification is based on the observation (or not) of particles >35 and >100 μm in the marine sediments core.

Period (AD)	Duration (yrs)	LW years	IW years	SW years
1754-1820	66	8 (12%)	49 (74%)	9 (14%)
1820-1878	58	2 (3%)	45 (78%)	11 (19%)
1878-1998	120	4 (3%)	81 (68%)	35 (29%)

Again, the second period appears as a transition between 1) the second half of the 18th century until AD 1820 when LWYs were particularly frequent (12% of the cases) and SWYs scarce (14%), and 2) the 20th century (AD 1878 – 1998) when very few cases of LWYs are observed (3%). In the latter case the proportion of SWYs doubles the one of P1 (AD 1754-1820) reaching 29%.

In the recent period of study, four particular years (AD 1982, 1983, 1994, and 1997) shown high values in the content of particles >100 μm (Fig. 3) with a flux of 3.03±0.65 part/mm^2/year, indicating that in addition to their frequency, the intensity of the SWY has also started to increase in the last 30 years of the 20th century. The fact that all the 4 years cited above coincide with 'strong' (1982-1983, 1997-1998) or 'moderate' (1994-1995) El Niño events (NOAA; http://www.cpc.ncep.noaa.gov/) might suggests that constructive interferences of the decadal and interannual oscillations could create in the coastal area of the subtropical southeastern Pacific conditions for the presence of stronger than usual winds. This is consistent with reduced low-cloud cover after the cold to warm PDO transition in the mid 70's associated with a slight increase in sea-surface temperature at Antofagasta (Rutllant et al., 1998), that resulted in stronger southerlies. A similar strengthening of the winds associated with a decrease in low-cloud cover during El Niño was reported for Lima, Perú by Enfield (1981).

3.4. Paleoclimatic and paleoceanographic implications

According to Vargas et al. (2007) and Caniupán et al. (2009), in the study area, proxies of primary productivity and lithic mineral fluxes in marine sediment cores (F981A and BC3) from the Mejillones bay, show an increasing trend in phytoplankton productivity since the late 19th century.

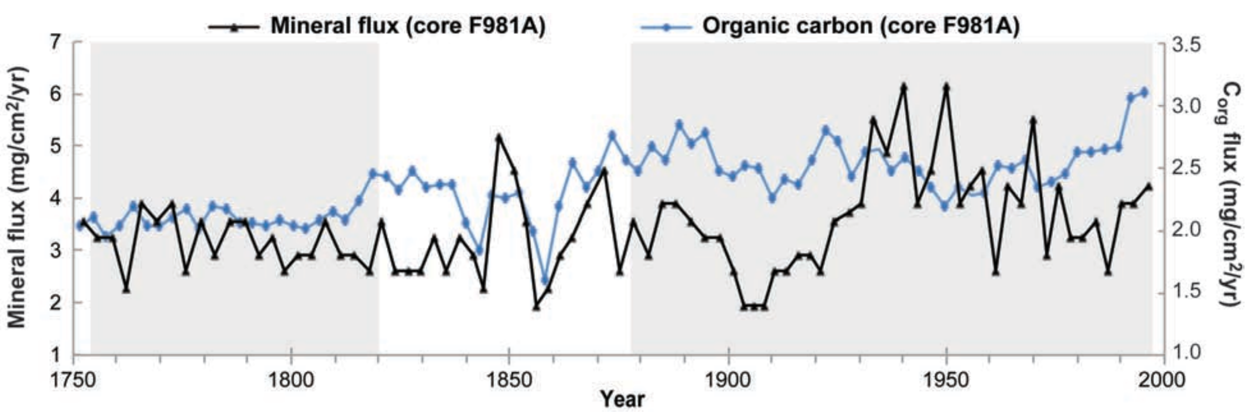

Figure 5. Mineral flux (FTIR) and organic carbon flux time series.

In particular, these authors defined two main periods of productivity: a pre-1820 period characterized by low organic carbon and low "chlorins", and consequently relatively low primary productivity and a post-1877 period where the proxies showed an increase in variability as well as in magnitude (Fig. 5; Vargas et al., 2007; Caniupán et al., 2009). A comparison between our results with these previous data shown a coincidence between the defined periods, confirming an increase of the southerly wind intensity and, thus, of the coastal upwelling in the studied area after the late 1870's.

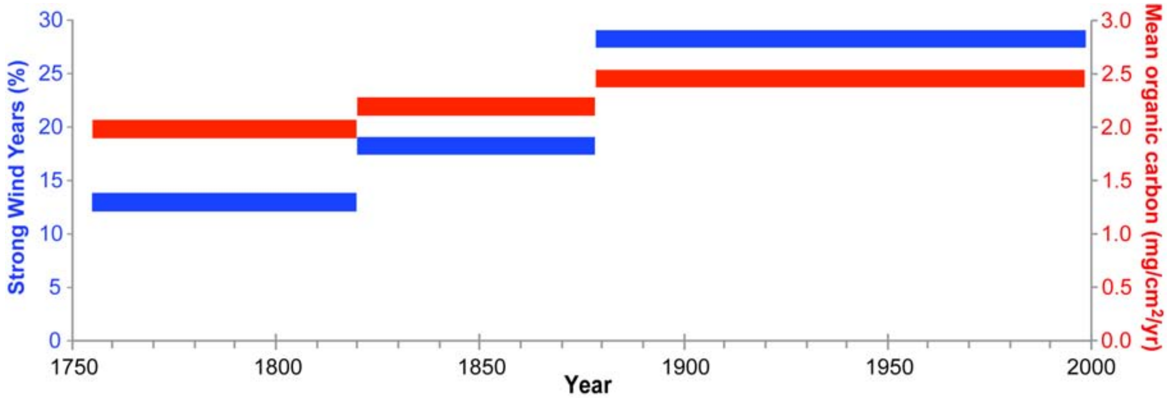

Figure 6. Comparison between the frequencies of the strong wind years and mean organic carbon.

