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## Wave Forecasting Dependent from Bottom Roughness: The Case of the Marano and Grado Lagoon

To cite this article: Sara Pascolo *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **960** 032035

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# Wave Forecasting Dependent from Bottom Roughness: The Case of the Marano and Grado Lagoon

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**Abstract.** Several forecasting curves have been developed in order to provide a useful estimation of the wind wave field generated on shallow depths. In particular, these equations can be successfully applied in confined and sheltered basins, such as lakes, or even lagoons and semi – enclosed estuarine in coastal environments. The important role of the bottom friction dissipation in the generation process has been deeply recognized, leading to a reformulation of the available curves in terms of the equivalent bed roughness. In the present study, the recent new set of equations is considered and applied to a coastal lagoon. The results in terms of significant wave height and peak period are compared to those derived from a complete numerical model and other previous curves. The performed application corroborates and further validate the forecasting equations.

## 1. Introduction

Wind waves are fundamental in the sediment transport processes that affect coastal lagoons, sheltered estuarine basins, and lakes [1,2]. These environments can be characterized by very shallow depths, which can strongly limit the current velocities and the relative bottom shear stresses; in this case, the wave component increases the maximum bed shear stress and triggers resuspension mechanisms when the critical erosion threshold is exceeded [3,4]. The combination with the drag effect of tidal and current flows leads to the main morphological changes. For this reason, the proper evaluation of the wave motion is an important task for the correct management of complex eco-systems such as estuarine and tidal mudflats, salt marshes, shallow lakes, given their high ecological and socio-economic value. In fact, the dynamic equilibrium of these contexts involves both physical and biological factors and it can interfere also with human-induced changes aimed at coastal protection and the maintenance of the navigability of waterways [5-8].

Numerical modelling is undoubtedly a complete and versatile tool to investigate wave hydrodynamics, especially where the phenomenon is complex, and it requires the interaction between several factors. However, the computational effort can be great, and in any case both the calibration and the validation of the model require the comparison with experimental or analytical data. The difficulty of finding field measurements of wave parameters, particularly at shallow depths, can involve the use of analytical-experimental forecasting systems. As an example, the SMB (Sverdrup–Munk–Bretschneider) [9] method offers the possibility to estimate the significant wave height and the peak period in deep water more rapidly than a complete numerical approach. This is a simplified but robust way to predict wind waves, and it still provides reliable values when a limited amount of data and time are available.



Bretschneider [10] and Young and Verhagen [11] have found the growth curves of wind waves locally generated on quite uniform topography and shallow depths, where the interaction with bottom severely limits the wave energy. These equations have been derived from measured data collected in lakes characterized by a low value of the bed roughness and the relative friction factor. The recent study by Pascolo et al. [12] suggests the possibility of making the equations dependent also on the bed roughness, presenting a new set of forecasting equations, that can be used in context with different bottom conditions. The curves have been derived in the hypothesis of fully developed state and they have been validated through an application to a real shallow lake. The obtained wave heights and periods have been compared to both experimental and numerical data in correspondence of a single measuring point.

The present study is a first attempt to extend the application of the new curves introduced by Pascolo et al. [12] to a bi-dimensional domain, which requires the reconstruction of the wave parameters on any of its points. The chosen context is the Marano and Grado lagoon, in the northern Adriatic Sea, Italy, which is characterized by extensive tidal flats with an almost uniform bathymetry. This condition is exploited in order to obtain an estimate of the wave motion by a simplified way. The results derived from the growth equations are compared to those derived from a complete numerical application [13] and those calculated applying the Young and Verhagen curves [11]. The comparison confirms the validity of the equations and the possibility of applying them in large and complex domains.

In section 2 a brief overview of the forecasting equations for wind waves generated on shallow depths is presented. The study site and the method setup are described in section 3, the results of the new forecasting equations are compared to the other results and discussed in section 4.

## 2. Forecasting curves of depth-limited wind waves

The forecasting equations, which describes the growth of wind waves locally generated in enclosed shallow basins, are expressed as follows:

$$\left(\frac{gH_s}{4U^2}\right)^2 = A \left(\frac{gd}{U^2}\right)^B \quad (1)$$

$$\frac{U}{gT_p} = C \left(\frac{gd}{U^2}\right)^D \quad (2)$$

if the sea state can be considered fully developed and therefore there is no dependence on fetch. Equation (1) links the significant wave height  $H_s$  to the water depth  $d$ ;  $g$  is the gravity acceleration, and  $U$  is the wind speed, taken at a reference height of 10 m. Similarly, equation (2) gives the peak period  $T_p$  as a function of water depth  $d$ . The coefficients  $A$ ,  $B$ ,  $C$ ,  $D$  are constant parameters according to the formulation provided by Bretschneider [10] and Young and Verhagen [11] as reported in Table 1. Differently, in the new set of equations proposed by Pascolo et al. [12], some of them have been determined as function of the equivalent bed roughness  $K_N$ .

