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How kilometric sandy shoreline undulations correlate with wave and morphology characteristics: preliminary analysis on the Atlantic coast of Africa

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Abstract. Sandy coasts are characterized by a number of rhythmic patterns like, amongst others, shoreline undulations or sandwaves at a kilometric scale. One hypothesis for their formation is that high angle waves (large incidence angle with respect to shore normal) could induce an instability of the shoreline (Ashton et al., 2001). More recently, a scaling for their wavelength has also been proposed (van den Berg et al., 2014). The existing studies rely mainly on modelling but quantitative field tests are lacking. We aim at investigating how both the formation hypothesis of these shoreline undulations and the theoretical scaling do fit with nature at a global scale. The first step, which is the goal of this paper, is to set up the methodology by analyzing the Atlantic African coast as test site. First, based on global databases, shoreline wavelength L_S, wave characteristics (obliquity θ_W and wavelength λ_W) and mean shoreface slope β are determined. Then the wave obliquity is confronted with the presence of shoreline undulations. Finally the values of the ratio $\beta L_S / \lambda_W$ are estimated and discussed in comparison with the estimate of van den Berg et al. (2014). It is found that the correlation between shoreline sandwave occurrence and wave obliquity is very good, allowing the identification of 5 new potential unstable shoreline stretches, whereas the results on the scaling are not conclusive and deserve further investigations.

1 Introduction

Sandy coasts are characterized by a number of rhythmic patterns like, for instance, cusps (metric scale), megacusps (hundreds of meters) and shoreline sandwaves (kilometric scale). The processes involved in the formation of cusps and megacusps have already been studied by field observation and modelling showing that cusps are related to swash zone processes and megacusps are related to surf zone processes. However, shoreline sandwaves are less known and according to some modelling studies (see, e.g., Falqués and Calvete, 2005 and Falqués et al., 2011) they would be mainly controlled by shoaling area processes.

On one hand it is theoretically clear that a rectilinear shoreline can be unstable in case of high wave incidence angle (High Angle Wave Instability: HAWI) and that from such instability a number of large scale shoreline features may appear (Ashton et al., 2001), including these kilometric scale shoreline sandwaves. This is now widely supported by a number of modelling studies, e.g., Ashton et al. (2006a), van den Berg et al. (2012), Kaergaard and Fredsoe (2013a), showing that the instability develops for deepwater wave incidence θ_W larger than about 42°, with respect to shoreline normal. In case of using the CERC formula for the sediment transport, other formulae giving a range between 35° and 50°.

On the other hand, looking at a global scale, it seems that kilometric sandy shoreline undulations do occur on many coasts: Fig. 1 shows 29 identified shoreline sandwave sites. 15 have been already identified and investigated in previous studies whereas the 14 others have been identified by eye by the authors based on punctual Google Earth visit, i.e.,

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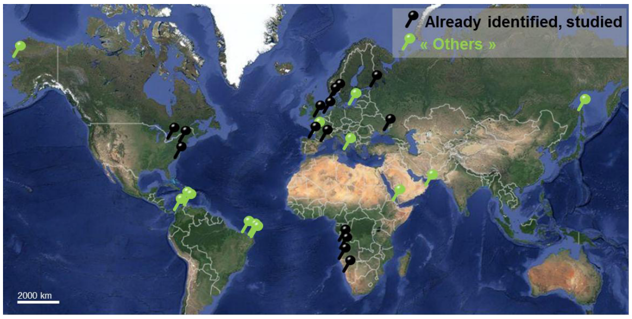

Fig. 1. Map of identified kilometric shoreline sandwave sites. Background image: Google Earth.

satellite images. No exhaustive identification has been done yet, so that the existence of many other kilometric shoreline undulations can be suspected.

A first research question (Q1) is therefore: how does the hypothesis of HAWI origin of shoreline undulations fit with nature? Presently, it is still not clear if the observed shoreline sandwaves result from HAWI. At some sites it seems that HAWI could be responsible for the origin and persistence of such undulations. For example, Ashton and Murray (2006b) studied the local wave climate north shore of Lake Erie (Canada) suggesting that unstable sandwaves have shaped the spit there (see also Davidson-Arnott and van Heyningen, 2003). Falqués (2006) investigated whether the subtle but systematic shoreline sandwaves along the Dutch coast (Ruessink and Jeuken, 2002) could be related to HAWI. That coast appeared to be at the threshold for instability and can be stable/unstable depending of some of the hypothesis of the study. Kaergaard and Fredsoe (2013b) investigated possible HAWI occurrence on the West coast of Denmark. The mean wave approach is quite oblique there, from the NW, but the angle with the shore normal is nearly at the threshold of instability. Kaergaard and Fredsoe (2013b) have done the corresponding stability analysis and concluded that only if the large storm waves were excluded from the wave climate the coastline would be unstable and shoreline sandwaves with the observed wavelength would emerge. Kaergaard et al. (2012) investigated also the cross-shore extent of coastline undulations on a site located on the West coast of Denmark, based on specific bathymetric surveys providing temporal and spatial data. This field approach allows a better understanding, but cannot be used for a global analysis, because of the lack of such bathymetric surveys. Thus, no extensive data analysis in a large scale environment has been done.

