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ORIGINAL ARTICLE

Wave climate and morphosedimentary characteristics of the Kenitra–Bouknadel sandy coast, Morocco

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Abstract The Bouknadel–Kenitra 20-km sandy coastline is of strong interest from the perspectives of beach amenity, tourism and erosion issues. This section of the Moroccan coastline has only received little attention in the literature so far and morphosedimentary characteristics as well as wave climate are poorly understood. The present paper provides the first extensive description of both wave climate and alongshore variability in the morphosedimentary behavior of these wave-dominated beaches, combined with accurate topographic surveys, 9-year long global wave model output time series and subsequently driven empirical longshore drift formula and shoreline change measurements from aerial photographs. Results show that the coast is mainly exposed to high-energy low steepness NW waves (mostly during the October–March period) generated in the North Atlantic by eastward traveling low pressure systems. Given the shoreline orientation, northward and southward longshore drift components generated by this wave regime nearly balance. In contrast, the lower-energy higher steepness N–NW wave regime (April–September period) contributes to an overall quantity of sand being transported southward similar to the yearly averaged net longshore drift. Beaches are mostly of the double-barred intermediate type. The southern beaches exhibit persistent rhythmic sandbars and rather steep beachface while the northern beaches are close to the dissipative state despite all the beaches are exposed to the same wave regimes. Beach states predicted using the Dean's number roughly match these observations. While previous studies elsewhere had shown that inherited geological factors may overwhelm contemporary dynamics in the determination of beach states, here differences are attributed to coastal protection works that appear to be important additional determinants of beach morphology.

Keywords Wave climate · Longshore drift · Wave-dominated sandy beaches · Beach state · Erosion

Introduction

The Bouknadel–Kenitra 20-km long coastline is located on the Moroccan coast (Fig. 1). It is a straight wave-dominated mesotidal beach environment aligned about 30° to the N–S direction. This coast delimits the North Atlantic Moroccan continental shelf and the subsident Gharb plain located at the junction between stable Meseta domain to the south and the Rifian domain to the north. Sandy beaches are mostly bordered by 5–20-m high consolidated aeolian dunes with the sediment consisting of medium sand ranging between 200 and 370 μm (Madouni 1997) with a gentle foreshore slope of 1–3%. Beaches are interrupted by the Sebou tidal inlet trained by two walls that extend approximately 600 m seaward from the low tide level shoreline (Fig. 2). These training walls were initially built

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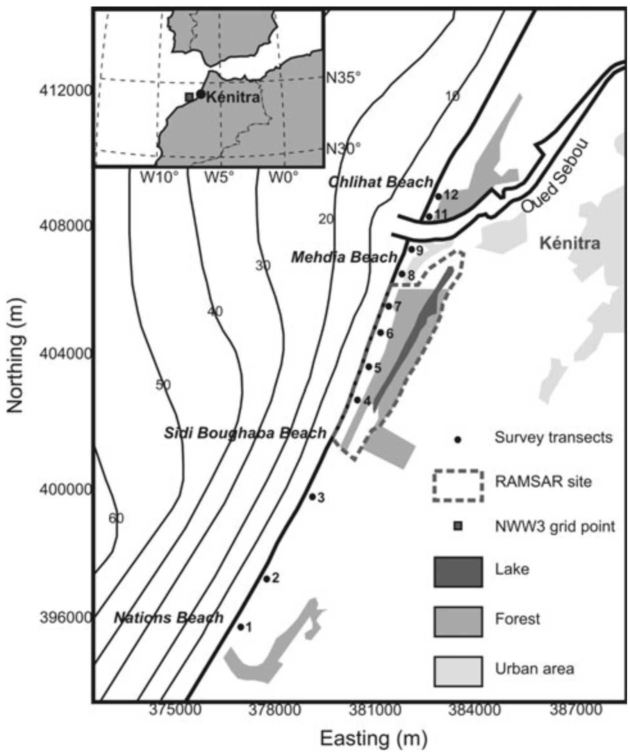

Fig. 1 Location and general settings of the Bouknadel-Kenitra coast together with locations of the NWW3 output grid point and topographic survey transects

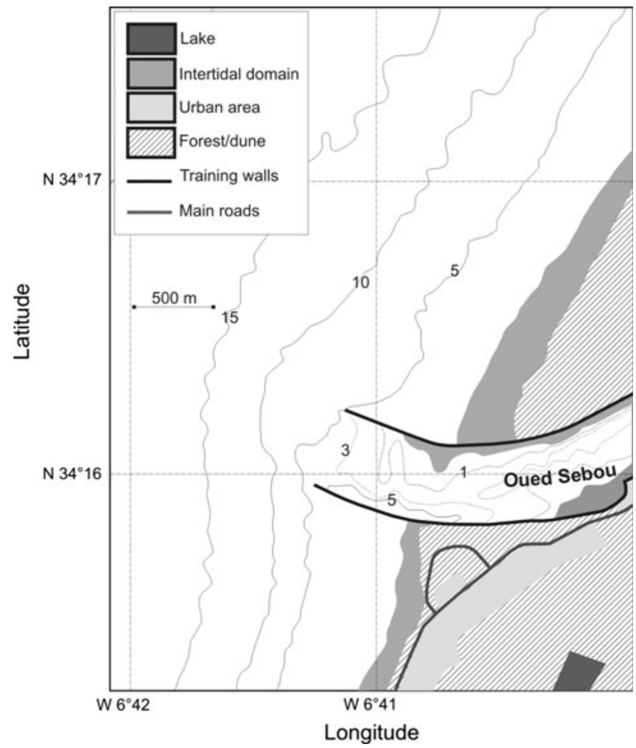

Fig. 2 Nearshore bathymetry of the Kenitra area and Sebou entrance from a survey undertaken in 1921 by the SHOM ("Service Hydrographique et Océanographique de la Marine") together with the current locations of urban areas, roads, forests, lake and training walls

to guide and constrain tidal currents in order to stabilize the inlet and subsequently improve navigation conditions at the entrance. The study area is delimited by Nations Beach to the South and, to the North, by the Kénitra highly populated area which comprises Mehdia Beach and Chlihat Beach to the South and to the North of the Sebou training walls, respectively (Figs. 1, 2). In between, the straight Sidi Boughaba Beach area is non populated with rather scarce beach access.

