Aeolian particles in marine cores as a tool for quantitative high-resolution reconstruction of upwelling favorable winds along coastal Atacama Desert, Northern Chile

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\textbf{Abstract}

Upwelling areas play a major role in ocean biogeochemical cycles and ultimately in global climate, especially in highly productive regions as the South Eastern Pacific. This work is based on the analysis of the aeolian lithic particles accumulated in laminated sediments off Mejillones (23°C176S) in the eastern boundary Humboldt Current System. It proposes a high-resolution quantitative reconstruction of the upwelling-favorable southerly wind strength in the past \textasciitilde250 years, comparing its variability with changes in organic carbon export/preserved changes to the sea bottom. The increase of the intensity and variability in fluxes of particles larger than 35\,\mu m and 100\,\mu m since the second half of the 19th century and during the 20th century confirms a general strengthening of southerly winds in the region. Spectral analysis on the complete time-series of yearly depositional fluxes indicates that sedimentary variability can be explained by a combination of interannual (ENSO) to decadal (PDO) oscillations similar to the ones yielded by the analysis of the Interdecadal Pacific Oscillation index. However, when applied separately to the lithic fluxes of the first and last centuries of the time-series, the method shows that relative to the one of the interannual mode of variability, the influence of the decadal mode has increased in the recent period.

Based on the presence/absence of particles with sizes larger than 35/100\,\mu m, each year of the time series is classified as a 'Low wind' (<6 m/s), 'Intermediate wind' (6–8 m/s), or 'Strong wind' (10 to >12 m/s) year. From the AD 1754–1820 period to the AD 1878–1998 one, the proportion of Low and Intermediate wind years decreased from 12% and 74% to 3% and 68%, respectively, whereas the proportion of strong wind years increased from 14% to 29%. For these periods the mean organic carbon also increased 22%, stating the strong relation between export/preservation productivity rate and southerly wind intensity.

In the recent period (from AD 1950 on) for which the Oceanic Niño Index is available, the strong wind years (AD 1982, 1983, 1994, and 1997) correspond to large values of this index, suggesting that constructive interferences that result from the interplay between interannual and decadal oscillations modes might explain in part the reinforcement of the winds along the North Chilean coast.

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\textbf{Introduction}

Paleoclimate reconstructions are one of the most important tools for understanding the Earth climate system. They provide essential information about the behavior of certain climatic patterns, including its past changes and its natural variability.

Moreover, they offer the possibility of testing and calibrating numerical models to improve simulations of realistic climate change, especially if the climate forcing can be appropriately specified and the response is sufficiently well constrained (Jansen et al., 2007). In theory, these modeling studies allow establishing the causal link between the forcings and the climate response at different spatial and temporal scales but, for this, high-resolution records documenting the climate variability are required for this. In the current context of increasing anthropogenic forcing, the recent period has drawn much attention and a growing number of hemispheric
and regional short-term (annual to decadal) multi-proxy reconstructions for the past 500–1000 years are becoming available, especially for Europe and North America (e.g., Mann et al., 1999; Luterbacher et al., 2004; Moberg et al., 2005). In comparison, studies focused on the Southern Hemisphere, including South America, are less numerous and a lack of data has long been evident for this area (Villalba et al., 2009).

In an attempt to fill in this gap, paleoclimate proxies such as tree-rings, corals, ice cores, glaciers and boreholes, are becoming more widely used in this region (e.g., Boninsegna et al., 2009; Espizua and Pitte, 2009; Le Quesne et al., 2009; Masokas et al., 2009; Vimeux et al., 2009). Laminated lacustrine (e.g., Rodbell et al., 1999; Jenny et al., 2002) and marine sediments (e.g., Vargas et al., 2007; Gutiérrez et al., 2011) also provide a continuous climate record spanning time scales ranging from annual to centennial. However, because their formation and preservation require very special environmental conditions their occurrence is not common and they usually cover only relatively short periods of time.