In addition, recent model experiments propose that the wavelength L_S of sandwaves initially emerging from high angle wave instability scales with the wavelength of surface waves λ_W (in deep water) divided by the mean shoreface slope β (van den Berg, 2012; van den Berg et al., 2014): $L_S \approx c\lambda_W/\beta$, with $c = O(1)$. A second research question (Q2) is then: how does this model based scaling fit with nature?

The present research aims at investigating kilometric sandy coastline undulations in a wide geographical perspective (global scale) within an effort to answer to the two questions Q1 and Q2. The present paper sets up the methodology for such analysis, based on the two following investigations: (1) correlation between wave obliquity and shoreline sandwave occurrence, (2) correlation between shoreline sandwave wavelength and wave and bathymetric parameters. As a first step, we focus on the Atlantic coast of Africa, a "natural environment", exposed to energetic wave conditions.

2 Method and data

From the literature, HAWI's occurrence relates with wave obliquity θ_W, whereas HAWI wavelength L_S should scale with wavelength λ_W and mean shoreface slope β. Thus, the 4 quantities should be estimated: L_S, θ_W, λ_W and β. Such estimate requires shoreline (for L_S), wave (for θ_W, λ_W) and bathymetric data (for β). Within an effort to set up a global method, such data analysis is based on the joint use of global shoreline, wave and bathymetric databases.

The selected shoreline database is the WVS® (NGA) database. The shoreline corresponds to high water contour. It is obtained from satellite images LANDSAT 2000. The accuracy is comprised between 250 and 50 m, whereas the spatial resolution is about 100 m. This shoreline data is processed in order to provide shoreline orientation (needed to estimate wave obliquity) and shoreline wavelengths. The shoreline wavelengths are obtained by analysing 40 km long sections of shoreline. Figure 2, which, for sake of clarity, shows only a portion of the entire processed Atlantic African coast, illustrates the type of processing which is done. First the raw data are spatially filtered to remove very long undulations of several hundreds of kilometres (these long oscillations can be seen on Fig. 2, middle panel). Then, for every 40 km section, a Fast Fourier Transformation is done focusing on the wavelengths ranging between 1 and 20 km. This FFT provides several amplitude peaks. In the analysis, among the 4 largest ones, we keep only the one which has the largest amplitude (in blue) and the one which has the smallest wavelength (in red), respectively called L_{SD} and L_{SS}.

The wave data comes from the IOWAGA project (Rascle and Ardhuin, 2013). Within that project global and local wave hindcasts have been done, using the WW3 model and the CEP wind data. In the present study we use the global wave hindcast, and, to set up the method, we focus on the 2012 year. From this database, we obtain the three following yearly averaged wave characteristics: significant wave height H_S, peak period T_p and direction α. They are used not only to estimate the parameters θ_W, λ_W, but also to characterise

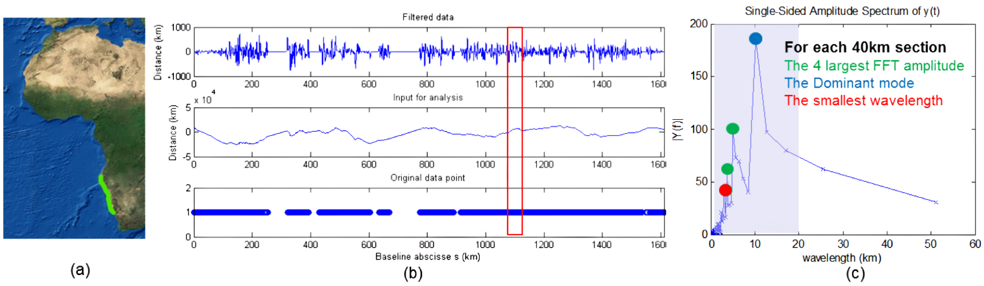

Fig. 2. Shoreline data analysis for the south portion of the Atlantic coast of Africa **(a)**: **(b)** input, filtered and original point data, **(c)** Fast Fourier Transformation shoreline amplitude on the 40 km section indicated by the red area. The points on Fig. 2c indicate the local maxima of FFT amplitude.