The continental shelf is gently sloping with a rather alongshore-uniform 150 m depth contour, considered as the seaward extent of the continental shelf, located at about 20 km from the shore (Jaidi 1981). At this distance from the shore depth contours are alongshore non-uniform with substantially shallower seabed elevation seaward of the Sebou inlet due to the presence of a large ebb delta. During the 1996–1997 period, it was computed that the Sebou river discharged major quantities of sediment at a rate of about 8.8×10^6 T/year (Haida 2000). Prior to the construction of dams upstream the Sebou inlet, a larger rate of 34×10^6 T/year was estimated over the 1940–1970 period (Haida 2000) which constitutes a major loss of sediment supply to the Kenitra littoral system over the past decades. For navigation issues, about 500,000 m^3/year of sediment is dredged from the entrance and further deposited seaward.

The Bouknadel-Kenitra coast is exposed to high-energy waves traveling roughly from the NW sector, which are generated by W–E tracking subpolar, deep, low-pressure systems over the North Atlantic Ocean and are, therefore, strongly seasonally modulated. Substantially higher waves are observed during the December–March winter period. It is hypothesized that significant wave heights can reach 7–9 m during severe storms (Benmohammadi et al. 2007). However, continuous nearshore wave measurements are strongly lacking along this section of the Moroccan coastline and numerous knowledge gaps remain on wave climate. The tide is of meso semi-diurnal type (Idrissi et al. 2004) with a tidal range of 2.2 m on average which can vary from 0.9 to 3.5 m during neap and spring tide, respectively. Tide-induced currents on the continental shelf are on the order of 0.2–0.3 m/s (Jaidi 1981; Charrouf 1989) with generally, northward and southward currents during flow and ebb, respectively. Coastal currents that have been observed to be highly variable and dependent on seasons and the local bathymetry are of the order of 0.1–0.5 m/s (Jaidi 1981; Cirac et al. 1989). In the nearshore region of Bouknadel-Kenitra, except in the vicinity of the Sebou inlet, coastal and tide-induced currents are non-significant in comparison with wave-induced

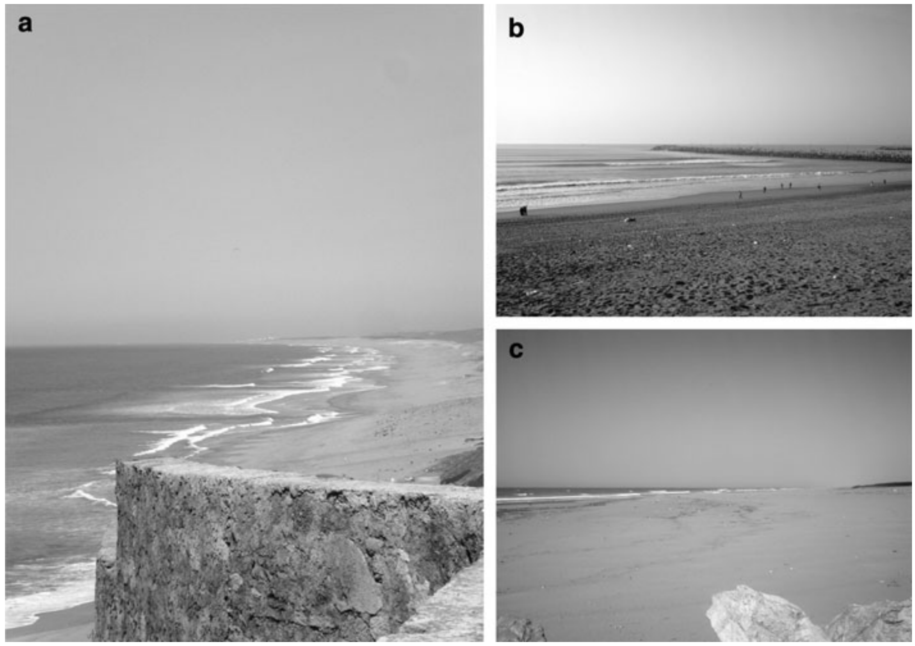

Fig. 3 Photographs taken the same day along the Bouknadel-Kenitra coastline showing **a** the presence of well-developed bar-rip morphology at Nations Beach, **b** a steep beach face and more complex surfzone sandbars at Medhia Beach which highly contrasts with **c** the very gently sloping wide dissipative-like Chlihat Beach

currents and beaches are considered as wave-dominated. Prevailing winds are westerly (63%; Aberkan 1989), particularly during the winter period, with only scarce gale events, while during summer persistent northeasterly tradewinds are observed.

Most of this section of coastline is non populated, except in the 3 km alongshore area immediately southward of the Sebou walls at Mehdia Beach (Fig. 1) where houses and restaurants were built on the dune and where erosion issues are the most worrying. Most of the region southward of the Sebou walls both faces coastal erosion problems and contains highly valuable forests and natural habitats. However, many real estate and tourist resort plans are in progress, some of them being literally beach front. In addition, sand is mined from the inland dunes northward of Chlihat Beach, which is likely to be a direct cause of erosion and impacts the local wildlife. Quarried sand quantities are thought to be about 4.10^6 m^3/year (Ahizoun et al. 2009). Despite this section of coastline is of strong interest from the perspectives of beach amenity, tourism, erosion issues and sand mining, it has only received little attention in the literature so far. The present paper aims at accurately describing the morphosedimentary behavior and variability of the beaches as a response to wave forcing in order to provide a comprehensive overview of this stretch of coastline. In Sect. 2 we describe the methodology used to (Sect. 3) describe the wave climate and to estimate the longshore drift and its spatial, seasonal and inter-annual variability as well as a beach state classification. Results are discussed and the conclusions stated in Sect. 4.

