Journal of Coastal Research	SI 56	1666 - 1670	ICS2009 (Proceedings)	Portugal	ISSN 0749-0258

Wave Climate Clustering to Define Threshold Values with Respect to the Expected Morphological Response

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ABSTRACT

VALCHEV, N. and TRIFONOVA, E., 2009. Wave Climate Clustering to Define Threshold Values with Respect to the Expected Morphological Response. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), 1666 – 1670. Lisbon, Portugal, ISSN 0749-0258.

The development of a flexible operational system providing warning of a potential morphological storm impact requires a preliminary assessment if a given wave regime may produce considerable changes in the coastal system. This study aims to present an approach to the increasing of the efficiency of such a system. It is achieved by setting up combined thresholds of storm impact the exceeding of which would bring a morphological response of a certain scale. The wave climate at the study site is estimated on the basis of hindcast data. It serves as a boundary condition for a cross-shore profile model calculating the wave transformation in shallow water. The model also takes into account the sediment motion regime and the linear length of the zone in which a sheet flow regime could be expected. A methodology for clustering of the wave climate is proposed, the sediment motion corresponding to each wave cluster is analyzed and the boundary thresholds are established. The latter differentiate the wave events that are capable of producing a noticeable morphological response from the rest of the cases and correspondingly provides a way to run the morphological module of the forecast system only in cases in which a discernible reaction is expected.

ADITIONAL INDEX WORDS: *Black Sea, numerical modeling, operational approach*

INTRODUCTION

The coastal zone is exposed to storms of different intensity. Although the IPCC (2007) concludes that there is no pronounced multiplication of storm activity observed, an increase of the amplitude of extreme climatic events is expected to occur. An augmentation of damage as well as devastation of coastal infrastructure and even casualties is anticipated. The changes of the natural environment are also an issue that tackles the question of the morphological impact of storms with different probability of occurrence and the resulting risks.

A flexible system warning of the possible morphological risk entails a preliminary assessment if storm waves of given parameters are capable of causing significant changes in the coastal system. Since the forcing of the morphological model requires considerable computing resources, the appropriate functioning of an operational system, forecasting the morphological storm impact, implies the imposing of certain restrictions. One of them is the area that is supposed to be covered by the prognostic models and for which the possible risk is to be estimated. Therefore, the efficiency of the operational approach drastically increases if the section over which the model would be applied is representative for the entire area and the results obtained could be considered reliable for any of its components. The system efficiency could be also improved by the setting up of combinations of thresholds of wave parameters the exceeding of which would cause a morphological response of a certain scale. The practical implementation of this concept will provide the grounds for the morphological module of the warning system to be run only in cases for which discernible impact is expected.

Given that morphological changes are defined by sediment transport, the factors controlling this process could be taken as a point of reference determining the conditions at which bottom deformations are likely to occur. Traditionally, in literature, three regimes of sediment transport are distinguished (NIELSEN, 1992; LEONT'YEV, 2001). An initiation of sediment motion can be defined in terms of the critical value of Shields parameter. SHIELDS (1936) applied dimensional analysis to determine some dimensionless parameters and established the incipient motion diagram. The Shields parameter is the ratio of mobilizing and stabilizing forces acting upon the sediment particle in the bottom boundary layer. The intensification of the wave impact forms a pattern of ripples on the sea bottom, the geometry of which depends on the wave parameters. The further wave growth causes the surface bottom layer to be dragged into motion, the ripples are erased and the so called sheet flow takes place.

From the coastal morphology point of view it is necessary to know the wave regimes within which discernible bottom and shoreline deformations could be expected. The critical value of the Shields parameter presents a clear view about the conditions for incipient sediment motions whereas certain considerable deformations could be expected exactly in the sheet flow motion phase. In this study the threshold value, the exceeding of which switches the sediment motion regime to sheet flow, is assumed as the criterion for morphological impact. Hence, a set of threshold values needs to be established accounting for the variety of wave configurations. The present available data of wave measurements, however, constitute an unrepresentative excerpt. Moreover, in the majority of cases they do not refer to storms of lower probability of occurrence but to those, which induce rather moderate morphological response. Such assessment for the western Black Sea is possible