Moreover, when comparing the frequency of the SWY (>12 m/s) and the mean organic carbon for these periods a remarkable relationship can be noted (Fig. 6). These results indicate that the export/preserved productivity increased 22% between the pre-1820 and post-1878 periods, related with the increase in southerly winds (114% in the frequency of SWYs), and also with the setting of oceanographic conditions that favored the preservation of increased fluxes of fish scales to the sea bottom since AD 1878 (Valdés et al., 2008; Díaz-Ochoa et al., 2011).

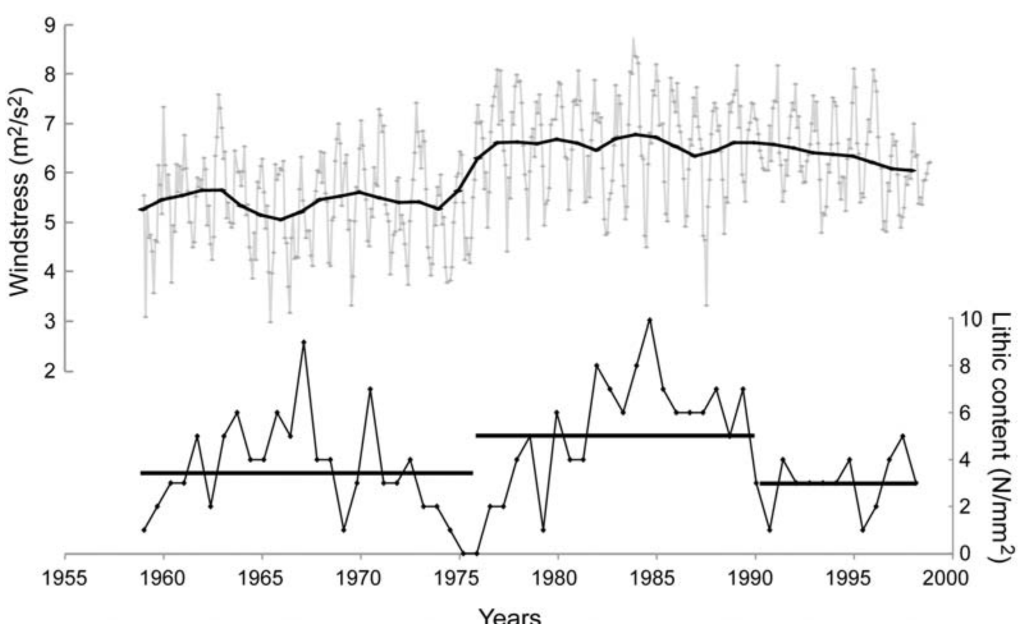

Figure 7. Windstress (historical data) and lithic particles (>35 + >100 µm) time series comparison since 1959 (black lines indicate shifts in mean values).

Furthermore, when analyzing in detail the aeolian lithic particles (>35 μm) time series for the period for which historical windstress data are available (since 1959) (Fig. 7), it is possible to see that the documented shift in windstress (and low-cloud cover) since the year 1976 (Rutllant et al., 1998) is consistent with the rise in lithic content from the mid-70's.

4. CONCLUSION

Time series of the lithic content of particles >35 μm and >100 μm confirms that the 19th century corresponds to a transition period between the second half of the 18th century, characterized by relatively moderate winds, and the 20th century, particularly in the last 30 years, in which erosion events on the surrounding hyperarid coastal Atacama Desert were more frequent and stronger.

Spectral analysis on these time series shows that the sequence evolves from a period when the influence of interannual ENSO and interdecadal PDO variability were relatively well balanced, to a period since AD 1878 when decadal variability dominates. This reinforcement is probably related to the general strengthening and larger variability of the eroding winds along the coast of the Atacama Desert. However, during the second half of the 20th century the observed coincidence between the years of larger depositional fluxes of particles >100 μm and strong El Niño events suggests that constructive interference between decadal and interannual oscillations might partly explain the occurrence of unusually strong winds along Northern Chile.

Our quantitative reconstruction of upwelling favorable wind variability agrees with previous results based on organic and inorganic proxies which recognized a period of lower phytoplankton productivity before AD 1820 and increased productivity since AD 1878 (Vargas et al., 2004: 2007; Caniupán et al., 2009), in the context of decreasing trend in SSTs during the 20th century off Northern Chile and Central Peru, associated to an intensification of the SEPSA and to enhanced alongshore winds due to increased sea-land temperature gradients (Vargas et at., 2007; Gutiérrez et al., 2011).

When comparing the frequency of SWYs and the organic carbon fluxes, we evidence a relationship in which an increase from 5.3% to 10.2% in SWYs, between the pre-1820 and post-1878 periods, relates to a rise from 9.5% to 11.4% in the mean organic carbon content in laminated sediments. These results highlights that the export/preserved productivity rate can be quantitatively related with the southerly wind intensity, and then with the ocean-climate system.

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