Materials and methods

Beach surveys

In order to grasp the alongshore variations of the beach morphology along the Bouknadel-Kenitra coast, 12 survey transects have been initially defined (Fig. 1). The beach surveys were undertaken at low tide during spring tide cycles with a dumpy level starting from a known benchmark. As indicated in Fig. 1, the 10th survey transect is not used in this study as the benchmark was lost during a winter storm. Here, we will show the measured transects in August 2008 and January 2009 to describe both the alongshore variability of beach profiles and the main changes that occur between the winter and summer periods. Of note the 2008–2009 period in between the beach surveys were rather typical in wave conditions with no extreme storm or extremely long periods of low-energy waves. Investigations on the alongshore variability of the beaches along this stretch of coastline was also motivated by the readily systematic strong differences in the visual observations of the beach face and surfzone sandbars at the different sites (Fig. 3). In addition, textural characteristics of the beaches were assessed by collecting surface sand samples from the foreshore along each transect. Three samples were collected on each profile: at the high-tide mark, the low-tide mark and at the center of the intertidal domain. The topographic data were further used to calculate intertidal beach slopes. Of note, given the strong potential short-term beach changes in response to storms and time-varying wave and tidal conditions that cannot be addressed herein because of the 1-year duration between the two surveys, only the alongshore variability of the transects was studied in this paper.

Beach morphodynamic state

Sandy beach morphologies are traditionally classified into discrete states within the conceptual model of Wright and Short (1984). Initially developed for single-barred, microtidal beaches, this conceptual model identifies three main beach states from dissipative to reflective with in-between, intermediate. The Dean's number Ω (Dean 1973), which incorporates both wave and sediment characteristics has been commonly used to discriminate each state with

$$\Omega = \frac{H_b}{W_s T}, \tag{1}$$

where H_b is the breaker height, W_s the sediment fall velocity and T the wave period. For each beach profile, W_s was computed considering the mean sediment size from the three sample sites along the given transect. Ω values less than 1 and larger than 6 are associated with reflective and dissipative states, respectively.

Wave data

The wave data used in this study for wave climate assessment and for driving the longshore drift computations was drawn from global wave model data gathered from the NWW3 model (Tolman 1991) over the period extending from January 1998 to December 2006. NWW3 uses the output from the National Centres for Environmental Protection Global Forecast System (NCEP GFS) as input for the operational wave models and generates global output on a grid measuring 1°*1.25° from latitude 78 to −78 (*1°) and from longitude 0° to 358.75° (*1.25°). The NWW3 model provides global wave field updates four times daily, at 4 am, 12 pm (midday), 6 pm and 12 am (midnight). The NWW3 variables used herein were significant wave height H_s, primary swell direction α_p and primary swell period T_p. NWW3 model data at the grid location N34°00′00 E7°15′00 were used throughout the study as it is the closest output grid point of our study area, at about 32 km from the shoreline. The global wave model data, when the output grid point is sufficiently close to the study area, have proven to be an efficient tool for estimating nearshore wave characteristics (see for instance Abadie et al. 2005; Browne et al. 2007) and are particularly suitable for areas where long-term wave data are scarce and discontinuous, which is the case for the Bouknadel-Kenitra coast.

Longshore drift computation

A significant number of empirical longshore sediment transport rate formulas have been developed in the 80s (CERC 1984; Bailard 1984; Kamphuis 1991). Recently, Kaczmarek et al. (2005) developed a new empirical formula for the longshore sediment transport Q from radioisotopic measurements. This formulation was chosen herein as it significantly restricts the number of free parameters to be calibrated in comparison with other methods. This formulation was also found to be more robust as shown by Bertin et al. (2008). The formulation of Kaczmarek et al. (2005) is as follows:

$$Q = 0.023\,\left(H_b^2\,V\right) \quad \text{if}\ \left(\mathrm{H}^2\mathrm{V}\right) < 0,15, \tag{2}$$

$$Q = 0.00225 + 0.008\,\left(H_b^2\,V\right) \quad \text{if}\ \left(\mathrm{H}^2\,\mathrm{V}\right) > 0,15, \tag{3}$$

where H_b is the breaking wave height and V and estimation of the longshore current within the surf zone given by

$$V = 0.25 \cdot k_v \cdot \sqrt{\gamma \cdot g \cdot H_b} \cdot \sin 2\alpha, \tag{4}$$

where α is the breaking wave angle, $\gamma = H/h = 0.78$ is the constant breaker parameter according to Battjes and Janssen (Battjes and Janssen 1978), H_b the breaking wave height, h the local water depth and k_v an empirical constant. Here, we used $k_v = 2.9$ according to the values in Bertin et al. (2008) and Castelle et al. (2009) in wave-dominated environments with similar sediment grain size characteristics.

To drive the longshore drift computations, we had to estimate the breaking wave height from the offshore wave characteristics provided by NWW3. For this we used the Snell-Descartes law instead of undertaking a more complex nested nearshore wave model strategy as described in Bertin et al. (2008) and Castelle et al. (2009), implying the assumption that offshore depth contours are alongshore-uniform. Preliminary simulations (not presented herein) with the nearshore wave model SWAN (Booij et al. 1999) showed that the alongshore-uniform assumption was valid in the area of Nations Beach, Sidi Boughaba Beach and Chlihat Beach, while for Mehdia Beach, wave refraction and wave energy focalization were substantial particularly for the prevailing NW wave climate. Therefore, in the following, we will focus on the computed longshore drift at the beaches of Nations, Sidi Boughaba and Chlihat. Wave parameters at the breaking point H_b and α were estimated through the Snell-Descartes law, with the water depth at the breaking point computed following Rattanapitikon and Shibayana (2000) and were subsequently used to drive the empirical longshore drift computations.