So far, most of the sediment records have been used to analyze changes in precipitation and atmospheric temperature, but they can also provide insights into river flow fluctuations, changes in oceanic circulation, variations in primary productivity, changes in sea surface temperature, and variability of paleowind circulation. Regarding the latter point studies are relatively scarce, and the few existing works only pose the wind reconstruction from a qualitative perspective (e.g., Stuut et al., 2002; Chauhan et al., 2010; Dietrich and Seelos, 2010). In addition, it is important to improve our knowledge on how efficiently the fluxes of exported/preserved phytoplankton-derived organic carbon from the surface ocean toward the sea bottom (e.g., Grimm et al., 1997), responds to ocean–climate changes, and ultimately contribute to biogeochemical cycles and especially to the oceanic pump of carbon dioxide in upwelling areas (Keeling and Shertz, 1992; Berger et al., 1989).

In the Mejillones Bay (~23°S) located in the South Eastern Pacific on the coast of the Atacama Desert (23°S, Fig. 1), the geological, oceanographic and meteorological conditions are particularly favorable for the accumulation and preservation of marine laminated sediments (Ortlieb et al., 2000; Valdés et al., 2004; Vargas et al., 2004). The characteristics of these sediments are well adapted to the development of high-resolution (interannual to centennial) paleoclimate studies aiming to reconstruct 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 modifications of the intensity of the strong southerly winds predominant in the area and produced by the combined effects of the Southeast Pacific Subtropical Anticyclone (SEPSA) and of local to regional atmospheric features (Vargas et al., 2004, 2007; Flores-Aqueveque et al., 2014a,b). The first section of this paper summarizes the local context of the study area and details the materials and method used. In particular, the principles of the method used to link the characteristics of the mineral content of the sediment cores with the intensity of the wind are reviewed. The second section presents the results of the lithic content time series as well as the wind intensity reconstruction generated from them. This variability is analyzed and discussed. Finally, the last section interprets the significance of the wind intensity time series considering its paleoclimatic implications.

**Local context and methods**

**Climatological and oceanographic setting**

In the Southern Hemisphere the subsiding branch of the Hadley cell determines the presence of a quasi-permanent zone of high pressures near 30°S, whose development over the Pacific Ocean is known as the Southeast Pacific Subtropical Anticyclone (SEPSA). The climatic influence of the SEPSA over South America is modulated by the El Niño Southern Oscillation (ENSO; Cane, 1998) and the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; Zhang et al., 1997) which act at different time scales: interannual in the first case and decadal in the second one.

The ENSO cycle corresponds to a coupled ocean–atmosphere phenomenon characterized by irregular (periodicity from 2 to 7 years) fluctuations between warm (El Niño) and cold (La Niña) phases (Cane, 1998, 2005). ENSO has a strong direct impact over coastal Ecuador and Northern Peru in austral summer, where it produces episodic rainstorms that locally interrupt the extreme aridity of the area (Vargas et al., 2000), and an indirect effect, through atmospheric teleconnections, over much of subtropical South America including higher-latitudes, in austral winter–spring. The precipitation and temperature anomalies associated with ENSO are considered as major expressions of the interannual variability in South America (Garreaud et al., 2009). Despite its importance and the multiple studies dedicated to ENSO, the phenomenon is still not well understood. The variations observed in the amplitude of the ENSO-related anomalies during the last century (e.g., Elliott and Angell, 1988; Acutino and Montecinos, 1993) increase the uncertainty attached to the extrapolation into the past of the present-day relationship between ENSO and interannual climate variability.

The PDO is a long-lived pattern of Pacific climate variability (Mantua et al., 1997) described as El Niño–like mainly because its warm (cold) phases are very similar to those of El Niño (La Niña) events (Garreaud and Battisti, 1999). Furthermore, though of smaller amplitude, the PDO-related anomalies of precipitation and temperature over South America are characterized by a spatial distribution similar to the one of the ENSO-related anomalies (Garreaud et al., 2009). However, as already mentioned above, the two phenomena have very different temporal behaviors: the PDO events persist over longer periods (20–30 years) than the ENSO ones (about 18–24 months) (Rasmussen and Carpenter, 1983; Allan, 2000; Horii and Hanawa, 2004). Both phenomena modulate the SEPSA and, consequently, influence climate over a large part of South America.

In addition to the SEPSA, the climate of the study area is also highly influenced by smaller scale (regional and local) effects such as complex land – ocean–atmosphere interactions. These factors induce extremely arid conditions fostered by the presence of the coastal and Andean Ranges (Rutlant et al., 2003), the cold oceanic waters of the Humboldt Current System (Strub et al., 1998), and the southerly wind-driven coastal upwelling events occurring throughout the year (Rutlant et al., 1998; Strub et al., 1998).