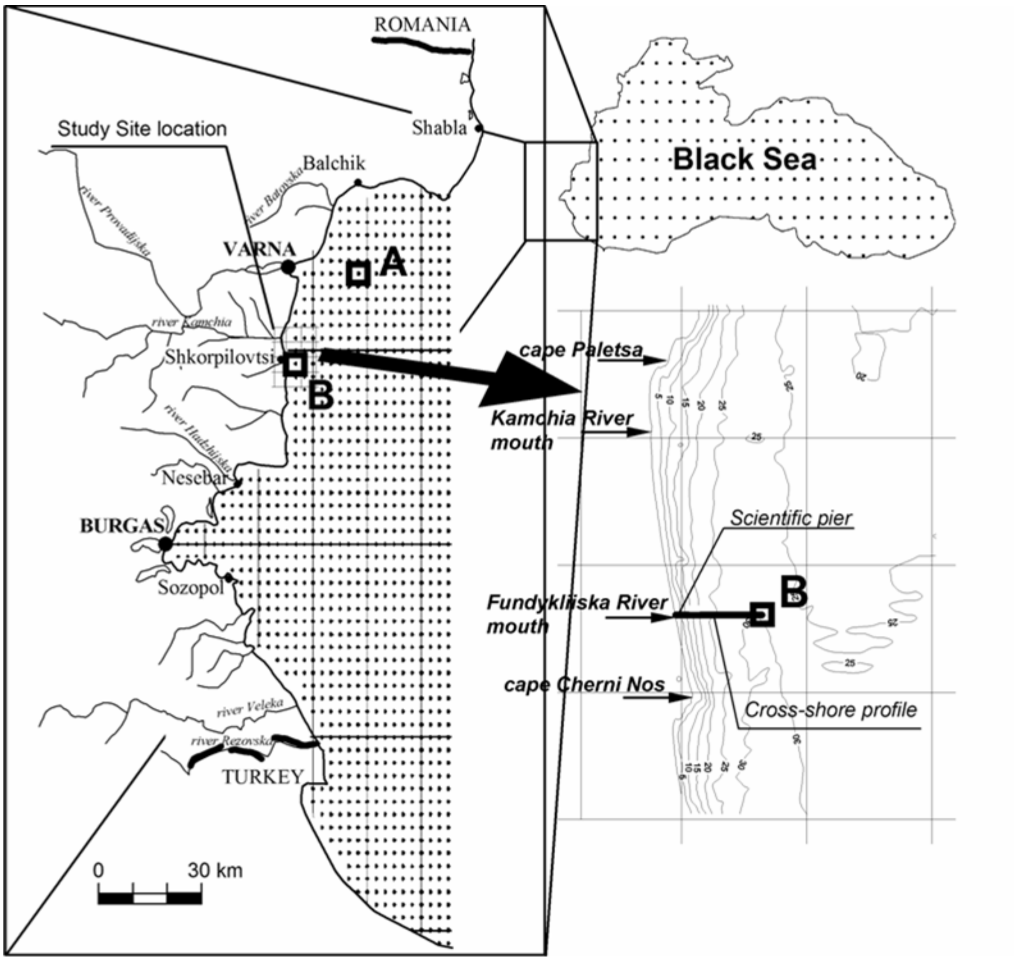


Figure 1. Study site location and features. The Black Sea (upper right) and western shelf (left) model grids are sketched. A and B are points which the wave climate is estimated for. At the site bathymetry map (lower right) the selected cross-shore profile is shown.

only by means of hindcast data. The available hindcast covers a 50-year period and the wave climate is estimated on that basis.

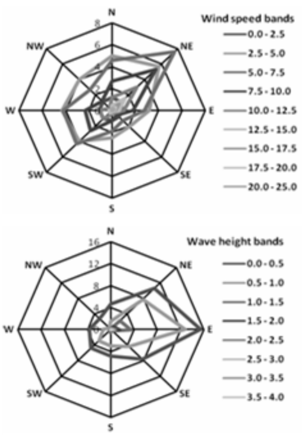
In this paper, the proposed approach is demonstrated in the case of the Kamchia-Shkorpilovtsi beach. In the next section, a short description of the study site and a general notion of the wind and wave climate of the adjacent deep water area are presented. A bottom profile is selected and its representativeness of the entire coastal section is outlined. The employed data and models as well as a methodology for the estimation of the combination of thresholds of wave parameters the exceeding of which would result in a noticeable morphological impact are highlighted in the third section. In the discussion section, a clustering of the wave climate is proposed, the results of sediment bottom motion corresponding to each wave cluster are analyzed and thresholds are established.

