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Morphology and dynamics of large subtidal dunes in Bahia Blanca estuary, Argentina

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ABSTRACT

The purpose of this paper is to carry out a detailed analysis of subtidal dune morphology and temporal variability and to estimate dune migration rate to improve knowledge of this topic, and so enhance the existing data on different marine environments in the world and especially in South America where this information is limited. Two swath bathymetry surveys were conducted across a dune field in the Bahia Blanca Estuary (Argentina). Morphometric parameters and migration rate according to the dune type, were analyzed. The field is composed of large dunes exhibiting two morphological configurations, which are differentiated into sinuous and barchan dunes. The dunes studied are the largest of the estuary, with heights and wavelengths greater than 5 m and 130 m, respectively. The crests of the large dunes are arranged with an orientation perpendicular to the axis of the channel. From geometrical analysis of the parameters, the dunes show a weakly positive correlation between dune height and wavelength as too between dune height and water depth. No clear relationship was observed between maximum height and wavelength parameters with water depth. Across the estuary, the bedforms migrate in the ebb direction, with mean rate of 43 m year^{-1}. Comparison of our results with previous data shows that during three decades the western boundary of dune field has been displaced 900 m towards the outer estuary, however the dune field configuration and distribution of diverse types of bedform appear to be relatively stable.

1. Introduction

Subtidal dunes or sand waves occur in all the world's shelf seas and coasts. The importance of studying dunes lies in the fact that they are direct evidence of sediment dynamics and bottom current direction (Kenyon, 1986). These features are common structures in marine environments, such as the seas around the British Isles (Van Veen, 1938), the Calais–Dover Strait (Besio et al., 2008) and the North Sea (Dingle, 1965; Houbolt, 1968; Mc Cave, 1971; Caston, 1972; Le Bot et al., 2000; Knaapen, 2009). Moreover, studies of continental shelves in deep water have found dunes in the Argentine basin (Flood and Shor, 1988), the northern Bering Sea (Field et al., 1981) and the Gulf of Cádiz in the NE Atlantic Ocean (Habgood et al., 2003). Recent studies have also mentioned the existence of large subaqueous dunes in deep areas in the Celtic Sea (Reynaud et al., 1999), the Irish Sea (Van Landeghem et al., 2009, 2012), the Australian continental shelf (Porter-Smith et al., 2004), and the western Brittany continental shelf in France (Franzetti et al., 2013).

Dunes are bedforms typical of seabed topography of many estuaries and have been widely researched; for example Ludwick (1972), Langhorne (1973), Boothroyd and Hubbard (1975), Bokuniewicz et al. (1977), Dalrymple et al. (1978), Dalrymple (1984), Aliotta and Perillo (1987), Harris (1988), Fenster et al. (1990), Berné et al. (1993), Ikehara and Kinoshita (1994) and Francken et al. (2004), among others. Subtidal dunes of different sizes are a common morphology in several areas of the Bahía Blanca estuary in Argentina. Dunes up to 2 m high have been found in the inner area of the numerous tidal channels (Aliotta et al., 2004; Vecchi et al., 2008; Ginsberg et al., 2009), while the largest dunes have been observed in the Principal channel, the navigation route (Ginsberg et al., 2001, 2003, 2009; Cuadrado et al., 2003; Spagnuolo, 2005; Lizasoain, 2007; Giagante et al., 2008; Vecchi et al., 2008). All these studies have focused specifically on the distribution and morphology of the dunes with the purpose of inferring the bedload sediment transport pattern. Specifically, at the entrance of the estuary there is a large field of dunes, with sand waves higher than 5 m, which are the highest in this estuarine environment (Aliotta, 1987). The presence of these large bedforms poses a constant danger to navigation, especially if they undergo significant changes due to anthropogenic activities, which alter sediment availability and distribution and disturb the natural balance of the system. Therefore, studying the morphological features of dunes and understanding their behavior

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(displacement and migration rate) is crucial in order to achieve sound management of estuarine navigation. This field of large dunes constitutes an excellent natural laboratory for analyzing this type of feature. Taking these considerations, we aim is to analyze dune morphology and identify the spatio-temporal variability of the different dunes that were found throughout this investigation in order to derive their migration rates. Therefore, the present paper is innovative for the South American coast due to the methodology applied and the level of detail used. Thus, an analysis of morphometric parameters and the difference in migration speed, according to the dune type, is performed. In addition, this analysis will provide new elements to expand the knowledge of the dunes in relation to environmental dynamic conditions. Moreover, the information analyzed was compared with previous data, allowing us to define the net displacement of the dune field over a period of three decades.

1.1. Study area

The Bahía Blanca estuary (Fig. 1), located in the south of Buenos Aires province, Argentina, presents a regional configuration characterized by a dense network of channels of different sizes, generally with a meandering pattern. Several flat-relief, low-altitude islands and vast, muddy tidal flats which are regularly covered by high tides complete the coastal physiography. The water motion in the estuary is dominated by a semi-diurnal, quasi-stationary tidal wave (Perillo and Piccolo, 1991) with a mean range, in the Principal channel, of 3.04 m for spring tides and 2.5 m for neap tides, which classifies the estuary as mesotidal. The currents are reversible, with maximum vertically-averaged values of 1.20 and 1.05 m s^{-1} for ebb and flood conditions, respectively (Nedeco-Arconsult, 1983; Serman, 1985). Two main tributaries, Sauce Chico river and Napostá Grande stream, contribute a mean annual fresh water flow of 1.9 and 0.8 m s^{-1}, respectively (Perillo et al., 1987). The estuary behaves as a hypersynchronous system because the tidal range and tidal current amplitude increase headward (Perillo and Piccolo, 1991). In the inner zone of the study area, the maximum depth-averaged flood current is 1.05 m s^{-1}, while the ebb current reaches 1.30 m s^{-1}. Outside the estuary, the average maximum value found is 1.05 m s^{-1} for the flood and 1.20 m s^{-1} for the ebb (Ginsberg et al., 2012).