**Table 1.** Values of the coefficients entering into the equations (1) and (2), according to different authors.  $K_N$  represents the equivalent bed roughness.

Authors	$A$	$B$	$C$	$D$
Bretschneider [10]	$1.4 \times 10^{-3}$	1.5	0.16	-0.375
Young and Verhagen [11]	$1.06 \times 10^{-3}$	1.3	0.20	-0.375
Pascolo et al. [12]	$0.0002 K_N^{-0.205}$	1.3	$0.307 K_N^{0.061}$	-0.40

The form of the equations (1) and (2) underlines the central role of the water depth in limiting the wave energy and the relative parameters. The wind energy, transferred to the sea surface, is balanced by the interaction with the bottom, and the dissipative action due to friction mechanism which develops within the wave boundary layer. The wave friction factor, on which the bottom shear stress depends, is

generally a function of both the wave characteristics near the bottom and the equivalent bed roughness. The importance of the friction factor in determining the growth of waves in shallow depths has been recognized by several authors [14,15], who underlined its variability due to the fluid-sediment interaction. In particular, the presence of bedforms or the heterogeneous composition of sediments with different particle size can cause a significant increase of the friction factor value.

Bretschneider [10] and Young and Verhagen [11] have developed the forecasting curves by plotting, in terms of the dimensionless variables defined above, the experimental data measured in the Lake Okeechobee, USA, and the Lake George, Australia, respectively. The curves have been determined as the upper bounds of the plotted data. Bretschneider assumed a constant and low value of the friction factor, equal to 0.01, while Young and Verhagen [11] made no assumptions about the bed roughness. However, they pointed out that Lake George is characterized by a flat immobile bed of cohesive mud, where ripples do not develop. Consequently, the bottom friction can be considered also in this case rather low.

Pascolo et al. [12] investigated the effect that different bed roughness values produce on the wave generation process and the relative wave characteristics by means of a numerical approach. The spectral model SWAN (Simulated WAVes Nearshore) [16] has been applied to generate wind waves in a regular computational grid with the prevailing longitudinal dimension aligned with the wind direction, and long enough to ensure fully developed wave conditions. Wind speed and water depth have been varied according to appropriate values typical of shallow coastal environments. The results in terms of significant wave height and peak period have been grouped by different bottom roughness height and the least square method has been applied to find regression curves. The coefficients entering in equations (1) and (2) have been expressed in terms of the equivalent bed roughness, as shown in Table 1. These new curves tend to those of Bretschneider [10] and Young and Verhagen [11], under different conditions of water depth and wind speed, if the  $K_N$  value is approximately equal to about 0.0005 m, that is, when the bottom is flat and immobile. For this reason, the equations dependent on the bed roughness can be applied, differently from the previous ones, in contexts characterized by more irregular bottoms, with bedforms, heterogeneous granulometry, and the presence of seagrass, as it happens for example in coastal lagoons. In the present study, the case of the Marano and Grado lagoon is considered and the curves are applied in order to estimate the wave characteristics on the extensive tidal flats of the lagoon.

### 3. Study site and method setup

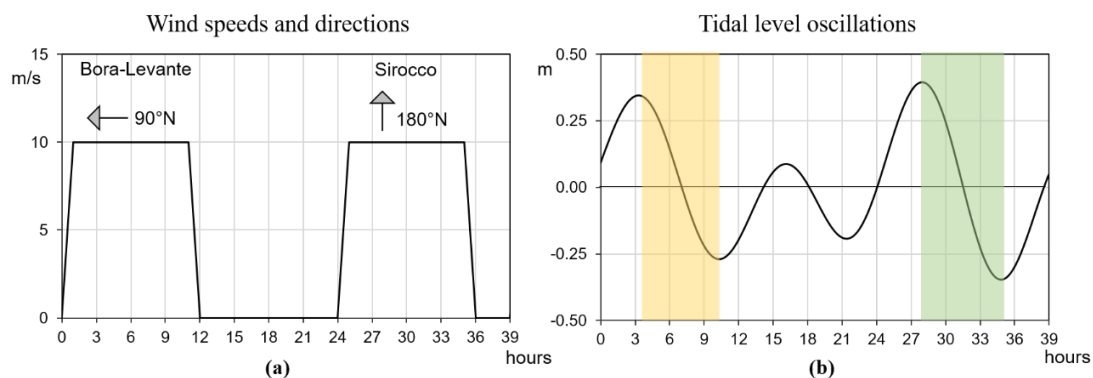
The Marano and Grado lagoon extends between the Friuli Venezia Giulia plain, in the North Est of Italy, and the Northern Adriatic Sea, as depicted in figure 1.



