„Dunărea de Jos" University of Galati
Industrial and Mechanical Engieneering Doctoral School

UNIVERSITAS GALATIENSIS

DOCTORAL THESIS

ABSTRACT

Studies concerning the evaluation of renewable energy resources in the Romanian Black Sea area

PhD Student,
Eng. **Niculescu** F.I. **Dragoș Marian**

Scientific coordinator,
Prof. dr. eng. **RUSU Eugen Victor Cristian**

Series: I6 Mechanical Engieneering Nr. 49

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Foreword

The world oceans and seas have always been exploited in terms of shipping, transport or by the oil sector. At global and local scale, it is estimated that energy needs will increase with climate change. As dependence on fossil fuels is not beneficial to the environment, solutions will have to be found to help avoid environmental problems. Therefore there is a great need to increase the production capacity of renewable energy. Because energy needs were and are increasingly higher every year at a global level, different studies and implementations have been made. Various solutions for collecting renwable energy have been found, be it from the wind on land or offshore, or from the energy that resides in the movement of the water masses which is a rich source of renewable energy.

This study is based on the need to discover new ways to produce renewable energy that have a lower impact on the environment

The paper aims to highlight the energy potential in the Romanian seaside area, be it from wind, waves or currents, as well as the posibility of obtaining this energy while fitting it into the existing utilities that are related to the marine space of Romania.

Another object of this study is the ability to integrate such facilities in the space already particularly limited, available at this point at the romanian coastal area. Thus, marine spatial planning along with integrated coastal zone management plays a very important role.

First of all, I want to thank the teachers and colleagues who helped me with the thesis, and supported me with they patience in the difficult times encountered when writing it. I have accumulated new knowledge, and it has been necessary to adopt new ways of thinking and problem solving. Now I have reached a new level of understanding about the scientific issues and deepened my knowledge about the aspects of human relationships.

I would like to express my sincere gratitude to the scientific coordinator, Professor Eugen Rusu, for the precious guidance given during these years and for his help in the elaboration of the doctoral thesis. Thank you once again for the continuous encouragement to turn an idea into a concrete achievement and for the privilege of being your student

Equally I wish to thank Mr. Teodor Cristescu for the long discussions on physical factors of marine phenomena, as well as how to see and understand things.

At the same time, I want to thank the members of the guidance committee for the advice and suggestions offered. I would like to thank Professor Lorena DELEANU, Professor Antoaneta ENE, and Mr. Răzvan Mateescu.

I also wish to express my gratitude to the Department of Oceanography, Marine and Coastal Engineering, of the National Institute for Marine Research and Development "Grigore Antipa" and to the staff of the Doctoral School, for the support given during the doctoral years.

Last but not least, I express my complete gratitude and thanks to my family, office colleagues and close friends for their confidence, understanding and support.

Galati, Mai 2019

Dragoș Marian NICULESCU

Content

Introduction

The approach is geared towards the energy potential of the Black Sea wind and the waves. The findings of this study have highlighted that the available wave power and coastal currents, which predominantly spread from north to south, do not seem sufficient to power energy converters. Considering that technology will evolve in the future, it is possible that these converters can be optimized for this wave field, or coastal currents.

Given the available surfaces that can be used to capture renewable energy, it can be said that there is the possibility of extracting a significant amount of energy from the offshore wind, possibly from waves or coastal current. But they will overlap on the sea surface. Thus, it is necessary to determine the technological solution and the geographic location of installation that has a better yield. By analyzing separately each renewable energy converter, it is concluded that wind energy is the most affordable, requiring lower costs to produce. In the first phase, it would be possible for these renewable energy converter devices to be built separately on a certain surface offshore, but for a better integration and use of the marine surface, these equipments can be built into a system that would allow their operation on the same sea surface, forming clusters of renewable energy. However, it must be taken into account that all these must consider the development pace of coastal and maritime activities in general, since the area upon these renewable energy farms can be installed, navigational lines may exist, or fish farms can be built and many more. A coastal management plan has to be considered in order to take full advantage of these renewable energy converters. By installing wave and current converters, it creates areas that are favorable to construct fish farms.

Depending on the converter structure, the wave energy can be absorbed totally or partially so as not to affect farm structure and functionality or farm maintenance operations. At the same time, these converters could be used to protect the coastline, preventing erosion by absorbing the wave energy that, in fact, causes coastal erosion.

The study is structured in several major topics.

1. wind, wave and current data analysis from field measurements and numerical models,
2. the use of numerical applications of the SWAN, MOHID and POM models,
3. the energies that can be used (types of solution to energy types),
4. assessing the potential of renewable energy in the context of planning the Romanian marine space.

I The actuality and importance of the theme

European policy on the production of energy from renewable sources and the promotion of the use of this form of energy is laid down in EU Directive 28/2009. Also, all EU Member States have the obligation to ensure at least 10% of the fuels for transport are from renewable sources by 2020. On 30 November 2016, the European Commission published a proposal for a revised directive on the procurement of energy from renewable sources in order to make the EU a world market leader in renewable energy by 2030. This directive aims to set national renewable energy targets for each member country, on the basis of each country's renewable energy potential. As a result, these targets vary from country to country, from a minimum of 10% for Malta to a maximum of 49% in Sweden.

Due to governmental energy policies and the rapid evolution of energy industry trends, it is increasingly necessary to properly assess the country's renewable energy potential.

The seas and oceans offer a huge renewable energy resource. At present, both at European and global level, technologies are developed to exploit the energy potential of waves, tides, marine currents, and the salinity gradient difference.

The continuous development of this sector will not only help achieve renewable energy targets and reduce greenhouse gas emissions but can also stimulate economic growth by creating new high quality jobs.

Therefore, in addition to the above, such analyzes are applicable to offshore industry, providing additional knowledge to the offshore maritime community by assessing the coastal energy resources in terms of wave power, up to a 90 m isobath. Another esential aspect is the application of this type of research (analysis of marine conditions to provide renewable energy) is essential in Maritime Spatial Planning (EU Maritime Spatial Planning Directive 89/2014 / EC).

These aspects were analyzed using numerical modeling of hydrodynamic processes concurrently with the processing of in situ collected data. In this respect, two numerical models, MOHID and POM, were used for modeling the marine currents in the Romanian coastal zone, aiming at a comparative analysis of the obtained results, identifying possible forecasting inaccuracies, which would later be used to optimize the application of these models at the Black Sea.

The results obtained will be useful for assessing the wind field, the wave field and the sea currents. Evaluating the results of these numerical models is a difficult process and although the results may seem to be consistent with the data obtained by field measurements, the comparative analysis of the data obtained from the running of the models is not always consistent, with some incompatibilities.

This long-term assessment of wind, wave and sea currents shows the trends of climate change and their effect on the evolution of coastal zone dynamics, which in turn is a particularly important aspect in the assessment and planning of marine activities.

Finally, on the basis of these results, several maps were produced. The areas of interest are represented from the a marine spatial planning point of view but also taking in account the areas identified as having a higher power density required to implement future energy converters.

The specific contributions that this work brings are:

- A methodological study illustrating the current situation and climatological trends. Analyzing the results of physical parameters that can lead to improved results.
- Contributions to improving existing knowledge on the estimation of energy resources in the Romanian coastal area.
- Analyze long-term, high resolution datasets to support the investigation of wind, wave, and marine current conditions through numerical models and energy resources at different points of interest.
- Perform numerical modeling approaches to the wave field strength to estimate available energy resources under specific conditions.
- Examine the performance of various devices and the feasibility of their placement in the marine environment, based on these analyzes.
- Identifying optimal areas based on the results of the marine agitation regime along the coast.
- Examination of feasible areas and their specific characteristics in which wave energy converters can be located.

- Provide additional information on the occurrence of potentially extreme situations, which will also help to improve the general understanding of the wind, wave and sea currents, especially in coastal areas.

II Research objectives

The main objective of this doctoral thesis is to analyze the renewable energy potential in the Romanian coastal area, using the data measured / recorded over the years, from the hydrometeorological stations on the shore or offshore from the Gloria Oilrig, in correlation with the results of the "Global Wind Atlas" (GWA), and comparing the results of the wind, wave and current analyzes with the numerical simulations of the SWAN and MOHID numerical models.

Another objective was to provide an overview of the climatic and hydrological conditions present at the Romanian seaside. The analysis of these data has been used to determine significant waves energy potential scenarios, up to the 90 m isobath. The current field has been analyzed to assess its energy potential, but because of the high cost of in situ data collection, only the measurements of a single experiment made in the southern part of the coast, summing up to 23 perpendicular profiles, up to the 15 m isobath, were analyzed.

Based on these approaches and analyzes, it was possible to highlight both the favorable areas for the installation of wind turbines, wave energy converters, as well as places where the sea current has a higher speed due to the configuration and orientation of the shore.

Based on the results obtained, a spatial analysis was carried out which included most of the prohibited areas, in terms of locating the ideal spot for some wind farms or wave converter parks. These results, ultimately, must take into account the outcome of Marine Spatial Planning (development scenarios), which is not yet completed. However, the shipping lines, anchorage areas, forbidden areas like the estuary of the Danube River, areas of the oil industry, sites of Community importance, as well as the space reserved for protected marine areas including the 2Mai - Vama Veche reservation. The remaining space could be exploited in terms of renewable energy, but the general assembly of marine space planning for the Romanian exclusive economic zone should be considered; the results are a contribution to the completion of marine planning.

III Structure of the thesis

The PhD thesis, entitled "Studies concerning the evaluation of renewable energy resources in the Romanian Black Sea area" is structured in six chapters and an annex. The structure and content of each chapter are as follows:

Chapter 1 contains the history of the first hydrographical studies on the Romanian Black Sea seaside, a study on the physico-geographic features of the Romanian coastal areas and sectoral characterization of the seaside.

Chapter 2 offers an introduction in the field of study regarding the wind, waves and marine currents.

Chapter 3 presents the theoretical elements of the numerical models SWAN, MOHID and POM.

The wind conditions in the western Black Sea are assessed, with particular attention given to the Romanian coastal area. The wind characteristics are studied in the Romanian Black Sea area, and a comparisons is made between the shore wind and the offshore wind, as well as an analysis of the incidence of storms in this area.

A wave data analysis from Constanta area is presented, the data is covering about forty years.

Instruments that collect and measure the coastal and offshore currents are presented, and an analysis of some sea current profiles made in an experiment, in the south of the coast, in order to draw a conclusion on the energy potential.

Also in this chapter, wave simulations are conducted for four main directions of wind propagation in the Romanian seaside area. The situation of sea currents during certain summer and winter periods was analyzed, especially the issue regarding the sea currents direction, which results from the comparison of the results of the two MOHID and POM numerical models with the wind data from the meteorological station Sulina.

Chapter 4 presents unconventional energy sources in the coastal area. It deals extensively with wind energy in Europe and technologies for capturing wind, wave or sea currents.

Chapter 5 highlights the potential of renewable energy on the Romanian seaside, whether wind or wave energy, and the possibility of obtaining this energy from the point of view of marine spatial planning. This chapter includes case studies on the various forms of renewable energy in the coastal area as well as estimates of the distribution of wind and wave power density along the Romanian coast.

Chapter 6 summarizes the main results obtained in this thesis and formulates conclusions. Taking into account that the chosen field of research is very dynamic, it has been chosen to point out some of the directions of study that could be addressed in the future.

Chapter 1. Physical-geographic characteristics of Romanian coastal areas

Since ancient times, the western shore of the Black Sea and mouths of the Danube have been thoroughly researched, at the knowledge level that was specific to those times. But the first scientific research on the Romanian seaside were made by some Romanian scholars, including Gr. Antipa, C. Bratescu and Al. Brăileanu. In the twentieth century. Gr. Antipa performs the first research and measurements respectively on the Black Sea, and at the same time is the first Romanian to make a map of the Black Sea current circulation in 1941.
In 1971, a team of researchers of the Oceanography Laboratory of the new IRCM set up an annual surveillance, focusing on particularities and spatial variations of the main physical and chemical factors of the coastal and marine environment (wind, wave, currents, level, temperature, salinity, density , transparency, etc.). [1] [2]

The research on the variability of the Black Sea currents, especially in the Danube mouths, began in 1857, after the formation of the Danube European Commission, with the aim of improving maritime navigation. From these observations the north-south current along the coast is reported. The same conclusion is reached by Russian researchers following the expeditions of 1871-1887. In 1896, Russian researchers launched 72 bottles in the water at key points, and recoverd only fifteen of them; thus demonstrating the existence of surface current.

On the basis of a Russian expedition in the period 1922-1924, a map of the currents was finally made on the basis of the direct measurements and observations, which showed that the Rim current main circuit can reach the Romanian seaside (Fig. 1.1).

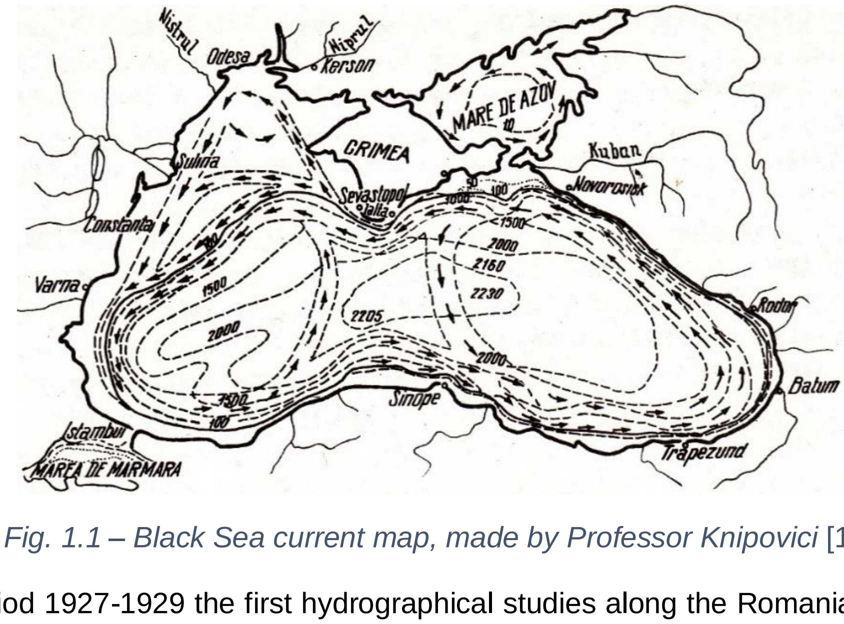


Fig. 1.1 – Black Sea current map, made by Professor Knipovici [1]

During the period 1927-1929 the first hydrographical studies along the Romanian seaside were carried out by the General Directorate of the ports and waterways in collaboration with the Military Marine Corps, through the hydrographical service, the current Maritime Hydrographic Directorate. This study looked at the influence of the hydrometeorological conditions on depositing alluviums around the mouths of the Danube's arms.