The Principal channel, access route to one of the most important harbor and petrochemical complexes in the country, is approximately 60 km long. In this channel, the ebb current has a net sand transport as bedload towards the outer area of the estuary (Aliotta and Perillo, 1987; Cuadrado et al., 2003), contributing to large shoals on the adjacent marine shelf, which form a large ebb delta (Aliotta, 1987). The study area (Fig. 1) is located at the estuary entrance, between 38° 56.45′ and 38° 59.5′ S and 61° 56.91′ and 62° 02.08′ W, near Puerto Rosales harbor. A large dune field stretches over this area, where the highest bedforms in the estuary occur.

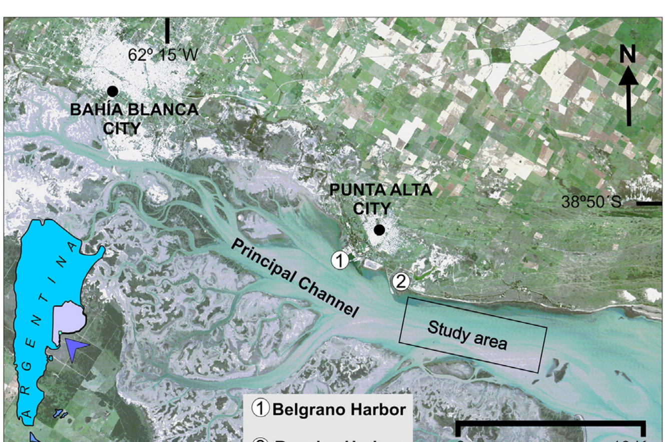

Fig. 1. Study area in Bahia Blanca Estuary, Argentina.

2. Methods

The present study was carried out analyzing bathymetric data gathered during two different periods (June, 2010 and October, 2011). To that end, a high-resolution multibeam bathymetric system (250-kHz GeoSwath Plus from Kongsberg GeoAcoustics Ltd., UK) was used on board the ship Buen día Señor, which belongs to the Instituto Argentino de Oceanografía (IADO). Transverse and longitudinal profiles were performed in the Principal channel. Position data were controlled in real time using a differential global positioning system (DGPS) connected to navigation software. Also, bottom samples for a general characterization of dune sediment were collected with a Shipek grab sampler.

Investigation of the shallow seismostratigraphy of the marine sub-bottom was done simultaneously with the first bathymetric survey, using a 3.5 kHz high-resolution seismic profiler. The data were collected digitally using GeoTrace 2009 software and processed with SonarWiz 5 software.

For tidal correction of bathymetric data, the depths were referred to the datum plane of Puerto Belgrano harbor. The bathymetric data obtained with the multibeam echosounder were processed to create a bathymetric map with a pixel resolution of 1 m, used as the basis for the analysis and characterization of bedforms.

Because there are several geometric parameters used for dune grouping and categorization, the terminology used for classifying dunes has become very confusing. Within this variety of nomenclature, in this study we follow the scheme proposed by Ashley (1990) because it is based on the classification suggested at the 1987 Mid-Year Meeting of SEPM in Austin, Texas where researchers achieved a broad consensus. Therefore, we consider the height and wavelength for classifying the dunes because we consider them to be the most distinctive parameters.

It is often assumed that fully developed dunes are in equilibrium with the prevailing hydraulic conditions when the steepness, the relationship between their height (H) and wavelength (L), follows the power law $H^{max} = 0.0677 * L^{0.8098}$ of Flemming (1988). This equation is considered to represent the global trend for dunes formed in any type of river or tidal flow system; a reference against which local trends can be compared (Bartholdy et al., 2002; Wienberg and Hebbeln, 2005; Kubicki, 2008). Therefore, we compared our data obtained with this power law.

3. Results and discussion

3.1. Characterization of the bottom types

Based on the analysis of the morphological, sedimentological and seismic data, collected at the entrance of the Bahía Blanca estuary, it was determined that the seabed presents a varied configuration as a result of the regional geology and the complex interaction between current velocity and direction, sediment size and water depth. The data collected with the multibeam echosounder enabled a high-resolution bathymetry and 3D visualization of the seafloor topography. Four bottom types were observed at the estuary entrance (Fig. 2), each of them with specific features.

Seabed outcrops forming terraces and escarpment levels with irregular edges (Fig. 2a) appear on the northern flank of the channel. Southwards, towards the greatest depths (15–19 m), isolated outcrops with the same sonar configuration as the terraces were identified, appearing in the form of plateau-like relicts. This bottom type is related to an ancient abrasion platform formed by the last marine transgression during the early Holocene (Aliotta, 1987; Aliotta and Perillo, 1990). In addition, time and altimetry correlations may be established between this ancient marine shelf located at the entrance of the Bahía Blanca estuary and the topographic scarps found by Aliotta et al. (1999) on the continental shelf outside the estuary.

Based on the lithostratigraphic features of the sub-bottom (Spagnuolo, 2005), the outcrop is related to the Pampiano Formation (Fidalgo et al., 1975), which is composed of Plio-Pleistocene silty