**Figure 1.** The Marano and Grado lagoon and its geographical location in the Italian context. In evidence: the six tidal inlets, the contours of the water depth, the seagrass distribution and the areas chosen for the compute of the generated wave parameters on the tidal flats.

It covers an area of about 160 km<sup>2</sup> with a shoreline that develops for an overall length of about 32 km. There are three main deep channels that branch out into the lagoon from the sea through the tidal inlets of Lignano, Porto Buso and Grado, which interrupt the barrier island together with the inlets of Sant'Andrea, Morgo and Primero. The inner part of the lagoon is characterized by quite uniform and extensive tidal flats, which have a mean depth of about 0.9 m. The sediments are fine and cohesive, even if sand content progressively increases towards the inlets. A significant portion of the central part of the lagoon is covered by seagrass, which exerts a stabilizing effect on sediment resuspension from the bottom, and it can strongly attenuate the wave motion. However, the lagoon bottom can be considered overall quite heterogeneous, both in composition and in the possible presence of bedforms, being made up of material that can be frequently suspended by the wave motion [17]. In some areas also the use of trawl nets and dredges for the shellfish farming can contribute to the mixing of sediments [18].

The morphological evolution of the Marano and Grado lagoon over the past forty years shows a deepening trend of the tidal flats [17], and the contemporary silting of the tidal channels which requires annual dredging operations. Petti et al. [13] investigated this phenomenon over an average year by means of a morphodynamic-spectral coupled model, which provided reliable results in terms of the sediment volumes, first suspended by wave motion on the tidal flats and then carried and deposited by tidal currents inside the channels. The numerical application required the correct representation of the wave characteristics locally generated by some wind events. In particular, it has been verified that winds with a velocity of 10 m/s contribute significantly to the silting of the channels. The two main wind directions are those of Bora-Levante and Sirocco, kept equal to 90° and 180° respectively. These speed and directions have been combined with the mean tidal oscillations according to the scheme reproduced in figure 2.



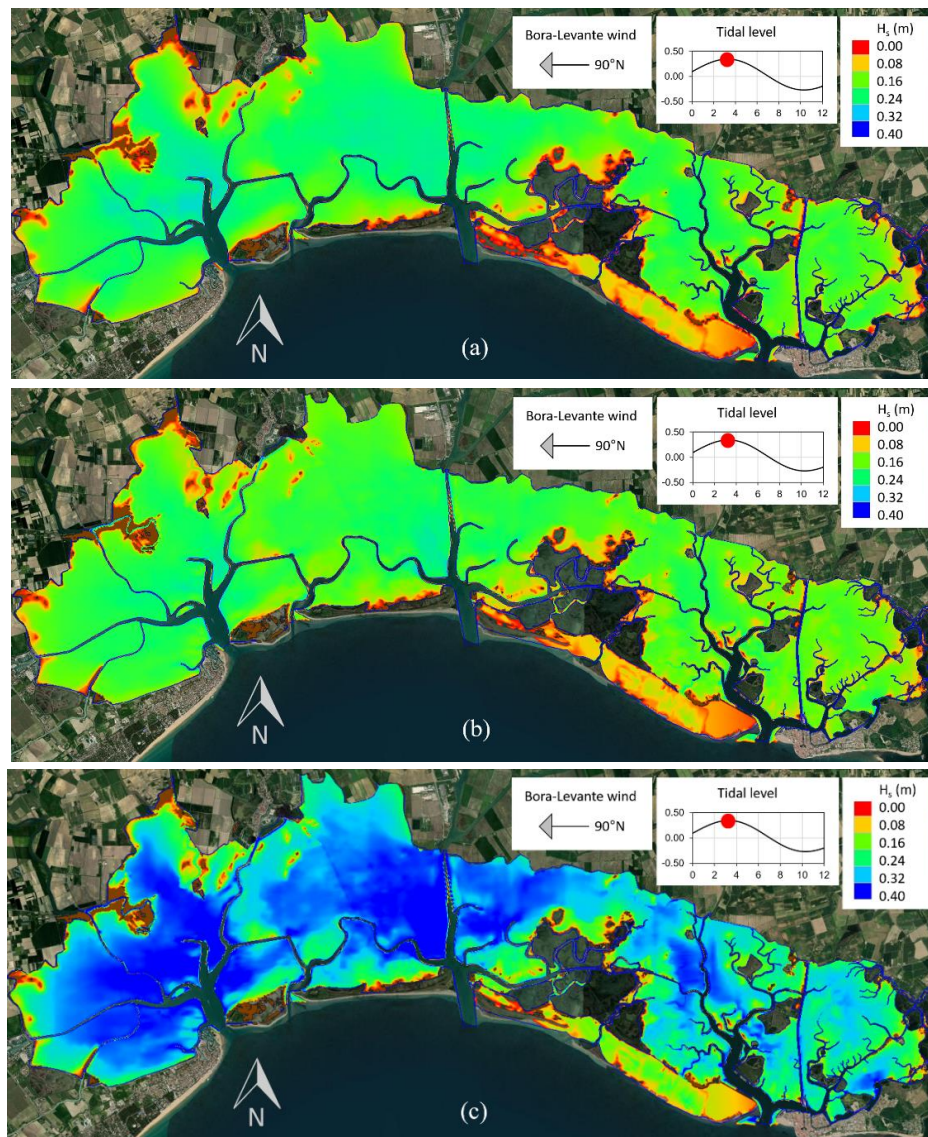
**Figure 2.** The sequence of (a) winds and (b) tides simulated by Petti et al. [13] with the morphodynamic-spectral coupled model. The coloured bands indicate the tidal level chosen in the present study to compute wave parameters for the Bora-Levante case in yellow and for Sirocco in green.