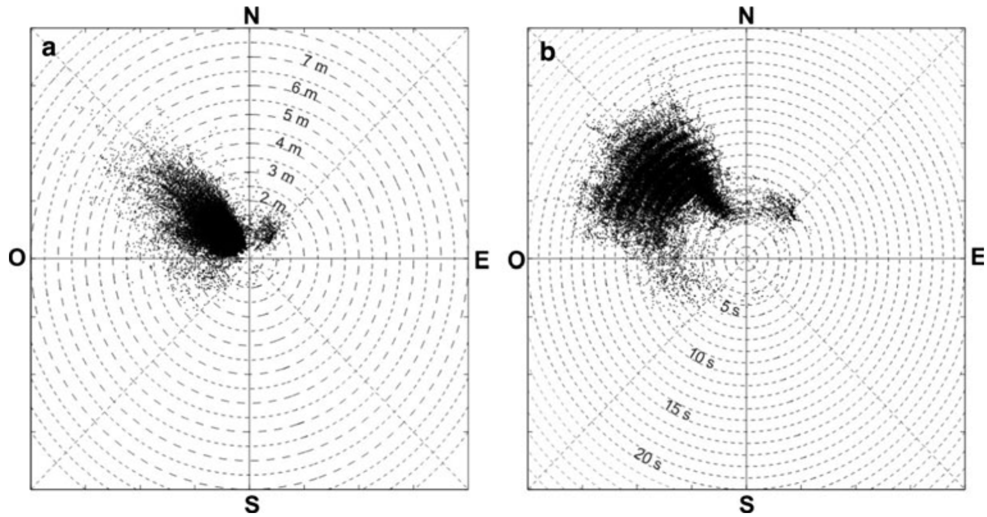

Fig. 4 Wave characteristics at the NWW3 Kenitra grid point: **a** Offshore significant wave height as a function of wave angle and **b** peak wave period as a function of wave angle

Shoreline change measurements from aerial photographs

Aerial photographs were used to quantify shoreline change at the Bouknadel Kenitra sandy coast on timescales of decennia. Since the number of aerial photographs covering this section of coastline was limited and most of the time did not cover the whole area, we used two sets of photographs: (1) 1969 and 2002 for Chlihat and Medhia beaches and (2) 1987 and 2002 for the southern beaches. The aerial photograph series were scanned and further rectified and georeferenced into the Lambert Maroc Zone I Grid using ArcGIS 9.1.

The shoreline can be defined as a line on a map representing the feature where land and water. This requires defining a 'shoreline indicator' whose changes can be mapped. As traditionally with aerial photographs, here we used as indicator the high-water-line because the border between light dry sand and dark wet sand is easy to identify (Dolan et al. 1980). For all the aerial photographs, the high-tide level was manually detected and further transformed into easting and northing coordinates. Combining the errors due to the measurement accuracy, the geo-referencing method and shoreline detection, the overall accuracy of our shoreline detection method was found to be ±12 m. Of note, a similar analysis was recently successfully used by Ahizoun et al. (2009) on approximately the same section of coastline with two sets of photographs taken in 1963 and 1993. Our shoreline evolution analysis will be therefore compared with the findings of Ahizoun et al. (2009).

Results

Wave climate

Figure 4 shows the variability of wave characteristics at the Bouknadel-Kenitra coast. Higher waves come from the NW direction as the region is sheltered from N–NE and S–SW long period swells by the coastline configuration (Fig. 4a). Waves coming from the N–NE and S–SW sectors therefore consist of short-period wind waves (Fig. 4b) generated by the tradewinds or local breezes. The sectors around N–NE and S–SW provide a rather negligible share of the total wave energy the coastline is exposed to, with most of wave energy share supplied by north-westerly waves generated in the North Atlantic by eastward-traveling low-pressure systems, with typical peak wave period ranging from 10 to 15 s. As indicated in Fig. 5, more than 70% of incoming waves have a significant wave height ranging from 0.5 to 2 m with a predominant NW direction. Given the shoreline orientation at the study site, this results in close to shore-normal wave angle to the shore at the breaking point which is expected to drive a rather low net longshore drift with respect to the generally high-energy wave regime.

Alongshore variations in beach morphology and beach state

As shown in Fig. 3, there are significant variations in beach shape along the Bouknadel-Kenitra coast. To the South, Nations Beach clearly exhibits a well-developed transverse bar and rip morphology (Fig. 3a) together with megacusps and more scarcely observed cusps. To the North of the Sebou entrance, Chlihat Beach exhibits a dissipative shape with spilling breakers (Fig. 3c). In between, a steep beach face and complex nearshore bar patterns are observed at Mehdia Beach (Fig. 3b). Figure 6 shows the beach surveys at the 11 studied transects along this coast during summer and winter. Interestingly, winter and summer transects show a rather similar shape. This is essentially because the beaches did not experience any severe storm shortly prior to the winter surveys. A general weak erosion trend between summer and winter is observed at the downdrift

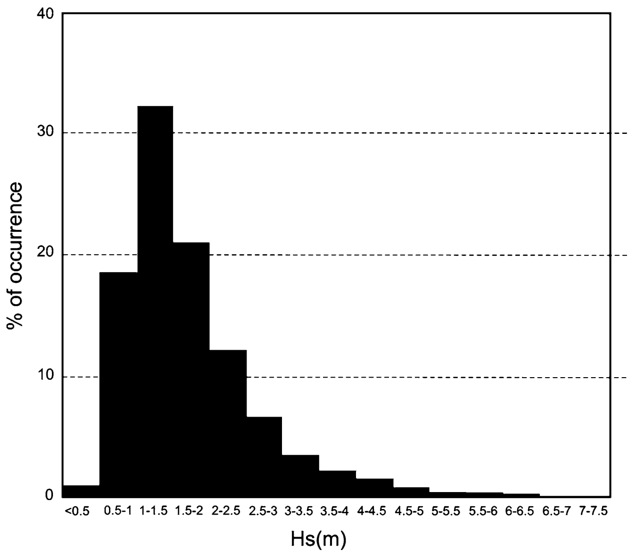

Fig. 5 Distribution of occurrence of significant wave height H_s at the NWW3 Kenitra grid point

beaches (transects from P1 to P9 in Fig. 6), while the updrift beaches are stable (transects P11 and P12 in Fig. 6). Beach profiles confirm the general trend sensed in Fig. 3 with, to the north (Chlihat Beach), a beach face characterized by wide, flat concave shape (beach slope on the order of 1:100) typical of close to dissipative beaches (transects P11 and P12 in Fig. 6). This contrasts with the steeper higher beach face (slope on the order of 1:30) which gradually decreases toward the low-tide mark, which is typical of intermediate beaches (transects from P1 to P9 in Fig. 6).