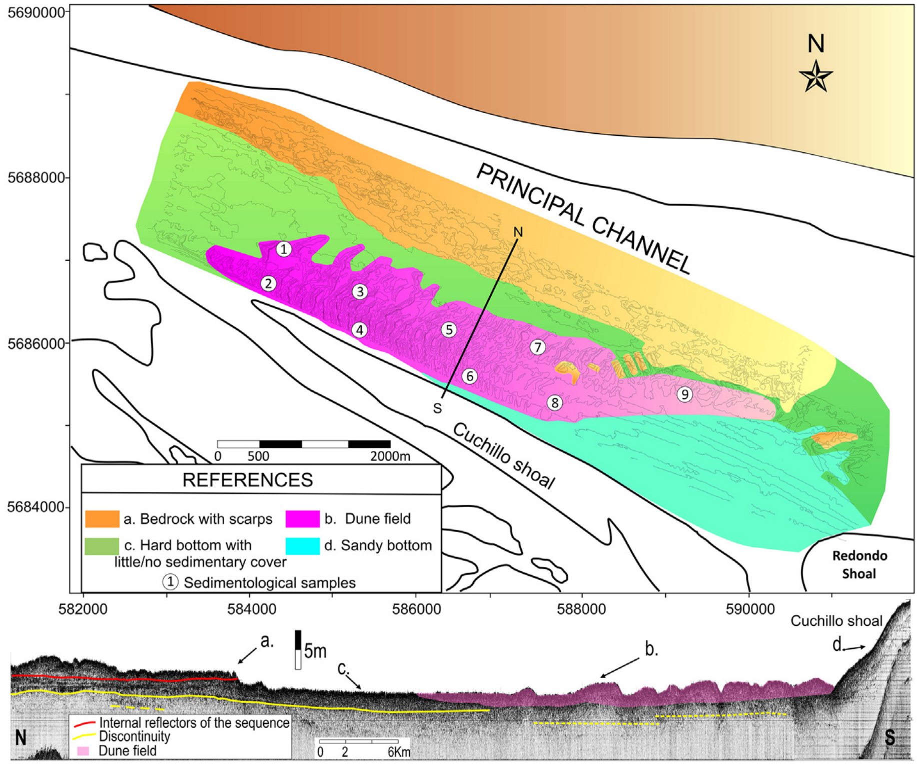

Fig. 2. Distribution of different morpho-sedimentological features in the study area. The circles are the locations of sediment sampling stations. N–S seismic profile showing morpho-sedimentological features and dune field location.

sandstone partially cemented by calcium carbonate. Towards the inner estuary, this formation has a wide regional distribution, constituting the basement rock of the transgressive–regressive sediments deposited during the Holocene (Aliotta and Farinati, 1990; Aliotta et al., 1992, 1996, 2014).

In the southern-central area of the channel, a sandy bottom, with a sedimentary cover up to 6–7 m thick, is observed (Fig. 2b). This area is characterized by the presence of large dunes, the analysis of which is the aim of this study. The surface samples collected (Fig. 2) indicate that the sediment characteristics of the dune field is medium to fine sand, with a varying proportion of shell fragments and small quartzite and siltstone pebbles (<0.5 cm diameter).

Between the dune field and the ancient abrasion platform on the northern flank of the channel is a relatively flat and highly reflective bottom with little to no surficial sediment cover (Fig. 2c). Interpretation of the seismic profile (Fig. 2, N–S) suggests that this bottom corresponds to the outcrops of an ancient sedimentary sequence, located stratigraphically below the rock material constituting the northern zone of the study area. The lithostratigraphic data from coastal boreholes (Oiltanking Ebytem, 2000) indicate that the seismic sequence underlying the Pampiano Formation consists of sandy, clayey silt, ranging from dark gray to light brown, with calcareous nodules and highly compact levels enriched with reddish clay. This unit correlates with the Arroyo Chasicó Formation (Aliotta et al., 2014) of the late Miocene (Tonni et al., 1998). Finally, towards the eastern zone, adjacent to the Cuchillo and Redondo shoals, a flat sandy bottom without bedforms (Fig. 2d) is observed.

3.2. Dune morphology

A large field of dunes of varying shapes and sizes, first reported by Aliotta and Perillo (1987), occurs in the deepest zone of the study area, with an elongated WNW–ESE configuration extending in the orientation of the channel (Fig. 2). In the eastern end, the field narrows and extends towards the northern flank of the channel. The total length is approximately 5.5 km, while the maximum width is 1.2 km. The field occupies a surface of approximately 4.7 km^2 at depths between 19 and 24 m. The geological boundaries of the dune field are, to the north, a hard substrate with no sedimentary cover and, to the south, the Cuchillo and Redondo shoals (Fig. 2).

According to diverse morphological configurations of dunes, we established the following parameters for their morphometric characterization. Dune wavelength (L) was defined as the trough-to-trough horizontal distance, taking the lowest point of the lee side, which indicates the advancing front of the feature, as the measuring point (Fig. 3). This

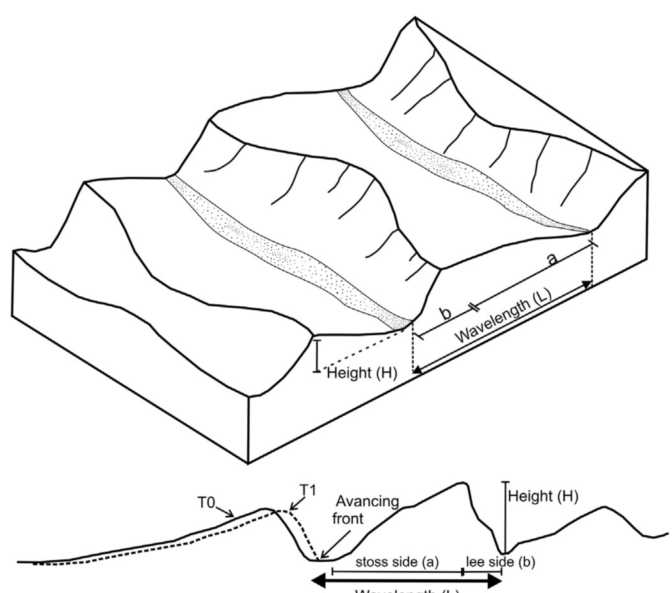

Fig. 3. Schematic representation of morphometric parameters used to describe the dune features. T0 and T1 define two successive moments of a dune crest during its migration.

measurement framework proves to be convenient when dune migration is analyzed as it does not depend on the morphological change that dunes may suffer during their migration process. Dune height (H) was determined as the vertical difference between the dune crest and the adjacent trough on the lee side. The crest was set as the highest point along the bedform. Moreover, in order to assess the symmetry index (Allen, 1980), the ratio (a/b), where a and b are the horizontal lengths of the dune lee and stoss flanks, respectively, was considered (Fig. 3).

Thus, following Ashley (1990), the observed dunes are classified from small, H ≥ 0.10 m and L = 10 m, to very large, reaching a maximum H of 5.3 m and L > 130 m. The small dunes constitute the most distinctive bedforms, being located on the stoss flanks of the largest dunes and on the plains between dunes. Dune geometry is determined by the interaction between flow and mobile sediment bed. Factors such as current velocity, water depth and substrate properties (sediment grain size and availability) are regarded as the main elements that determine dune size and shape (Aliotta and Perillo, 1987; Ashley, 1990; Dalrymple and Rhodes, 1995; Carling et al., 2000; Hoekstra et al., 2004; Ernstsen et al., 2005; Li and King, 2007). Also, the development of this type of dune has been related to the existence of a thin layer of sandy sediment (Allen, 1968; Aliotta and Perillo, 1987). Specifically, the bedforms determined here show a wide range of shapes and sizes.