The numerical results in term of significant wave height and peak period are used in the present study as comparison values with those deriving from the growth curves. In order to apply the forecasting curves (1) and (2), the fully developed hypothesis of the sea state needs to be satisfied. The study proposed by Pascolo et al. [12] on the role of the bottom roughness in the development of the wave motion and the relative bed shear stress on shallow depths, underlined that the fully developed state can already be achieved with fetch on the order of a few km. This condition is reached especially in presence of moderate winds, which are strong enough to resuspend sediments, and in presence of heterogeneous bed composition and forms, which increase the equivalent roughness value. In this sense, for simplicity but in accordance to what stated above, the wave heights and the periods have been calculated at each point of the lagoon tidal flats, assuming the developed sea conditions everywhere. The coloured bands in figure 2b refer to the sequences of water level considered to compute the wave parameters generated by the Bora-Levante wind in yellow, and the Sirocco wind in green, respectively.

The total water depth entering in equations (1) and (2) in the dimensionless variable  $\delta$  is calculated, instant by instant, as the sum of the water level given by the graph in figure 2b and the distance between the still water level and the bottom, available from the bathymetry of the lagoon [13]. The equivalent bed roughness, on which the coefficients  $A$  and  $C$  in Table 1 depends, is equal to 0.05 m, as the value set in the numerical application by Petti et al. [13]. Both the forecasting curves proposed by Young and Verhagen [11] and Pascolo et al. [12] are considered and the comparison between the relative results and that derived from the numerical model is made.

#### 4. Results and discussions

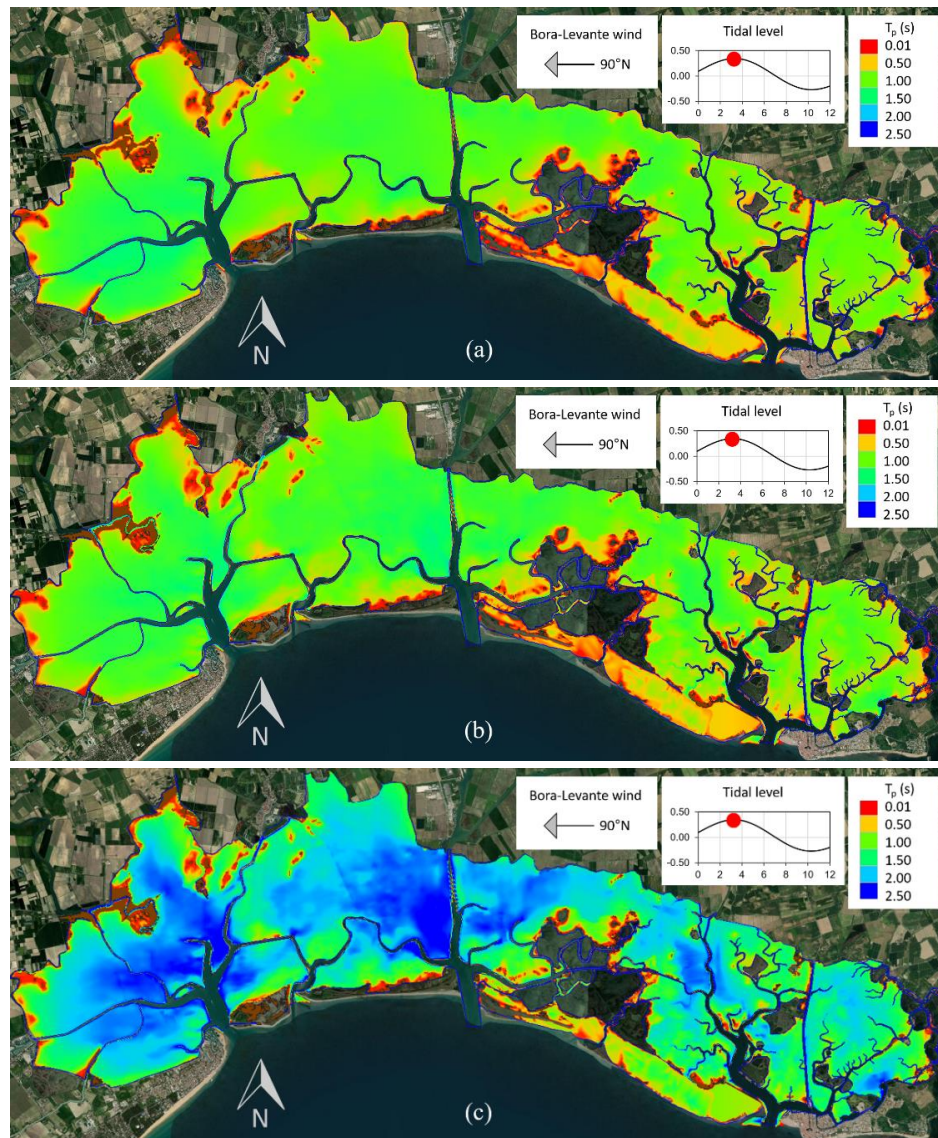
The results in terms of the significant wave height on the overall domain are reported in figure 3.