1.1. Sectoral characterization of Romanian coastal areas

One of the most important environmental processes, which has a negative impact on the coastal infrastructure of the Black Sea, is the erosion process. In the last decades, this process has affected the Romanian shore, slowly diminishing large areas of sandy beaches. In the last decades, the northern unit of the Romanian seaside, as well as the coastal sectors in the south, have changed due to the coastal processes, which have a great impact on it. This is linked to an unbalanced sediment budget, due to the construction of the two hydropower dams along the Danube River and due to the river navigation infrastructure at the mouth of the Sulina channel.
Environmental factors that leave their mark along the Romanian shore are not always made by natural causes. Causes for the erosion process include anthropogenic factors that cannot be resolved easily or soon enough. One way to improve this problem is to build artificial beaches by spreading and expanding different coastal structures (embankment and submersion dams) to maintain the balance of the coastline at a desired distance.
The cause of the problem can not be solved easily because there is the problem with the alluvial source that is created by the two dams (Iron Gates I and II). The Iron Gates I barrage was completed in 1972 and the Iron Gates II dam was completed in 1986. The Romanian coast is divided into two geographical units: the northern unit and the southern unit, with Cape Midia as an inflection point.

Fig. 1.2 – Topographic system on the northern seaside of Romania installed in 1961 [3]

The northern sector is about 170 km long and includes the Danube Delta, which is an important part of it. This sector extends from the border with Ukraine to Midia port. Since the Danube Delta forms a large part of this Nordic sector, a representative feature is the presence of lagoons and low-altitude sand dunes (belts) which generally do not exceed a height of 2 m [4] [5].

The southern sector is about 74 km long and stretches from Midia Port to the border with Bulgaria. This sector is characterized by high cliffs, which have a maximum height of 80 m in the Constanta port region. Compared to the northern sector, the southern sector has small beaches with a multitude of coastal protections, and in some sub-sectors the beach eroded completely, allowing the waves to break directly into the base of the cliffs.

The erosion process and its expansion on the Romanian coast has been observed and systematically monitored since 1962 on the basis of a network of topographical landmarks extending over a length of approximately 140 km, being operational since 1961 along the Danube Delta (Fig. 1.2).

Fig. 1.3 – The topographical system of the Romanian southern sector, installed in the 1973 - 1975 [3]

In the southern sector, systematic monitoring began in 1980, after the first topographic network was installed in this area (Fig. 1.3) [6].

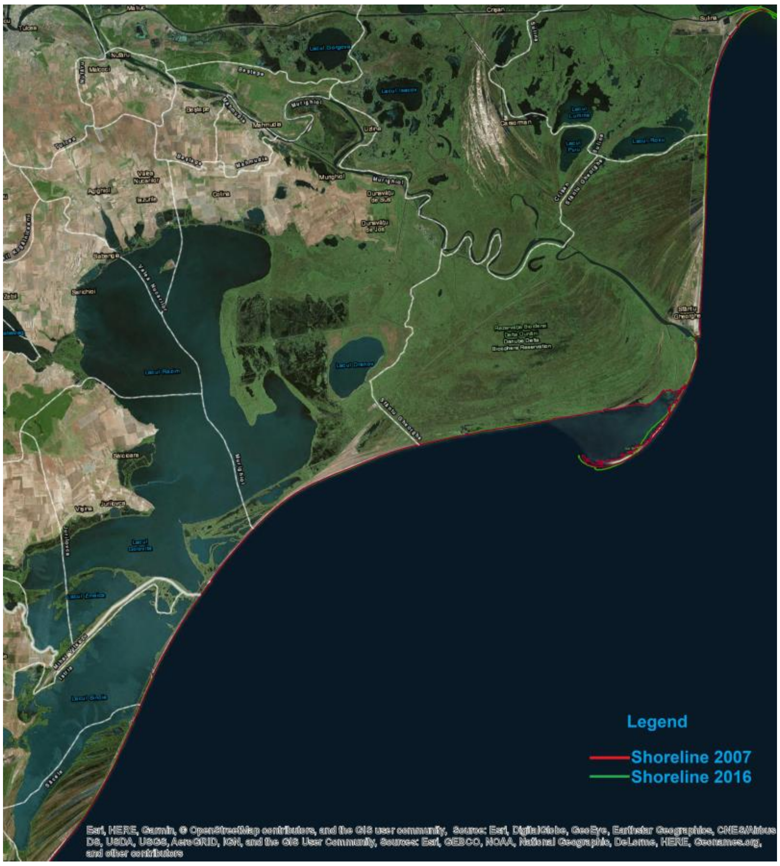


Fig. 1.4 – Changes in shoreline between 2007 and 2016 [3]

The northern landmark system is badly affected, since out of all 60 landmarks that were installed in 1985, only 18 landmarks are still in use today. Many landmarks have been lost due to the intense erosion process. In the southern part of the northern sector, two landmarks (CSA 1 and 2) are without access since they were installed in a military area. Therefore, no measurements were made on the two landmarks. Even so, the remaining network supports the monitoring process at an annual or, in some cases, seasonal interval, to capture geomorphological changes after a storm that can affect the coast to a significant level [7].

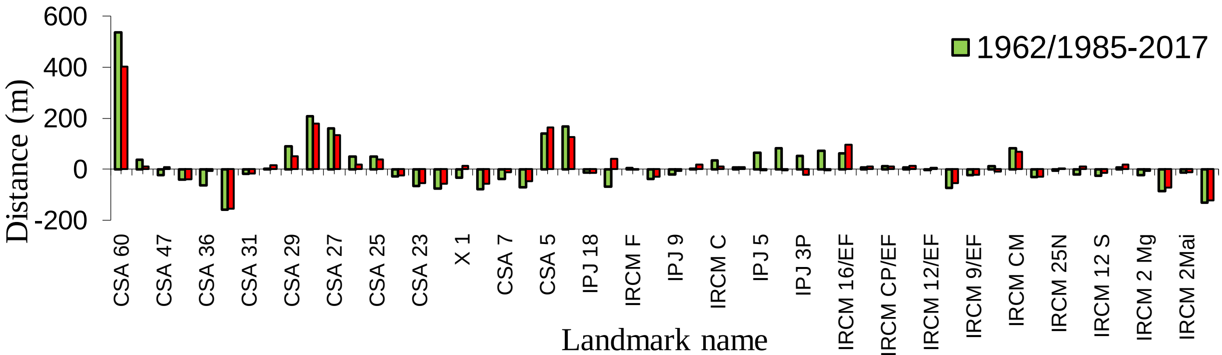


Fig. 1.5 – The sedimentation and erosion values along the topographic network for the two periods of time that were considered (1962/1985-2017 and 1962/1985-2006)

The comparison highlights the evolution of the shoreline between the two periods 1962 / 1985-2006 and 1962 / 1985-2017 respectively. This provides conclusive information on shore state. Generally, the difference is small, as the period between the two coastlines is only 11 years (Fig 1.4 and Fig 1.5).

Chapter 2. General factors affecting the coastal area

Numerous oceanographic centers (around 80) worldwide collect environmental data in oceanographic stations on vertical columns of water in all seas and oceans around the world, the main parameters being temperature, salinity, oxygen, phosphate, nitrate and silicate. They are analyzed at standard depths. The main interest is this work is towards the analysis of wind, wave and current data. These environmental factors, in particular waves and currents, are interdependent on the action of the wind (with the sun as a primary source of energy).

Wind speed at sea has been measured for centuries. A series of observations have been made by passionate scientists, who understand the important role of meteorological information for marine research. For this reason, meteorological observations have been made in several coastal stations, including Sulina since 1857 [8].

2.1. Wind and induced force

Wave generation depends on wind speed and duration, but also on the surface that it blows, called fetch.

Storms generate random waves that depend on the speed and direction of the wind. The waves continue to rise until the sea is no longer influenced by wind energy, in which case it is fully developed under the impact of that storm.

Distant storms announce their imminence due to big uniform waves called swells. They can travel hundreds or thousands of kilometers before they reach the shore. Thus, multiple swell waves generated by different storms located at thousands of miles away can hit a particular place on a coast.

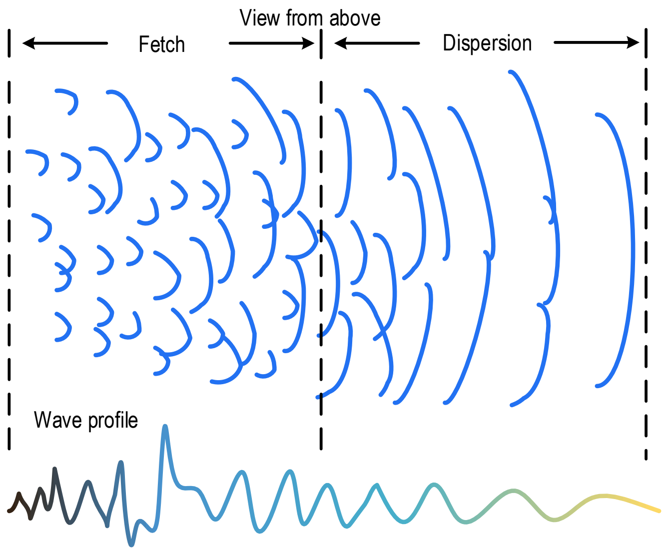


Fig. 2.1 – Wave transformation due to wind force [9]

A wind acting parallel to the surface of a mass of water transfers its energy by friction. In this way, the transfer of potential energy produces a drift stream at the surface of the water. At the same time, the surface is deformed under the action of wind, forming capillary waves. Figure 2.1 shows the interaction between the wind power and the water surface, characterized by the Beaufort scale.

The magnitude of the wind force on a surface is estimated by the shear wind equation. The equation parameterizes the shear stress induced as a wind speed function at a given surface height.

$$\tau_{wind} = \rho_{air} C_f v_h^2 \qquad \text{Eq. 2.1}$$

Generally for such calculations, the height is 10 m from the surface of the water.

The C_f function is determined by an empirical equation by laboratory and / or field experiments. Depending on the wind speed, many researchers have created different equations to better solve the problem, taking into account several mechanical aspects and subtle interactions. [10]

2.2. Marine waves

The wave is a physical phenomenon of a non-permanent nature that manifests itself by deforming the surface of a liquid. Wave energy is proportional to the variation of the displaced water surface. Waves on the surface of the seas and oceans are primarily generated by the wind acting on the air-water interface, with an important amount of wave energy being dissipated in the areas near the shore. These wave-like phenomena are classified as: wind waves or maintained waves (irregular waves, forming a three-dimensional surface with short increments and periods between 0.25 and 10 seconds, being generated due to the direct action of the wind), swell waves or free waves (with two-dimensional regular shape, with longer and well-defined ridges with periods between 10 and 30 seconds, propagating out of the generation area after the wind has ceased due to inertia), and mixed waves (created when maintained waves overlap swell waves). Thus, waves can influence beach geometry, coastal landscaping, port planning and conception, and coastal protection measures.
Wind-generated waves take up a significant amount of wind energy, transporting it to the sea, so that this energy can finally be dissipated to coastal areas, both near the shore and the shoreline. Thus, the wave becomes an energy transfer agent to coastal areas, generating coastal currents that in turn influence sedimentary transport, thus becoming a major cause of shore erosion.
The particle orbit diameter increases with the magnitude of the wave, decreases with depth and is equal to the height of the wave. Thus, the energy of the wave penetrates the mass of water to a certain depth, this limit is known as the base of the wave, and beyond that, the particle motion tends to zero (Fig 2.5) [11].

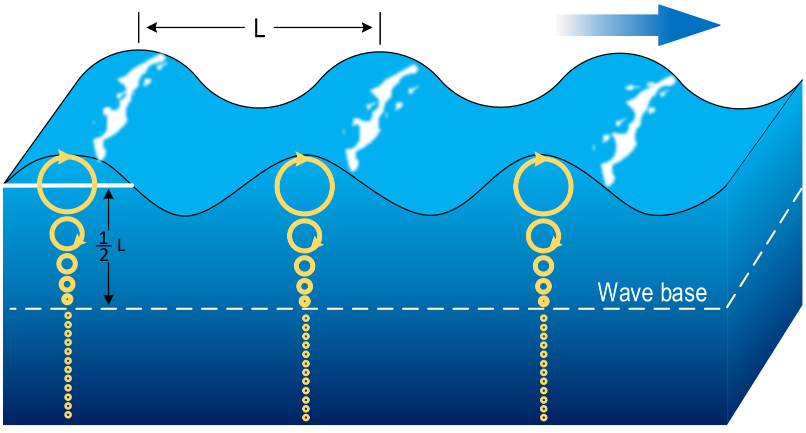


Fig. 2.2 – Wave profile [12]

2.3. Marine currents

The horizontal displacement of the water masses in a marine basin under the action of an assembly of forces is called the sea current and is determined by the geostrophic processes, meanders and vortexes. Water masses are influenced by two types of forces: main forces that trigger and sustain movement, and secondary forces that attenuate and direct the movement. These main and secondary forces act simultaneously, but with different weights in most cases.
The main causes of current generation in the Black Sea Basin are the effect of wind on the sea, the inhomogeneous density of water masses, the accumulation of river waters in the spill areas and the inclination of the sea surface due to atmospheric pressure.
Secondary forces come into action once the movement is started. Frictional force seeks to reduce movement, Coriolis's force seeks to rotate the motion direction to the right and the centrifugal force tries to rectify its trajectory.
Depending on the weight of the main forces that trigger the movement, the currents can be: geostrategic, density and wind made. [13]

2.3.1. Currents generated by the wind in the coastal zone

Atmospheric circulation and temporary winds are of particular importance, creating drift currents and wind currents. Depending on the sea topography these currents lead to the formation of horizontal or vertical gradient current structures.