During the austral spring/summer season, the sea–land thermal gradient intensifies, particularly during sunny afternoons, and the speed of the dominant S–SW winds along the coast strengthens (Rutlant et al., 2003). This favors in turn the occurrence of (1) strong upwelling events in Punta Angamos (Fig. 1), and (2) wind
erosion events at the surface of the hyperarid pampa Mejillones. During these erosion events lithic particles are transported toward, and eventually fall into, the Mejillones Bay, a shallow marine basin located north of the Mejillones Peninsula (23°S).

Due to the protection offered by the near shore orography in the peninsula, the Mejillones Bay remains almost unaffected by the direct S–SW winds (upwelling shadow) for a significant part of the day and by the coastal currents of the upwelling area (Marín et al., 2001, 2003). This, in combination with a northerly sea-breeze from mid morning to early afternoon results in a cyclonic water circulation around the bay which, combined with the anoxic conditions prevailing within it, favors the preservation of laminations in the sedimentary record (Ortlieb et al., 2000; Valdés et al., 2004; Vargas et al., 2004). At water depths greater than 50–75 m below sea level (b.s.l.), the middle of the basin (Fig. 1) constitutes a depocenter for hemipelagic sedimentation of biogenic rests, organic matter and lithic particles (Valdés et al., 2004; Vargas et al., 2004). The sedimentary sequence is characterized by millimetric to centimetric layers composed of diatom remains (mainly Chaetoceros sp.) related to the upwelling events, organic matter and other biogenic rests (50–90%), together with lithic particles (5–10% on average) of aeolian origin (Vargas et al., 2004, 2007; Flores-Aqueveque et al., 2014b). The variability in the distribution of these components reflects the changes in the magnitude of the upwelling events, themselves forced by variations of the intensity of the S–SW winds (Vargas et al., 2004, 2007).

Materials and methods

Wind erosion and transport of lithic material to the bay

The observation of lithic material of aeolian origin inside the laminated marine sediments of Mejillones Bay (Flores-Aqueveque et al., 2014b) and the idea that it would be possible to invert their characteristics (quantities and size-distribution) for reconstructing the past variability of the wind in the area (Vargas et al., 2004, 2007) boosted the interest for this region. For establishing the quantitative link between the strength of the wind and the characteristics of the deposition flux in the bay, two field campaigns were designed and carried out in 2006 (EOLOS 2006) and 2008 (EOLOS 2008). The first one documented the response of the surface of Pampa Mejillones to the stress exerted on it by the prevailing southerly winds. In particular, the results of this campaign were used to propose a quantitative model of the sand movements at the surface of the pampa (Flores-Aqueveque et al., 2010). During EOLOS 2008, meteorological parameters and sand movements were also monitored at the surface of the pampa, but in parallel marine sediment traps were installed in the bay for collecting the wind eroded particles falling into it. This not only demonstrated the aeolian origin of the lithic particles but also allowed the assessment of the intensity and size distribution of the flux of sedimenting particles (Flores-Aqueveque et al., 2014b). The fact that these measurements were performed in parallel with those at the particles source also allowed the calibration of a simple model (Alfaro et al., 2011) 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. For testing the sensitivity of the characteristics of the deposition flux of lithics to the natural variability of the wind, the statistical distribution of 14 years (1991–2004) of hourly wind speeds measured at the surface of the pampa was determined (Flores-Aqueveque et al., 2012). It was shown that the wind speed values of each individual year can be distributed into three Weibull modes. The winds of the lowest of these modes are too weak to move the sand grains at the surface of the pampa, but this is not the case for the winds of the intermediate and high speed modes which are able to erode the arid surface and transport particles to the bay. The interannual
variability of the wind speed distributions is essentially the result of the variations of the importance of the high speed mode (HSM, which mobilizes particles >100 μm). The model of Alfaro et al. (2011) shows that in periods when this HSM is not observed, only particles with sizes between 35 and 100 μm can reach the point of the bay from which the sediment cores analyzed in this study were retrieved. Conversely, in other years particles larger than 100 μm can be transported to the bay and their flux is directly linked to the weight of the HSM in the overall distribution of the yearly hourly wind speeds. For instance, between 1991 and 2004 this flux is predicted to vary between 0 and close to 400 particles/cm²/year whereas in the same time the flux of particles >35 μm varies between 30 and 800 particles/cm²/year. Note that if the flux of particles >100 μm can be considered as a quantitative tracer of the importance of the high speed mode at the surface of the pampa, the variations of the flux of particles >35 μm are more complex to interpret because they cannot be ascribed unequivocally to either the intermediate or high speed modes. In the following, we will consider the flux of particles >35 μm as an indicator of the wind erosive activity at the surface of the pampa.