**Figure 3.** Significant wave heights derived from: (a) numerical model by Petti et al. [13], (b) Pascolo et al [12] and (c) Young and Verhagen [11] forecasting curves, during the Bora-Levante event.

In particular, the waves generated by the Bora-Levante wind by means of the forecasting curves depending on the bed roughness [12] are shown in figure 3b, as an example. These results are compared to those obtained from the complete numerical modelling [13] (figure 3a) and those derived by means of the Young and Verhagen curves [11] (figure 3c). Similarly, figure 4 reports the distribution of the

wave peak periods. The time chosen for the comparisons coincides with the maximum tidal level during the Bora-Levante event, as indicated by the red circle in the graphs.

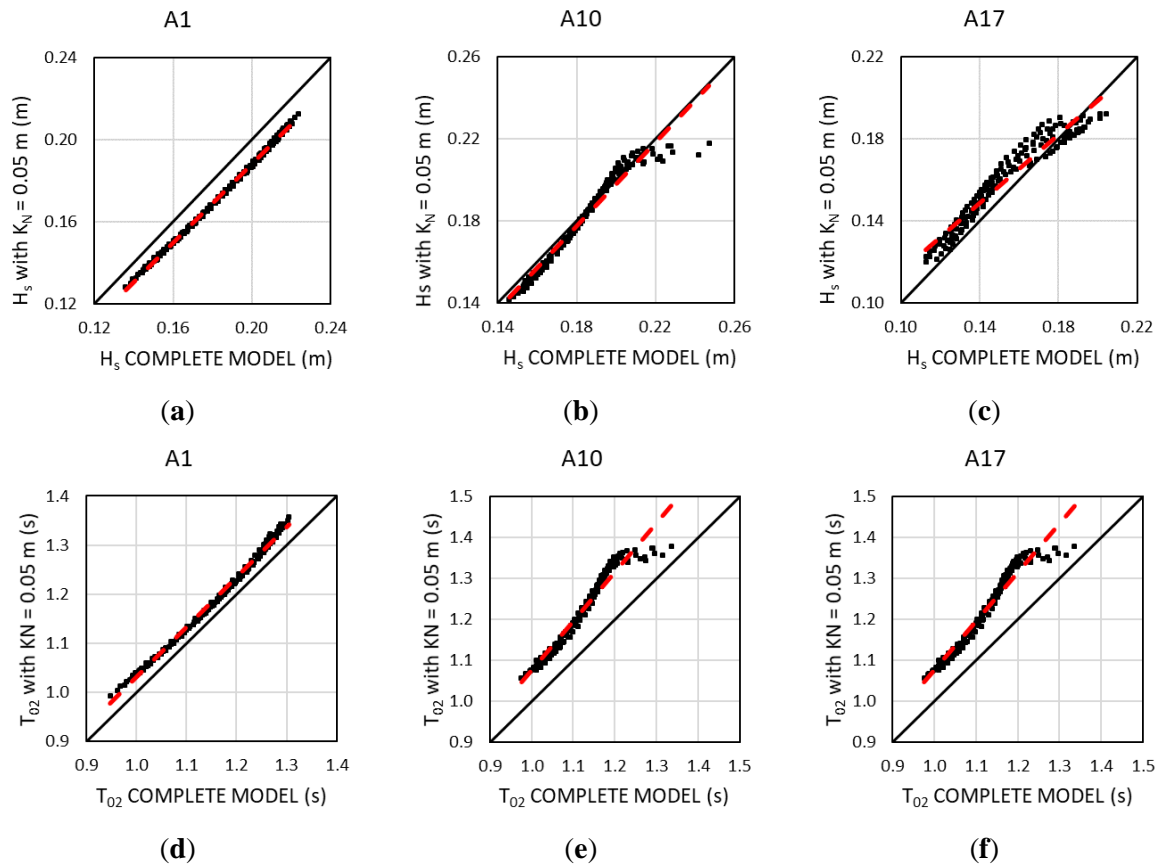


**Figure 4.** Wave peak periods computed by means of: (a) numerical model by Petti et al. [13], (b) Pascolo et al [12] and (c) Young and Verhagen [11] forecasting curves, during the Bora-Levante event.

The tidal channels are excluded from this analysis as the application is limited to the tidal flats. The comparison shows the good agreement between the results obtained by the curves depending on the bed roughness and those derived from a complete numerical approach. Differently, the curves of Young and Verhagen [11] overestimate the wave field.

To better quantify the correspondence between the results, the punctual comparison between the analytical and numerical methods is made in some points taken inside the areas indicated with numbered circles in figure 1, with the same colours as the bands in figure 2b to distinguish which are chosen for the Bora-Levante case and which for Sirocco. These areas have been selected from a previous study by Petti et al. [17] on the stability of the tidal flats of the Marano and Grado lagoon. The correlation graphs are depicted in figure 5 for the Bora-Levante case, selecting some representative areas of the different

lagoon portions: one for the eastern basin of Lignano, one for that of Porto Buso and finally the eastern basin of Primero. The main statistical parameters derived from the comparison between the significant wave heights and the  $T_{02}$  wave periods are shown in table 2 and 3, for all the selected areas.



**Figure 5.** Correlation graphs made in correspondence of the areas A1, A10, A17 between the wave parameters estimated by means of the complete 2D numerical model and those obtained through the forecasting curves: (a) - (b) - (c) the significant wave heights; (d) - (e) - (f) the  $T_{02}$  period. The wind event is Bora-Levante. The regression line of the points is depicted in red.

**Table 2.** Wave height coefficients: *BIAS*, bias parameter; *RMSE*, root mean square error; *SI*, scatter index;  $R^2$ , correlation coefficient. Bora-Levante wind is considered.