Table 1 lists the mean grain size d_{50} measured at the three samples along each of the 11 beach profiles during the summer and winter surveys. Overall, it is found that $200\ \mu m < d_{50} < 400\ \mu m$ with generally more homogeneous cross-shore distribution of d_{50} at the southern beaches. On average, coarser (finer) sand is found near the low-tide (high-tide) mark. Table 2 summarizes the mean grain size d_{50} averaged along the profile, the intertidal mean beach slope β, wave characteristics and corresponding Dean's numbers for each transect for both the winter and summer surveys. There is a significant alongshore variability in predicted beach states. Overall, for both winter and summer surveys, beaches are predicted to be of the intermediate type. Beaches northward of the Sebou inlet were found to be more dissipative (larger Ω) than downdrift beaches, which is consistent with

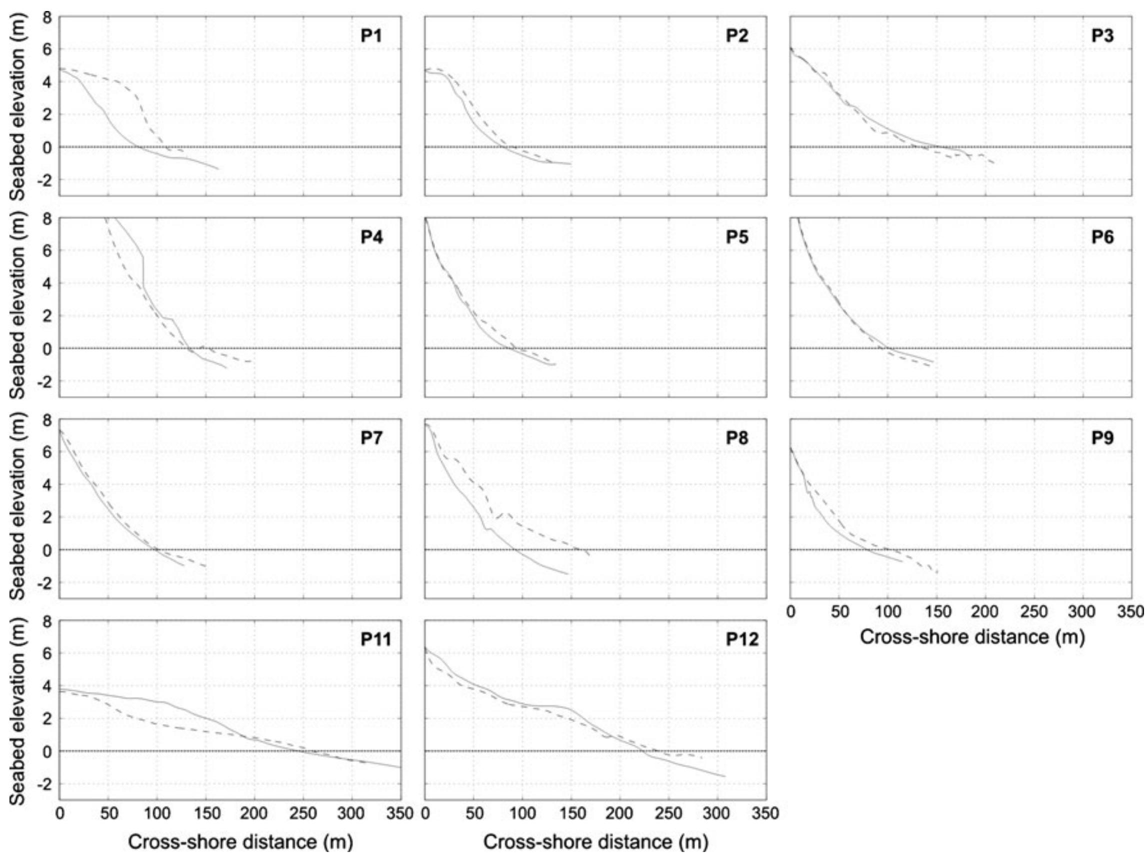

Fig. 6 Profile sections measured at the 11 transects (see Fig. 1) during the summer (*dotted line*) and winter (*solid line*) surveys. The *horizontal thick dotted line* indicates the mean sea level

Table 1 Mean grain size d_{50} (m) measured at three samples collected along each profile: at the low-tide mark (LT), the mid-tide level (MT) and the high-tide level (HT) during the winter survey (W) and the summer survey (S)

	W-LT	W-MT	W-HT	S-LT	S-MT	S-HT
P1	388	359	356	380	351	344
P2	272	315	303	278	325	293
P3	314	285	287	321	299	303
P4	349	323	293	351	328	321
P5	281	299	272	312	323	301
P6	295	332	297	314	339	310
P7	316	312	267	332	330	307
P8	327	336	251	342	334	277
P9	366	325	248	366	330	261
P11	329	320	248	365	330	262
P12	307	285	230	330	397	275

observations. Unsurprisingly, all the beaches are found to be more dissipative in winter than in summer. More intriguingly, there is no drastic difference in Dean's numbers between the updrift and downdrift beaches despite the readily apparent strong differences in beach shape. In addition, a Ω of about 3 is found at Chlihat Beach in summer (Table 2) which corresponds to a typical transverse bar and rip or rhythmic bar and beach classification, while observations suggest a persistent alongshore-uniform flat concave shape typical of longshore bar and trough or dissipative beaches. Therefore, despite beach states predicted with the Dean's number roughly match the observations, significant differences are pointed out in the vicinity of the Sebou training walls.

Longshore drift

The spatial variability assessment of the longshore drift along Bouknadel-Kenitra coast has never been attempted despite it is hypothesized to be significant given the variations in shoreline orientation. As indicated in the longshore drift computation methodology section, our longshore drift computations are expected to be inaccurate in the Medhia Beach area. Therefore, Fig. 7 shows the longshore drift quantities computed from 1998 to 2006 at Chlihat Beach (Fig. 7a), Sidi Boughaba Beach (Fig. 7b) and Nations Beach (Fig. 7c). The net longshore drift averaged over the 8-year duration at Chlihat Beach, Sidi Boughaba Beach and Nations Beach are found to be southward of about 85,000, 340,000 and 200,000 m^3/year, respectively. These net longshore drift values are found to be rather low with respect the persistent high-energy waves this section of coastline is exposed to. This is because the intense northward and southward components nearly balance, especially at Chlihat Beach (see Table 3). Another interesting feature is the strong inter-annual variability in the longshore drift (Fig. 7). For instance, at Chlihat Beach (Fig. 7a), the net longshore drift varied from less than 20,000 m^3/year in 2006 to about 340,000 m^3/year in 1999 which suggests significant inter-annual variability of both shoreline migration updrift of the Sebou training wall and the resulting loss of sand supply downdrift.