An overview of the dune field (Fig. 4) demonstrates that the crests of the large bedforms are arranged with a general NE–SW (N50°E) orientation, normal to the channel. Many of the crests show high continuity, reaching lengths of 1.2 km, although in 75% of cases length ranges from 100 to 500 m. In general, the crests of the large and very large dunes have a sinuous configuration (Fig. 4, DS). The northern and southern ends of these sinuous dunes tend to bend towards the outer area of the estuary (Fig. 4b). Also, some large dunes have bifurcated crests (Fig. 4, Db). According to Costa et al. (2009), these bifurcations indicate different flow regime zones. In addition, in the northern area of the field, there are large barchan-type dunes (Fig. 4, DBs, DB), markedly arc-shaped and with the convex side towards the inner estuary. As for the configuration of their lateral ends (horns), which point towards outer zone of the estuary, it may be symmetrical (Fig. 4, DBs), with horns of similar length (Fig. 4a, I y b, I) or asymmetrical (Fig. 4, DB), with horns of different lengths (Fig. 4a, II). Garlan et al. (2008) found that dune type (barchan or sinuous) is associated with different sediment availability. They remarked that when the current cannot set all the sediment particles in motion or when there is a sand deficit, most dunes are barchan-shaped dunes, whereas, when the current is saturated with sediments, they have a sinuous shape. Therefore, the observed barchan-shaped dune formation could be related to less sediment availability because these dunes are located in the northern zone of the field where there is an area with no sedimentary cover, limiting the zone where these dunes occur (Fig. 2, zone c).

Regardless of dune crest configuration (sinuous or barchan), in cross-sectional view all these structures show a highly asymmetrical profile (Fig. 4, a and b), with the steepest (lee) slope facing the outer area of the estuary. Numerous investigations have demonstrated that asymmetrical dunes indicate sediment transport direction for unidirectional currents, or reversible currents over time (Johnson et al., 1982). Therefore, the lee flank position reveals the displacement direction of these bedforms towards southeast, in agreement with reported by Aliotta and Perillo (1987). Besides asymmetry, another important feature to take into account in the analysis of dune morphodynamics is lee flank angle (Ludwick, 1972; Langhorne, 1973). In this regard, Taylor and Dyer (1977) stated that most dunes have lee side flank

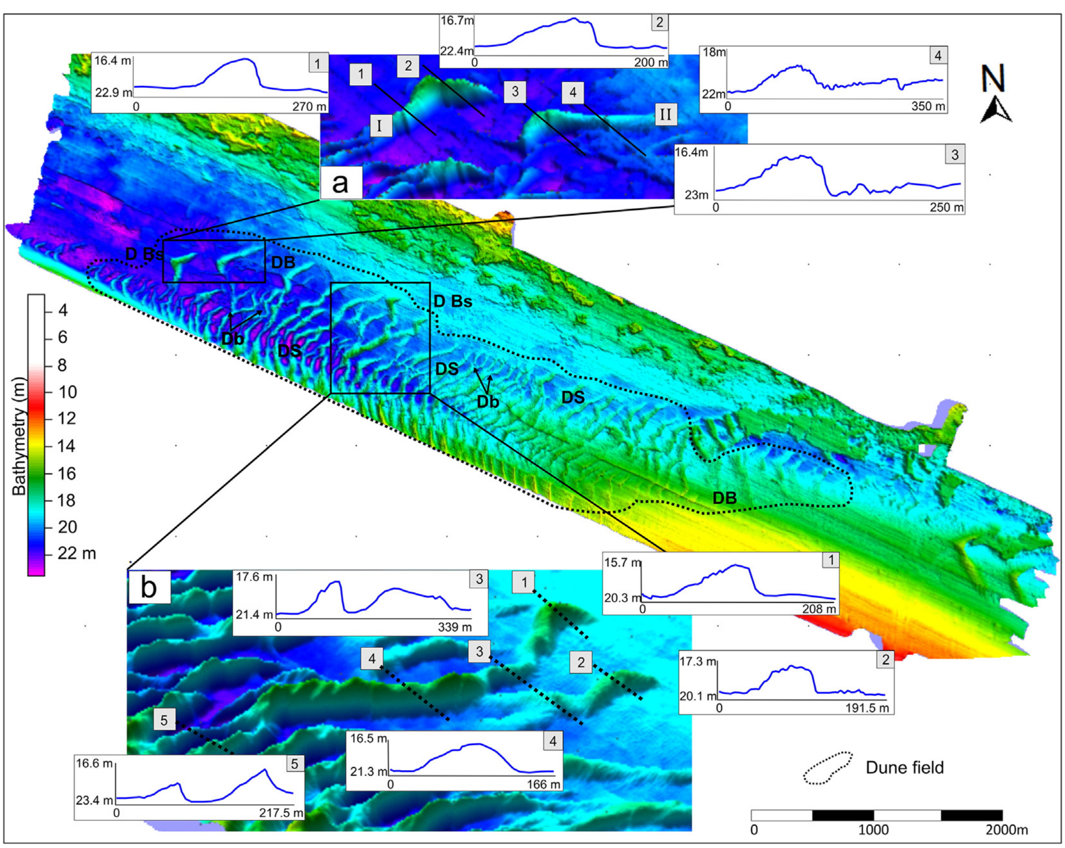

Fig. 4. Multibeam bathymetric image showing the details of the morphologic features. The area outlined by dashed black lines denotes the dune field. DB: barchan dune, DBS: symmetrical barchan dunes, DS: sinuous dunes, Db: bifurcation dunes. (a) Detail of an area: the black solid line frame indicates an area of barchan dunes and profiles highly asymmetrical in cross-section. (b) The black solid line frame shows an area of sinuous dunes with asymmetrical profiles in cross-section.

angle of less than 10°. Lobo et al. (2000) determined similar values for dunes in the Gulf of Cádiz, and also dunes in the Bristol Channel (England) have lee flank angles of 1.5° to 7° (Harris, 1988). However, in other works (Aliotta, 1987; Aliotta and Perillo, 1987; Waage, 2012) slopes reaching 16° have been reported. Specifically, in this present study lee slopes (flank angles) showed average values of 11°, although it should be noted that inclinations above 14° were found in 15% of the observations.