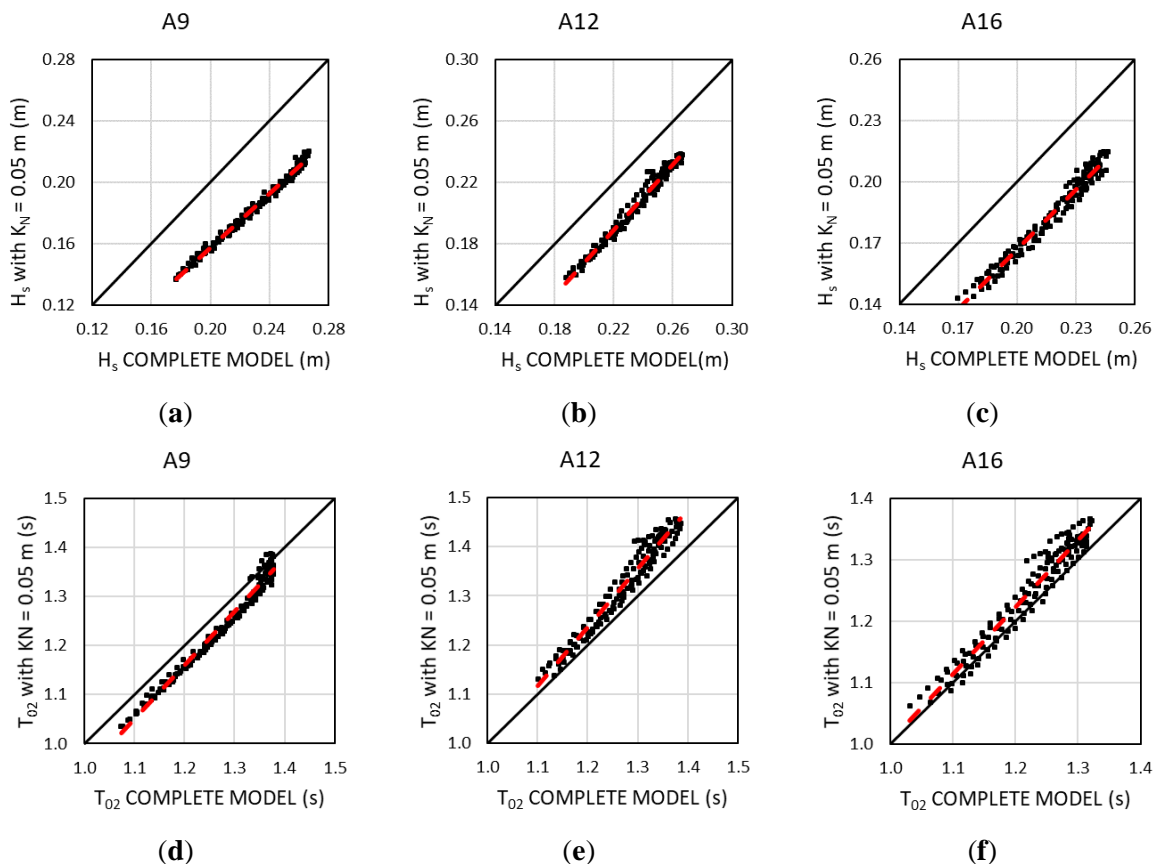
	A1	A4	A6	A8	A10	A17	A19
<b>Complete Numerical Model - Forecasting Curves with <math>K_N</math></b>							
<i>BIAS</i>	-0.0112 m	-0.0128 m	-0.0039 m	0.0012 m	-0.0025 m	0.0065 m	0.0020 m
<i>RMSE</i>	0.0113 m	0.0140 m	0.0054 m	0.0051 m	0.0058 m	0.0095 m	0.0118 m
<i>SI</i>	0.0616	0.0728	0.0258	0.0264	0.0315	0.0616	0.0792
$R^2$	0.9980	0.9422	0.9807	0.9793	0.9442	0.9284	0.9605
<b>Complete Numerical Model - Forecasting Curves of Young and Verhagen</b>							
<i>BIAS</i>	0.1082 m	0.1118 m	0.1375 m	0.1356 m	0.1232 m	0.1177 m	0.1072 m
<i>RMSE</i>	0.1092 m	0.1131 m	0.1387 m	0.1371 m	0.1244 m	0.1185 m	0.1137 m
<i>SI</i>	0.5960	0.5875	0.6680	0.7118	0.6776	0.7701	0.7600
$R^2$	0.9980	0.9422	0.9807	0.9793	0.9442	0.9284	0.9605



**Table 3.**  $T_{02}$  period coefficients: *BIAS*, bias parameter; *RMSE*, root mean square error; *SI*, scatter index;  $R^2$ , correlation coefficient. Bora-Levante wind is considered.

	A1	A4	A6	A8	A10	A17	A19
<b>Complete Numerical Model - Forecasting Curves with <math>K_N</math></b>							
<i>BIAS</i>	0.0340 s	0.0378 s	0.0655 s	0.1110 s	0.0996 s	0.1645 s	0.1429 s
<i>RMSE</i>	0.0349 s	0.0405 s	0.0707 s	0.1147 s	0.1032 s	0.1657 s	0.1624 s