STUDY SITE

The study area, called "Kamchia-Shkorpilovtsi", is situated in the western Black Sea, and spreads from cape Paletsa to cape Cherni Nos (Figure 1), located 25 and 40 km to the south of Varna city, respectively. It comprises the longest and the largest sandy beach along the Bulgarian Black Sea coast, with well-developed dunes and the two rivers' mouths, these of the Kamchia River and the Fundakliiska River. In the middle of the site, near the mouth of the Fundakliiska River the Scientific Research Base "Shkorpilovtsi" run by the Institute of Oceanology is located. A scientific pier is built perpendicularly to the shoreline, reaching 4.5 m water depth. Since 1977 a series of field experiments have been conducted, including measurements of waves, bottom deformations and sediment sampling.

The adjacent shoreline is open to waves of the eastern half. In the case of severe storms the wind speed magnitude can reach 35-40 m/s and 9 m height of maximum significance wave at depths of about 1000 m.

The large seasonal variability is one of the most marked features of the wave climate. The winter storms are much more frequent than the summer ones. In the western Black Sea the most frequent are the winds from northeast and east, which trigger the most severe storms (Figure 2a). The northeast winds prevail in the north and middle sections of the shelf zone, while the impact of east winds increases southward. Generally, the southeast winds are less significant in terms of storm intensity but are still relevant in particular for the north shelf part (VALCHEV *et al.,* 2008). The winds from other directions of the north quarter are of medium frequency. Usually, they succeed each other in the course of a storm event and have minor effect on the coastal zone in terms of wave evolution. The winds blowing from other directions have much lower probability of occurrence.



(a) (b)

Figure 2. Wind and wave roses, representing the probability of occurrence in percentage of winds with given direction and speed (a) and waves with given significant height and mean direction of propagation (b) estimated for point A.

As for the wave climate, most frequent are waves propagating from the east and northeast (Figure 2b). The eastern waves, followed by northeastern waves, are predominant within the entire shelf zone. The importance of the southeastern waves augments northwards. The waves propagating from other directions are of negligible weight both in terms of probability of occurrence and wave height. They are distinguished for fetch-limited conditions of their growth and are less significant for the coastal processes.

The main morphological feature of the study area is its rectilinear shoreline with almost parallel isobaths. The bottom slope is covered with sands of different size. In its upper part down to 2.5 m depth, over 95 % of bottom sediments consist of coarse and medium sand fractions. As the depth grows, the content of these fractions decreases and at 8-10 m over 90 % of the sediment grain size is less than 0.25 mm. The medium and coarse sands contain mostly quartz.

A cross-shore profile located in the middle part of the site and with west-east orientation is chosen to be modeled. The most shoreward portion of the profile overlaps with the scientific pier and is marked with a small bar submerged at 150 m offshore. The difference between the foot of the bar (depth 4.16 m) and its top (depth 3.11 m) come up to about a meter (non-published data gathered during field experiment in 2007). The most seaward profile point coincides with a wave model grid point B for which the wave climate is estimated (Figure 1). The selected profile is considered representative for the entire coastal area due to the availability of long term data series of measurements of wave transformation, distribution of sediments grain size, and regimes of sediment motion in storm conditions.

DATA AND METHODS

Despite the technological advance nowadays, wave measurements in extreme conditions covering large areas are difficult to be carried out. Hence, such kind of data is rare in particular for a specific basin as the Black Sea. This complexity can be overcome by numerical modeling in terms of hindcast data. This approach provides a way to reconstruct waves in the open sea and coastal zone occurred as far in the past as possible on the basis of continuous meteorological forcing. The wave climate is assessed by means of this tool for the purposes of the study.

