Scientific Report

concerning the implementation of the project

Data Assimilation Methods for improving the WAVE predictions in the Romanian nearshore of the Black Sea - DAMWAVE

in the period January – September 2016

In the fourth stage of the project implementation (last stage) carried out in the period above mentioned, the specific objectives of the project were pursued:

- Finalization of a complex DA procedure to be associated to the wave prediction system in the Black Sea, focused on the Romanian coastal area
- Dissemination of the last results and conclusions

1. Finalization of a complex DA procedure to be associated to the wave prediction system in the Black Sea, focused on the Romanian coastal area

1.1 Data assimilation method based on the Kalman filter

There are various data assimilation methods, but nowadays there is a growing interest in the use of the Kalman filter, because in this method the error statistics of the system are calculated by the recursive use of the recent observations. Due to its computational complexity, the Kalman filter is not directly applicable to large scale systems. On the other hand, it is a very efficient tool for the local scale applications when might be used externally to correct the wave parameters.

The ensemble Kalman filter (EnKF) algorithm is a particular implementation of the Kalman filter designed to correct the output of the statistical models . This is a sequential data assimilation algorithm based on the application of the ensemble Kalman filter and it is used to correct the wave predictions provided by the SWAN model by means of an external application of the filter. The general formulation of the EnKF is defined by the following equation:

$$\mathbf{x}_j^a = \mathbf{x}_j^b + \mathbf{K}_j\left(\mathbf{y}_j^o - H\mathbf{x}_j^b\right) \quad (1)$$

where for the ensemble *j*, $\mathbf{x}_j^a$ is the analysis, $\mathbf{x}_j^b$ is the background simulated by the SWAN model, $\mathbf{y}_j^o$ represent the observations of the same wave parameters, H the observational operator that transforms the forecast space in the observational space and $\mathbf{K}_j$ the Kalman gain. The data assimilation ensemble has been set to a constant number of fifteen data points, which is renewed at every time step with the new predictions simulated by the SWAN model, while the older data are cleared.

The Kalman gain is defined as:

$$\mathbf{K}_j = \frac{\mathbf{C}_j\mathbf{H}^T}{\left(\mathbf{H}\mathbf{C}_j\mathbf{H}^T + \mathbf{R}\right)} \quad (2)$$

where $\mathbf{R}$ represents the observational error covariance and $\mathbf{C}_j$ is the ensemble covariance.

At each time step, the forecast predicted by the model is corrected with the result of the multiplication between the innovation $\left(\mathbf{y}_j^o - H\mathbf{x}_j^f\right)$ and the Kalman gain. When the predictions are forecast, the available observations are only from the past, and in this case the observations at the forecast time *j* are computed with the following relationship:

$$\mathbf{y}_j^o = H\mathbf{x}_{j-1}^a \quad (3)$$

where $\mathbf{x}_{j-1}^a$ was computed with the equation (1). The value $\mathbf{y}_j^o$ in equation (3) is used then to compute x_j^a , followed up by an update (analysis) step in which the observation at time *j* is available.

A similar methodology was applied in various locations of the Mediteranean Sea (Galanis et al., 2009) and on the west Iberian coast (Almeida et al., 2015). In the present work the data assimilation algorithm is applied for H_s, and also for the parameter mean wave period (*Tm*), and the results are presented next.

The EnKF algorithm is used to correct the predictions of the wave modelling system carried out at the location (44.52°N/29.57°E) of the Gloria drilling unit, at around 30 km offshore from the Romanian coast. The measurements recorded four times per day at Gloria platform are available for both wave parameters only for a nine year period (1999-2007). These data are used as observations to apply the data assimilation algorithm.

The impact of the post processing data assimilation methodology is evaluated by means of the statistical parameters commonly used to evaluate the wave model output. First, the statistical parameters are computed considering the predictions simulated by the wave model, and the results are presented in Table 1 (marked with gray background - without DA). Then, the EnKF algorithm is applied to correct the predictions. It is well known that such type of algorithm has some limitations in its application, since it can be applied only a continuous flow of observational data is available. In order to fill the gaps present in the measurements, some assumptions were made. The missing measurement for a certain time moment was replaced with the value of the prediction corresponding to the same time, corrected with the average value between the measurements and the simulations between the *j* dataset.

Table 1. Statistical results for H_s and T_m corresponding to the nine-year period (1999-2007), without and with data assimilation. N represents the number of data points.