The longshore drift magnitude is also strongly seasonally modulated as a result of the offshore wave seasonal variations that were described in the introduction section. Figure 8 shows this seasonal variability with the northerly, southerly and net monthly longshore drift averaged from 1998 to 2006 at Chlihat Beach (Fig. 8a), Sidi Boughaba Beach (Fig. 8b) and Nations Beach (Fig. 8c). Interestingly,

Table 2 Survey transects used in the study showing all their major characteristics with β the intertidal mean beach slope, d_{50} (m) the mean grain size averaged over the three samples along the transect (see Table 1), W_s (m/s) the sediment settling velocity and Ω the Dean number

	Winter (H_b = 2.39 m, T = 12.48 s)				Summer (H_b = 1.12 m, T = 8.05 s)			
	β	d_{50}	W_s	Ω	β	d_{50}	W_s	Ω
P1	1.49	368	0.0543	3.53	2.12	358	0.0528	2.64
P2	1.64	297	0.0430	4.47	2.18	299	0.0433	3.21
P3	1.47	296	0.0428	4.49	1.26	307	0.0447	3.11
P4	2.69	322	0.0471	4.08	1.72	333	0.0489	2.85
P5	2.10	285	0.0409	4.69	2.12	312	0.0455	3.06
P6	1.89	308	0.0448	4.29	1.95	321	0.0470	2.96
P7	2.35	298	0.0431	4.45	2.00	323	0.0473	2.94
P8	1.83	305	0.0443	4.33	1.78	317	0.0463	3.00
P9	2.05	313	0.0457	4.21	1.72	319	0.0466	2.98
P11	0.79	300	0.0435	4.42	0.69	319	0.0466	2.98
P12	1.29	274	0.0390	4.92	1.02	301	0.0437	3.19

Fig. 7 Inter-annual variability of northward, southward and net longshore drift at **a** Chlihat Beach (N–S shoreline orientation of 33°), **b** Sidi Boughaba Beach and (N–S shoreline orientation of 26°) **c** Nations Beach (N–S shoreline orientation of 30°) over the 1998–2006 period

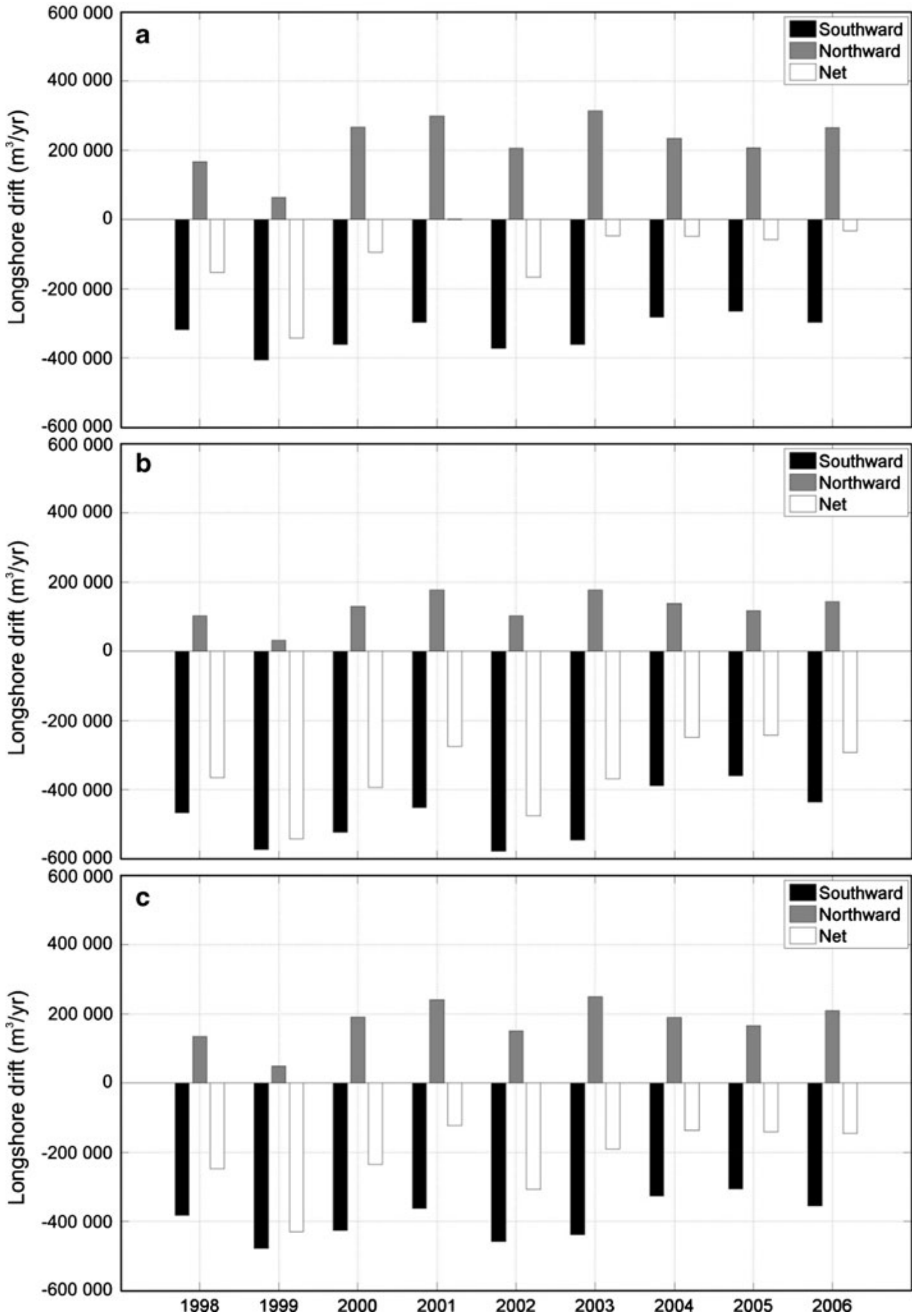

Table 3 Southward, Northward and net longshore drift (m^3/year) computed at Chlihat Beach (N–S shoreline orientation of 33°), Sidi Boughaba Beach (N–S shoreline orientation of 26°), and Nations Beach (N–S shoreline orientation of 30°), and averaged over the 1998–2006 period