Wind induced upwelling

The steady wind action as direction and duration with a speed of more than 8 m/s determines the development of currents on a vertical scale in the coastal marine area. Thus, a surface current develops in the upper layer, and in the bottom layer a bottom current develops with the direction opposite to the surface current. This process causes the rotation of the currents with 90 degrees, the water flows to the right when compard to the wind direction in the northern hemisphere due to the Coriolis force. This type of currents (Ekman transport) that have an average value of up to 50 cm/s generate the upwelling processes (lifting cold water from the bottom of the sea) and downwelling (reverse process) (Fig. 2.9). At the Romanian coast these two processes have an important influence on the ecosystem because the cold water masses with nutrient intake are pushed to shore, a process generated by the wind when it blows from the south. [14]

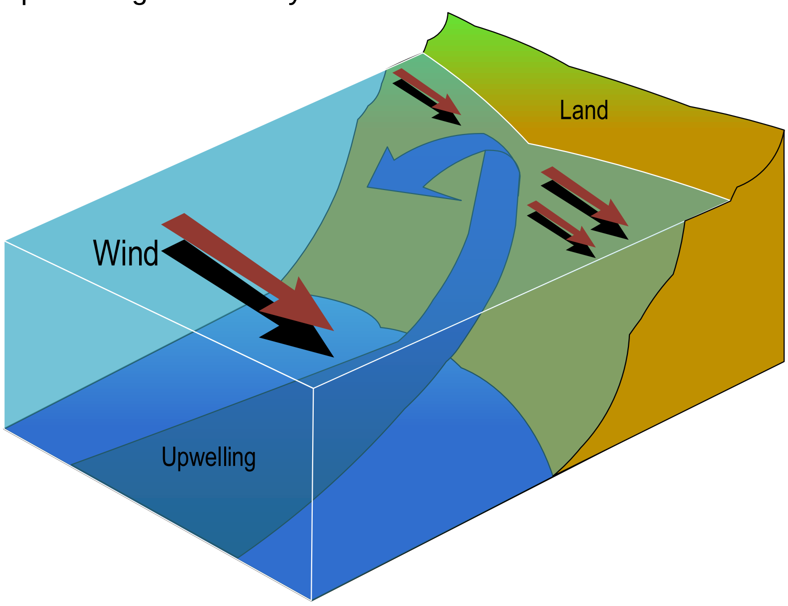


Fig. 2.3 – Upwelling or Ekman transport [15]

Chapter 3. Research concerning the wind, wave and marine current regime

3.1. Theoretical elements on numeric models

3.1.1. Description of the SWAN model „Simulating WAves Nearshore”

In the present paper the ISSM program was used (acronym for SWAN and SURF models) [16], it is a user-friendly model developed for a rapid assessment of waves and currents near the shore. This is a computational framework that combines the SWAN spectral model with the 1D SURF model. SWAN "Simulating WAves Nearshore" [17], is probably the most used waves model. Despite the fact that the scope of applicability was further extended, the model was originally designed as a model for shallow waves with parameterization for some physical processes near the deferring area, including a diffraction pattern.

SURF is a simple but very efficient model for near-shore current circulation [18], also known as the "Navy Standard Surf Model". This is a 1D parameter model that estimates the currents induced by the waves that break along the shore by solving the impulse component of the equation equilibrium. Therefore, such a model can only estimate the longitudinal component of near-shore currents, while a 3D model can estimate the cross-sectional component and the vertical variation of the currents. The justification for the existence of the 1D model is that the most relevant currents for coastal applications are the longitudinal ones in the immediate vicinity of the coast.

3.1.2. Description of the MOHID model “MOdelo HIDrodinamico”

At present, in the NIMRD, the MOHID model is being studied for its implementation at the Black Sea and local level at a higher resolution along the seashore.

The model is built on the complex modular principle, respectively each module can request or receive information / results from other modules, thus ensuring a continuous correlation in the successive calculation steps.

The hydrodynamic module is based on hydrostatic flow in the context of Boussinesq approximation. The spatial discretization is done at finite volumes, and the network is octagonal, respectively in generic coordinates in the horizontal and vertical plane respectively. Network computing points are defined by the Arakawa C method, with Euler or Lagrange transport modules.

The input files for the hydro module (are the largest and most complex) contains the work parameters for turbulence. Using the GOTM model algorithms for calculating vertical viscosity and diffusion evolution, it allows the use of several most commonly accepted methods. Only nine variants are possible for length scale calculation, so it can be considered that this essential component of flow modeling is well done.

3.1.3. Description of the POM model “Princeton Ocean Model”

The POM model was implemented in the NIMRD „Gr. Antipa” in collaboration with MHI (Marine Hydrographic Institute of Sevastopol) and runs since 28.01.2009, presenting almost daily, on www.rmri.ro, forecasts (on 3-5 days, at a three hours interval) on sea level, temperature and salinity, as well as the sea currents for the Romanian coast to the 30º5' E longitude, the forecasts are in the form of animations (three-hour forecasts in succession) .

The POM (Princeton Ocean Model) consists of a master program and a set of modules, totaling approximately 15,000 lines of code. The main program is found in various variants (POM98, POM2K, OZPOM, etc.) and contains the initialization and separation operations for the iteration calculation of the three-dimensional internal mode. These operations are carried out with the help of the subroutines: advq, profq, advu, profu, advv, profv, advt (for temperature or salinity), proft (temperature or salinity), advare. The model belongs to a class of models addressing mesoscale circulation phenomena, which is used in different areas as part of the forecasting programs. A feature of the model is the inclusion of a turbulence closure module, a factor that allows for the correct determination of the Eckman surface and the bottom layer dynamics. The POM model is designed to represent marine physical processes at a scale of 1-100km for 1-30 days [19].

3.2. Wind regime

3.2.2. Statistical analysis of wind data in the Western Black Sea

In order to describe the evolution of the wind regime, an analysis was made, taking into account the data recorded from nine meteorological stations on the Black Sea shore (Constanta, Sulina, Odessa, Yalta, Inebolu, Zonguldak, Kaliakra, Shabla and Mangalia) (Fig. 3.1), which has the longest records during the period 1932 – 2013.

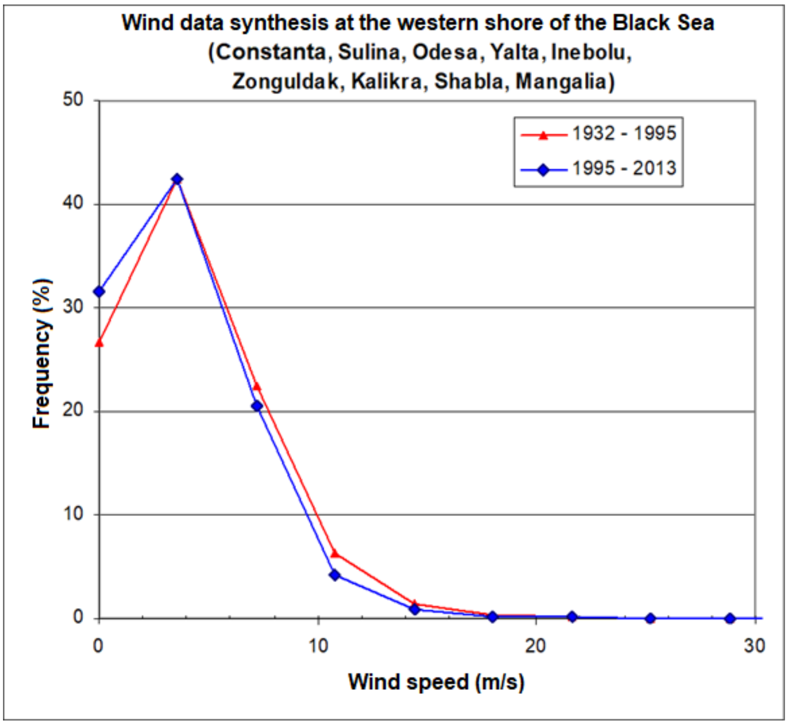


Fig. 3.1 – The distribution of wind speed at the shores of the Western Black Sea

Data has been integrated into a single set of values arranged in a chronological order. By dividing the entire set into two equal parts and representing the data distribution, we see a shift of distribution to low values.

Whereas, on the one hand, the periods of equal lengths of data sets (63 years and 18 years respectively) are very different, and on the other, when defining a climatic meteorological characterizations the periods used are between 20-40 years, the data set was divided into two intervals of 40 years (the last interval being divided into two subintervals of 20 years).

The distributions corresponding to the four sets of data outlined above clearly show the time shift (for 40 years) of the wind speed distribution to the low (red, blue to blue).

Differences between the sets of 20 years (1973-1993 and 2003-2013) are slightly lower and would indicate a reverse trend as the chart for the period 2003-2013 is close to the 40-year chart (1932-1972) which means that the wind speed values have increased over the last 20 years.

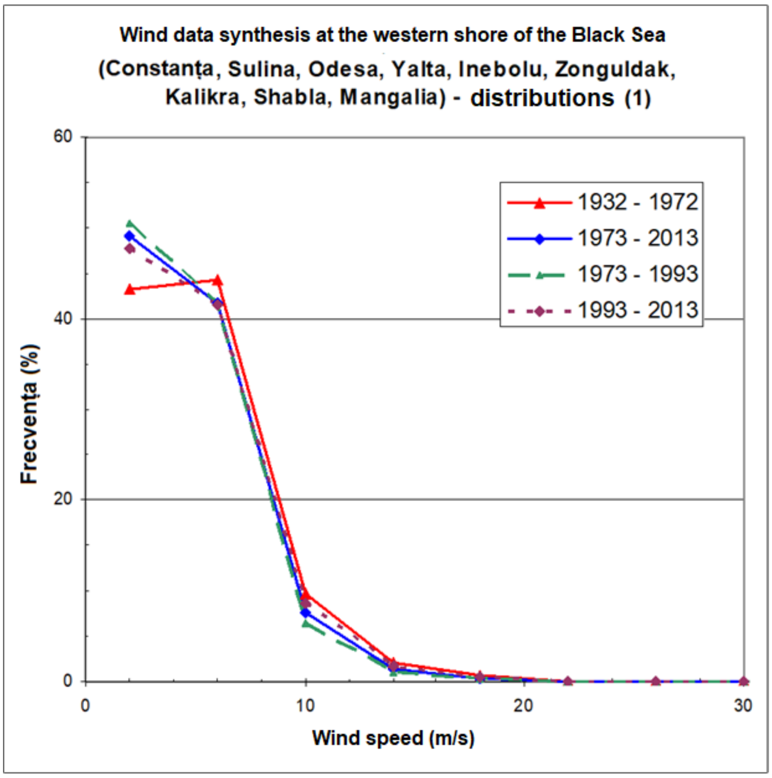


Fig. 3.2 – Wind speed distribution at the Black Sea shores (climatic periods)

Analyzing first the sets of 40 years, the average speed difference is lower than the previous approach (0.38 m/s), but remains significant with confidence levels above 95%. It is noticeable that the excess is higher in the second set, indicating a better data grouping, although the maximum set speed is higher. The detailed analysis of the statistical parameters and the percentile and quartiles values indicate changes in the frequency of the wind speed distribution (Fig. 3.2) in the percentile and quartile 1 range. To assess at least approximately the risks of extreme phenomena (apparently increasing from the data presented above), the analysis in the following graph was performed (Fig. 3.3). From this it follows that the slopes of the distribution (for speeds above 10 m/s) increase in absolute value, so the probabilities of extreme phenomena tend to decrease. Two observations should be made:

- for the set obtained between 1932 and 1972, the scatter points are larger (r^2 = 0,90), while for the next 40 years the linearity is better (r^2 = 0,98) and the „slopes" of – 0,3 and – 0,35 are clearly different;
- for the two sets of data for the 20-year periods the slopes are – 0,36 and – 0,35; the previous values show that the difference between the two given sets for the 20-year periods is not as great as it seemed at first sight.

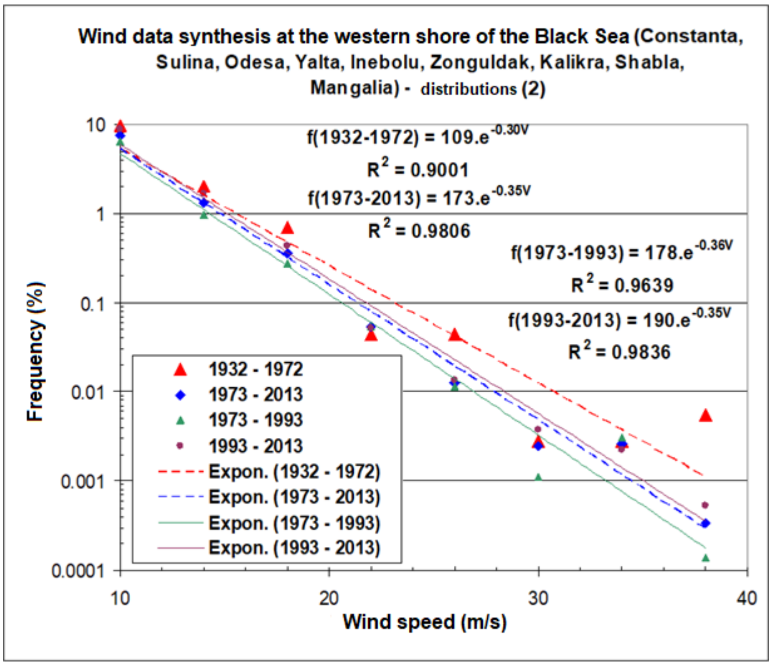


Fig. 3.3 – Wind speed distribution on the Black Sea coast (climatic periods)

It can be concluded that, in normal statistical terms, there is a highlight that the average wind speed at the shores of the Western Black Sea has decreased over time. It should be noted that this statement contains, in fact, an erroneous term of analysis: wind distributions are not normal with a fairly high degree of confidence, so that classical statistical comparisons can not be made. However, visual analysis of distributions and specific statistical values indicate the same.

