Measurements and Numerical Modelling of Surface Waves in Front of the Port of Split

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ABSTRACT: Wind generated surface waves were measured at V2 station (φ=43°29.3' N; λ=16° 27.9' E) in the Brački Kanal Channel area of the Middle Adriatic, in front of the port of Split. This was undertaken in the time interval from November 2007 to June 2008, by using Datawell MKIII waverider with all its compo-nents. For the analysis and description of extreme sea states maximum recorded wave height Hmax and sig-nificant wave height H1/3 were presented as well as associated wave spectra. The measurement results show that much larger waves appear in the open Adriatic compared to the Middle Adriatic channel area. Numerical modelling of wave generation in the Brački Kanal Channel area and wider island area of the Middle Adriatic Sea was performed by using Mike 21/SW numerical model. Wind field used for the forcing in numerical simulations relies on the results of the prognostic atmospheric model Aladin-CRO. For verification of model results, results of measurement at a waverider station V2 located in front of the port of Split were used. It was concluded that measured and modelled significant wave heights were very well matched.

1 INTRODUCTION

A concept of wave in physical oceanography is understood to be "vertical movement of sea surface". Wind-generated surface waves are only one group of waves among the other waves as: tidal waves, storm surges, tsunami, infra-gravity waves, swell waves, wind waves and capillary waves. Sea surface waves generated by wind are the waves arose following dynamical pressure of wind blowing above the sea surface. They have period from 0.25 s to 30 s with appropriate wavelength of 0.1 to 1500 m (in deep sea; Munk, 1950).

Scientists are more interested in investigation of dynamics and kinematic of waves; how they are generated by wind, how they travel and transform and how they disappear from sea surface. On other side "Engineers" (naval architects, mariners, hydraulics, builders and etc.) are most interested for the project, which includes: ships, platforms, ports, breakwaters, piers, beaches and etc. The real waves on sea surface, in situations with storm and hurricane wind, looks very chaotic while swell waves appeared very regular.

At present, five methods are available to deal with description of sea state under action of waves at particular sea area or location (Goda, 2000): significant wave representation method, highest wave representation method, probability calculation method, irregular wave test method, and spectral calculation method. Numerical modelling methods of wave generation and dissipation have been used too (e.g. Bertotti and Cavaleri, 2009).

Intense investigations around the world of wind generated sea surface waves during 60th and 70th

years of 20th century initiated an interest for this phenomenon in the Adriatic Sea.

In eastern part of the Adriatic first knowledge about sea surface waves are based on collected visual observations from the ships (e.g. Zupan, 1961). Statistical analyses of collected data from ships have been done continuously over the time. One of the statistical presentation of ships visual wave observations covering the east Adriatic Sea is given by Leder (2002) showing relative frequencies of wave heights (H) for different seasons. First instrumental wave measurements along the east Adriatic coast started in 1967 based on short-term experiments (Tabain, 1985), while contemporary long-term instrumental waves measurements started in 70th years of 20th century. These years locations are founded where had to be deployed waveriders at the open Adriatic Sea; southeast of lighthouse St. Andrija near Dubrovnik (South Adriatic, Smirčić et al., 1998); near Palagruža Island (Middle Adriatic, Smirčić and Gačić, 1983) and in the area of gas fields IKA and IVANA (North Adriatic, Leder et al., 1998).

Measurements of the wind-generated surface waves along the eastern part of the Adriatic Sea in coastal areas are rare: previous systematic measurements have been carried out in the open sea (Leder et al., 2010).

It should be emphasized that knowledge of the elements of the wave climate is very important for navigation on the waterway and berth in the port or anchoring in front of the port.

The Port of Split, situated at exceptional geographic position in the Mediterranean, with extraordinary maritime characteristics for reception of vessels, has earned the rank of one of the most important centres for local and international maritime traffic. As of 2017, the port ranks as the largest passenger port in Croatia and the largest passenger port in the Adriatic, (https://portsplit.hr/en/). In this paper results of measurements and numerical modelling of wind generated surface waves in front of port of Split are presented and compared with results of measurements of waves in the open Adriatic Sea area.