N= 12427	MedObs	MedSWAN	Bias	RMSE	SI	R	S	
H_s	0.99	0.92	-0.07	0.39	0.40	0.85	0.90	without DA
(m)	0.99	0.96	-0.02	0.35	0.35	0.89	0.96	with DA
T_m	5.04	4.69	-0.36	1.63	0.32	0.39	0.94	without DA
(s)	5.04	4.98	-0.06	1.30	0.26	0.56	0.99	with DA

In Table 1 are also presented the statistical results obtained after the comparison between the measurements and the corrected predictions with the EnKF algorithm (with DA). It can be observed that the post-processing data assimilation methodology leads to an improvement of all statistical parameters, for both wave parameters. In the case of T_m the improvement seems to be higher, probably due to the fact that this wave parameter simulated by the spectral wave models in enclosed seas presents higher errors compared with H_s.

For a better observation of the time evolution of the EnKF algorithm corrections, the time series comparisons between the measurements recorded at Gloria platform and the predicted wave parameters (without and with DA) are illustrated in Figure 1. In order to illustrate this, from all the period it was selected only an interval, which was considered more representative (10.01.2004-25.02.2004). In this time interval a significant number of storms, some of them even extreme, have been noticed in the western side of the Black Sea.

For both the wave parameters considered, we can easily notice that after applying the algorithm important corrections of the SWAN simulated values have been operated. This fact occurs more obvious in the case of the extreme event that was registered in 23.01.2004, when the SWAN results showed a more rapid decay of the wave parameters H_s and T_m, reducing in this way the storm duration. On the other hand, after applying of the EnKF the agreement between measurements and model simulation results became very good.

As the results show, the assimilation of the observations reduced the errors in the predicted values of the wave parameters at the location where the sea states were recorded. The methodology herewith implemented showed high performance at low computational cost. It can be thus concluded that, the proposed methodology appears to be effective in increasing the accuracy of the wave predictions in the Black Sea. More details there are in Rusu (2016).