**Marine sediment core F981A**

The core F981A was extracted in 1998 at a water depth of ca. 75 m b.s.l. in the central part of the basin (23°04′S–70°27′W) (Fig. 1), which is to say in the area dominated by the hemipelagic sedimentation of biogenic rests. A gravity box corer of 20 cm width and approximately 50 cm length was used for its extraction. Then the core was preserved at 2 °C before it was submitted to different analyses.

Geochronological determinations from detailed 14C and 210Pb data were obtained by Vargas et al. (2007). The determination of the high resolution variability of the mineral content and its grain size distribution was performed through a polarized-light microscope using an ocular lens of 10× and a magnification of 4× in four thin sections prepared every 10 cm according to the resin replace procedure described in Vargas et al. (2004). Due to dehydration, each thin section had its length reduced by approximately 2 cm after treatment.

A millimetric graduated grid located behind the thin section helped demarcate the area to be studied. These optical analyses complemented the X-ray observations and provided valuable information about lamination thickness and sedimentological structures.

The quantification of lithic particles, mainly quartz, feldspar and amphibole, was completed millimetre to millimetre over an area of 1 mm² approximately (Fig. 2A). Because they are strongly correlat-
ed to the strength of the southerly winds (see above), the counting was focused on particles with sizes >35 μm and also on those >100 μm. This counting was performed using an automated image analysis software (Image Pro Plus, v6.2). Because the core was dat-
ed every 5 mm, the determination of the accumulation speed (in mm/year) is easy to determine at each depth by interpolation. Combining the number of particles counted in each mm² with this speed directly yields the deposition flux of particles (in parti-
cles/mm²/year) of each of the two counted size classes. Note that if several values of the flux were obtained in the same year, these values were averaged.

**Spectral analysis of the times series**

Several methods can be used to extract crucial information from univariate time-series (see Ghil et al., 2002, for a detailed review of these methods and their pros and cons). One of the most popular is based on the Fourier theory which stipulates that any given time series can be associated to a function of the frequency, S(f), called its spectral density. The frequency domain is bounded by a lower limit whose value is the inverse of the length of the initial time series, and S(f) is generally a continuous function of f, which means that all the frequencies of the domain are necessary to reconstruct the signal. One of the main interests of the method is that examination of the frequency spectrum usually allows distinguishing individual peaks superimposed on a blurrier pattern. Though not always easy to interpret physically, these frequencies play a particular role in the temporal variability of the studied signal. The application of the method requires that a value of the signal is available in each temporal bin of the time window. As will be shown below this condition is met by the time series of the deposition flux of particles >35 μm for which a value has been determined for each of the 245 years separating the bottom of the core (AD 1754) from its top (AD 1998). Note that in order to detect a possible evolution in the temporal structure of the signal, the spectral analysis can be applied to time windows narrower than the global one. For instance we will apply the method to the first, and to the last, hundreds years of the period covered by the core.

**Results and discussion**

**Stratigraphy of marine laminated sediments**

The microscope observations indicate that the general structure of these deposits is characterized by a succession of dark and light laminae, of millimetric to centimetric thickness with variable content in diatom and other biogenic rests, organic matter and lithic particles, agreeing with previous similar observations described by Vargas et al. (2004, 2007), and with those from Caniupán et al. (2009) who found similar characteristics in core BC3D (23°03.3’–70°27.4’W), extracted near the core F981A. These layers are limited by sharp and often irregular contacts (Fig. 2B). In some dark laminae it is possible to find lenses or bands of diatoms (Fig. 2D), whereas in light layers there are nodules or agglomerates of organic matter (Fig. 2C).