2 MATERIAL AND METHODS

Wind generated surface waves were measured at V2 station (φ=43°29.3′ N; λ=16° 27.9′ E; Fig. 1) in the Brački Kanal Channel area of the Middle Adriatic, in front of the port of Split. Wave measurements were part of the scientific and research program – „The Adriatic Sea Monitoring Program" (Andročec et al., 2009) and were undertaken in the time interval from November 2007 to June 2008, by using Datawell MKIII waverider with all its components. For the analysis and description of extreme sea states maximum recorded wave height Hmax and significant wave height (Hs or H1/3) will be presented as well as associated wave spectra.

The process of formation and development of surface waves may be considered as a function of three basic variables, and this functional relation is usually given as the simple analytical expression:

$$F = F[(\omega,v),P,T_t] \tag{2.1}$$

where:
(ω,v), wind direction and speed,
P, length of fetch over which the wind blows,
T_t, duration of wind of a particular direction.

From the aspect of surface wave generation at V2 station in Brački Kanal Channel, the following winds are predominant (Fig. 1):
– Sirocco (or Scirocco), ESE-SE direction, fetch about 100 km;
– Bora, NE-ENE direction, fetch about 3.5 km;
– Libeccio, SW direction, fetch about 15 km;
– Maestrale, Pulenat, W – WSW direction, fetch about 30 km.

Figure 1. Lenght of fetch for dominant winds at the station V2 near port of Split.

For easier understanding, brief definitions of parameters applied in the analysis and description of a certain sea state are given below, using terminology and symbols adopted in the worldwide literature of oceanographers, shipbuilders and hydrotechnic engineers (Smirčić, 1985):
$H_{1/3}$ or H_s - significant wave height, representing average height of 33% of waves in a particular record. This unit has characteristics of visually observed wave heights;
$H_{1/10}$, - average height of 1/10 of highest waves in a particular record;
H_{max} - maximum recorded wave height in a record;
H_{av} - average wave height in a record;
$T_{1/3}$ or T_s - significant (mean) wave period for a particular recording interval;
T_{av} - average wave period for a particular recording interval;
T_{max} - maximum wave period for a particular recording interval;
L_{sr} - mean value of a wave length, representing mean value of horizontal distances between adjacent wave crests in a record. It is calculated from known values of mean periods using the simple empirical relation:

$$L_{sr} = 1.56 \, T_{av}^2 \tag{2.2}$$

where T_{av} is given in seconds and L_{sr} in metres, while maximum error is about 10% if $d/L_{sr} = \frac{1}{2}$ where d = sea depth.

Furthermore, the above mentioned magnitudes can be determined using the method of spectral analysis, whose major task is to obtain the

distribution of total wave energy by frequencies, knowing the spectrum moments m_i (i=0, 1), using the simple relations:

– significant wave height

$$H_{1/3}=4\sqrt{m_0}, \quad m_0 = \tfrac{1}{2} \int S(f)\, df \tag{2.3}$$

where S(f) is wave energy, f is wave frequency (f=1/T), and

– significant (mean) period

$$T_{1/3}=2\pi\,(m_0/m_1), \quad m_1=\tfrac{1}{2} \int S(f)\, f\, df \tag{2.4}$$

Numerical modelling of wave generation in the local waters of the channel and island system of the southern Adriatic Sea was undertaken using Mike 21/SW. Wind field used for the forcing in numerical simulations relies on the results of the prognostic atmospheric model Aladin-CRO. For verification of model results, results of measurements at a waverider station V2, located in front of the town of Split, were used, covering the period from 1 November 2007 to 19 June 2008.

In the numerical model Mike 21/SW, full spectral formulation based on the papers of Komen et al. (1994) was used. For discretization of the spectral frequency domain, logarithmic scale with the minimum frequency of 0.08 Hz (wave period 12.5 s) to the maximum frequency of 1.15 Hz (wave period 0.87 s) was used, through 28 discrete steps. The mentioned range provides coverage of all relevant spectral periods that may be expected in the analysed area. The model includes the processes covered by the wind wave generation, non-linear wave interaction, refraction and shoaling, as well as whitecapping. Dissipation coefficients were used with constant values of 3.9 and 0.5 (Lončar et al., 2010). Reflection and diffraction have not been treated using this model. Time integration is carried out with fractional steps, whereby for the propagation of wave action multi-sequence Euler's explicit method was used. The function of sources in the wave action conservation equation is treated on the basis of 3rd generation models, and their numerical integration is carried out according to the DIA (Discrete Interaction Approximation) method shown in the papers of Komen et al. (1994) and Hercbach and Jannsen (1999).