Unlike what the evolution of the shore wind values indicate, the existing offshore wind data indicate an inverse temporal evolution. Thus, for data recorded by vessels in the western half of the Black Sea - whose distribution is represented in (Fig. 3.4) – a displacement of the distribution to high values is observed.

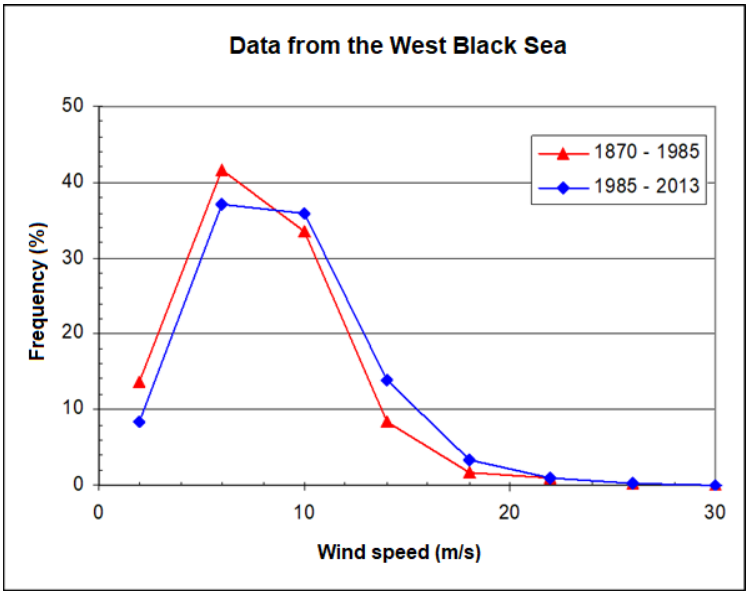


Fig. 3.4 – Wind speed distribution off the Black Sea coast ($\lambda \leq$ 34°5 E)

The data set was divided into two equal parts as number of records, determining the two periods of 115 and 28 years. The increase in the average wind speed (by 0.85 m/s) between the two data sets „MN A” (1870-1985) and the "MN B" (1985 - 2013) is appreciable and, assuming, however, a certain normality of the velocity distribution for the two sets of data, the confidence level for the difference clearly exceeds 95%.

Net differences occur with the statistical parameters, asymmetric and excess, the excess indicating a stronger flattening of the distribution curve, and thus an increase in the probabilities of the extreme values. The same thing results from the analysis of quartiles and percentiles, up to and including P90.

A similar analysis to the one above was performed on a set of data representing all offshore records (including ship records) for the entire Black Sea, which also indicates a shift of distribution to high velocity values (Fig. 3.5). The sets have equal numerical lengths, corresponding to 97 years and 38 years respectively, enough to define distinct climatic periods. The average increase of 0.53 m/s has a confidence level of over 95%, while the excess is higher for the second interval. From Q1 to P95 the values are higher for the second interval, which confirms the previous statements.

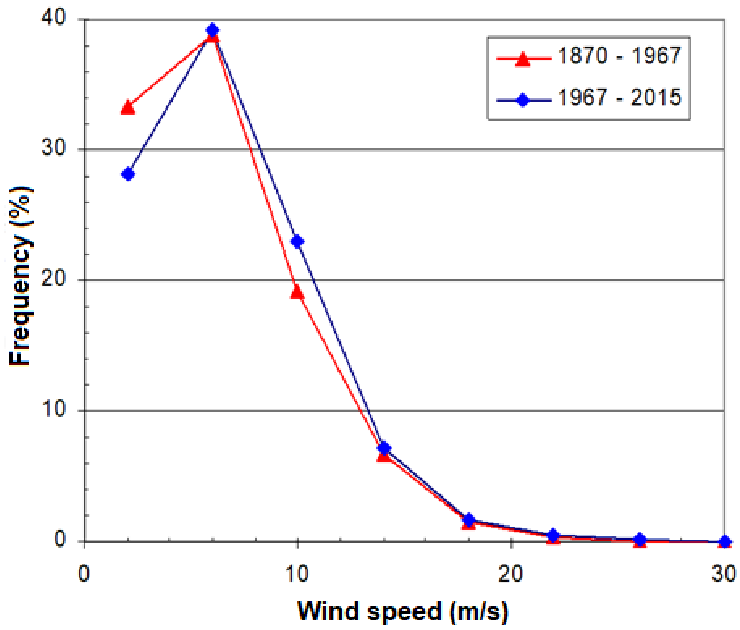


Fig. 3.5 –Wind speed distribution in the Black Sea

From the two types of data, on shore and offshore, there is clearly an interesting difference: while on land the average speed has fallen, at sea the average speed has increased. Different explanations can be found:

- the effect of modifications generated by inevitable constructions near meteorological stations;

- passage of meteorological stations from plate speed estimation to modern anemometers;

- the relatively high uncertainty of ship measurements due to the estimation system,

- any overestimation of offshore speeds generated by the economic interests of shipmasters.

All the explanations considered seem sufficiently convincing to consider that the results presented above are actually a real phenomenon. We can assume that an increase in the extreme weather preponderance is facilitated by sea conditions (the lower net roughness index of the sea than that of the land).

3.2.3. Wind characteristics in the Romanian area

To characterize a small area in terms of wind action, it is necessary to know the main directions of the various events and their distribution. However, for a larger area such as the Black Sea, it is necessary to know the types of wind action on the entire region, which may depend on several factors [20] [21] [22]. As local wind, breezes, the mountainous – vally circulation, around the Black Sea, have a remarkable impact on the atmospheric circulation in the coastal area. The speed of breezes varies between 1-3 m/s along the shore, and offshore is 3-5 m/s.

All data used was obtained from free sources [http://gis.ncdc.noaa.gov] with WMO being the main source. The paper brings together five sets of data, three along the shore, giving a spatial image of how wind values can vary from north to south, not only offshore.

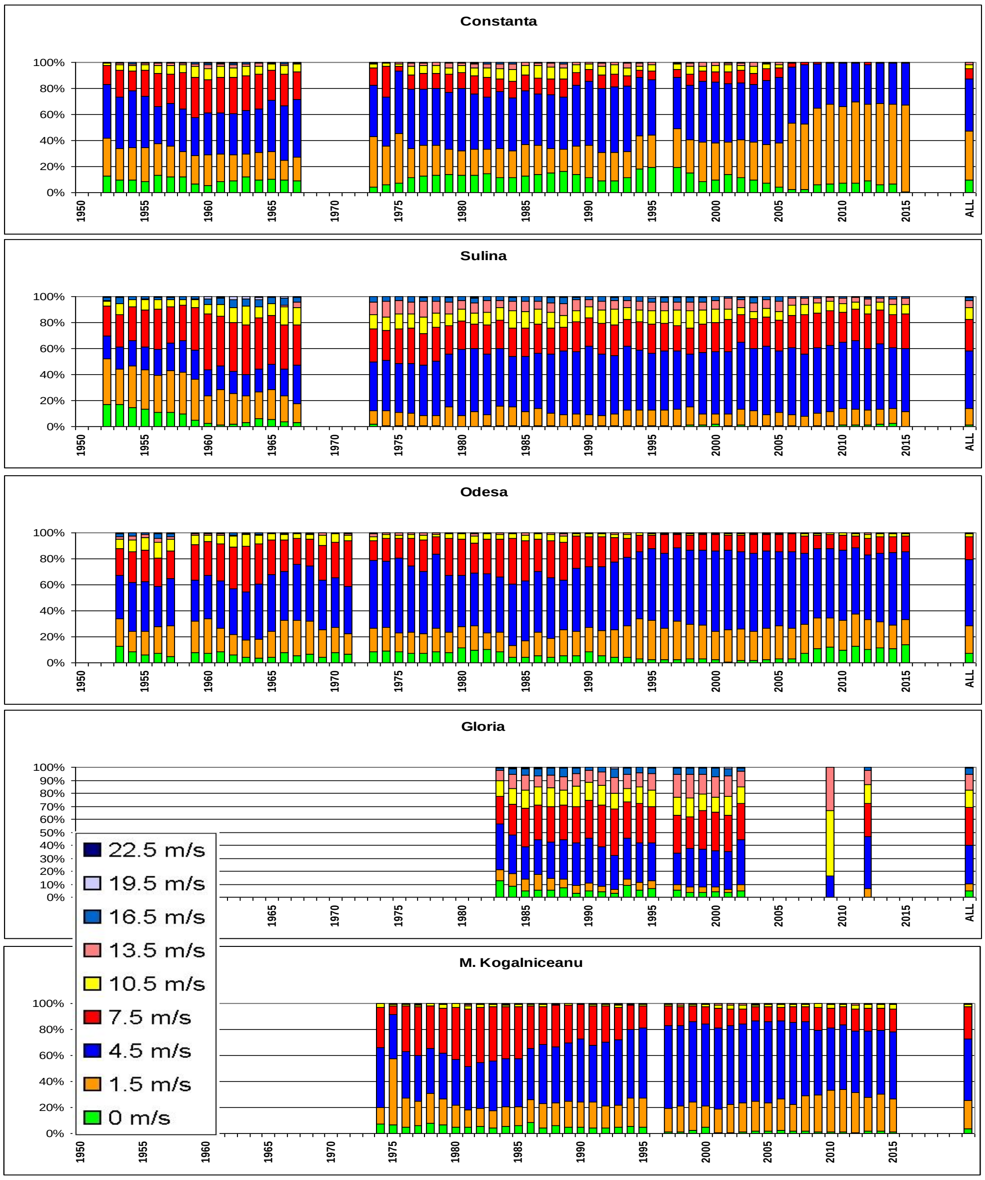


Fig. 3.6 – Multi-annual wind speed distribution (average values) for each set of data (1950 - 2015)

Wind velocity results were analyzed as a percentage of the entire distribution (in classes from 0 m/s to 22.5 m/s) for each year (Fig. 3.6). In the last decade, wind speeds in Constanta have begun to decrease, as nearly 95% of wind speed is in the range 0-6 m/s. This result may be related to the fact that the meteorological station is surrounded by new buildings (which have been developed since 2005), which have affected the flow of air (and, of course, the wind speed, as it is recorded).

For the Sulina station, the wind speed classes are almost stable, but the higher speed class (10.5 - 16.5 m/s) are getting smaller. Even so, in this dataset the wind speed values reach 19.5 m/s, and the global wind speed percentage that exceeds 10.5 m/s is almost 20% per year, but for the Constanta and Mangalia stations this percentage is less than 5%. At the beginning of the data set there is a notable period when the wind speed distribution from 0 to 3 m/s was about 40%, probably corresponding to a warmer period.

For Odessa station, more than 50% of the distribution corresponds to the speed class of 4.5 m/s. Thus, comparing the overall distribution of the three stations on land, the distribution of Odessa station values is somehow in the middle. And for the Gloria Platfroma station, the wind speed of 9 m/s and above, occupies 30% of the range; calm and breeze are less than 10%, and the remaining 60% is divided between the 4.5 and 7.5 m/s classes.

The speed classes of M. Kogalniceanu do not vary as much, their distribution shows that 75% of them are in the value range 0 - 6 m/s.

It was intended to present the general wind conditions in offshore areas along the coast and in land. Based on the analysis and the results obtained, there is a change in the distribution of small values.

3.2.5. The storm regime

Hydrodynamic processes occurring in the marine environment are generated by the complex phenomena of interactions between the sea and the atmosphere. Kinetic energy exchanges between the two environments determine the formation of sea currents and waves. In both cases, the movement is provided by tangential wind tension at the sea surface, which turns into quasi-uniform circulation in active layers and in wave-motion on the surface of the water.

The wind regime is characterized by local physical and geographic conditions, the landform having the most important role. The dynamics of air masses in Romania's coastal area is characterized by seasons. More specifically, in summer, the wind is determined by the dorsal azoric anticyclone, and in winter by the dorsal of the Siberian anticyclone.

Complete or partial analysis has been performed on several data strings:

– the data set from Gloria Platform station ANM, purchased by NIMRD;

– the data set from Mangalia, Constanta, Sulina, Odessa and Gloria stations [23] [24] [25], according to the international meteorological stations standard reports.

The data sets periods are in the following order: 1995-2006, 1975-2013,1964-2002, 1952-2016, 1952-2016, 1953-2016, 1983-2002, the sets having 84621, 62291, 138946, 286056, 256792, 535137, 62283, 627594 values.

The analysis was conducted for wind direction distribution (winter and summer) (Fig. 3.7).

In the first column there are the wind roses that took into account the periods or the days of calm in which the wind speed was 0. In the second column there are presented the wind roses of the Gloria Platform with and without the calm period. In the third column the wind roses of the four stations are presented without the calm period.

The wind roses were based on all values over the entire date range of the datasets, as a percentage. Thus, in the case of the Mangalia station, when the wind rose includes periods of calm, it can be seen how this period coincides with approximately 15% of the distribution, and when it does not include periods of calm, the distribution in the west and west-northwest direction increases the percentage exceeding the 15% limit of the rose. The roses colored in blue are those that include the period of calm in the distribution.