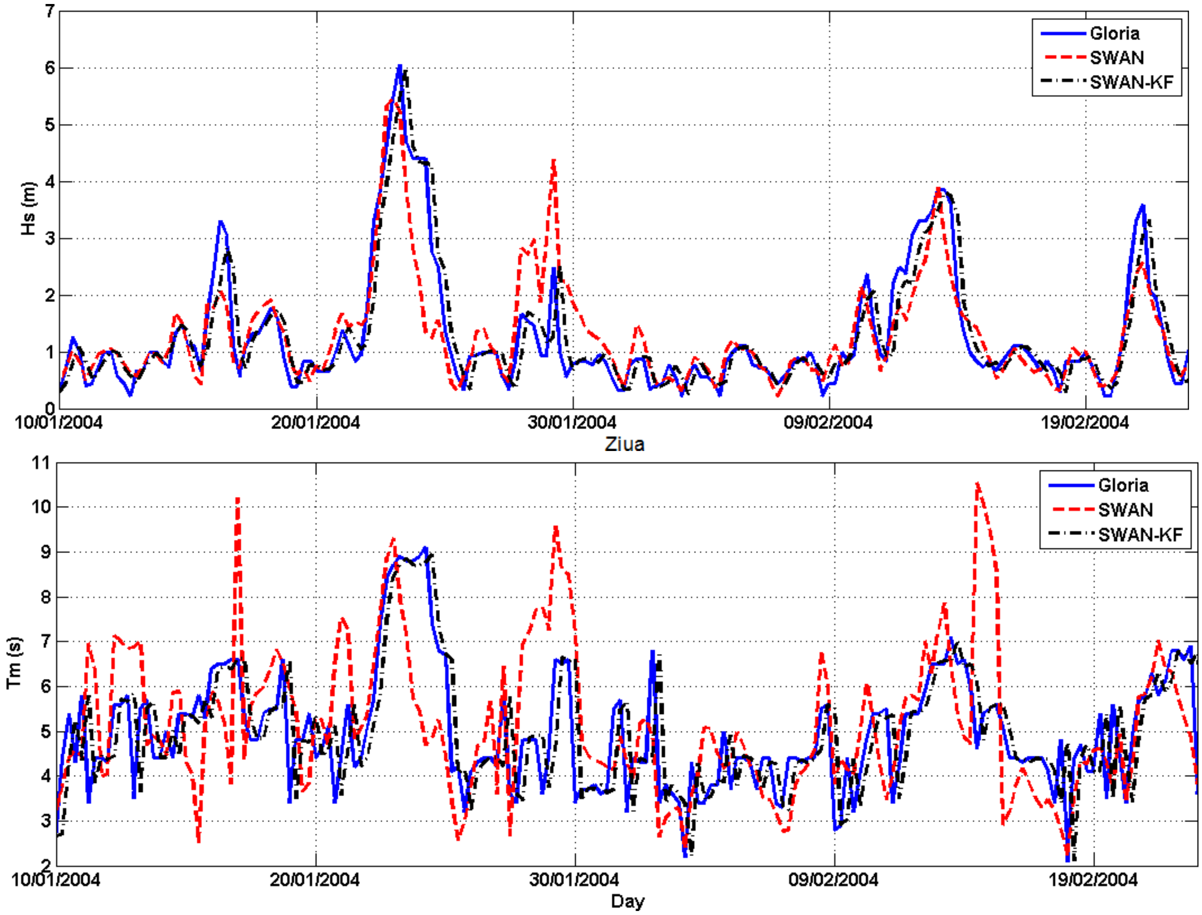

Figure 1. H_s time series (top panel) and T_m time series (bottom panel), comparison between the measurements from the Gloria drilling unit and the results of the SWAN simulations, without DA and with after the KF implementation.

1.2 A multi parameter data assimilation approach for wave predictions in coastal areas

The multi-parameter DA procedure for Romanian coastal area was implemented by Rusu and Raileanu (2016) and it represents an extension of the method initially applied only for H_s by Butunoiu and Rusu (2014). The DA procedure assumed to be implemented in Romanian nearshore (local scheme) considers the use of the in situ measurements performed at the Gloria drilling unit in order to correct the wave predictions in the computational domain corresponding to the coastal level. That is to propagate the correction between the measurement at Gloria and the result of the SWAN simulations, corresponding to the same location and time frame, in the geographical space and particularly in the boundary points of the higher resolution computational domain that focuses on the central part of the western side of the Black Sea.

In a first approach, the parameters considered for data assimilation are the significant wave height (*Hs*) and the peak period (*Tp*). Thus, in a point *F* (located on the boundary of the high resolution computational domain) the assimilated value of the wave parameter corresponding to the simulation performed for the time moment (*t*) is computed with the following relationship:

$$X_{Ft}^{(A)} = X_{Ft}^{(P)} + K(F,t)\left(\Delta X_{Mt}\right), \tag{1}$$

$X_{Ft}^{(P)}$ represents the model predicted value at the point *F,* the coefficient $K(F,t)$ is computed as the ratio between the model predicted values in the point *F* and that corresponding to the point *M* (at the location of the measurement), respectively, of the wave parameter considered:

$$K(F,t) = \frac{X_{Ft}^{(P)}}{X_{Mt}^{(P)}}. \tag{2}$$

Finally, by ΔX_{Mt} the difference between the measured and the predicted values of the wave parameter at the location of the measurement is denoted:

$$\Delta X_{Mt} = X_{Mt}^{(M)} - X_{Mt}^{(P)}. \quad (3)$$

Thus, in equations (1), (2) and (3) the superscript *(A)* indicates the assimilated values of the wave parameter, *(P)* the predicted values and *(M)* the measured values. The subscript *F* indicates the frontier point, while *M* is the point where the measurement is performed (in this case the location of the Gloria platform).

In this approach the real wave spectrum is replaced with an equivalent JONSWAP spectrum. The construction of the theoretical spectrum is based on four wave parameters. These are: significant wave height, peak (or alternatively mean) period, peak wave direction (*DIR*) and directional spreading of waves (*DSPR*). The first three are standard wave parameters and their definitions can be found for example in the SWAN user manual. The directional spreading, or directional standard deviation, represents the one-sided directional width of the spectrum (in degrees), defined and computed as conventionally for pitch-and-roll buoy data (Kuik et al., 1988):

Thus, the approach proposed herewith considers the correction of the above mentioned wave parameters (*Hs, Tp, DIR, DSPR*) according to the methodology defined before and then replacing in the boundary points of the real wave spectrum with a JONSWAP spectrum built on the basis of the corrected wave parameters.