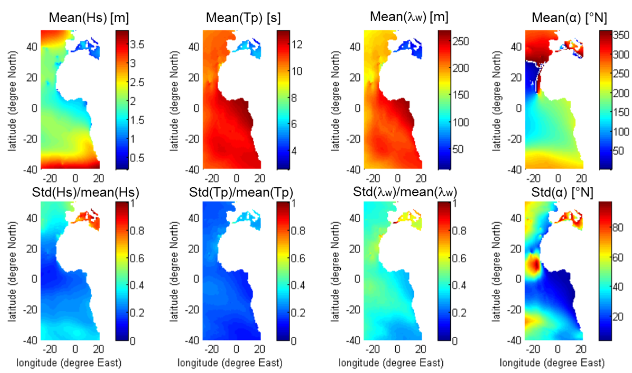

Fig. 3. 2012 Wave Climate. Yearly averaged values of: significant wave height H_s (m), peak direction T_p (s), wavelength λ_W (m), wave direction α (°, clockwise from North), together with the normalized standard deviation. Source: IOWAGA wave hindcast database (Rascle and Ardhuin, 2013).

the wave climate of the study area (see Fig. 3). The spatial resolution is 0.5°.

For the bathymetry, the GEBCO (NOAA) database is used (Amante and Eakins, 2009), with a spatial resolution of 1′ ($\sim$ 1.9 km in the study area). This database allows estimating the slope β. In the present analysis, this slope is computed based on the distance between the shoreline and the 100 m bathymetric contour. It should be said that the ocean wave wavelength is quite large in this area (about 200 m, Fig. 3), such that the computed slope corresponds to the slope between the bathymetric contour of the ocean wave base ($\lambda_W/2$) and the shoreline. The bathymetric data is also of use for intermediate step, like estimating the location of the limit of wave action on the sea-bed (wave base) (wave parameters must be estimated there, and not too far or too close from the coast).

3 Wave obliquity and Kilometric coastline undulation

Figure 3 shows the main characteristics of the wave climate over the 2012 year. First, we can notice that the yearly averaged significant wave height ranges from about 1.5 to 3 m, with larger values at the North and South of the Atlantic Africa coast. The peak period are comprised between 10 and 13s, with the largest values in the central part of the coast. The wave direction comes mainly from the North – North West ($\alpha \sim 350°$) in the northern part of the studied area, and from the South – South West ($\alpha \sim 200°$) in the southern part. At this stage, even without any wave obliquity computation, regarding the shoreline orientation, we can expect areas of strong wave obliquity. These values are yearly averaged values, such that it is worthwhile to analyse the standard deviation of these parameters. Figure 3 shows that these parameters are quite constant (small standard deviation), except for the wave direction at the 10° latitude. This can be explained by the fact that, in this area, the wave climate is characterised by two dominant wave directions: one from the North and one from the South (see wave rose on Fig. 4). This is consistent with the location of the limit between the north wave dominated areas, and the south wave dominated areas.

The next step is to estimate quantitatively the wave obliquity θ_W along the entire coast and to determine whether or not wave obliquity is correlated with the existence of shoreline undulations. Figure 4 shows the areas of high-angle wave incidence (blue and red, such that $|\theta_W| > 45°$) and low-angle wave incidence (grey, such that $|\theta_W| \leq 45°$). There are two main areas subject to high wave obliquity (one at the North (blue) and one at the South (red)), and one area subject to low angle waves. As a preliminary investigation, a crude analysis of the shoreline is done, based on Google Earth in order to identify large shoreline undulations (satellite images) but also the sediment composition of the coast (photos) and the presence of anthropic modifications (hard defences, harbour, ...). The type of the coast has also been validated using local studies (e.g. Fayet, 2010). Figure 4 shows the roughly estimated sandy areas, as well as satellite images in the three main areas. In the Northern area, subject to high obliquity from the North, large kilometric shoreline undulations are observed in three main locations (green marker, Fig. 4), but not systematically along the coast. All the observed undulations are asymmetric towards the South, indicating a