The lack of bioturbation and the sharpness of the contacts suggest that changes in lamination style are due to variations in hemipelagic sedimentation processes in response to upwelling events and the concomitant increase of primary production, as previously proposed by Vargas et al. (2004). The good state of preservation of the layers indicates that low oxygen levels in bottom waters intercepted the sediments, thus restricting bioturbation (Valdés et al., 2004; Vargas et al., 2004).

Dark laminae are characterized by higher contents of diatoms of the Chaetoceros r.s. type (species related to upwelling events), agglomerates of organic matter, foraminifer remains, and lithic particles showing maximum sizes between 35 and 250 μm approximately (Fig. 2A and C). Conversely, light laminae are dominated by pennate and centric diatoms (Fig. 2D), and show a lower lithics content with particles of smaller sizes. These observations coincide with those of Caniupán et al. (2009) and Vargas et al. (2004) who also showed that the dark layers are relatively denser and have lower water content than the light layers, which are composed of a more porous material. Dark laminae are generally enriched in lithic particles, 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).

Gray scale contact prints show that generally the layers are arranged nearly horizontally, especially in the lower 30 cm. At the top of the core, the layers are sloping gently (Fig. 3). Based on the style of lamination, two different segments can be identified (Fig. 3): the first 15 cm approximately (from the base to the top) display massive, relatively dark laminations. This segment is fol-
ed by a sequence of fine to medium-thickness alternations of
dense dark and porous light layers in similar proportions but with a dominance of dark facies toward the top. According to Bull and Kemp (1996) the variations in the style of lamination could indicate that marine sediments record the changes in ocean–climate conditions occurring at centennial to decadal, or even interannual and seasonal, time-scales. In the present case, these changes could represent variations in the frequency of the upwelling events and of the associated primary productivity rate.

Considering the geochronological determination from this sediment core (Vargas et al., 2007), this segmentation suggests that from at least the mid-18th century (AD 1754; 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 (15–70 years) periods of relatively weak winds and moderate upwelling. This relatively steady period was followed by a phase, between AD 1878 and the top of the core (AD 1998), in which the conditions favoring the hemipelagic sedimentation processes became more frequent, especially toward the end of the record (second half of the 20th century). The higher frequency of laminations in the first part of this segment, namely between AD 1878 and AD 1900, suggests more rapid (<10 years) changes of sedimentation conditions with a dominance of dark layers (Fig. 3).

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. 3) the layers become thicker and dark facies dominate toward the top. This suggests that from the second half of the 19th century 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 were dominant (Vargas et al., 2004).

High-resolution quantification of lithogenic components

As mentioned before (Section ‘Wind erosion and transport of lithic material to the bay’), among the particles contained in the laminated sedimentary record only those with sizes >35 and >100 μm will be used for the reconstruction of the variability of the southerly winds intensity in the coastal Atacama Desert.

The flux of particles >35 μm (Fig. 4A) tends to increase with time, or equivalently from the bottom of the core to its top. The 10 years running mean of this flux is less than 2 particles/mm²/year at the base but reaches values close to 8 particles/mm²/year near the top. A similar increasing trend was observed by Vargas et al. (2004) who determined the FTIR (Fourier Transform InfraRed) mineral flux of two cores extracted from the centre of Mejillones Bay.

Based on the values of the annual flux of particles >35 μm, three different periods can be roughly distinguished. The first one (P1) corresponds to the lower 10 cm and extends approximately from AD 1754 to 1820. With a mean of less than 2.05 particles/mm²/year, a mode of 2.35 particles/mm²/year, and a maximum of 4.69 particles/mm²/year (Fig. 4A), this period is characterized by its low and relatively stable flux of lithics. The next period (P2) extending approximately from AD 1820 to 1878 seems to constitute a

Fig. 2. Features and components of the marine laminated sediments (thin sections of core F981A): (a) microscope images of core thin section taken at different depths, (b) sharp and irregular contact between light (up) and dark layers (down), (c) typical dark layer containing lithic particles (back arrows), organic matter agglomerate (white arrows), diatoms of *Chaetoceros* r.s. type (gray arrow) and foraminifera remains (dark gray arrow), (d) diatom lenses of *Coscinodiscus* sp.
transition period leading to the long and most recent phase (P3) of 120 years (AD 1870–1998, approximately). P3 presents the highest flux of lithics with a mean of 4.68 particles/mm$^2$/year, a mode of 5.68 particles/mm$^2$/year and a maximum of 10.72 particles/mm$^2$/year (Fig. 4A). This segmenting is somewhat arbitrary but it is consistent with the intervals proposed by Vargas et al. (2007) who, on the basis of the mineral flux FTIR analysis of the Mejillones Bay cores, defined two stages separated by an upwelling transition period running from AD 1820 to 1878.