1.3 Evaluation of the impact in the geographical space

In order to assess the impact of the assimilation scheme in the geographical space, simulations in the first 6 months of the year 2006 were carried out. A case study corresponding to the time frame 2006/01/19/h00 will be presented next. The differences between the measured and the predicted values of *Hs* and *Tp* at the Gloria location, are defined as:

$$\Delta H_s = H_{sM}^{(M)} - H_{sM}^{(P)}, \ \Delta T_p = T_{pM}^{(M)} - T_{pM}^{(P)}. \quad (4)$$

In this case the model overestimates the measurements and the following values result for the differences between the measured and the predicted wave parameters: $\Delta H_s = -0.69m, \ \Delta T_p = -2.41s$. Related to this case study, Figure 2 presents the results of the model simulations in the target area, without and with data assimilation, in terms of the significant wave height scalar fields, wave vectors and peak periods, respectively. The mean wind speed and direction are also suggested in the figure. In this situation the waves are coming from the south, while the wind direction is from the southwest with an average speed of 12 m/s. More case studies are presented in Rusu & Răileanu (2016).

Comparisons against satellite data

In order to assess the impact in the accuracy of the wave predictions induced by the DA scheme implemented, a comparison with the satellite measurements crossing the target area in the 6-month period considered was also employed. First, as an example, Figure 3 illustrates the satellite tracks over the target area for the month of March 2006.

Further on, corresponding to the 6-month time interval (2006/01/01-2006/07/01), Figure 4 illustrates a direct comparison in terms of *Hs*, satellite measurements, SWAN without DA and SWAN with DA. The results presented in this figure show that, in general, the assimilation process improves the wave predictions. It has to be however noticed, that there are also some energetic peaks when the assimilation process increases the differences in terms of *Hs* between the model results and the remotely sensed measurements. Most of them are at the end of January 2006, when high energy conditions are encountered and also high variations of the significant wave height in a relatively short time interval. From this perspective, the differences might be also generated in this case by some inaccuracies of the measurements.

For the same 6-month time interval considered, the significant wave height statistics in the high resolution computational domain, SWAN model results (without and with DA) against satellite data are presented in Table 2. The results presented in Table 2 show a clear improvement due to the assimilation of all statistical parameters, except the symmetric slope.