The morphometric parameters related to the size of the investigated dunes reveal that those located in the western area of the field, at depths reaching 22 m, generally have an average L = 230 m and a H ranging between 4 and 5 m, with some cases of L = 290 m and H > 5 m. Moreover, crests were observed to extend continuously for more than 350 m. In the southern area of the field, however, an average L = 104 m and a maximum H between 2 and 4 m were determined. In addition, a 100 m × 100 m grid of the dune field was drawn in order to assess dune height in detail. The heights of the bedforms contained in each square were averaged so as to obtain an average height value for each particular square, thus determining spatial distribution of the H parameter (Fig. 5) throughout the field. The resulting distribution indicates that the greatest average heights (3 to 5 m) are grouped in a wide central-southern area of the field.

Several investigations (Harris, 1982; Lees, 1983; Twichell, 1983; Collins et al., 1995; Reynaud et al., 1999; Hennings et al., 2000) have shown that the dunes' asymmetry and geometry in cross-section have been widely used as indicators of net bedload sediment transport and hydrodynamic conditions. Following these concepts, the asymmetric shape and orientation of large and small-scale dunes in our study area clearly reveal the ebb flow dominance in the navigation channel. This is also supported by tidal current velocity measurements carried out by Ginsberg et al. (2012) at the inner zone of study area. These authors found that the maximum flow velocity is greater during ebb (1.30 m s^{-1}) than during flood (1.05 m s^{-1}).

3.3. Analysis of morphometric parameters

Geometric features of dunes reflect certain conditions of the marine environment, especially current velocity, wave regime and sedimentary features (Flemming, 2000). Hence, dune size and spacing have been widely analyzed, both in natural environments (Kenyon, 1970; Stride et al., 1982; Van Dijk and Kleinhans, 2005; Van Dijk et al., 2008), in laboratories (Baas, 1994; Bennett and Bridge, 1995; Venditti et al., 2005) and through morphological modeling (Németh, 2003). Such investigations have been done with the aim of inferring hydro-sedimentological conditions of the environment based on morphometric relationships shown by dunes. In general, large bedforms are relatively stable, keep their shapes and only suffer small morphological changes over periods of several months (Harris and Collins, 1984; Ashley, 1990; Fenster et al., 1990; Houthuys et al., 1994). With the aim of providing new information to extensive existing data from different regions of the world, we carried out an assessment of the data collected in the Bahía Blanca estuary. To that end, the relationships between the following dune parameters were considered: height (H), wavelength (L), water depth (d) and symmetry index (a/b). Determinations were completed along six transects parallel and longitudinal to the channel (Fig. 11). These lines were equidistantly arranged 150 m away from each other and, as they extended over the entire dune field, it was possible to determine several dune features.

In order to assess dune height (H) variation in relation to wavelength (L) and water depth (d), H/L and H/d relationships were plotted. Only dunes higher than 1 m were considered. Taking into account the upper limit of dune height of $H^{max} = 0.16\ L^{0.84}$, established by Flemming (1988), in our study we used H^{max} for analyzing H in order to avoid data dispersion, as suggested by Schmitt et al. (2007). The clouds of points illustrated in Fig. 6a and b, determine a general positive trend line for the H^{max}/L and H^{max}/d relationships. For the several bedforms, our data (Fig. 6c) lie in an adjacent area below the $H^{max} = 0.16\ L^{0.84}$ relationship proposed by Flemming (1988). Then, our acquired data indicate that the relationship established by this author may represent the upper limit of dune height. This result was also found by Aliotta and Perillo (1987) for dunes in the Bahía Blanca estuary.

In addition, our morphometric analysis of dunes included depth (d) as a third variable. As illustrated in Fig. 7, the data on the H^{max}/L relationship, classified according to the water depth of the measuring site, were included. The dispersion of our collected data shows a certain relationship between H^{max} and L at depths less than 23 m. Schmitt et al. (2007) suggested that, at depths less than 25 m, dunes tend to flatten; this tendency could arise from increasing resuspension and bedload caused by the movement of surface waves, which are likely to intensify in shallow water. However, for dunes below 23 m, our H_{max}/L data indicate high dispersion, with no clearly-defined relationship. Since the range of depths in this study is narrow (19–24 m), we consider that this analysis may not be sensitive enough to yield a conclusive result.

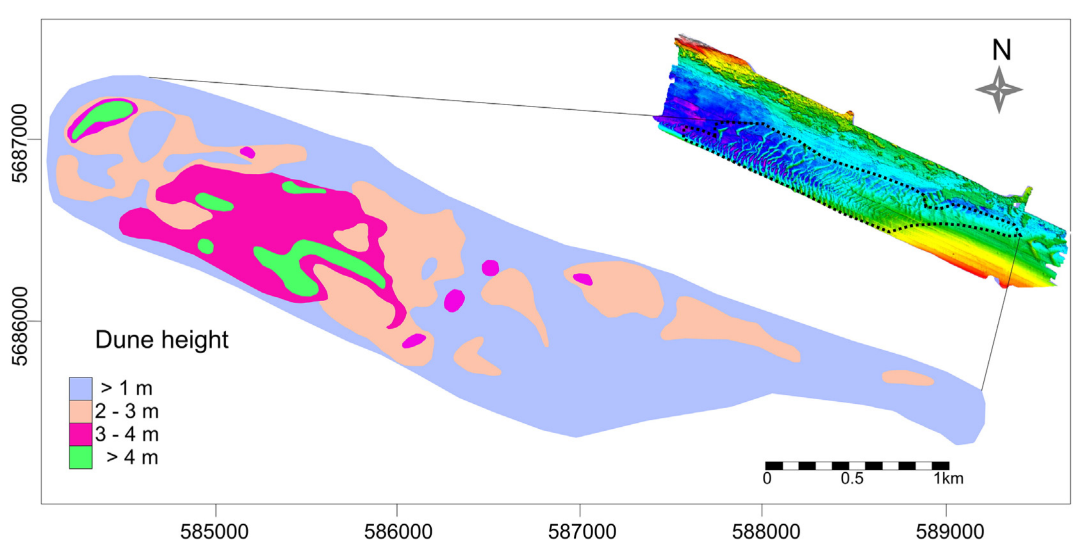

Fig. 5. Spatial distribution of the height of dunes throughout the field.