Roza vânturilor (%) (inclusiv v=0)	Roza vânturilor (%) Gloria (inclusiv v=0) Gloria (fară calm)	Roza vânturilor (%) (fără perioada de calm)

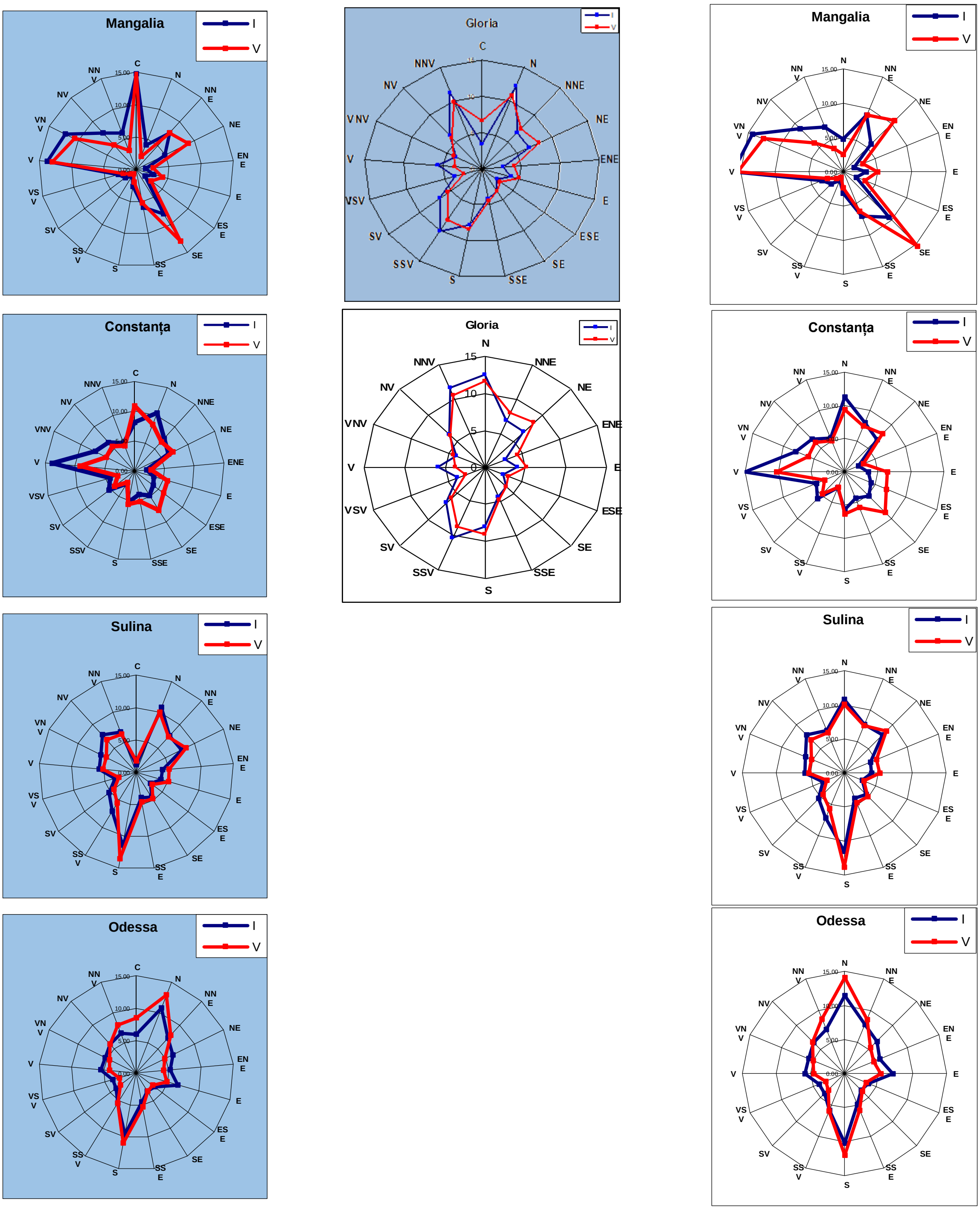


Fig. 3.7 – Distribution of wind direction (winter - I and summer - V) with a period of calm and no period of calm from the total of recordings

The unusual appearance of roses for Mangalia and Constanta, in relation to Sulina and Gloria Platform stations, suggests particular local conditions.

Annual distributions (Fig. 3.8) of the wind speed (classes of 3 m/s starting from 0, but with the class 0 separate) allow for more interesting considerations:

– in the period 1952-1964 the speeds below 6 m/s decreased from 80% to 60% and the speeds below 9 m/s, from 93% to 86%;
– in the period 1973-1988 the speeds below 6 m/s and 9 m/s fluctuated a little (5% -6%), the percentage of calm situations rising to 15%;
– between 1990 and 2003 speeds below 6 m/s fluctuated between 80 and 90%;
– after 2006 the percentage of speeds below 6 m/s was net above 95%;
– the contribution of speeds below 3 m/s fluctuated between 20 and 30% by 2005, then increasing to over 50%.

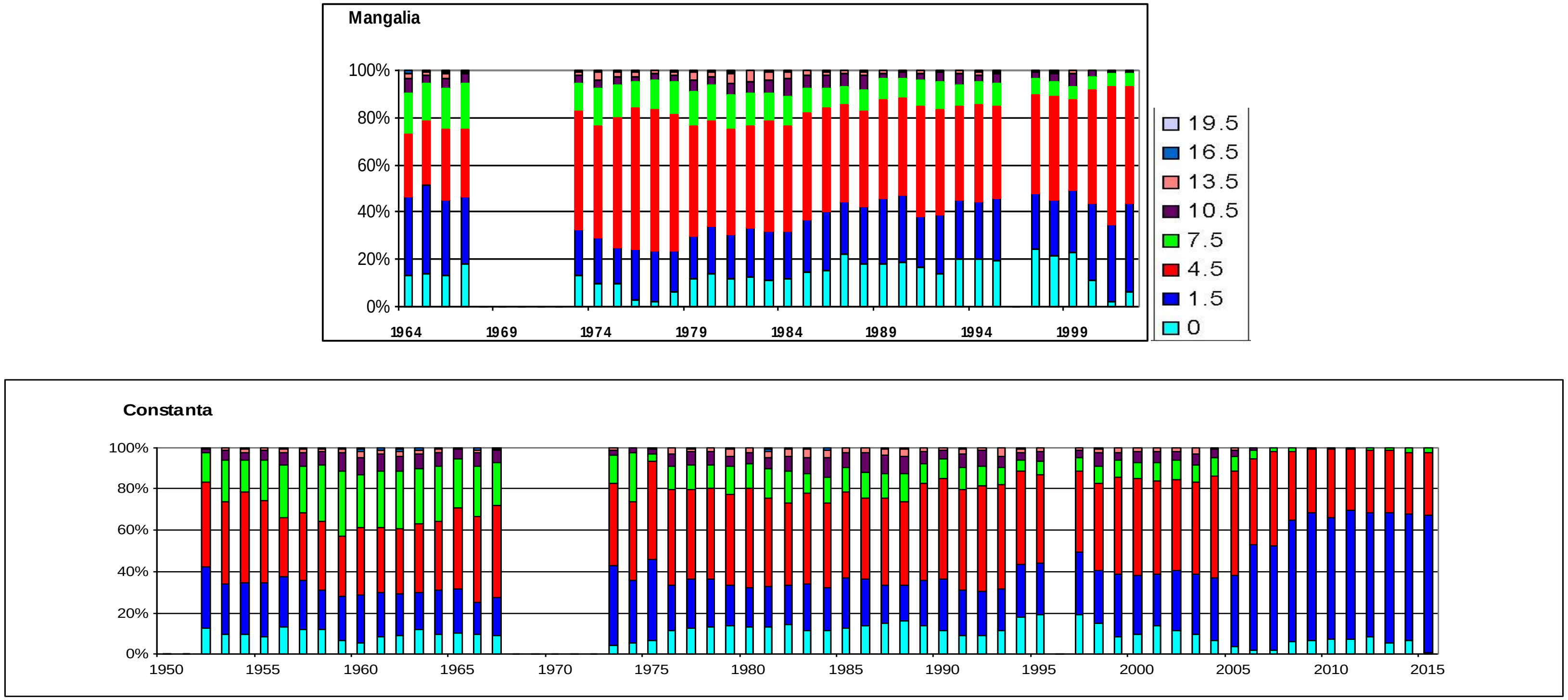


Fig. 3.8 – Annual wind speed distributions at Constanta and Mangalia stations

The above considerations suggest, in addition to the influence of landscape modifications, a (current) decrease of the wind energy in the Romanian seaside area.

Storms over 7 m/s are more often than in the past, but their duration has fallen sharply. In Fig. 3.9, storms with the longest duration may be observed, depending on the meteorological station where they were recorded.

The maximum or average values of the storm duration are based on the environment of each station. Based on this, one can deduce which station is most affected by the surrounding topography.

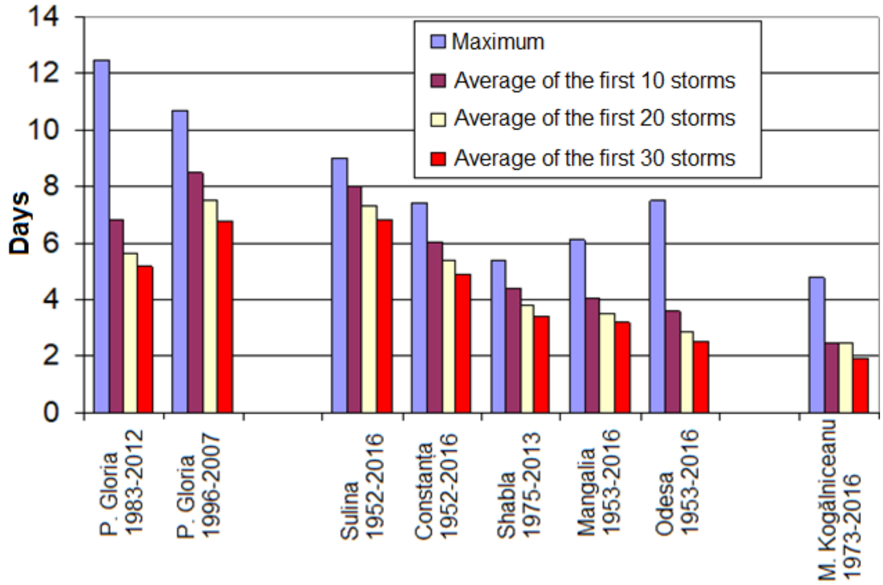


Fig. 3.9 – The duration of the storms for each meteorological station

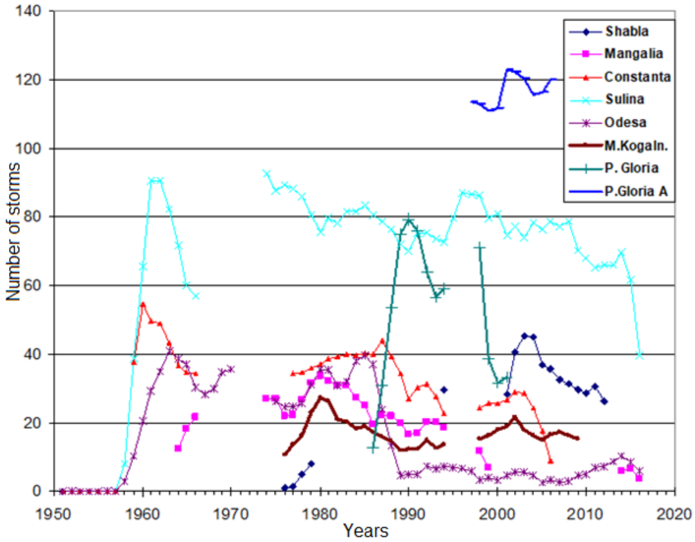


Fig. 3.10 – The number of storms (v> 7 m/s) lasting more than 12h

In Fig. 3.10 a three-value sliding average was chosen for an easier comparison.

Regarding the extreme storms that occur from time to time, the biggest recorded storm was clearly at the Gloria Platform (Fig. 3.9), and it lasted 12 days. The storm's lasting values show a trend that at first does not seem plausible, but after the three mediations of the first 10, 20, and 30 storm duration values, there may be a pattern. Even though P. Gloria is offshore, exposed to strong storms and, in this case, to the longest, the Sulina area seems to have more lasting storms (Fig. 3.9), in the case of the first 10 values, the result shows in an eight-day storm, while for the area surrounding Gloria Platform the value is about 7 days.

3.3. Wave regime

When modeling the sediment transport along the coast, the main parameter of any model is the wave data. The required parameters for such a modeling contains a series of wave data (height, period and direction), location coordinates, and the bathymetry of the area. Although the wave spectra can be calculated using satellite wind data models, it is preferable to use measured data.

The availability of measured wave data over a long period time in the north is nonexistent. Since 2013, the GeoEcoMar Institute has been running a project through which three buoys have been installed with multi-parameter probes that measure marine currents, waves and other physical parameters, the data is available on demand or partially through the EMODNET portal. The only wave data that has a continuity over a long period of time are the visual observations and those recorded with the perspectometer, the visual observations are not scientifically accurate, being subjected to subjectivity during the measurement, and those performed with the perspectometer were interrupted.

3.3.1. Analiza datelor de val

Marine agitation for May-September 2014 is evaluated based on data from the regional model FNMOC-WW3-MEDIT (grid 0.2 ° x 0.2 °, 3-day forecast and 6-hour step) extracted from the online platform http://www.ngdc.noaa.gov/, for the Constanţa location (459 values), compared to the reference period (1971 - 2013). The wave observations during the reference period were performed with the Ivanov perspectometer between 1971-1995 (Far Genovez location, Constanţa) and from 1996 to 2013, with a frequency of 3 measurements per day (only on working days).

The wave distribution on directions of propagation is determined by the wind dominant directions and the general orientation of the shore. The asymmetry of their distribution in the shallow water is due, to the limitation of fetches for winds in the western sector and the effect of the refraction that makes the wave crests parallel to the shoreline. Thus, between May and September 2014, 53.81% of wind waves propagate from NE, NNE, ENE and E (Fig. 3.11).