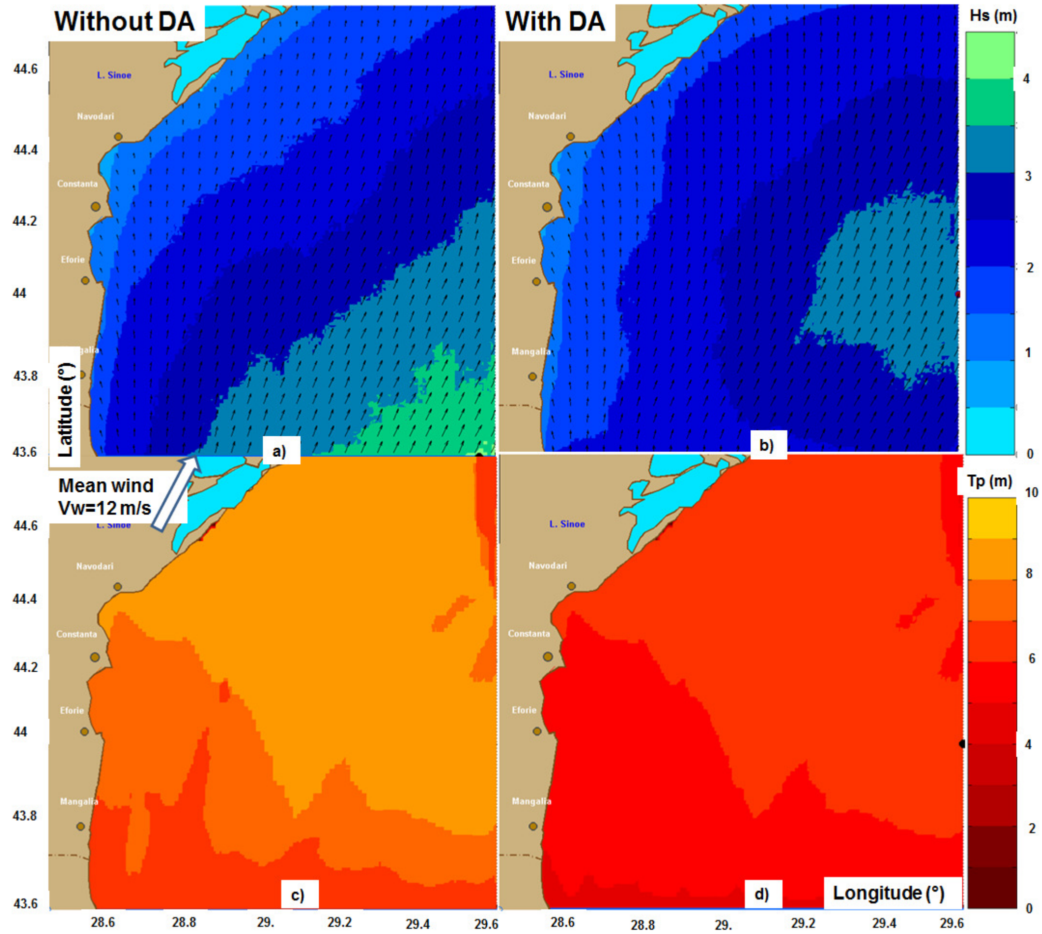

Figure 2. Results of the model simulations in the target area without and with data assimilation, time frame 2006/01/19/h00, the model overestimates the wave parameters *Hs* and *Tp* in relationship with the measurements performed at Gloria. Significant wave height scalar fields and wave vectors: a) without DA; b) with DA. Peak period: c) without DA; d) with DA.

Table 2: *Hs* wave statistics in the high resolution computational domain. SWAN model results (without and with DA) against satellite data for the 6-month period, 2006/01/01-2006/07/01.

	MeanObs	MeanSWAN	Bias	MAE	RMSE	SI	R	S	N
H_s(m)	1.21	1.22	-0.01	0.28	0.38	0.32	0.88	1.04	612
$H_{s\text{-}A}$ (m)	1.21	1.24	-0.03	0.26	0.33	0.27	0.92	1.07	612

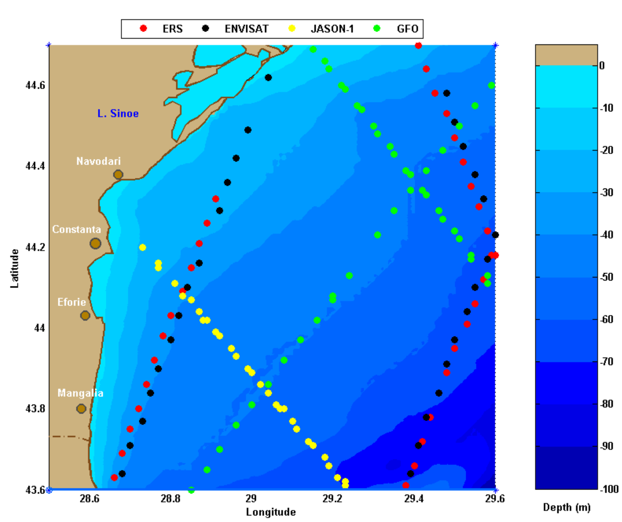

Figure 3: March 2006, the satellite tracks over the target area.