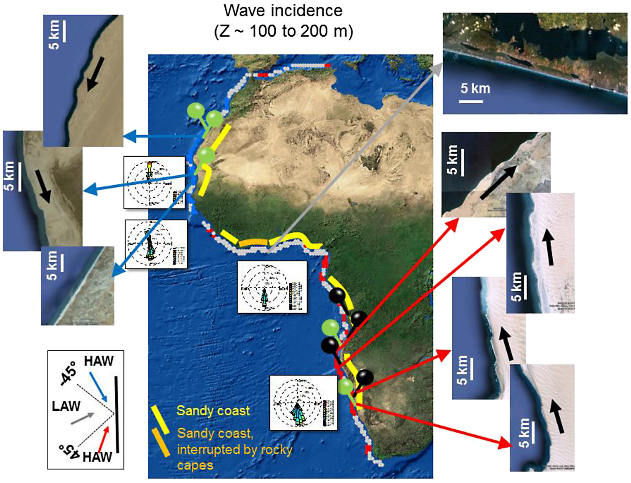

Fig. 4. Wave incidence (2012) and shoreline undulations. Incidence larger than 45° and smaller than −45° are indicated resp. in red and blue on the shoreline, whereas low angle waves are indicated in grey. HAW means High Angle Wave. Green symbols indicate shoreline undulations not identified as such before this study. Black ones indicate already identified shoreline sandwaves. Wave roses illustrate the wave direction. Satellite images (Google Earth) illustrate the undulated or un-undulated character of the shoreline.

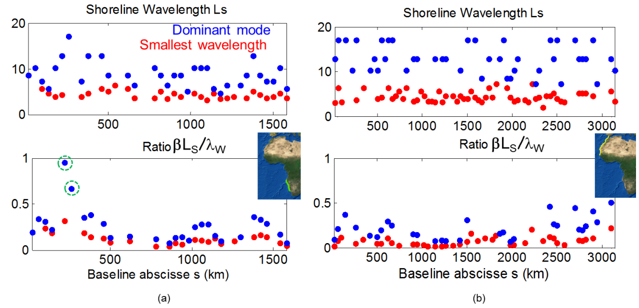

Fig. 5. Shoreline wavelength and computed ratio for **(a)** the South (red area) and **(b)** North part (yellow area) of the Atlantic coast of Africa.

southward migration. This is consistent with the mean wave direction oriented toward the South. These are new potential sites for HAWI that had not been previously identified. In the area subject to low wave obliquity (grey arrow), the shoreline is highly straight, without any undulation. In the southern part (red), subject to highly oblique waves from the South, many shoreline undulations are observed. In these areas, van den Berg (2012a) already observed shoreline undulations probably related to HAWI's (black markers), whereas the present study has identified a few more potential sites for HAWI (green markers). Again, the shoreline undulations are asymmetric, now toward the North, which is consistent with the mean wave direction (oriented towards the North too).

4 Shoreline wavelength, wave and morphology

From the databases analysis, the following parameters have been computed: L_{SD}, L_{SS}, θ_{W}, λ_{W} and β. Figure 5 shows the longshore variation of the shoreline wavelengths of the dominant mode (L_{SD}) and the smallest wavelength (L_{SS}), as explained in Sect. 2, for 2 shoreline sections exposed to high angle wave incidence: one at the South (Fig. 5, left panel), one at the North (Fig. 5, right panel). These sections are respectively 1600 and 3100 km long. In the southern area the dominant mode has a wavelength varying by a factor 2, with a mean wavelength of about 10 km, whereas the smallest wavelength varies between 4 and 6 km. At the North, the dominant mode has a larger wavelength, in average equal to 12 km, with spatial variations of a factor 2 too, whereas the smallest wavelength has a mean value of about 4 km.