Generation of wave dynamics requires data on the wind (intensity and direction) in the spatial domain of the numerical model at 10 m above the sea surface. These data were obtained from the prognostic numerical atmospheric model Aladin with a horizontal resolution of 8 kilometres and a temporal resolution of three hours (Courtier et al., 1991; Brzović and Strelec-Mahović, 1999; Ivatek-Sahdan and Tudor, 2004).

Spatial domain of the numerical model which includes the area of the Splitski kanal, Brački kanal, Hvarski kanal, Korčulanski and Neretvanski kanal Channels is shown in Figure 2. with bathymetry based on the spatial continuous raster grid data of 7.5' in the longitudinal and latitudinal directions and model domain discretization with an unstructured grid of triangle finite volumes.

Numerical distances between nodes, set in the centres of finite volumes, are variable, ranging from 150 m to 500 m. The model domain does not have active open boundaries and all land boundaries are completely absorbent. The exclusion of open boundaries is apparently inherent with the process in the nature (see Fig. 2; links between the islands of Šolta and Hvar, and of Hvar and Korčula), causing an error in cases when waves coming from the west. Given the intensity, frequency and duration of the wind with prevalent W direction, it may be concluded that the entered error very rarely has an impact on model results, and namely only in the area close to the links between the islands. Initial conditions (1 November 2007) were defined with a zero spectra, i.e. the absence of the initial wave motion throughout the model spatial domain is assumed.
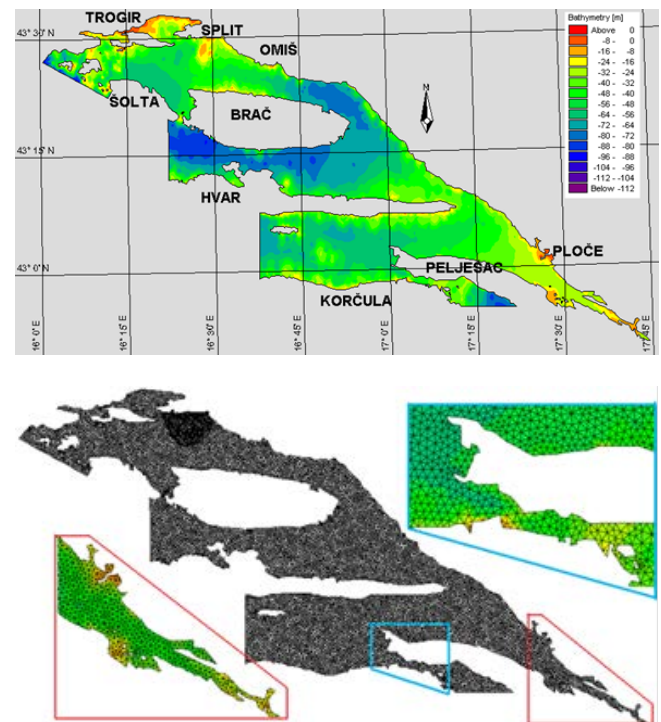

Figure 2. Spatial domain of the numerical model of wave generation.

3 RESULTS AND DISCUSSION

3.1 *Results of wave measurements*

Maximum and significant wave heights measured at V2 station between 1 November 2007 and 20 June 2008 are shown in Figure 3.

Maximum wave height of 2.84 m was measured in a half-hour record (06:11 – 06:41 hours) on 3 December 2007, during strong Sirocco (SE) wind. Significant wave height during this record was 0.92 m. Maximum significant wave height of 1.35 m was measured in a half-hour record (04:30 – 05:00 hours) on 6 March 2008, during strong Bora (NE) wind.

For the overall interval of wave measurement (1/11/2007 - 20/6/2008) average maximum wave height was 0.42 m, while average significant wave height was 0.22 m. So the following relation between maximum wave height and significant wave height is obtained:

$H_{max}=1.91\ H_{1/3}$ (3.1)

Table 1 gives monthly maximum data of wave elements during the measurement period from November 2007 to June 2008 associated with values of the ratio between maximum and significant wave height ($H_{max}/H_{1/3}$) and prevailing wind direction. In the periods marked (*) the measurement data are missing. It can be seen that only for December 2007 and February 2008 (strong Sirocco in both situations) ratios between H_{max} and $H_{1/3}$ are significantly different from relation (1), probably due to the rapid change of the Scirocco and Bora winds (or Libeccio) that occurs very often in the area of Brački kanal Channel.