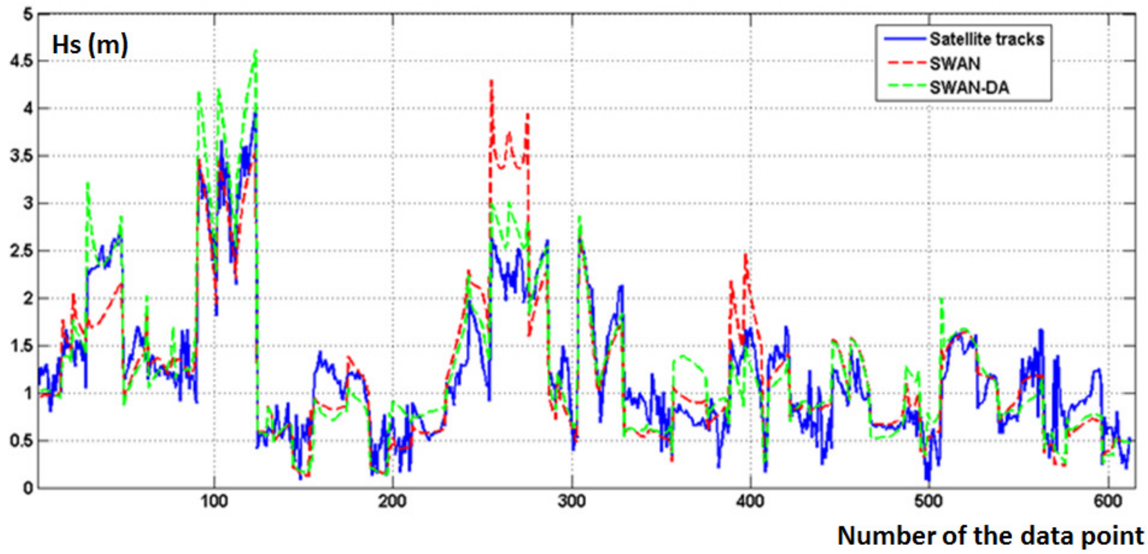

Figure 4: Direct comparisons in terms of *Hs*, satellite measurements, SWAN without DA and SWAN with DA, corresponding to the 6-month time interval 2006/01/01-2006/07/01.

In Figure 5 the DA schemes are applied both globally (Black Sea) and locally. More details and comparisons between different methodologies proposed can be found in Rusu (2016) and Răileanu et al., (2016).

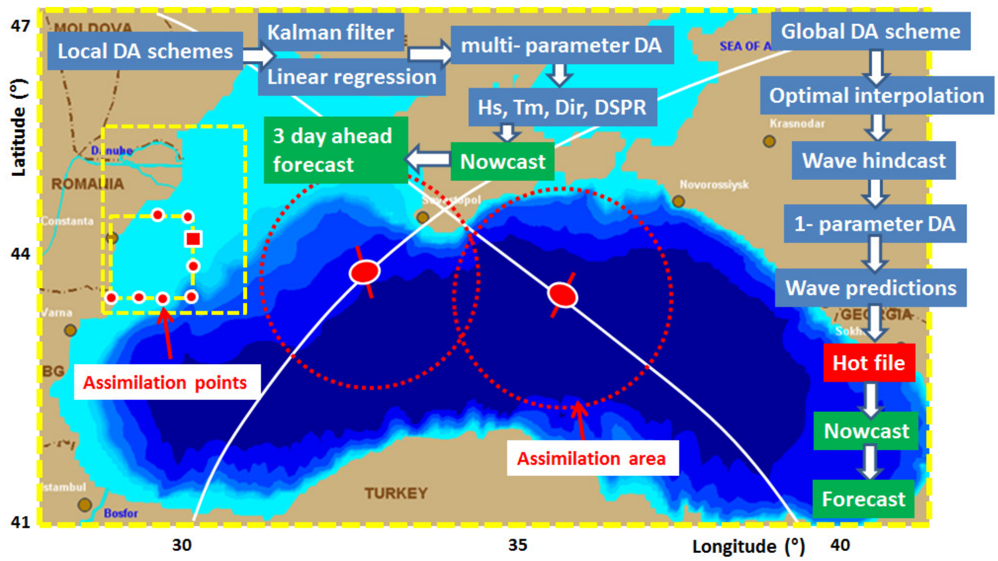

Figure 5. The data assimilation schemes considered for the local computational domains and for the entire sea basin.

2. Conclusions

In the last stage of the project implementation it can be said that for this stage all project objectives were achieved, as well as for the entire project. These objectives were included in the project implementation scheme. The results were disseminated through various means, a detailed presentation can be found in the following section.

3. Dissemination of the results

3.1 Preparation of the scientific articles, a monograph, oral presentations and posters to disseminate the results

During the project implementation the team members have been collaborating with Master and Doctoral students, and post-doctoral researchers. As a result of these collaborations, various studies directly related to the project theme or with connected domains have been concluded.

Also, Professor Eugen Rusu (member of the research team) was the scientific coordinator of the doctoral thesis entitled: *Implementarea de metode de asimilare de date pentru îmbunătățirea predicției valurilor cu modele spectrale în bazinul Mării Negre* (Data assimilation methods to improve the wave predictions of the spectral models in the Black Sea basin) - drd. Ing. Alina Răileanu (member of the research team). The doctoral thesis was presented at the coordination committee on 09.09.2016, the public presentation being scheduled on 10/14/2016.