<i>SI</i>	0.0302	0.0342	0.0563	0.0981	0.0915	0.1700	0.1714
$R^2$	0.9946	0.9805	0.9320	0.9759	0.9397	0.9565	0.9616
<b>Complete Numerical Model - Forecasting Curves of Young and Verhagen</b>							
<i>BIAS</i>	0.9655 s	0.9910 s	1.0846 s	0.5580 s	0.5327 s	0.5735 s	0.5370 s
<i>RMSE</i>	0.9681 s	0.9937 s	1.0876 s	0.5605 s	0.5349 s	0.5744 s	0.5532 s
<i>SI</i>	0.8381	0.8395	0.8666	0.4795	0.4740	0.5895	0.5838
$R^2$	0.9949	0.9809	0.9326	0.9763	0.9396	0.9561	0.9614

Similarly, figure 6 shows the correlation graphs for the Sirocco case and table 4 and 5 the main computed statistical parameters for the wave heights and the periods, respectively.



**Figure 6.** Correlation graphs made in correspondence of the areas A9, A12, A16 between the wave parameters estimated by means of the complete 2D numerical model and those obtained through the forecasting curves: (a) - (b) - (c) the significant wave heights; (d) - (e) - (f) the  $T_{02}$  period. The wind event is Sirocco. The regression line of the points is depicted in red.

**Table 4.** Wave height coefficients: *BIAS*, bias parameter; *RMSE*, root mean square error; *SI*, scatter index;  $R^2$ , correlation coefficient. Sirocco wind is considered.