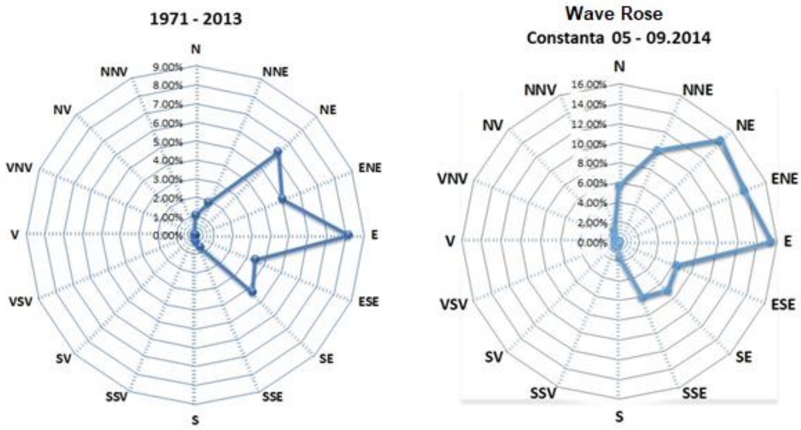


Fig. 3.11 – Distribution of wave propagation direction frequencies in Constanta - left – reference period (1971 - 2013) and right – 05-09.2014 period

Due to the methods and the time period of the observations, the values for the reference period are not homogeneous. Thus, 68.62% of the 47121 wave direction values are missing. Only 27.2% of wind waves propagate from NE, ENE, E, ESE, SE directions (Fig. 3.11).
The sea maximum degree of agitation, on the Beaufort scale, was 5-7 (height of 4.0 m), recorded in May (Fig. 3.12).

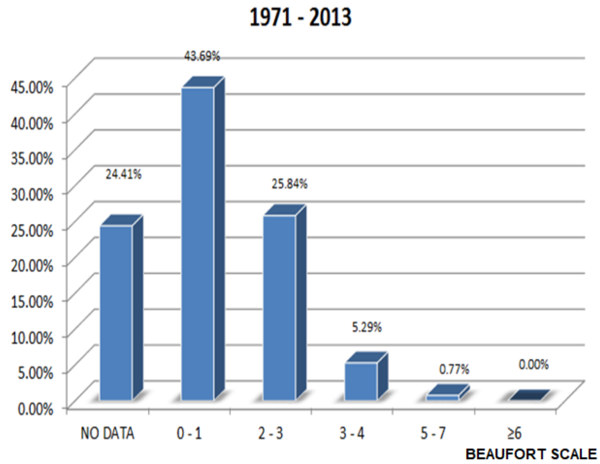


Fig. 3.12 – The sea agitation state during the reference period (1971 - 2013) and the period 05 - 09.2014 (the Beaufort scale)

The degree of agitation 2-3 on the Beaufort scale shows a higher frequency in May-September 2014, 77.8%, compared to the reference period (25.9%).

Different causes determine the maximum parameter values of 2014. The highest recorded ENE height (4 m) - in the spring season (May 22) - is caused by the strong dominant winds that blow from this direction. The maximum wave period recorded was 8 s (15 and 19 May) for a wind generated wave from the N and NV directions. The maximum wave period for a swell is 7 s, from the E direction, this was recorded in the autumn, September 27 (Fig. 3.13).

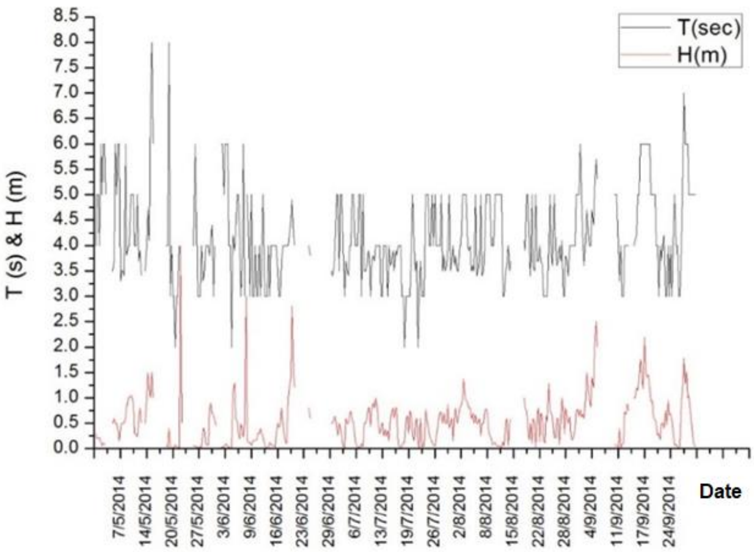


Fig. 3.13 – Evolution of wave parameters (height and period) at Constanta, 01.05 – 30.09.2014 (FNMOC-WW3-MEDIT)

3.4. Marine current regime

The sea currents circulation in the Black Sea is influenced, on one hand, by the cyclonic structure of the wind, on the other hand by the contrast between the ascent force of the fluvial freshwater flows and the intake of salt water from the Bosphorus Strait. All these combined with Coriolis force induce the cyclonic circulation in the west basin.

The marine current circuit has a peculiarity that makes it unique. In the upper layer there is a permanent, peripheral, current (RIM current) that forms, on a large scale, a cyclonic swirl. This current encompasses two secondary circuits in the east and west of the basin.

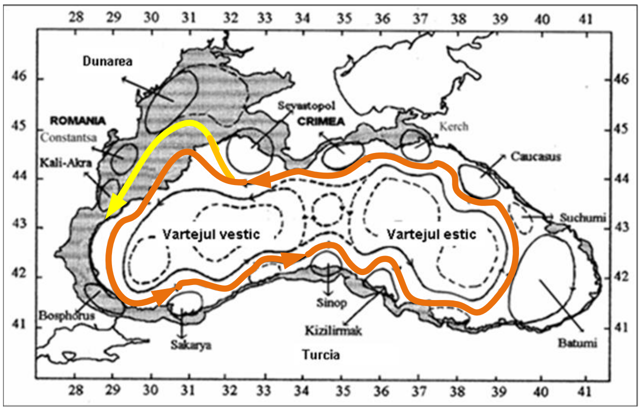


Fig. 3.14 – Currents circulation in the Black Sea Basin [26]

The average RIM / CPMN current is 0,3-0,5 m/s, and at the center of the jet it reaches 0,4-0,6 m/s, under favorable conditions it can exceed 1,5 m/s. Cyclonic circuits have speeds of 0,2-0,4 m/s at the periphery and 0,1-0,2 m/s at the center. Between them, there is an unstable area with currents that have low speeds, and the RIM / CPMN ramifications extend to the western continental shelf (Fig. 3.14).
Since the dynamic method can not be applied to the continental shelf, the spatial expansion of these phenomena can only be determined by direct measurements. Due the transiting phenomena it's difficult and random to obtain the necessary data.

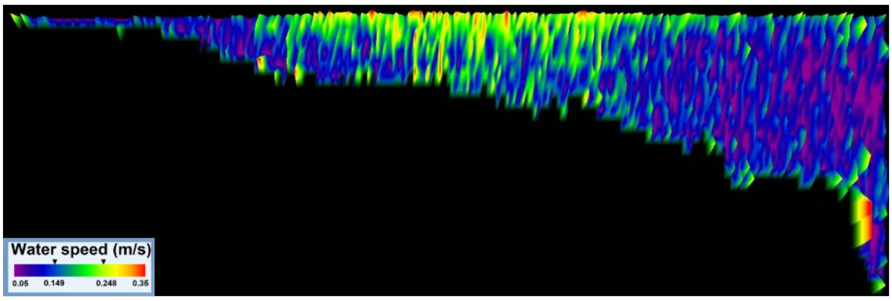
For direct high spatial resolution measurements (both horizontally and in depth), an Acousting Doppler Current Profilers (ADCP) was used.

3.4.1. Analysis of current measurements made in the southern part of the Romanian seaside

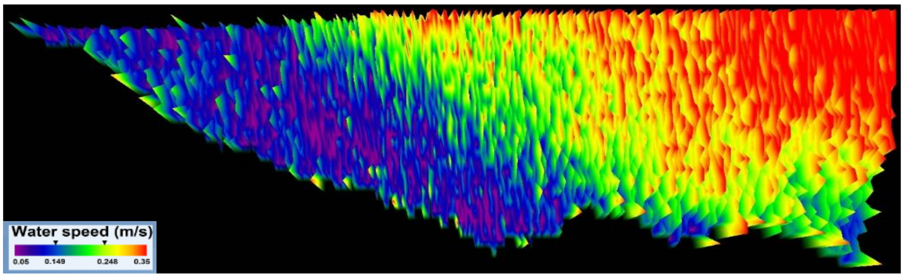
Currents can be measured using ADCP instruments, which can be anchored either to the bottom of the sea or by buoys or attached aboard different navigation vessels. Anchored instruments are launched / recovered by a boat or a research vessels and can operate for months within the capacity of the batteries. Although these devices have a high value, they are the most common instrument when it comes to register direct current measurements. The instruments can measure up to a depth of 150 m - 160 m, but there are others that have a better performance when it comes to distance, exceeding 1000 m. The instrument measures the displacement of water masses using three, four or five ultrasonic beams.
The data was processed using three programs; Winriver II, Velocity and ArcMap.

For this experiment, only the surface data was extracted, the rest of the values were not used.

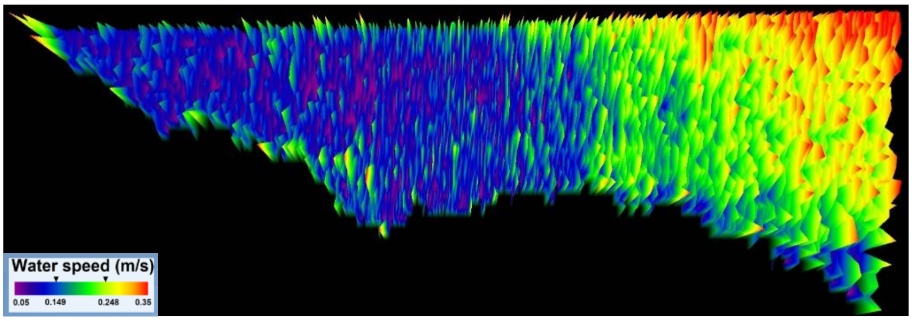
For a better view of profile data, the Velocity program was used. The profiles are listed from north to south (1 being the first profile north of Cape Tuzla and 23 the last profile from Vama Veche). In the images below (Fig. 3.15) one can observe the current velocity (intensity), using an artifact of exaggerating the values to be observed three-dimensionally.



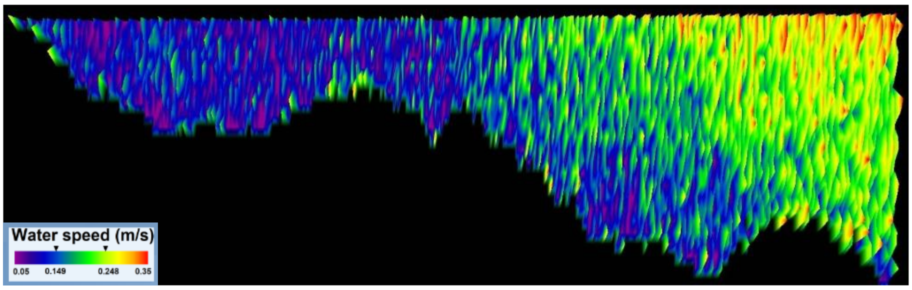
Profile 1



Profile 18



Profile 21



Profile 23

Fig. 3.15 – Current profiles

Since the measurement frequency is high, the amount of data collected is very high and it has been necessary to mediate it at a 5-second interval. The images above are the result of mediation.

Surface current values were extracted and inserted in ArcMap, where the data could be vectorized in the form of arrows. The values interpolation was only possible after they were mediated over long time intervals so that the distance between the profiles and the distance between the values would no longer be a problem for the interpolation method. Thus, for all 23 profiles, 262 values were used, meaning that for each profile has around 11 values (Fig. 3.16).

Based on the maps, the general direction of the current it can be seen, it runs from the north to the south, except for the first profile from the north, which shows that in that area the current was oriented to the north.

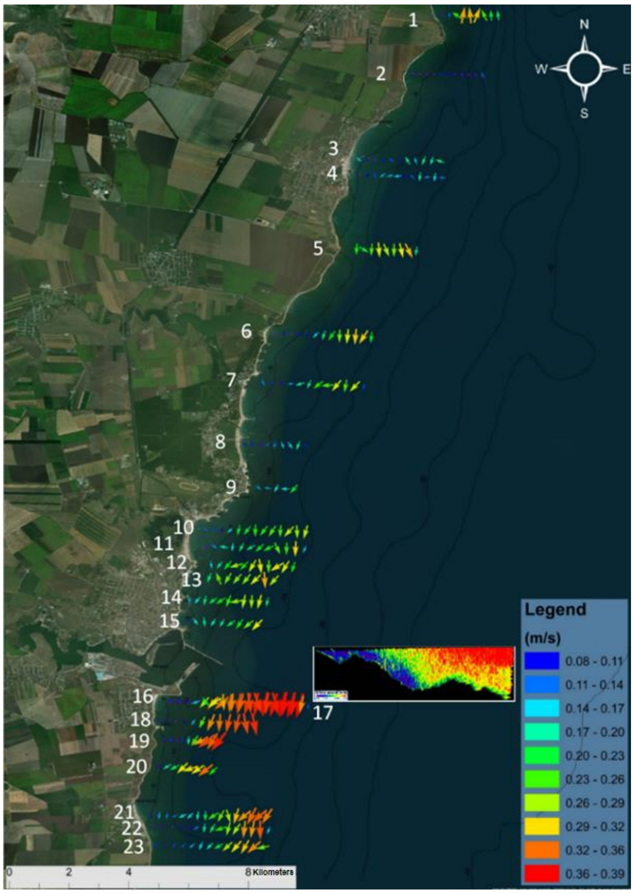


Fig. 3.16 – Water flow speed and direction

It's necessary to mention that the first profile was made at a few minutes apart from the second one, not the next day. However, the current speed intensity to south for profiles 3 and 4 is reduced and in the case of the second profile the current is smaller and the directions of the vectors indicate that it is heading north with extremely slow speed (0.004-0.06 m/s). One possible explanation would be that a swirl was encountered in that area, but with no other measurements between profiles, it is impossible to sustain this assumption.