The global atmospheric pressure reanalysis spanning 50 years (1958-2007) carried out by the European Centre for Medium-range Weather Forecast (UPPALA et al., 2005), is employed in order to calculate the wind forcing of wave models. Since atmospheric pressure fields have rather coarse resolution (2.5° spatial and 6 hours temporal), the wind input spatial resolution is downscaled to 0.5° via regional atmospheric model (LAVRENOV, 1998). The output wind fields are stored in every third hour.

Two state-of-the-art models are employed for the wind wave hind casting: spectral parametrical model (SPM) (DAVIDAN and DAVIDAN, 2001) and the SWAN model (BOOIJ et al., 2004). A coupled system is set up in the following manner. The SPM wave model is adapted for fetch-limited conditions and is run for the whole Black Sea basin. SWAN is nested to SPM in order to simulate waves in the western shelf zone. The SPM output provides lateral boundary conditions in terms of significant wave height, H_s, mean wave period, T_m, and mean wave direction, θ_m.

A digital bathymetric database for the western shelf with about 4 km resolution is prepared. SPM is implemented with 0.5° spatial resolution for the deep water case. Integrated parameters and total sea and swell spectra output are obtained at each 3rd hour as well. SWAN is implemented on a grid with 2′ spatial resolution. Integrated parameters of total sea and swell spectra output are obtained at each hour. Areas of simulation, as well as the basin - wide and the nested grids are presented in Figure 1. Both models are validated for the conditions in the Black Sea and the results are published for example by VALCHEV et al. (2008).

The model for wave transformation in the shallow water, used in the study, was developed in the department of Coastal zone dynamics at the Institute of Oceanology (TRIFONOVA, 2006). It calculates the changes of wave vectors and wave heights along the cross-shore profile on the basis of preliminarly known offshore mean wave height, period, and direction of propagation.

The changes of the local wave vectors due to refraction are described according to Snell's law, and the wave heights are calculated on the basis of the equation of wave energy conservation. The rate of wave energy dissipation is calculated after BATTJES and JANSSEN (1978), and for the calculation of the fraction of breaking waves the approach suggested by RATTANAPITIKON and SHIBAYAMA (1998) is assumed. The output of this model allows calculating the maximum near-bottom wave orbital velocity u_m

$$u_m = \frac{1}{2}\frac{H\omega}{\sinh kh}, \qquad (1)$$

where H is wave heights, ω – wave angular frequency, k – wave number, and h – local depth. The model is verified against field data collected during experiments at the scientific pier (TRIFONOVA, 2006).

Due to wave action non-cohesive bottom sediments begin their motion that gives rise to morphological changes of bottom relief. In order to determine the critical wave conditions triggering the sheet flow sediment motion, the approach of WIKRAMANAYAKE and MADSEN (1994) is employed. Ratio of skin friction Shields parameter, ψ'_m, and sediment-fluid parameter, S_*, is empirically obtained and denoted with Z (ARMY CORPS OF ENGINEERS, 2002). If Z exceeds a value 0.18, or $\psi'_m > 0.35$, the bed is assumed flat corresponding to sheet flow conditions. Skin friction Shields parameter is calculated as

$$\psi'_m = \frac{0.5 f_w u_m^2}{(\rho_s/\rho - 1) g d_s}, \qquad (2)$$

where f_w is wave friction factor, ρ and ρ_s are water and sediment density, respectively, g – acceleration due to gravity, and d_s – sediment diameter. Sediment-fluid parameter is calculated from

$$S_* = d_s / (4\nu) \sqrt{(\rho_s / \rho - 1) g d_s} \,, \qquad (3)$$

where ν is the kinematic viscosity of the fluid, ν=10^{-6}m^2/s.

The proposed methodology includes several steps in keeping with the main objectives of the study. Firstly, the wave climate in terms of probability of occurrence is estimated for the most seaward point B of the selected profile (Figure 1) and clustered in H_s, T_m and θ_m bands. This statistical dataset comprises variety of wave regimes that represent wave boundary conditions forcing the wave transformation model in shallow water. Subsequently, the 250 m-long cross-shore profile along the pier is combined with available bathymetry data and extended to point B. The sediment properties array is prepared as well. This input data serve as morphological and lythological boundary conditions, respectively. The wave transformation model is run along the profile and the output is used for calculation of sediment transport regime according to (2) and (3). Thus, if at any point along the cross-shore profile conditions for sheet flow motion arise, it is assumed that the corresponding wave climate cluster is capable of generating morphological impact of given magnitude.