	A2	A7	A9	A10	A11	A12	A13	A15	A16
<b>Complete Model - Forecasting Curves with <math>K_N</math></b>									
<b>BIAS</b>	-0.044 m	-0.036 m	-0.046 m	-0.047 m	-0.052 m	-0.030 m	-0.028 m	-0.039 m	-0.033 m
<b>RMSE</b>	0.044 m	0.037 m	0.046 m	0.047 m	0.052 m	0.030 m	0.029 m	0.040 m	0.034 m
<b>SI</b>	0.2117	0.1557	0.2019	0.1944	0.2225	0.1293	0.1343	0.1868	0.1541
<b>R<sup>2</sup></b>	0.9961	0.8475	0.9898	0.9899	0.9829	0.9767	0.9580	0.9760	0.9679
<b>Complete Model - Forecasting Curves of Young and Verhagen</b>									
<b>BIAS</b>	0.0711 m	0.1054 m	0.0812 m	0.0893 m	0.0751 m	0.1115 m	0.1005 m	0.0812 m	0.0949 m
<b>RMSE</b>	0.0725 m	0.1075 m	0.0823 m	0.0904 m	0.0763 m	0.1131 m	0.1023 m	0.0842 m	0.0960 m
<b>SI</b>	0.3444	0.4475	0.3580	0.3697	0.3243	0.4828	0.4777	0.3939	0.4390
<b>R<sup>2</sup></b>	0.9961	0.8475	0.9898	0.9899	0.9829	0.9767	0.9580	0.9760	0.9679

**Table 5.**  $T_{02}$  period coefficients: *BIAS*, bias parameter (s); *RMSE*, root mean square error (s); *SI*, scatter index;  $R^2$ , correlation coefficient. Sirocco wind is considered.

	A2	A7	A9	A10	A11	A12	A13	A15	A16
<b>Complete Model - Forecasting Curves with <math>K_N</math></b>									
<b>BIAS</b>	-0.0211 s	-0.0046 s	-0.0332 s	-0.0349 s	-0.0734 s	0.0489 s	0.0776 s	-0.0122 s	0.0251 s
<b>RMSE</b>	0.0234 s	0.0565 s	0.0373 s	0.0401 s	0.0766 s	0.0548 s	0.0804 s	0.0482 s	0.0330 s
<b>SI</b>	0.0198	0.0426	0.0294	0.0302	0.0585	0.0431	0.0688	0.0399	0.0270
<b>R<sup>2</sup></b>	0.9939	0.6702	0.9786	0.9647	0.9602	0.9552	0.9673	0.8897	0.9416
<b>Complete Model - Forecasting Curves of Young and Verhagen</b>									
<b>BIAS</b>	0.3942 s	0.4533 s	0.4026 s	0.4155 s	0.3617 s	0.5070 s	0.5156 s	0.4118 s	0.4628 s
<b>RMSE</b>	0.3962 s	0.4595 s	0.4046 s	0.4175 s	0.3642 s	0.5091 s	0.5175 s	0.4182 s	0.4644 s
<b>SI</b>	0.3346	0.3465	0.3182	0.3143	0.2782	0.3999	0.4426	0.3463	0.3808
<b>R<sup>2</sup></b>	0.9941	0.6709	0.9790	0.9652	0.9607	0.9554	0.9673	0.8909	0.9418

The estimate of the wave field by means of the Pascolo et al. [12] curves is overall very good on the whole domain. The statistical parameters confirm that there is a better agreement between the results of the numerical model and those derived taking into account a greater bottom friction dissipation, compared to those obtained through the Young and Verhagen curves [11]. The eastern part of the lagoon seems to be not well represented by the results of the curves. This can be justified by the fact that this basin is very small and closed, and with a very complex and irregular geometry. In the case of the Sirocco wind, there is a tendency of the curves to underestimate the wave height, compared to the complete modelling. This is probably because the blowing wind presents an important directional spreading, much more than the direction of the Bora-Levante, which instead is aligned with the longitudinal development of the lagoon. Therefore, the spectral approach manages to give a better representation of the Sirocco generation process because it takes into account the bi-dimensional development of the domain, unlike the forecasting curves.

## 5. Conclusions

In the present paper, the new set of forecasting curves developed by Pascolo et al. [12] has been applied to a bi-dimensional domain in order to estimate the wave field generated on the shallow depths of the Marano and Grado Lagoon. This is the first application of the curves to such a large and complex context, and the comparison with available numerical results show a good agreement with a complete

spectral model. This outcome underlines the versatility of the curves and confirms their usefulness in semi-enclosed coastal basins, where the bottom is heterogeneous in composition and shapes and the shallow depths can strongly increase the friction dissipations. Compared to a complete spectral model, the curves show a weakness if the wind direction is such as to suffer a strong directional spreading. In fact, the forecasting equations has been developed considering a predominant development of the domain along the blowing wind. However, the simplicity and reliability of the results corroborate the advantage of using the curves not only as a replacement but also to complement a model in its calibration and validation phases.

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