Computed longshore drift (m^3/year)	Southward	Northward	Net
Chlihat beach	310,000	226,000	84,000
Sidi Boughaba beach	457,000	119,000	338,000
Nations beach	371,000	172,000	199,000

one can readily subdivide the longshore drift behavior into two contrasting periods. From October to March, both northerly and southerly components are intense but they nearly balance, particularly at Nations Beach and Chlihat Beach. From April to September, the northerly longshore drift is non-significant. At the same time, the southerly longshore drift is rather weak but actually contributes to an overall substantial quantity of sand being transported southward for this 6-month period (once again this is particularly true for Nations Beach and Chlihat Beach). For instance, at Chlihat Beach the yearly averaged 85,000 m^3/

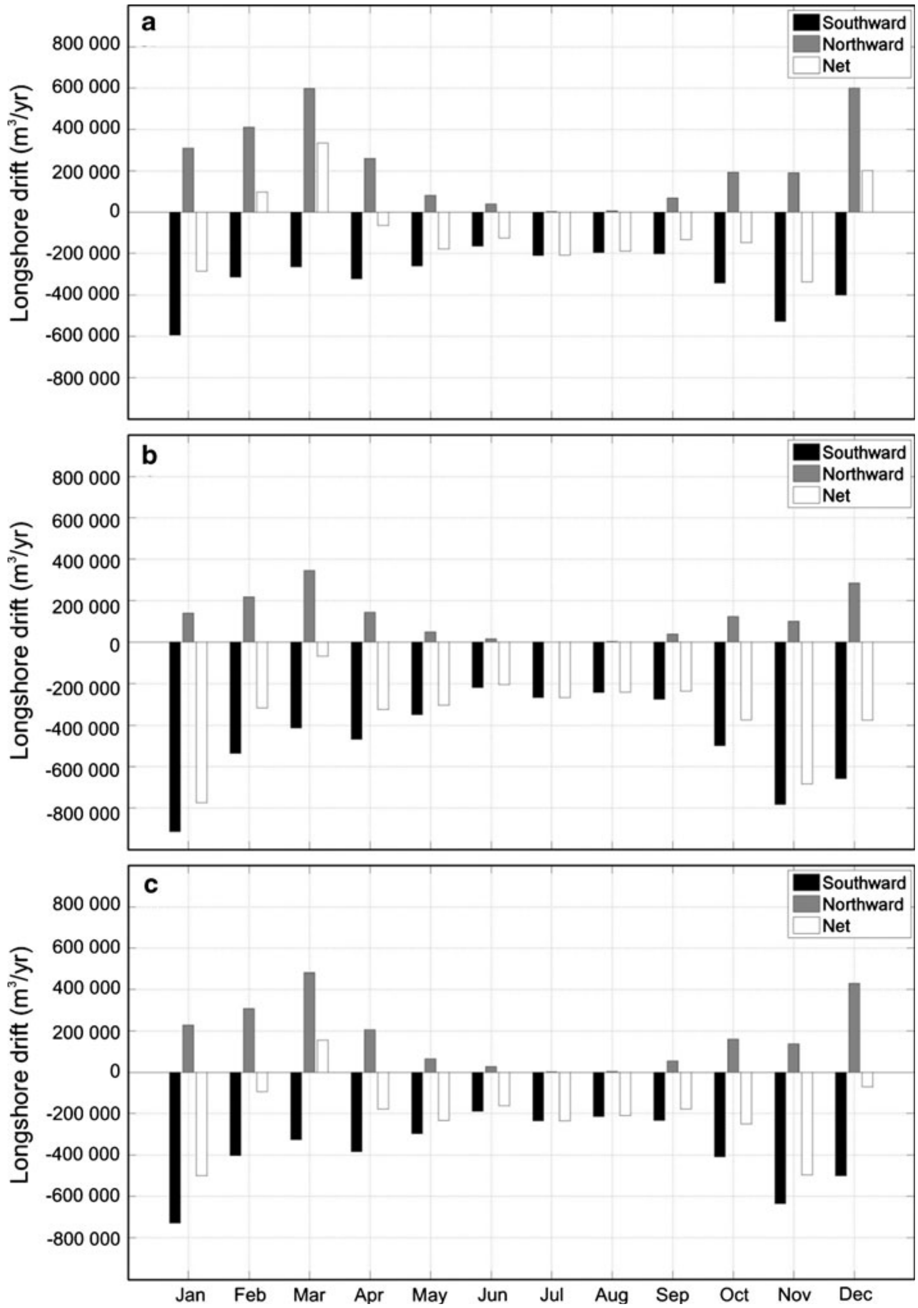

Fig. 8 Seasonal variabilty of the computed northward, southward and net longshore drift at **a** Chlihat Beach (N–S shoreline orientation of 33°), **b** Sidi Boughaba Beach (N–S shoreline orientation of 26°) and **c** Nations Beach (N–S shoreline orientation of 30°) averaged over the 1998–2006 period

year net southerly longshore drift is actually generated during the April–September period.

Shoreline evolution on timescales of decennia

Figure 9 shows an example of shoreline evolution in the vicinity of the Sebou walls between 1969 and 2002. In 33 years, shoreline position changed significantly with a striking seaward migration and landward migration at Chlihat and Medhia, respectively. During this period, Medhia (Chlihat) beaches experienced a shoreline retreat (advance) of 0.5 (1.1) m/year. Further south, we observed alternating sections of shoreline stability, advance and retreat. Shoreline position was found to be fairly stable immediately southward of Medhia (transects 5, 6 and 7 in Fig. 1) and then to significantly retreat along a 2-km section near transect 4 (Fig. 1) at a rate of 1 m/year. To the south Nations Beach is stabled with, in-between Nations Beach and transect 4, an alternation of shoreline stability and shoreline advance at a rate that can reach 1 m/year.