In 99.4% cases significant wave height was lower than 1 m, while in 99.9% it was lower than 2 m.

Density spectrum of energy and direction of surface waves for episode on 3 December 2007, when maximum wave height was recorded, is shown in Figure 4. Maximum density spectrum of energy $S(f)=0.29$ m²/Hz corresponds to wave period of 3.45 s, or frequency of 0.29 Hz matching the significant wave height $H_{1/3}=0.69$ m. The figure also shows the dispersion spectrum of wave directions by frequencies in a half-hour record, demonstrating that the predominant wave direction was SE.
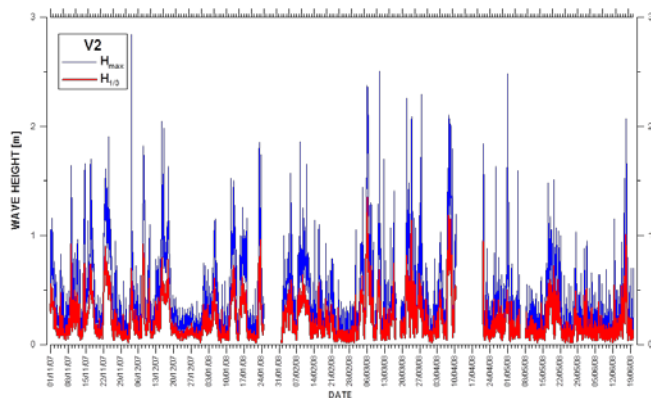

Figure 3. Maximum and significant wave heights measured at V2 station from 1 November 2007 to 20 June 2008.
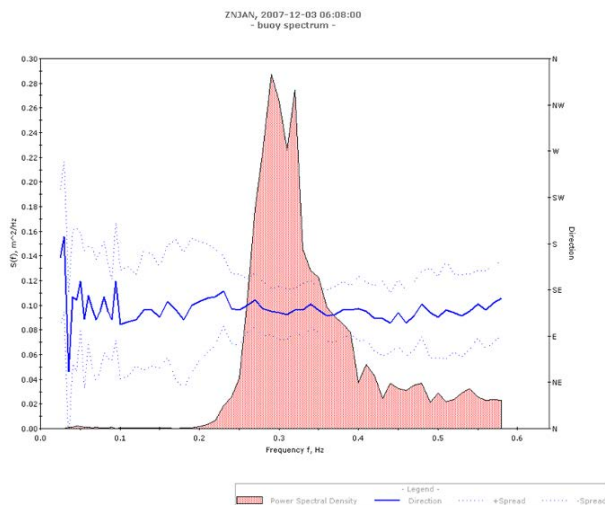

Figure 4. Density spectrum of energy and direction of surface waves on 3 December 2007, station V2.

Rose of significant wave heights $H_{1/3}$ is shown in Figure 5. Waves from ESE and SE directions are the most frequent, while the frequency of calm is also significant (31.7%).

Table 1. Monthly maximum values of wave elements for the period extending from November 2007 to June 2008 in the sea area of waverider station V2 (*28 December 2007; 25-31January 2008; 17-19 March 2008; 10-21 April 2008; 06-08 May 2008 are missing).

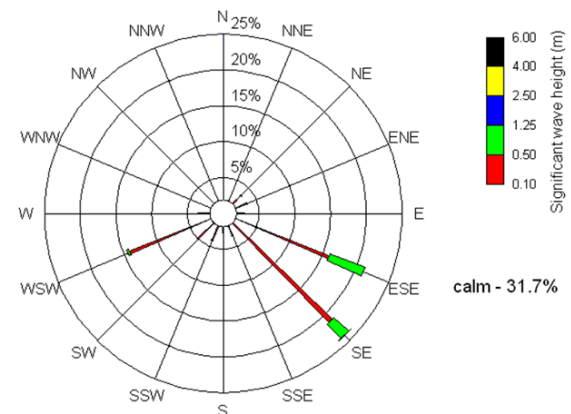| Month/Year 2007/2008	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	$H_{max}/H_{1/3}$	Prevailing wave direction
November	1.91	1.14	0.92	2,08	ESE
December*	2.84	1.16	0.92	3,09	SE
January*	1.85	1.19	0.96	1,93	ENE
February	1.86	0.80	0.64	2,91	ESE
March*	2.51	1.69	1.35	1,96	NE
April*	2.48	1.50	1.19	2,08	NNE
May*	1.59	0.93	0.72	2,21	SE
June	2.07	1.27	1.01	2,05	NNE

Figure 5. Rose of significant wave heights $H_{1/3}$ at station V2 from 01 November 2007 to 20 June 2008.