RESULTS AND DISCUSSIONS

The whole range of values hindcast for main wave parameters – H_s, T_m and θ_m – for point B represent a 3D array that includes a great variety of combinations. Therefore, these climate estimates are divided into even bands with increments 0.2 m, 0.5 s and 11.25°, respectively. As commented in study site section, waves propagating from western half are not significant with respect to morphological storm impact. Therefore, angles of wave approach ranging between 181° and 359°, which constitute 16.5 % of all cases, are not considered. Described clustering allows examining diverse wave regimes. For each cluster, the joint probability of occurrence is estimated. Figure 3 graphically represents the projections of this clustered 3D array onto 2D planes defined by H_s-T_m (Figure 3a) and H_s-θ_m (Figure 3b). Shaded in grey 2D clusters outline all combinations of wave parameters, which can actually occur, and numbers correspond to probability of occurrence in percentage of waves falling into a given cluster.

It is assumed that slight seas (wave heights less than 0.5 m) do not cause noticeable bottom deformations (NIKOLOV and PYKHOV, 1980) and for that reason they are shut out from further calculations. It should be noted, that slight seas are about 45 % of all shoreward waves that reduces greatly the number of analyzed combinations. In that way, only 754 3D clusters are considered for further computing of wave transformation and regime of bottom motion along the profile.

The profile model output gives the linear length of the zone in which sheet flow motion conditions are expected. This allows defining the surface separating wave climate clusters capable of producing discernible morphological response from the remaining part. The projection of this surface is drawn in a similar to Figure 3 manner. Result is presented in Figure 4, in which regimes that could induce bottom deformations of certain rate are depicted with black points and grey points refers to cases with absence of sheet flow motion. The described surface in H_s - T_m - θ_m space represents the 3D threshold the authors searched for. As preliminary

T_m \ H_s	<0.5	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6
<0.75																						
1	0.46																					
1.5	6.58																					
2	16.78																					
2.5	19.22	2.8	0.01																			
3	10.29	8.5	2	0.03																		
3.5	5.95	3.42	3.76	2.02	0.15																	
4	2	2.16	1.15	1.42	1.78	0.55	0.03															
4.5	0.02	0.96	0.56	0.34	0.47	0.92	0.8	0.23	0.02													
5		0.03	0.26	0.21	0.15	0.17	0.25	0.52	0.43	0.15	0.01											
5.5			0.01	0.1	0.07	0.05	0.05	0.07	0.19	0.29	0.21	0.09	0.02									
6					0.03	0.03	0.02	0.02	0.02	0.04	0.08	0.15	0.15	0.05	0.01	0.01						
6.5						0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.07	0.07	0.04	0.02					
7								0.01						0.01	0.02	0.04	0.08	0.02	0.01			
7.5																	0.01	0.01	0.02	0.01	0.01	0.01
8																			0.01	0.01	0.02	0.01
8.5																						0.01
9																						0.01
Total	61.3	17.87	7.76	4.11	2.65	1.74	1.16	0.86	0.67	0.49	0.32	0.26	0.21	0.14	0.11	0.1	0.11	0.05	0.04	0.02	0.02	0.01

(a)