Our results go with those given in Ahizoun et al. (2009) who found a shoreline seaward migration at Chlihat of 1.73 m/year decreasing to about 0.5 m/year at 2 km to the north of the Sebou northern wall. At Medhia Beach

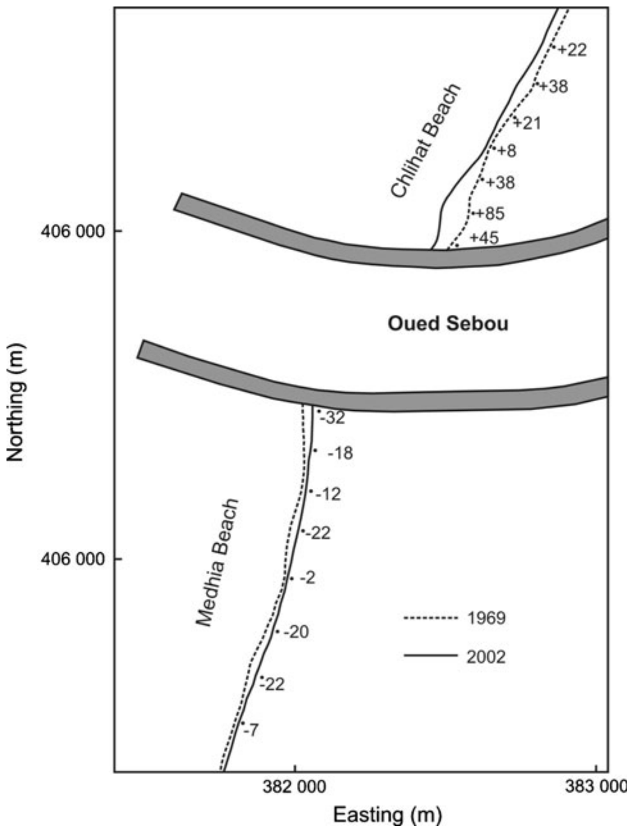

Fig. 9 Changes in shoreline position at Medhia and Chlihat beaches between 1969 (*dashed line*) and 2002 (*solid line*)

Ahizoun et al. (2009) found a shoreline retreat of about 1 m/year. Overall, the same trends as in Ahizoun et al. (2009) are observed in our study with, of note, a factor two in the computed migration rates near the Sebou walls. The reasons for such differences are at this stage unclear.

Discussion and conclusions

Our results provide for the first time an extensive wave climate description along this poorly documented section of the Moroccan coastline. As indicated by the analysis of the 10-year long NWW3 output time series seaward of the study area, the coast is mainly exposed to low steepness NW waves generated in the North Atlantic by eastward traveling low-pressure systems. Higher steepness lower-energy N–NW wind waves can be generated by tradewinds during the April–September period. This low-energy wave regime actually contributes to an overall large quantity of sand being transported southward. For instance, at Chlihat Beach this quantity corresponds to the annual net longshore drift as the large southward and northward longshore drift components generated by higher-energy waves during the October-May period nearly balance. This suggests that the persistent shoreline seaward migration at Chlihat Beach is mainly generated by the higher steepness N–NW waves generated by tradewinds and the more northward-tracking low-pressure systems over the North Atlantic Ocean during the summer period while higher-energy waves during winter do not result in a significant net cross-shore shoreline migration.

Despite this is a high-energy sandy coast, the estimated net longshore drift is found to be reasonably small in comparison with other sandy open beaches exposed to the same swell sources. For instance, the net southerly longshore drift is assumed to be on the order of 1–2 $\times$ 10^6 m^3/year in the north-western beaches of Portugal (Andrade et al., 2007), decreasing to about 700,000 m^3/year on the northern French Aquitanian coast (Castelle et al. 2007). The smaller longshore drift rates computed along the Bouknadel-Kenitra are due to both the lower incoming wave energy at the coast as the swells need to travel larger distance than for reaching the French and Portuguese coastlines and because the shoreline in the Kenitra region is oriented such as waves in the nearshore region are most of the time close to shore normal. These low net longshore drift values at Chlihat Beach (85,000 m^3/year) are supported by the observations updrift of the Sebou training walls (Chlihat Beach, Fig. 1). Our aerial photograph analysis, combined with the earlier study in Ahizoun et al. (2009), shows steady seaward migration of the shoreline at Chlihat of the order of 1 m/yr. This updrift accretion rate is much smaller than the observations of Castelle et al. (2009) on the Gold Coast (Australia), with similar inlet entrance training settings, but with an updrift net longshore drift of the order of 500,000 m^3/year. These low longshore drift values are also corroborated by the observation of almost persistent shore-normal and more scarcely weakly skewed rip channels at Nations Beach. This brings confidence to our longshore drift estimations and corresponding annual and inter-annual variability. This global wave data combined with the methodology used herein appear particularly suitable for assessing large-scale longshore drift characteristics in nearshore areas where long-term wave data are scarce and discontinuous, which often constitutes a first step in the understanding of the morphosedimentary behavior of a sandy coastline.

Comparison of observed and predicted beach states showed that beaches most of the time typically matched the expected criteria. However, while observations suggest that all the beaches located to the North of the Sebou entrance are readily close to the dissipative state in summer, predicted states are obviously intermediate. Lack of agreement between predicted and observed beach states has been reported elsewhere and attributed to failings in the RTR and Dean's parameter (see for instance Anthony 1998; Masselink and Pattiaratchi 2001). In addition, Jackson et al. (2005) identified geological factors as important constraints on actual beach state with, encompassing a larger number of beaches along the Irish coast, inherited geological factors appearing to be more important determinants of beach morphology than contemporary dynamics in most of the studied beaches. Herein, despite beach states predicted through the Dean's number roughly match observations, differences are hypothesized to be due to the presence of the Sebou as coastal protection works that are additional important determinants of beach morphology.

Given the Bouknadel-Kenitra coast is of strong interest from the perspectives of beach amenity and tourism, almost the entire section of this coast is exposed to real estate and touristic projects. In addition, intense sand mining is also a significant threat to the littoral system in some of the remote areas to the North of the Sebou entrance. However, this sandy coastline is highly vulnerable with erosion issues and highly-variable shoreline position over the past decades which require for the undergoing projects a much more in-depth investigation of the morphosedimentary characteristics of this coast. While the present study provides first insights of this sandy coast dynamics, it also motivates further investigations involving additional recurrent beach surveys and development of process-based models implemented in this area.

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