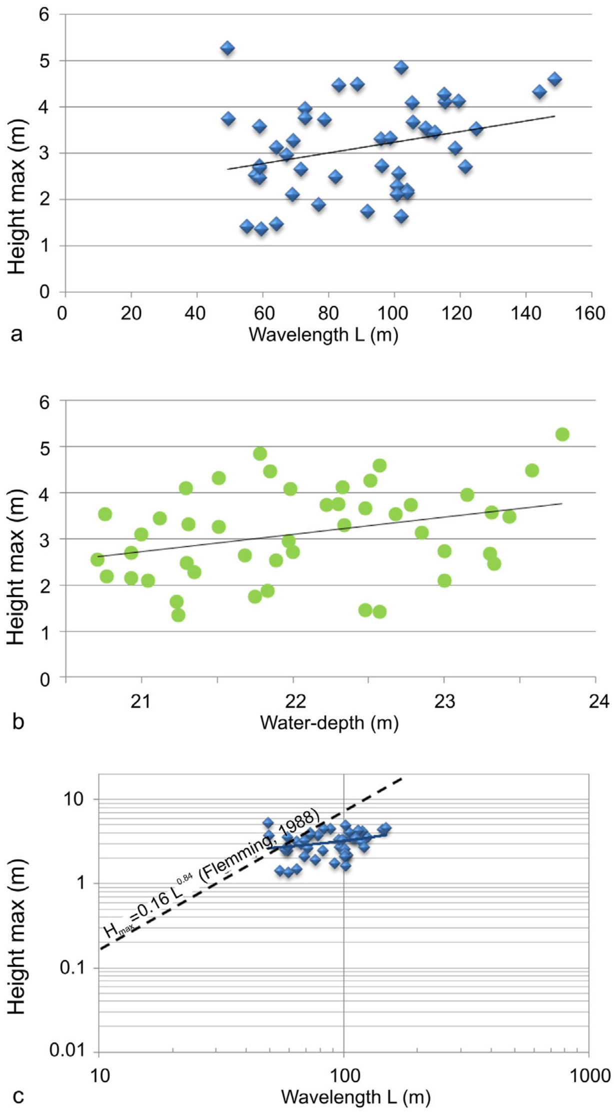

Fig. 6. Scatter diagrams showing the relationships between geometric parameters of the dunes. a) Maximum height — wavelength of dunes, with the corresponding linear regression fit indicated by the solid line. b) Maximum height — water depth, with the corresponding linear regression fit indicated by the solid line. c) For comparison, the points indicate the relationship between maximum height and wavelength of dunes from the study area and dashed line the upper limit predicted by the study of Flemming (1988).

This type of assessment was carried out by Smith et al. (2007) on dunes at water depths between 10 and 25 m, finding a clear relationship only for the deepest ones.

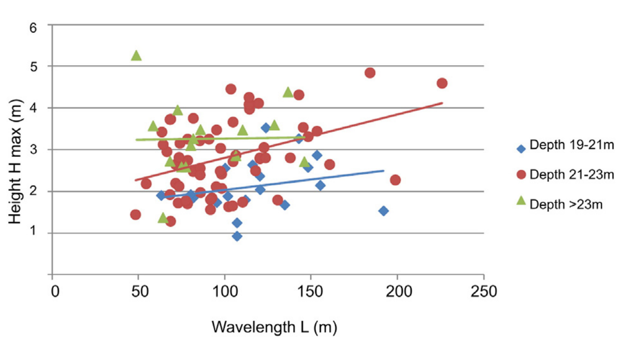

Fig. 7. Scatter diagram showing the relationship between maximum height-wavelength of dunes according to water depth.

In relation to symmetry index of the dunes we find values where the horizontal stoss length is up to 4 times longer than the horizontal lee length, with the average value slightly greater than 2.

3.4. Migration

Sequential multibeam images may be used to estimate the direction and magnitude of sand wave migration (Shaw et al., 2000; Ernstsen et al., 2005; Smith et al., 2007). The accuracy of these estimates depends on the overall quality of the images, the time interval between the surveys and the regularity of the dunes. These bedforms in two consecutive images may be difficult to correlate due to either the poor quality and/or irregularity of the sand wave field examined or the potential "aliasing" caused by the long sampling interval between the two surveys (Xu et al., 2008).

We determined the dune migration based on the displacement of each bedform between two surveys separated by a 16-month interval (June, 2010 and October, 2011). To that end, displacement was examined over six transects longitudinal to the channel and representative of the several features of the dunes. Considering that most bedforms kept their general configuration between the two surveys, identification of each of them made it possible to quantify their displacement. For this type of analysis, many authors have determined migration comparing crest movement (Knaapen et al., 2005; Cuadrado and Gómez, 2012; Van Landeghem et al., 2012, among others). As crest position may be modified by a variation of symmetry without dune displacement (Németh et al., 2002), we chose to measure migration using the lowest point of the lee side, which represents the advancing front of the dune (Fig. 3).

Numerous works have reported the migration rate of estuarine dunes. A value of 4.9 m $year^{-1}$ was established for small dunes in St. Andrews Bay, USA, by Salsman et al. (1966), while the migration rate of very large dunes (H up to 8 m) in the Thames Estuary does not exceed 25 m $year^{-1}$ (Langhorne, 1973). Higher migration values were found in the Gower Peninsula (UK), where dunes between 2 and 5 m high migrate between 24 and 37 m $year^{-1}$ (Schmitt et al., 2007). Calculation of the migration rate of the dunes studied in the Bahía Blanca estuary shows that they migrate at rates ranging from 18 m $year^{-1}$ to 62 m $year^{-1}$, with a mean value of 43 m $year^{-1}$, towards the outer area of the estuary. This value, found by comparing high-resolution bathymetries, is 10 m $year^{-1}$ higher than the migration value determined by Aliotta and Perillo (1987) for the same bedforms. Since these authors used an analog echosounder without DGPS, the difference between their estimates and ours may be related to the positioning system used in each study.