The time series of particles $>$100 µm also displays an increase of abundance toward the end of the 20th century (Fig. 4A). From the beginning of the record to AD 1900 approximately, the frequency of coarse particle deposition as well as the magnitude of the flux are very low. Coarse particles are even totally absent in the periods AD 1754–1770 and AD 1883–1903. Between AD 1903 and 1963 the frequency of particles $>$100 µm increases as denoted by the increase of the 10 years running mean, but the yearly flux itself remains relatively low, with a maximum of 1.42 particles/mm$^2$/year. From AD 1963 to the end of the record the deposition of coarse particles shows an important increase in both frequency and amounts, reaching a maximum of 4.00 particles/mm$^2$/year (Fig. 4A). Noteworthy is the fact that these values and those of the flux of particles $>$35 µm are within the ranges of fluxes predicted (see above) by the transport model of Alfaro et al. (2011).
A comparison of the segments defined independently on the basis of the (1) lithic content quantification, and (2) stratigraphic description with those proposed by Vargas et al. (2007) indicates that there is a good correlation between the direct quantification and the FTIR mineral flux analyses. However, the periods defined by the stratigraphic analysis show important differences relative to the other two methods indicating that if the stratigraphic analysis is a good help to interpret the information contained in cores it must also be complemented with more precise data.

In order to assess more precisely the time-scales involved in the changes of wind intensity regimes indicated by the variations of the magnitude and size-distribution of the flux of lithic particles >35 μm, the spectral analysis method has been applied to the 245 year-long (AD 1754–1998) time series. The periodogram (Fig. 5A) displays three marked peaks centered on 16, 27, and 82 years showing the importance of these decadal periods in the reconstruction of the observed signal. Secondary peaks corresponding to periods shorter than 10 years are also present indicating the influence of interannual oscillations of the ENSO type. Finally, a significant portion of the spectrum is occupied by periods larger than 100 years. This seems to suggest the presence of a centennial transition in the last 250 years but a core covering a longer time period would be necessary to ascertain this point.

The causes of these oscillations are not known but they can probably be linked to already documented large scales oscillations, such as the PDO. In an attempt to detect commonalities in the temporal scales of the deposition of lithics and the PDO, the spectral analysis has been applied to the annual mean of the Interdecadal Pacific Oscillation (IPO). The concept of the IPO was introduced by Power et al. (1999) based on the work of Folland et al. (1999). Shortly after these preliminary works, Folland et al. (2002) showed the near equivalence of the PDO and IPO. A recently updated (2008) version of the monthly IPO index for years 1871–2008 is distributed online (www.iges.org/c20c/IPO_v2.doc) by the UK Met Office. Note that because we do not want to discard the possibility of observing the interannual variability, we are using in this work the unfiltered version of the IPO time series rather than the low-pass (11 years) filtered one also proposed online. The obtained periodogram (Fig. 5B) is characterized by the presence of major peaks centered approximately on 20–28, and on 50 years. More rapid (interannual) oscillations are also present in the spectrum. The presence of similar decadal oscillations with periods between 20 and 30 years in the periodograms of the lithics and IPO time series suggest an influence of the IPO on the wind regimes at the surface of Pampa Mejillones. This also can be observed in Fig. 4B where a coincidence between the cycles of both series is noticeable.
If one takes into account that the theoretical upper limit of the periods which can be retrieved by the analysis of the IPO time series is shorter (138 years) than in the case of the lithics (245 years), the presence of a multidecadal oscillation in the two periodograms (80 years for the lithics and 50 for the IPO) also seems to support the hypothesis of an influence of the global scale on regional winds.