3.2 Results of numerical modelling

Wind speed time series and the wind rose, obtained from the Aladin-CRO model, at the position of the waverider V2 for the time interval from 1 November 2007 to 19 June 2008 is shown in Figure 6.
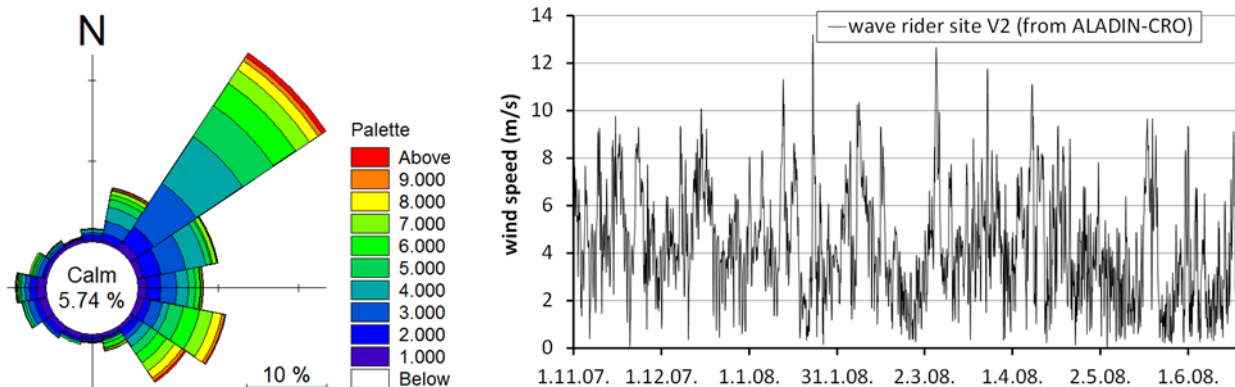
Figure 6. Wind rose (left) and wind speed time series (right) for the period 1/11/2007 - 19/6/2008, obtained from the results of Aladin-CRO model at the waverider station V2.

Figure 7 shows a comparison of the measured and modelled significant wave height time series for the waverider station V2. Model verification was performed by calculating the following statistical parameters: root mean squared error RMSE=0.14 m, mean absolute error MAE=0.10 m and relative absolute error RAE=0.75 (e.g. Komen et al., 1994). It can generally be concluded that the modelled significant wave values are very well matched with the measured values. In situations where a sudden increase of significant wave heights occurred, because of the strengthening of the wind, the model also simulated an increase of significant wave heights, but in some situations with extremely rapid changes (e.g. 23 January and 6 March 2008) the model significantly underestimated the measured values of significant wave height. It could be explained that numerical model Mike 21/SW was forced by the Aladin –CRO model which has a prognostic character and usually does not forecast extreme wind speed and direction changes.
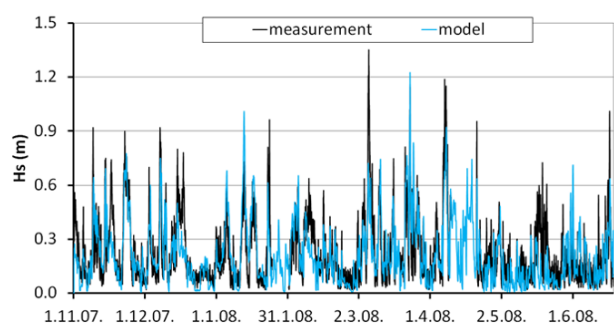

Figure 7. Comparison of the measured (waverider) and modelled (Mike 21/SW) significant wave height H_s time series for the waverider station V2.