In general, the dune field configuration, as illustrated in Fig. 8, and the distribution of diverse types of dune also observed by Aliotta and Perillo (1987) is very similar to the present. Therefore, we can infer that over a 30-year period, the dunes keep their morphological characteristics. Even though the long time interval that has elapsed since the earlier study makes it impossible to identify the same dunes, observation enables us to infer that the position of the northern and southern ends of the field is broadly similar to their position three decades previously. Although the boundaries of both fields were acquired with different positioning systems, we found this comparison to be acceptable because the system used by Aliotta and Perillo (1987) includes a less than 3 m error, which we considered minimal in comparison with field displacement value. We make an approximate assessment of the migration of this field based on displacement of the boundaries between both. Thus, the migration of the western limit towards the outer area of the estuary may be estimated as approximately 900 m. We postulate as a hypothesis that this migration process might be associated with a decrease of sand supply from the inner estuary. This, reduced availability of sediment transported as bedload might limit the generation of dunes, causing the displacing dunes towards the mouth of the estuary and thus altering the initial boundary of the field.

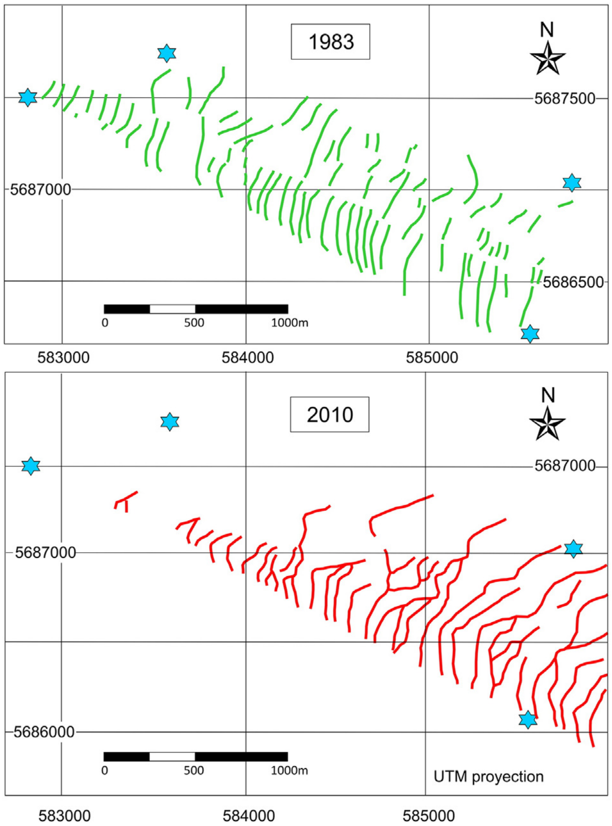

Fig. 8. Detailed maps of spatial distribution of the dune crest identified by Aliotta and Perillo (1987) (a) and this study in 2010 (b). Stars indicate the boundaries of the dunes field identified in 1983.

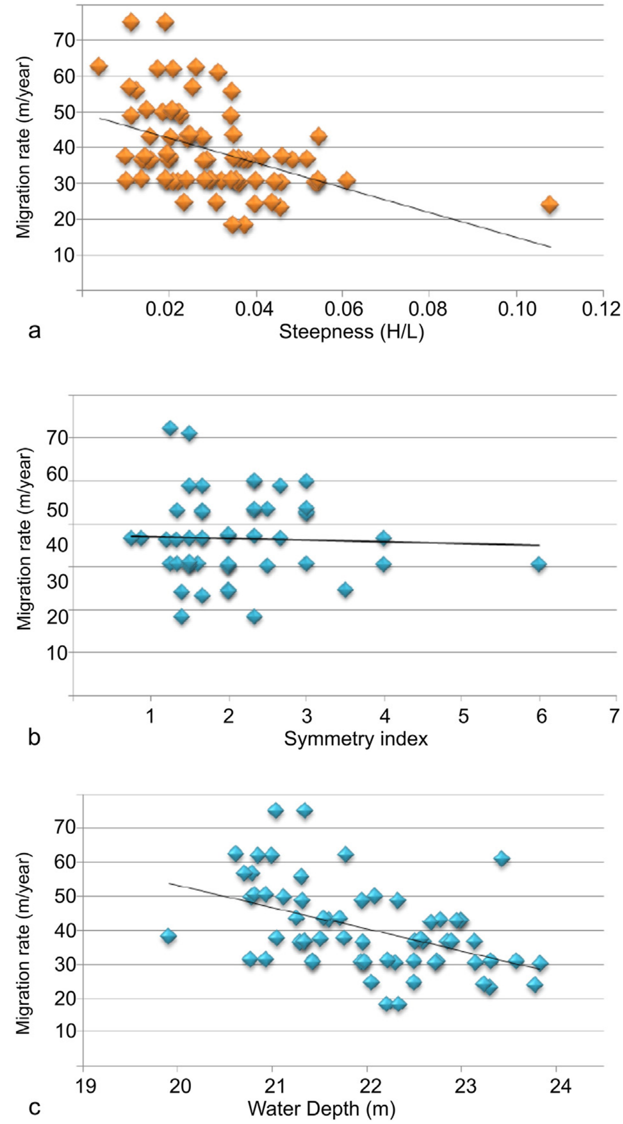

Fig. 9. Scatter plots of dune migration rates against dune steepness (H/L relationship) (a), symmetry index (b) and water depth (c).

On the other hand, some studies suggest that H/L relationship (or slope) could be linked with rate of dune mobility. Thus, an evolution towards lower and longer dunes (gentler slopes) may indicate loss of bedform mobility (Kubicki, 2008; Ferret et al., 2010). However, when we analyzed our data (Fig. 9a), we noticed that there was no agreement with this thesis since the highest migration rates occur with the least steep slopes. As for the relationship between migration and the symmetry index (Fig. 9b), our data show that migration remains constant for different symmetry indexes. Thus, the data obtained in the Bahía Blanca estuary indicate that the migration rate is independent of the symmetry index of the bedform, agreeing with findings by Van Landeghem et al. (2012). However, this contrasts with results from other authors, for example Knaapen (2005), Xu et al. (2008) and Li et al. (2011), who found a strong correlation between dune shape and migration rate.