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. 5C and D). In the most recent period, almost all the variability of the lithic flux can be explained by decadal oscillations, and interannual variability seems to play only a secondary role. Conversely, in the first 100 years of the period, if the slow multidecadal increase of the flux is well denoted by the importance in the periodogram of periods larger than 50 years, the relative weights of the interannual and decadal oscillations are much more balanced than in the 20th century. This shows that the increase in the deposition of lithics >35 µm which occurred in Mejillones Bay during the 19th century was accompanied by the 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 the Pacific Oscillation.

**Implications for the variability of the wind stress**

In good agreement with the physics underlying the modeling (Alfaro et al., 2011) of the transport and deposition of lithic particles into the Mejillones Bay, the examination of the yearly fluxes (Fig. 4A) shows that when particles >35 µm are not observed, particles >100 µm are also absent. This corresponds to years when the wind stress remained constantly below the threshold of erosion over the pampa’s surface. The fact that there are 7 such years (AD 1760, 1761, 1769, 1777, 1783, 1791, and 1797) of particularly low winds (hereinafter referred to as ‘low wind years’, or LWY) in the second half of the eighteenth century that compare with only 3 (AD 1813, 1847 and 1876) and 4 (AD 1900, 1916, 1946, and 1975) in the course of the nineteenth and twentieth centuries, respectively, is consistent with the general intensification of wind erosion already commented. In a similar manner, the years when erosion did occur can be classified into two categories: (1) years of intermediate winds only (IWY), during which particles >35 µm are transported to the bay but not particles >100 µm, and (2) years with strong winds (SWY) when particles >35 and >100 µm are observed simultaneously. As shown by Flores-Aqueveque et al. (2012), the statistical distributions of hourly wind speeds of SWY years are characterized by a significant contribution of the high-speed mode, which is to say 10-m winds speeds exceeding 12 m/s. Table 1 presents the relative distribution of LWY, IWY and SWY years in the three defined time intervals.

Again, P2 (AD 1820–1878) century appears as a period of 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 over the total (120 years) reaches 29% (Fig. 6A).

As it can be seen from the flux of particles >100 µm depicted in Fig. 4A, the frequency of observation of SWYs increases from AD 1754 to approximately AD 1984 but their intensity remains in
the same order of magnitude with an average flux of $1.30 \pm 0.10$ particles/mm$^2$/year for each SWY in this period. In the last 30 years of the period of study, four particular years (AD 1982, 1983, 1994, and 1997) are well above this average with a flux of $3.03 \pm 0.65$ particles/mm$^2$/year. This indicates 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 El Niño events classified as ‘strong’ (1982–1983, 1997–1998) or ‘moderate’ (1994–1995) by the NOAA (http://www.cpc.ncep.noaa.gov/) might be coincidental but it also suggests that constructive interferences of the decadal and interannual oscillations might 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-1970s 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).

Paleoclimatic and paleoceanographic linkages

While there is little doubt about the expected general correlation between sea surface temperature variability and primary productivity in coastal upwelling areas, controversial views arise when projecting upwelling-favorable wind variability and trends in climate change simulations along the tropical and subtropical west coast of South America induced by increased concentrations of greenhouse gases in the atmosphere.

Vecchi et al. (2006) observe and predict a weakening of the Walker circulation that could possibly result in a weakening of the SEPSA. However, as mentioned in the preceding paragraph, a similar weakening also characterizes the warm phase of the ENSO cycle during which stronger winds have been observed along the coast of Perú (e.g., Enfield, 1981), results that are consistent within El Niño-like longer time scale oscillations in northern Chile (Rutllant et al., 1998; Vargas et al., 2007). In all these cases, an increase in the land–sea thermal contrast enhancing alongshore wind intensity has been suggested in connection with a decrease in low-cloud cover, departing from the classical Bakun’s (1990) hypothesis.

Strengthening of the upwelling-favorable winds concomitant with lower sea surface temperatures (SSTs) along the coast have been reported for subtropical Chile by Falvey and Garreaud (2009) since the last quarter of the 20th century. In these cases, as also documented in a recent coastal wind climatology by Rahn and Garreaud (2013), the main mechanism driving alongshore winds in subtropical and tropical Chile would be the alongshore pressure gradients conditioned by the poleward expansion of the subtropical edge of the Hadley cell (e.g., Johanson and Fu, 2009). More recently Belmadani et al. (2013) claim a projected strengthening of the winds off central Chile south of 30–35°S and a weakening elsewhere along the arid west coast of South America.