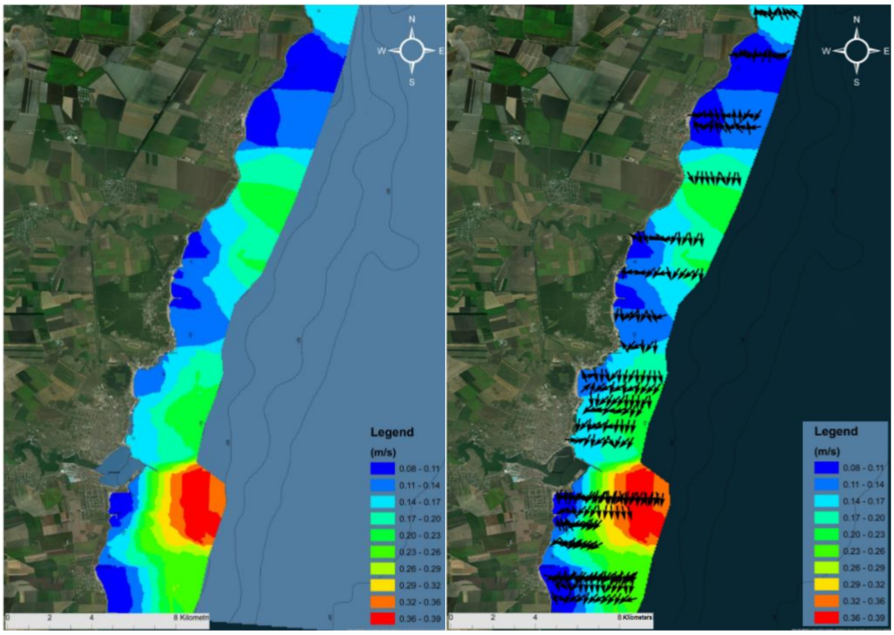


Fig. 3.17 – Speed of current along the coast

In the south (Fig. 3.17) a high current velocity can be observed, which may be due to the bathymetry getting small realy fast (the difference between profile 15 and profile 16 or 17 can be noticed), forcing the water mass to increase the speed and than decrease it due to the increased depth (according to bathymetry, depth difference is 5 m), another factor that would cause this is the northern dig of port Mangalia, which pushes the water mass outwards, thus creating a kind of "funnel" in that area.

The marine current data was registered up to the 15 m isoboth, this can also be seen in the maps due to the fact that the profiles do not have the same length.

Further, the vector components of the current were decomposed to produce two maps of the components U and V. The resulting values were interpolated using the Kriging method and on the basis of the resulting maps the vector components can be observed which emphasize the movement of the water masses on north-south and east-west directions.

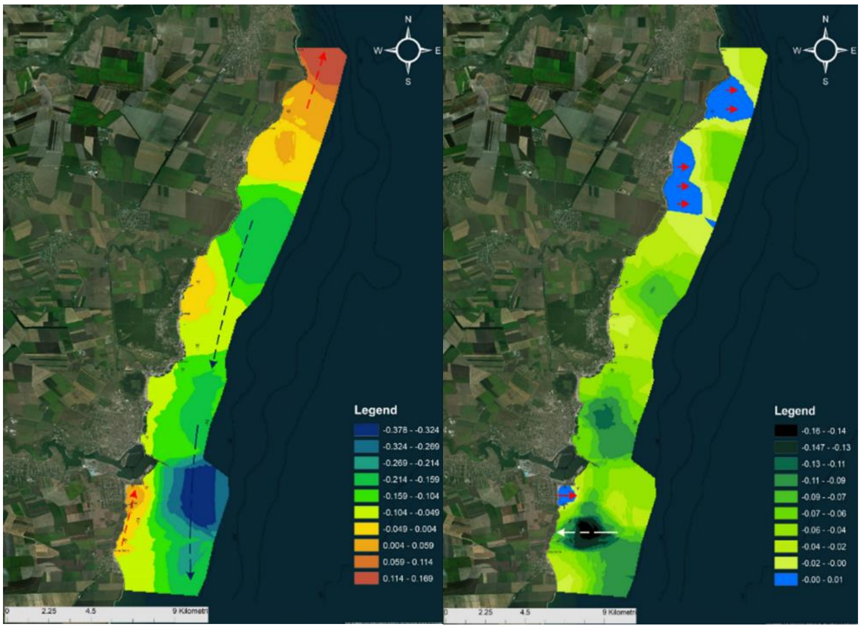


Fig. 3.18 – Current according to vector components U (left figure) and V (right figure)

In the left image of the Fig. 3.18, it can be seen that in the immediate vicinity of the port (in blue, from -0.378 to -0.324) the value of the U component is smaller (minus), suggesting that the water mass is heading south. As a response to this, in the shore area (in orange) a compensation current was formed flowing northwards, with a value between 0.059 and 0.114 m/s.
In the north, the value of the U component is positive along the profile, and the water mass is heading north, without any compensating current near the shore. Most likely, this is happening offshore.

In the left image of Fig. 3.18 the V vector component can be observed, in which the current is represented in the horizontal direction. Following mediation, almost all values are negative, and interpolation has highlighted the small areas where V is positive. The blue area at south of Port Mangalia, shows the local topographic response (bathymetric) that creates a return current as a response to the pressure exerted on the coast by the current.

Following the visual analysis of the resulting maps and values, it can be said that the profiles are not sufficiently close or long enough to fully capture the current movement during this experimental period [27].

It would have been desirable to have a better spatial resolution to capture the currents in the immediate vicinity of the coast of up to 5 m depth, as well as profiles over a larger distance (somewhere up to the 60 m isobath) to capture the process on a larger scale.

At this level of data collection, it is not possible to carry out detailed analyzes of the interactions between the offshore currents and those near the shore along the coast.

Based on the data analyzed, it can be concluded that, from an energy production point of view on the coastal current intensity is week, the most favorable area would be to the south of Mangalia harbour and probably the same situation would be with the Port of Constanta, where , due to the configuration of the shoreline (the northern dikes of the two ports) and the bathymetry in the area, the water mass is subject to increased pressure and as a result the marine current is stronger. This statement can only be applied if the coastal flow moves from north to south.

The maximum measured values, of 0.36 - 0.39 m/s, are not high enough to justify the construction costs of a submersible turbine park. The submersible marine turbines presented in the paper need a current speed of minimum 1.5 m/s. These measurements were made when the sea state was good, with maximum waves of 0.5 m high. There is the possibility that during a storm, the current in these places will be stronger (exceptionally, it could reach 1.5 m/s), but this would be rare.

$$P = \frac{1}{2} \cdot \rho \cdot V^3 \qquad \text{Ec. 3.1}$$

Using equation 3.2, it can be observed that, for the maximum speed recorded during the experiment period, the current power has an approximate value of 0.03 kW/m^2. If the velocity of the marine current would be 1.5 m/s, the power would be equivalent to 1.71 kW/m^2. Generally, most marine turbines start operating at a minimum current of 0.5 m/s - 1 m/s, depending on their construction [28] [29].

3.5. Numerical simulation results (SWAN, MOHID and POM)

3.5.1. Wave regime study in the Romanian area using the SWAN model

The computational domain characteristics for SWAN simulations are defined and physical parameterizations are valid for large scale and high resolution simulations.
Two sets of wind data and one set of wave data were analyzed for this study. The place where the values were recorded was the Gloria Platform. A set that belongs to ANM (Constanta National Meteorological Administration) center has a higher degree of confidence than the second data set, which has no quality control. The first set of data corresponds to a 10-year period (1996-2007) and the second one to a 19-year period (1983-2002). The first 30 highest values of the ANM set are in the range of 26-40 m/s, while in the second set of data there are maximum values that exceed 80 m/s (the interval for the first 30 values is 29.94 - 88.05 m/s).
A value of 40 m/s was chosen to simulate the wave field on four directions of wind propagation.
The decision to have only three main directions for the wind propagation was made by taking into account the large sea distances on which the wind would have a great effect on the wave field.
Due to a very high distribution frequency the NW wind propagation direction was chosen.

The results of the SWAN model can be seen below; In the first image (Fig. 3.19) one can observe the distribution of the significant wave height along the Romanian coast, when the wind blows from the north. Based on the distribution, it can be seen that the wave reaches a maximum development in the southern area, which was to be expected. And the shortest distance from the shore to this area where the wave height is considerably higher lies between Cape Tuzla and Vama Veche, starting around the 40 m isobath.

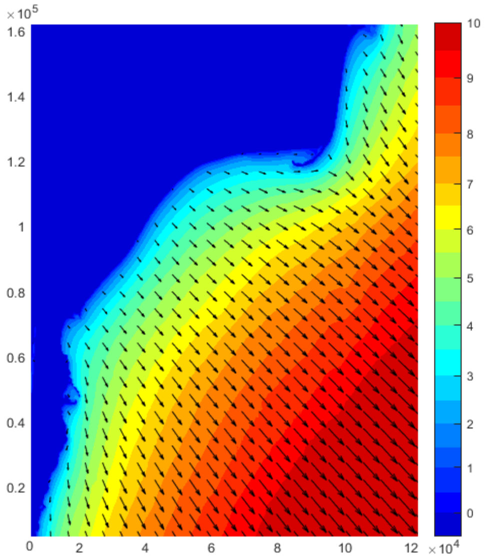


Fig. 3.19 – Significant wave height distribution - wind from NW - maximum HS = 13.5 m

3.5.2. The influence of a wind turbine park on the wave field

A simulation was carried out using the SWAN model to observe the impact of the pillars (wind turbine support) on the wave field. There are some other studies that track the impact of other marine energy conversion equipment on the wave field [30].

For this, an artificial bathymetry was developed for the pillars, and after the first pillar park, three more were made in different areas of interest. The optimal spacing of wind turbines depends on the rotor diameter, typically this is calculated by multiplying with seven the diameter of the turbine, thus, resulting in the spacing between the turbines in a wind farm. [31]

The total number of bathymetry values (xyz points) was approximately 1070000. This set included also the land values that form the ports, the dikes, the shoreline as well as the Sahalin Island.

Since the pillars have a diameter of 6 m, they are visible only if the interpolation resolution is high, for instance in the case below the grid was 5x5 (Fig. 3.20).

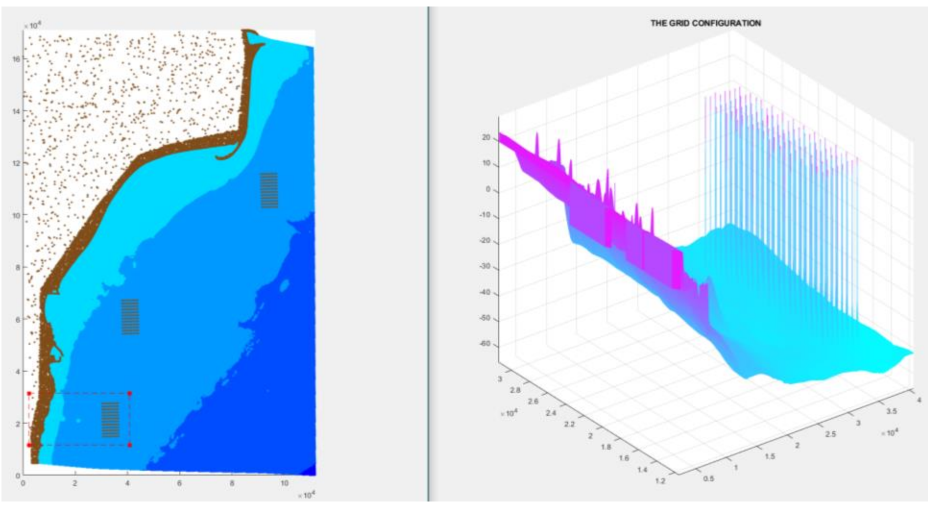


Fig. 3.20 – Bathymetry points selection and result of the interpolation

Unfortunately, the SWAN model fails to run a wave simulation with such a resolution. Still, pursuing a result, many resolutions were attempted until a 40 by 40 network was reached, resulting in a final result (Fig. 3.21), which allowed the model to run.

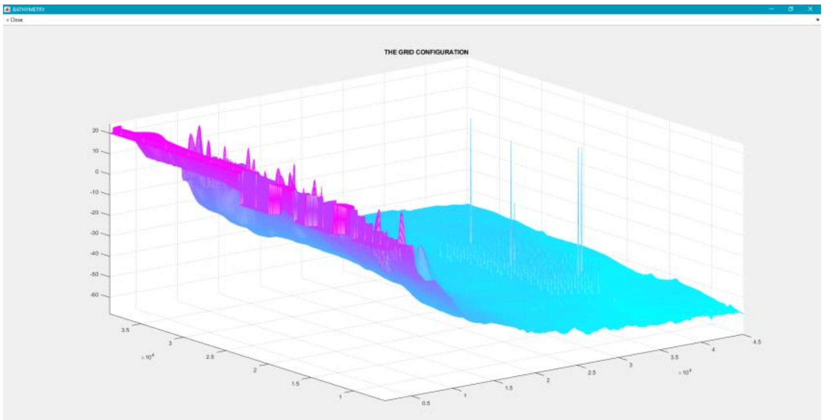


Fig. 3.21 – The 40 x 40 interpolation result

It can be noticed how in this situation the pillars will not reach the surface except for a few. To observe the influence of the pillar on the wave field, namely, at what distance from the pillar does the wave front regenerates, the model was run with the interpolation from the Fig. 3.21.