- Publications in international journals with ISI quotation (6)

1. Rusu, L., Onea, F., 2016. The performance of some state-of-the-art wave energy converters in locations with the worldwide highest wave power, Renewable and Sustainable Energy Reviews, *in press,* http://dx.doi.org/10.1016/j.rser.2016.11.123 (IF 6.798)
2. Rusu, E., Raileanu, A., 2016. A multi parameter data assimilation approach for wave predictions in coastal areas, *Journal of Operational Oceanography* 9(1), 13-25. http://dx.doi.org/10.1080/1755876X.2016.1192013 (IF=1,263)
3. Rusu, E., Onea, F., 2016. Estimation of the wave energy conversion efficiency in the Atlantic Ocean close to the European islands, *Renewable Energy* 85, 687-703, http://dx.doi.org/10.1016/j.renene.2015.07.042 (IF=3,404).
4. Rusu, E., Onea, F., 2016. Study on the influence of the distance to shore for a wave energy farm operating in the central part of the Portuguese nearshore, *Energy Conversion and Management* 114, 209-223, http://dx.doi.org/10.1016/j.enconman.2016.02.020 (IF=4,801).
5. Onea, F., Rusu E., 2016. Efficiency assessments for some state of the art wind turbines in the coastal environments of the Black and the Caspian seas, *Energy Exploration & Exploitation* 34 (2), 217-234. (IF=1,094). http://eea.sagepub.com/cgi/reprint/0144598716629872v1.pdf?ijkey=XVTtfIWsevdeozD&keytype=finite
6. Onea, F., Rusu E., 2016. The expected efficiency and coastal impact of a hybrid energy farm operating in the Portuguese nearshore, *Energy* 97, 411–423, http://www.sciencedirect.com/science/article/pii/S0360544216000128 (IF=4,292).
7. Onea, F., Deleanu, L., Rusu, L., Georgescu, C., 2016. Evaluation of the wind energy potential along the Mediterranean Sea coasts, *Energy Exploration & Exploitation* 34 (5), 766-792 http://dx.doi.org/10.1177/0144598716659592 (IF=1,094).

- Publications in international journals (1)

8. Rusu, E., 2016. Reliability and applications of the numerical wave predictions in the Black Sea, *Frontiers in Marine Science*, Article 95, pp. 1-13. http://journal.frontiersin.org/article/10.3389/fmars.2016.00095/abstract

- Monograph (1)

9. Rusu, L., Raileanu, A., Onea, F., 2016. Asimilarea de date cu aplicaţii la predicţia climatului de val în bazinul Mării Negre, Ed. Zigotto, Galati, 300p, ISBN 978-606-669-182-6.

-Participations at international conferences and publication in their proceedings (7)

10. Rusu, L., 2016. Assessment of the synergy between wind and wave power in the Black Sea based on a 15-year hindcast. In: *Proc. of 11th Conference on Sustainable Development of Energy, Water and Environment Systems* (SDEWES2016), 4-9 September, Lisbon, Portugal. http://www.lisbon2016.sdewes.org/
11. Rusu, L., 2016. Assessment of the renewable energy resources in the Romanian nearshore at the Black Sea, paper presented at *Int. Conference on Advances on Clean Energy Research* (ICACER2016), 16-18 April, Bangkok, Thailand, http://www.icacer.com/ **received 'Best presentation award'.**
12. Rusu E., 2016. Analysis of the Effect of a Marine Energy Farm to Protect a Biosphere Reserve, paper presented at *Int. Conference on Advances on Clean Energy Research* (ICACER2016), 16-18 April, Bangkok, Thailand http://www.icacer.com/, and published in proceedings of MATEC Web of Conferences, Open Access proceedings in Materials science, Engineering and Chemistry, Vol. 62, 1-5 (indexată ISI). http://dx.doi.org/10.1051/matecconf/20166206004
13. Rusu, L., 2016. Data assimilation method based on the Kalman filter associated with the wave modeling in the western Black Sea. In: *Proc. of 16th International Multidisciplinary Scientific GeoConference* (SGEM2016) – Marine and Ocean Ecosystems, June 28 - July 6, Albena, Bulgaria, Book3 Vol. 2, 727-734. http://www.sgem.org/sgemlib/spip.php?article7936 (indexată ISI)