Moreover, high-resolution alkenone time series document a decrease in SST along the main upwelling areas off Northern Chile and Peru (≈23°S and 14°S, respectively) (Vargas et al., 2007; Gutiérrez et al., 2009, 2011). This reconstructed cooling, especially observed since the mid-20th century, coincides in sign and magnitude with the changes of coastal SST measured directly since 1979 (Falvey and Garreaud, 2009) suggesting that the entire region responds to the same regional-scale forcing processes that could be related with an intensification of the SEPSA (Falvey and Garreaud, 2009). In the study area, proxies of primary productivity and lithic mineral fluxes in marine sediment cores (P981A and BC3D) from the Mejillones Bay, show an increasing trend in phytoplankton productivity since the late 19th century (Vargas et al.,

Table 1

<table>
<thead>
<tr>
<th>Period (AD)</th>
<th>Duration (yrs)</th>
<th>LW years</th>
<th>IW years</th>
<th>SW years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1754–1820</td>
<td>66</td>
<td>8 (12%)</td>
<td>49 (74%)</td>
<td>9 (14%)</td>
</tr>
<tr>
<td>1820–1878</td>
<td>58</td>
<td>2 (3%)</td>
<td>45 (78%)</td>
<td>11 (19%)</td>
</tr>
<tr>
<td>1878–1998</td>
<td>120</td>
<td>4 (3%)</td>
<td>81 (68%)</td>
<td>35 (29%)</td>
</tr>
</tbody>
</table>

Fig. 6. Comparison between the frequencies of the strong wind years (SWY) and mean organic carbon variations.
In particular, they defined two main lapses of productivity: a pre-1820 period characterized by low organic carbon and low “chlorins” indicating relatively low primary productivity and a post-1877 period where the proxies showed an increase in variability as well as in magnitude (Fig. 4C; Vargas et al., 2007; Caniuipán et al., 2009).

As depicted in Fig. 4, these periods are consistent with our results, confirming an increase of the southerly wind intensity and, consequently, of the coastal upwelling in the studied area after the late 1870s. Moreover, when comparing the frequency of strong wind years (>12 m/s) determined from the lithic content (ratio 1754–1820) to the second period (AD 1820–1878) an increase of 5.3% in frequency of SWYs can be associated with an increase of 0.197 mg/cm²/yr (9.5%) in the average organic carbon, whereas in the transition from the second to the third period (AD 1878–1998) a rise of 10.2% in the SWYs relates to an intensification of 0.261 mg/cm²/yr (11.4%) in the average organic carbon. 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 establishment of oceanographic conditions that favored the preservation of increased fluxes of fish scales to the sea bottom since AD 1878 (Valdés et al., 2008; Diaz-Ochoa et al., 2011).

Furthermore, when analyzing in detail the aeolian lithic particles (>35 µm) time series for the period for which historical wind data (windstress) 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-1970s.

**Conclusion**

Aeolian particles have been widely used to interpret past ocean–climate variability from many sites and sedimentary records, however, we have few opportunities for developing quantitative reconstructions of paleowind intensity and indeed paleoclimate–paleoceanography. The examination of time series of lithic particles (>35 µm) from laminated sediments in Mejillones Bay (23°S), spanning the period between AD 1754–1998, confirms that the 19th century in the broad sense has marked a transition period between the second half of the 18th century, characterized by relatively moderate winds, and the 20th century in which erosion events on the surrounding hyperarid coastal Atacama Desert were more frequent, and possibly stronger. This last assumption is confirmed by the time series of particles >100 µm which features an intensification during the 20th century, and particularly in the last 30 years, of both frequency and amplitude of strong erosive events.

Spectral analysis on the lithic particles–time series shows that the 19th century constitutes a transition 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 of the decadal oscillations in the last centuries is most probably at the origin of the general strengthening and larger variability of the eroding winds along the coast of the Atacama Desert. However, as denoted by the fact that in the second half of the 20th century the years of larger depositional fluxes of particles >100 µm coincide with El Niño, it is suggested 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; Caniuipán 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 al., 2007; Gutiérrez et al., 2011).

When comparing the frequency of SWYs (winds >12 m/s) and the sedimentary 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 indicate 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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