Considering that the resulting wind speed and direction fields are derived from the Aladin –CRO model which has a prognostic character (the results are pre +12 h), they need to be critically analysed. By comparison of the resulting wind directions obtained by the Aladin-CRO model at the position of the waverider station (Fig. 6) with registered directions of waves on the waverider station V2 (Fig. 5), there can

be seen a significant difference in the frequency for the wind and wave directions NE-ENE and ESE-SE. It must be pointed out that waverider station V2 is located about 1.4 km from the coast, where waves generated by Sirocco and Bora are channeled in E-ESE direction in relation to topographic configuration of Brački Kanal Channel.

Therefore a set of time intervals (situations) of interest for further analysis is obtained (Tab. 2). It should be noted that from the overall interval of monitoring (1/11/2007 - 19/6/2008) only time intervals in which wind speeds exceeding 5 m/s continuously appear and when the results of wind directions from the Aladin-CRO model coincide with measured directions of wave propagation at the waverider site V2 were exempted and analysed. This analysis does not include situations with wind speeds exceeding 5 m/s continuously and changes of wind direction.

The values of the ratio between measured and modelled H_s, for situations enumerated in Table 2, are given in Figure 8. The ratio has values around 1 for all analysed situations except those with the Sirocco (situations 11, 12 and 13 in May and June 2008) when model significantly underestimated measured wave values (Fig. 7).

This confirms the fact that the numerical model interprets the state of the wave climate with a degree of reliability that corresponds to the reliability of prognostic data on wind speed from the Aladin model.
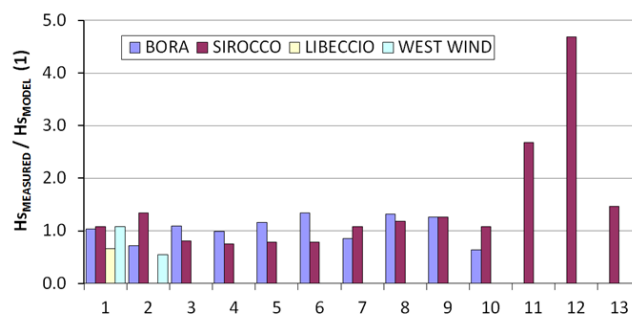

Figure 8. Values of the ratio between measured and modelled H_s for situations given in Table 2.

Table 2. Time intervals (situations) where wind speeds are continuously higher than 5 m/s and when the results of wind directions from the Aladin-CRO model coincide with measured directions of wave propagation at the waverider site V2.

Bora - NE (>5 m/s)	Sirocco - SE (>5 m/s)	Libeccio - SW (>5 m/s)
1 09.11.07. 21h → 10.11.07. 00h	1 22.11.07. 12h → 25.11.07. 03h	1 30.10.07.15h→30.10.07.18h
2 12.11.07. 09h → 12.11.07. 15h	2 07.12.07. 18h → 08.12.07. 15h	**West Wind - W (>5 m/s)**
3 13.12.07. 09h → 14.12.07. 00h	3 04.01.08. 12h → 06.01.07. 00h	1 31.05.08.12h→31.05.08.15h
4 14.12.07. 12h → 14.12.07. 21h	4 11.01.08. 15h → 13.01.08. 21h	2 01.06.08.09h→01.06.08.15h
5 01.01.08. 09h → 01.01.08. 18h	5 15.01.08. 12h → 18.01.08. 00h	
6 23.01.08. 14h → 23.01.08. 21h	6 03.02.08. 09h → 05.02.08. 06h	
7 07.02.08. 09h → 07.02.08. 24h	7 10.03.08. 09h → 11.03.08. 09h	
8 15.02.08. 15h → 16.02.08. 00h	8 16.03.08. 09h → 16.03.08. 21h	
9 16.02.08. 21h → 17.02.08. 00h	9 07.04.08. 03h → 07.04.08. 18h	
10 05.03.08. 06h → 07.03.08. 09h	10 30.04.08. 21h → 01.05.08. 12h	
	11 17.05.08. 03h → 19.05.08. 06h	
	12 20.05.08. 00h → 21.05.08. 12h	
	13 16.06.08. 21h → 17.06.08. 21h	