14. Raileanu, A., Rusu, L., Rusu, E., 2016. Data assimilation methods to improve the wave predictions in the Romanian coastal environment. In: *Proc. of 16th International Multidisciplinary Scientific GeoConference* (SGEM2016) – Photogrammetry and Remote Sensing, June 28 - July 6, Albena, Bulgaria, Book2 Vol. 2, 855-862. http://www.sgem.org/sgemlib/spip.php?article8396

15. Răileanu, A, Onea, F., Rusu, E., 2016. *Spatial and seasonal variations of the environmental conditions along the Black Sea shipping routes*. In: *Proc. of 16th International Multidisciplinary Scientific GeoConference* (SGEM2016) – Marine and Ocean Ecosystems, June 28 - July 6, Albena, Bulgaria, Book3 Vol. 2, 829-836. http://www.sgem.org/sgemlib/spip.php?article7983 (indexată ISI)

16. Onea, F., Răileanu, A., Rusu, E., 2016. *Evaluation of the wave energy potential in some locations where European offshore wind farms operate*. In: *Proc. of 3rd International Conference on Maritime Technology and Engineering* (MARTECH2016) - Maritime Technology and Engineering 3, Vol 2, 1119-1124, Taylor & Francis Group, London, 4 - 6 July, Lisbon, Portugal (ISI indexed)

- Publications in national journals indexed in international databases (3)

17. Onea, F., Raileanu, A., Rusu, E., 2016. Analysis of the extreme wind and wave conditions in the Black Sea as reflected by the altimeter measurements, *Mechanical Testing and Diagnosis* VI (1), 5-12. http://www.om.ugal.ro/mtd/download/2016-1/1%20MTD_2016_Volume%201_Onea.pdf

18. Unga, R., Rusu, E., 2016. Study of the variability of wind energy resources in Romania, *Mechanical Testing and Diagnosis* VI (1), 20 -28. http://www.im.ugal.ro/mtd/download/2016-1/3-MTD_2016_Volume%201_Unga.pdf

19. Onea, F., Rusu, E., 2016. Coastal protections provided by energy farms in the Romanian nearshore, *Mechanical Testing and Diagnosis* VI (2), 5-16. http://www.im.ugal.ro/mtd/download/2016-2/1%20MTD_2016_Volume%202_Onea%20xx.pdf

- Participations at national conferences (2)

20. Rusu, E., 2016. Coastal Protection and Extraction of the Marine Energy in the Romanian Nearshore, invited lecture at *4th Edition of the Scientific Conference of the Doctoral Schools*, 'Dunarea de Jos' University of Galati (CSSD-UDJG2016), 2-3 June, Galati, Romania. http://www.cssd-udjg.ugal.ro/files/invitatie/Program_detaliat_al_conferintei_2016.pdf

21. Raileanu, A., Rusu, E., 2016. Advances in increasing the reliability of the wave predictions in the Black Sea by implementing data assimilation techniques, at *4th Edition of the Scientific Conference of the Doctoral Schools*, 'Dunarea de Jos' University of Galati, 2-3 June, Galati, Romania. http://www.cssd-udjg.ugal.ro/files/invitatie/Program_detaliat_al_conferintei_2016.pdf http://www.cssd-udjg.ugal.ro/index.php/abstracts

3.2 Continuous updating of the project DAMWAVE site. http://www.im.ugal.ro/DAMWAVE/index.htm

During the project unfolding the web page of the project was continuously updated with the activities and the results of the project.

4. Evaluation of the result dissemination

Stage / Publicationsi	Stage I	Stage II	Stage III	Stage IV	Total
Journals with ISI quotation	1	4	6	7	**18**
International journals	-	4	-	1	**5**
International journals BDI indexed	1	1	2	3	**7**
Monograph	-	-	-	1	**1**
International conferences	12	7	18	7	**44**
National conferences	-	2	2	2	**6**
Total	**14**	**18**	**28**	**21**	**81**

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Rusu, E., 2016a. Reliability and applications of the numerical wave predictions in the Black Sea, *Frontiers in Marine Science*, Article 95, pp. 1-13. http://journal.frontiersin.org/article/10.3389/fmars.2016.00095/abstract

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Rusu, L., 2015b. Wave modelling with data assimilation to evaluate the wave energy patterns in the Black Sea. In: *Proc. of 15th International Multidisciplinary Scientific GeoConference* (SGEM2015), 16-25 June, Albena, Bulgaria, Vol. 4, pp. 597-606.

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