θ_m \ H_s	<0.5	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6
6	0.99	0.08	0.01																			
17	1.37	0.23	0.06	0.01																		
28	1.79	0.46	0.22	0.07	0.01																	
39	2.43	0.83	0.46	0.24	0.12	0.05	0.02	0.01														
51	3.34	1.34	0.85	0.49	0.34	0.2	0.13	0.09	0.04	0.02												
62	4.21	1.87	1.05	0.69	0.48	0.36	0.23	0.16	0.12	0.1	0.07	0.05	0.02	0.01	0.01							
73	4.29	1.86	1.13	0.78	0.54	0.4	0.3	0.24	0.18	0.13	0.08	0.07	0.06	0.03	0.02	0.02	0.03	0.01				
84	4.25	1.94	1.08	0.62	0.46	0.33	0.24	0.19	0.19	0.16	0.1	0.08	0.08	0.06	0.05	0.04	0.05	0.01	0.02	0.01	0.02	
96	4.82	2.15	0.9	0.51	0.34	0.21	0.13	0.11	0.1	0.06	0.05	0.05	0.05	0.04	0.03	0.02	0.03	0.01	0.01	0.01		0.01
107	4.71	1.82	0.48	0.19	0.1	0.07	0.04	0.03	0.02	0.02	0.01	0.01	0.01									
118	3.38	1.26	0.33	0.09	0.06	0.02	0.02	0.01														
129	2.36	0.76	0.21	0.06	0.02	0.01	0.01															
141	2.06	0.51	0.14	0.04	0.02	0.01	0.01															
152	1.76	0.38	0.13	0.05	0.03	0.02	0.01															
163	1.59	0.42	0.17	0.09	0.03	0.02	0.01															
174	1.43	0.41	0.19	0.09	0.06	0.02	0.01															
Total	44.78	16.32	7.41	4.02	2.61	1.72	1.16	0.84	0.65	0.49	0.31	0.26	0.22	0.14	0.11	0.08	0.11	0.03	0.03	0.02	0.02	0.01

(b)

Figure 3. Clustered wave climate estimated for point B in terms of joint probability of occurrence of: (a) H_s-T_m and (b) H_s-θ_m

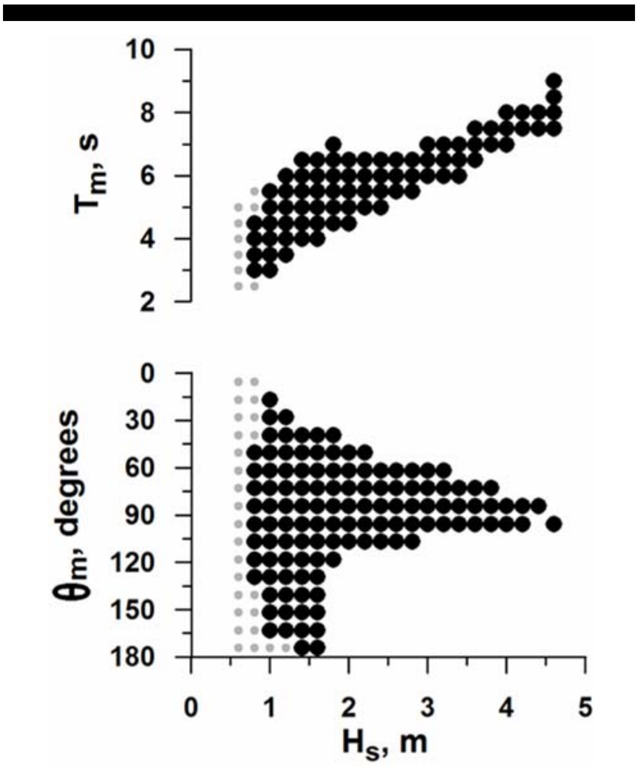


Figure 4. Projection of the threshold surface separating wave climate clusters onto: H_s-T_m plane (top) and H_s-θ_m plane (bottom)

expected, all conditions described with significant wave height of 0.6 m do not satisfy the criterion set; the same is valid for about 50 % of cases with waves of 0.8 m significant height approaching obliquely to the shore. Generally, morphological impact of certain scale could be expected in only 20.5% of all cases while in 79.5% no morphological impact could be foreseen.

CONCLUSIONS

Methodology for setting of wave regime threshold with respect to expected morphological impact is developed. The defined threshold represents a surface that separates wave climate clusters capable of producing discernible morphological response from the remaining part. Tangible results are obtained for a study site situated at the western Black Sea coast. Main conclusion is that only 1/5 of all real clusters in the wave height-period-direction space are likely to pass the threshold. The outcome strongly contributes to improvement of an operational system, warning for potential morphological storm impact.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement n° 202798 (MICORE Project).

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