As explained in the introduction, van den Berg et al. (2014) proposed a scaling of the shoreline wavelength with the wave wavelength divided by the slope. Thus, the ratio $\beta L_{\mathrm{S}} / \lambda_{\mathrm{W}}$, is computed for every 40 km long sub-sections. Figure 5 (bottom panel) shows the spatial variations of this ratio. For the southern part, which is characterised by a wave period of about 12 s, a significant wave height of 2.5 m, and a slope β smaller than 0.02, if we exclude two outliers (green circles), the ratio is comprised in the following ranges: [0.1–0.4] for the dominant wavelength L_{SD}, [0.05–0.3] for the smallest wavelength L_{SS}. Thus, whatever the wavelength type, the ratio is in the range [0.05–0.4]. In the Northern part, which is characterised by wave period of about 10 s, a significant wave height of 2 m, and a slope β smaller than 0.005, the ratio is in the range [0.02–0.5] ([0.1–0.5] for the dominant wavelength and [0.02–0.2] for the smallest wavelength). Table 1 summarizes the ratio variations and the wave and slope conditions. As it can be seen, the parameter variations are not very large (large wave height, large wave period, small slope), such that no significant correlation can be found. Coming back to the model experiment of van den Berg et al. (2014), we can notice that the experiment has been done for a Dean profile, a shoreface slope β ranging from 0.004 to 0.013 (with a mean value of 0.09) and a wave height of 1 m. However, using these results for the wave period range corresponding to the ones along the two studied shoreline portions, we can deduce from the model a ratio value ranging between 0.1 and 0.4. Table 1 summarizes the comparison between the ratio obtained from data, and the ones obtained from the van den Berg (2012) study. As a first draft comparison, the data provides a ratio ranging between 0.02 and 0.5, whereas the model provides values varying between about 0.1 and 0.4. Thus, the results are of the same order of magnitude, roughly consistent but not conclusive.

Several limitations make the data – model scaling comparison not straightforward. First, the model of van den Berg et al. (2014) provides the wavelength of the initial shoreline

Table 1. Ratio βL_S / λ_W obtained from data analysis (this paper) and the modelling results (van den Berg et al., 2014), with the corresponding wave (for the data analysis: averaged over year 2012) and morphological characteristics.

	Data analysis	Modelling results
Ratio βL_S / λ_W	[0.02–0.5]	[0.1–0.4]
Wave height H_S	[2–3] m	1 m
Wave period T_p	[10–12.5] s	[10–12.5] s
Slope β	< 0.02	[0.004–0.013]
Bathymetry	Complex	Dean profile
Nature of L_S	Largest amplitude (L_{SD}) and smallest wavelength (L_{SS})	Fastest growing mode in the linear regime (initial wavelength)

undulations. However, in nature, non-linear processes occur, such that the shoreline is characterised by many wavelengths at the same locations. Also, larger wavelengths than the initial one can form with time. At the end, it is difficult to determine which wavelength corresponds to the initial one. Second, the bathymetry of the study area is complex and not longshore uniform whereas the one used in the model analysis was based on a longshore uniform Dean profile. Thus, in reality there is no longshore uniform "basic state" and high angle waves are modified by updrift bathymetry with a cross-shore profile that can be different from the local one. Third, the Atlantic coast of Africa is exposed to larger wave height and period than the ones used in the model analysis. Forth, as suggested by Kaergaard and Fredsoe (2013b), the smallest waves within the wave spectrum arrive with a larger obliquity at the coast and can contribute to the shoreline instability even more than the dominant waves. Finally, the sensitivity of the ratio results should be analysed taking into account the data quality.

5 Conclusions

The present paper sets up a global scale methodology to answer to the two questions Q1 and Q2: "how does the hypothesis of HAWI origin of shoreline undulations fit with nature?", "how does the model based wavelength scaling fit with nature?". The proposed methodology is based on three databases: WVS for the shoreline, IOWAGA for the waves and GEBCO for the bathymetry. These databases allow estimating the parameters required for the analysis: shoreline wavelength L_S, wave obliquity θ_W and wavelength λ_W, and the mean shoreface slope β. The application on the Atlantic coast of Africa provides some preliminary results. First, a good qualitative correlation has been found between wave obliquity and shoreline sandwave occurrence (Q1). Areas of high wave obliquity are characterized by the presence of shoreline undulations while areas of low obliquity are characterized by straight shoreline. Even new shoreline sandwave sites not previously described were discovered from the knowledge of the wave climate (i.e., wave obliquity on a sandy coast seems to be a good predictor of shoreline undulations). These first results are promising for the identification of potential HAWI sites at the global scale. Within future explorations, using wavelet analysis would be worthwhile to investigate shoreline undulation (Tebbens et al., 2002; Lazarus et al., 2011) and automatically detect potential HAWI sites. Second the analysis of the ratio between the shoreline wavelength L_S, the mean shoreface slope β and wave wavelength λ_W, in comparison with the scaling proposed by van den Berg et al. (2014), does not provide conclusive results (Q2). Indeed, the data analysis provides a ratio (βL_S / λ_W) ranging from 0.02 to 0.5, which is only "roughly" consistent with the tested scaling. This illustrates that the comparison between data analysis results and model based formula is not straightforward. There are several reasons (complex bathymetry, several shoreline wavelengths, wave climate, data quality) for such inconclusive results. Further investigations should be done, based on global scale analysis, together with a wider model exploration.

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