Another parameter that seems to have an important influence on dune migration is depth. Dune migration rates are higher in shallow water than in deep water (Li et al., 2011). In our study area, dunes occur at a depth range restricted between 19 and 24 m. Under these conditions, the relationship between migration rate and water depth (Fig. 9c) indicates that the migration rate is indeed higher for dunes in shallow water than for those in deeper water.

Moreover, our study indicates that dunes undergo morphological changes during migration. Although no significant change of shape was observed in large dunes, those located in the southern area of the field (shorter wavelength) showed the greatest variation, with changes of lee and stoss slopes or variations in the bedform height (Fig. 10).

Even though the correlation between dune size and migration rate is still under discussion, our analysis shows that dune size is not correlated with migration rate. This result coincides with findings by Van Landeghem et al. (2012) in the Irish Sea. On other hand, our detailed analysis of the migration rate of dunes perpendicular to the channel indicates variability of the migration rate between them. Average, maximum and minimum values of migration rate were determined along six bathymetric cross-sections equidistantly spaced across the width of the studied dune field, covering most of it (Fig. 11). Our data clearly show that migration rate is higher for the dunes located in the northern area of the field (Fig. 11). In this strip, which coincides with the central area of the Principal channel, dunes migrate 51 m year^{-1}, while those located in the south migrate at a mean rate of 34 m year^{-1}. The configuration in plan view of dunes (northern area: prevailing barchan type; southern area: prevailing sinuous type) constitutes a morphological expression that indicates a difference in migration between both areas of the dune field. The relationship between dune type and migration rate has also been pointed out by other authors (Kleinhans, 2004; Franzetti et al., 2013), who agree on the fact that barchan dunes show a higher migration rate than linear-sinuous ones.

4. Conclusions

Our study focusses on the entrance of the Bahía Blanca estuary in Argentina. Bathymetric data were correlated with seismic records to determine spatial distribution of four bottom types (bedrock with relict structures, a wide area with large dunes, a hard substrate with a thin

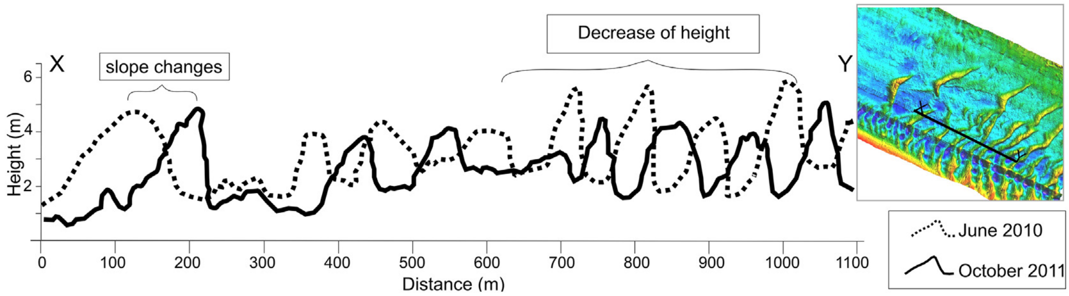

Fig. 10. Topographic changes of large dunes along line X–Y between the surveys in 2010 and 2011, identified with dashed and solid lines, respectively.

to no surficial sediment cover, and a flat sandy bottom). The dunes lie on an ancient abrasion platform from the Early Holocene.

In the deepest zone, between 19 and 24 m, dunes of different sizes, grouped in a large, elongated dune field (6.0 × 1.5 km), occur. These dunes have a markedly asymmetrical topographic profile, indicating sediment transport out of the estuarine system. Our detailed analysis of height distribution showed that the largest sizes (4.0–5.5 m) tend to occur in the western area and towards the south of the field.

Based on dune morphology, two types of bedform configuration were differentiated: sinuous and barchan. The crests of sinuous dunes are continuous, extending from 100 to 500 m, while those of barchan dunes have ends ("horns") towards the outer area of the estuary.

The morphometric analysis of dunes indicates that H/L and H/d relationships show a positive trend, i.e., height is directly proportional to wavelength and depth. If we consider the pioneering equation of Flemming (1988), our data suggest that the H/L equilibrium condition proposed by this author constitutes the upper limit of dune height. When we assessed water depth as a third variable, we could not clearly establish if this physical factor is related in some way to height and wavelength of the bedform. This may probably be due to the narrow depth range (19–24 m) where the studied dunes occur.

Determining spatial–temporal variability of dunes in an environment dominated by tidal currents is important as these data not only clearly demonstrate prevailing hydro-sedimentological conditions but also enable comparison with other authors' findings in different marine environments. At the entrance of the Bahía Blanca estuary, a mean migration rate of 43 m $year^{-1}$ in the ebb direction was found. Overall, high stability of dune morphology was observed in the period covered by our study (16 months). Comparison of our results with previous data shows that in a 30-year period the western boundary of dune field has been displaced 900 m towards the outer area of the estuary.

The analysis of the dune migration rates cannot be associated with their degree of symmetry or with their heights. However, it was possible for us to determine a difference in the migration rate between the northern area (51 m $year^{-1}$) and the southern area (34 m $year^{-1}$) of the dune field. This confirms that the configuration in plan view of these bedforms (northern area: prevailing barchan dunes; southern area: prevailing sinuous dunes) constitutes a morphological expression of bedform dynamics. The difference in shape may arise, in addition to sediment availability, from a higher residual velocity of the tidal current in the central area of the channel. This hypothesis may be examined in a future study of the hydrodynamics of this marine environment.

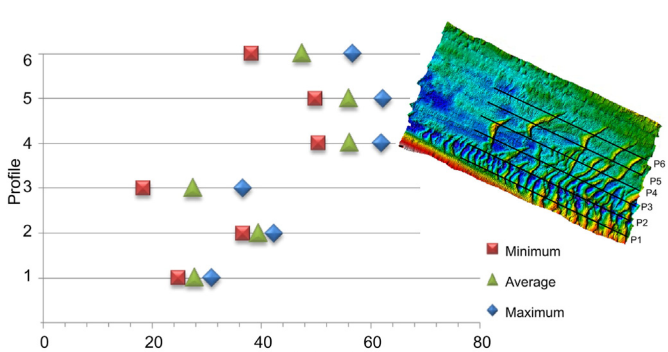

Fig. 11. Maximum, average and minimum migration rates of the dunes along six bathymetric cross-sections.

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