Figure 9 shows the field of significant wave heights Hs in the period of wind transition from Sirocco (23.3.2008., 18:30 hours) to Libeccio. At the term 18:30 hours SE waves were modelled (Hs≈0.60 m) in the eastern part of the Brački kanal Chanell, while in front of port of Split model shows S waves with Hs≈0.90 m. At the term 23.3.2008., 21:30 hours model reach maximum values of Hs≈0.80 m for SW waves (generated by Libeccio) on the measurement station V2.
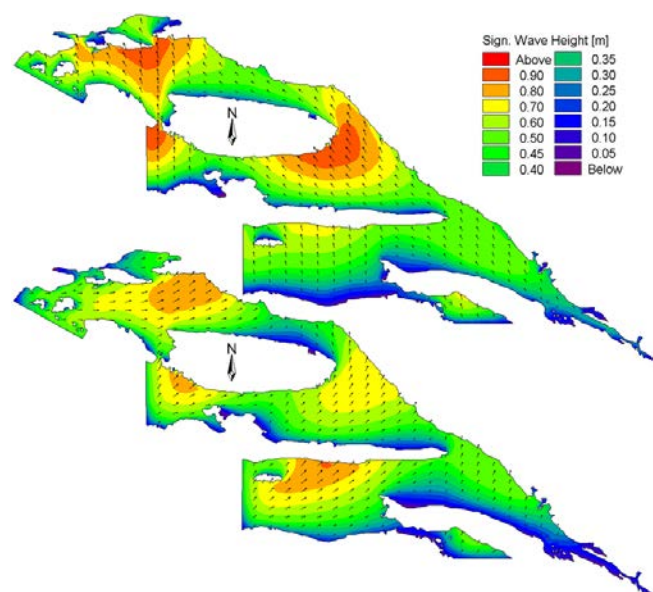

Figure 9. Significant wave heights Hs fields for 23/3/2008 18:30 hours (above, Sirocco) and 21:30 hours (below, Libeccio).

4 CONCLUSION

Wind generated surface waves were measured at V2 station in the Brački Kanal Channel area, in front of the port of Split in the time interval from November 2007 to June 2008. These measurements represent the first systematic wave research in front of one of the most important Croatian ports.

Maximum wave height of 2.84 m was measured on 3 December 2007, during strong Sirocco (SE) wind. Significant wave height during this record was 0.92 m. Maximum significant wave height of 1.35 m was measured on 6 March 2008, during strong Bora (NE) wind. Relation between maximum wave height and significant wave height was $H_{max}=1,91$ $H_{1/3}$, but in extreme situations ratios between H_{max} and $H_{1/3}$ were significantly different from this relation, probably due to the rapid change of the Scirocco and Bora winds (or Libeccio) that occurs very often in the area of Brački Kanal Channel.

Density spectrum of energy and direction of surface waves on 3 December 2007, when maximum wave height of 2.84 m was measured indicated wave period of 3.45 s and predominat SE wave direction.

For the overall interval of wave measurements, waves from ESE and SE directions were the most frequent, while the frequency of calm was also significant (31.7%). In 99.4% cases significant wave height was lower than 1 m, while in 99.9% it was lower than 2 m.

Instrumental measurements of wind generated waves show that absolute maximum of wave height in the Adriatic Sea $H_{max}=10.8$ m was measured in the open North Adriatic and extreme expected value of wave height in the Adriatic is about 14 m (Leder et al., 1998). Maximum waves greater than 8 m have been recorded in the open sea area of the Middle and South Adriatic (Leder, 2004). So it can be concluded that in the semi-enclosed area of the Brački Kanal Channel, where dimensions of fetch are considerably smaller, the occurrence of such large waves is impossible. Generally, it can also be concluded that length of fetch is the major limiting factor in the sea state development in the Adriatic Sea.

Numerical modelling of wave generation in the local waters of the Brački Kanal Channel was undertaken using Mike 21/SW numerical model. Wind field used for the forcing in numerical simulations relies on the results of the prognostic atmospheric model Aladin-CRO. Comparison of the measured (waverider) and modelled (Mike 21/SW) significant wave height Hs time series for the waverider station V2 in front of the port of Split has revealed that the modelled wave values are very well matched with the measured values. In situations where a sudden increase of significant wave heights occurred, because of the strengthening of the wind, the model also simulated an increase of significant wave heights, but in some situations with extremely rapid changes the model significantly underestimated the measured values of significant wave height. It could be explained that numerical model Mike 21/SW

was forced by the Aladin-CRO model which has a prognostic character and usually does not forecast extreme wind speed and direction changes.

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