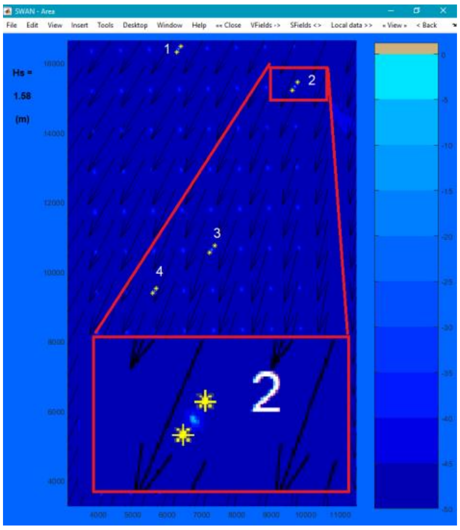


Fig. 3.22 – SWAN Model result

Values of significant wave height were extracted before and after the four pillars. The measurement points were in their immediate vicinity (Fig. 3.22).

Based on these results, one can see how the wave increases, being closely dependent on the fetch surface. The first two measured points are in the north of the park, while points 3 and 4 are further south, where the significant wave height is higher. According to other research in the field [32], a wave-reduction factor could be calculated depending on the size of the wind farm and its impact on the shore.

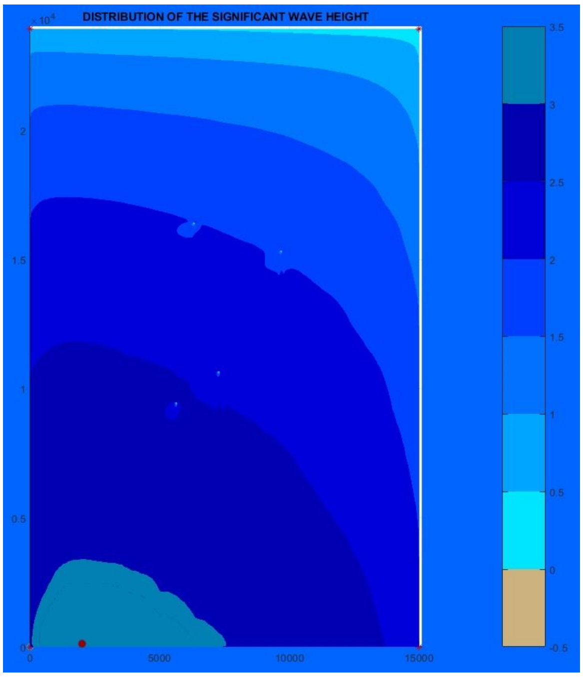


Fig. 3.23 – Significant wave height distribution

Based on this distribution, we can see the small impact of the pillars on the wave height (Fig. 3.23), and how the wave regenerates faster when it is bigger. So after about 300 m, the influence of the pillar on the waves disappears.

Probably if larger diameter pillars were used (for example, the pillars used in the Gemini wind farm with a diameter of 7.5 m) and if the wind farm could be simulated in its entirety, the result would have been different.

3.5.3. The results analysis of the two models, regarding the direction of the sea currents during special meteorological events

Obviously, the logic of the "road" to describe the results obtained for the two models starts from the Sun to the atmosphere, the waves and the currents; the weak point of this road is that of the atmosphere: at local level, the low air density implies little inertia and therefore great instability, justifying the joke that the fla[of a butterfly's wing in America generate cyclone in China.
However, the main problem can be noticed if, all the implemented models are verified, calibrated, run correctly, etc., a comparison is made between the results obtained from the two models (compared to the field data).
The first test / verification was made by attempting to highlight changes in the marine current field produced by wind from a constant direction.

The wind data reported at Sulina station was used [23] because the speed and direction distribution is the closest to those corresponding to the Gloria Platform (located offshore). After identifying some periodes in which the wind direction was constant, the module averages (|v|) and wind velocity vector (v) for the considered period and for the previous 24-hour period have been calculated. The estimation maps of the marine current field were obtained by using the model, were based on the start and end of the constant wind period. The same speed scale (0 - 1.74 m/s) was used for all representations. Where it was possible, the estimates made by the POM model were extracted for comparison. The model was implemented in NIMRD in a scientific collaboration on the Black Sea between Romania, Ukraine and Turkey - these have different scales attached to each representation.

For MOHID's estimates, the figures are associated with the letters a) and c) for the Romanian area of interest and for the whole Black Sea, the POM forecasts have attached to the figure number the letter "b)". Each estimate corresponds to the a time date and calculated wind values described above.

Before attempting an analysis of the results, some general features should be emphasized.

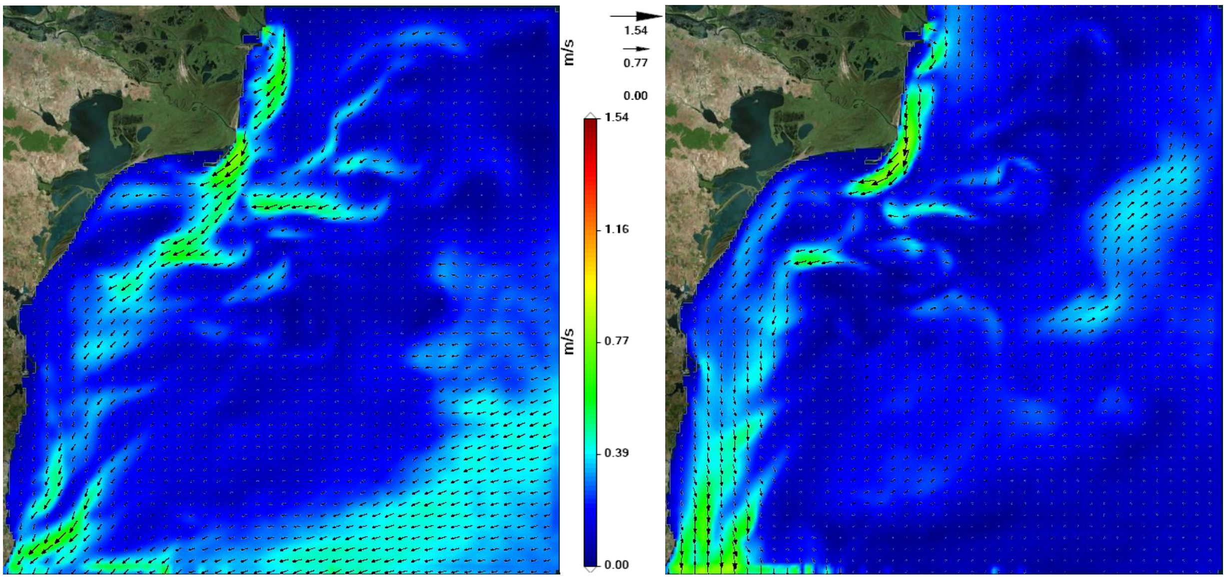
- The geography of the Romanian area is special in the sense that the water masses corresponding to equal surfaces vary strongly from north to south (according to how the isobates approach the shore). Consequently, in the north, it's expected that the wind has a greater effect over the shore area, and that the offshore current field would have a significant effect on the current near the shorelines.
- The stability states of the Black Sea currents system are in fact quite unstable, between 7 and 8 different situations (even if the RIM current is statistically mose of the time at the romanian coastal zone).
- When the wind blows at small angles to the shore, compensation whirlpools are generated, (whose positions and dimensions are variable), because they interact and sometimes create offshore vortexes the estimates are inaccurate.
- The estimation comparison of the two models is only partially correct, because for POM the calculated state is for a 2.5 m depth, while for MOHID the estimation is for the surface layer 0 - 2.5 m.
- The assumed wind field was uniform and equal to the one measured at Sulina station (which is unlikely)

Below are some of the situations considered.

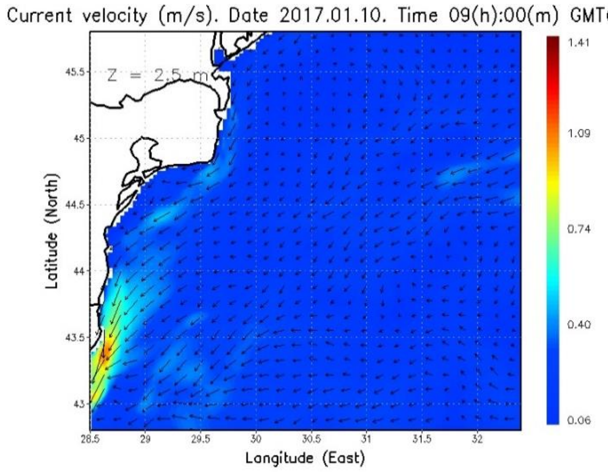
The first cases, from A to F, are for winter events, and from G to K the summertime events.

Case A

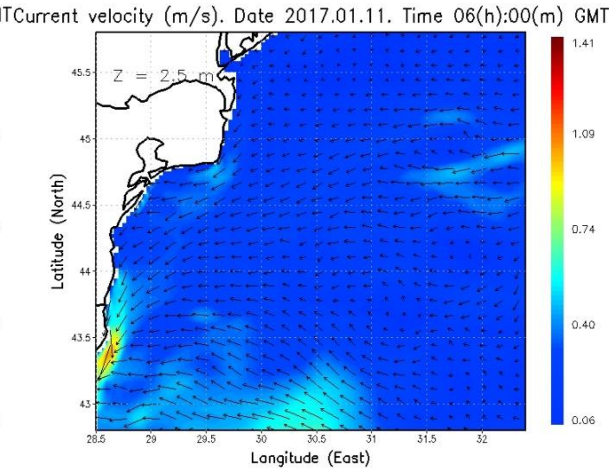
Date	2017.01.10	2017.01.11
Hour	9^{00}	5^{00}
V_{mean} (m/s)	4,3	12,5
Direction (˚)	311	29
$\|V\|_{mean}$ (m/s)	4,5	12,6



a) a)



b)
Fig. 3.24 – The model resut 10.01.2017



b)
Fig. 3.25 – The model resut 11.01.2017

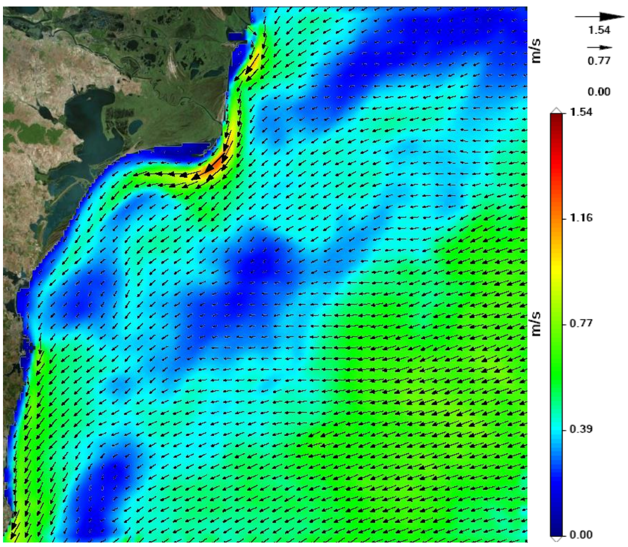
Changing wind direction with - 78˚ (between Fig. 3.24 and Fig. 3.24) slightly modifies the field of currents in the area of the Danube mouths, offshore, east of Sahalin Island to the east Periboina, the direction of currents changes from E to N - NE. In the southern area, at the shore, the current flows from SSW and SW to S, and offshore the flow to WSW is canceled. It is noted that the changes predicted by MOHID (Fig. 3.24a and Fig. 3.24a) they do not seem to correlate with measured wind data.

POM estimates (Fig. 3.24b and Fig. 3.24b) indicates low directional changes offshore in the northern area, and more intense in the southern area (from W - SW to NW - W), the changes in direction and intensity after 21 hours are minor.

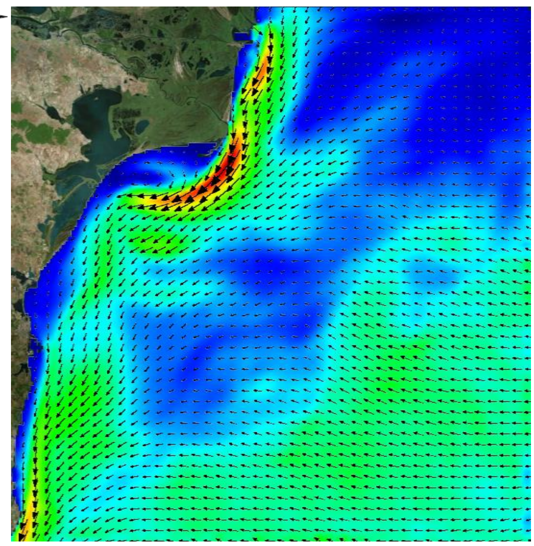
The forecasts of the two models are different from each other and also to the correlation expectations with measured wind data.

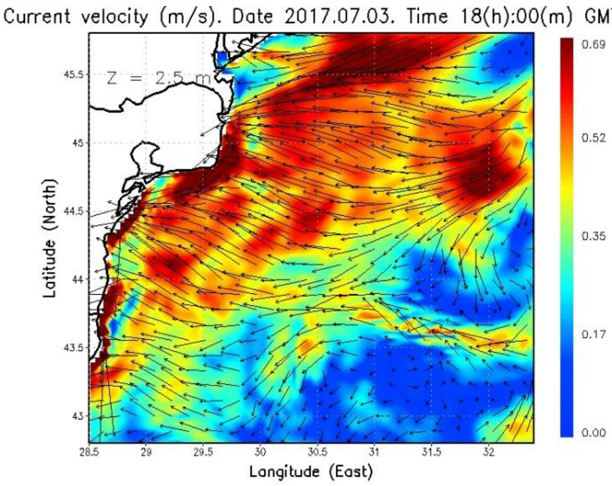
Case D - presents situations during the summer of July 2017.

Date	Data	2017.07.03	2017.07.04
Hour	Ora	17^{00}	15^{00}
V_{mean} (m/s)	V_{mediu} (m/s)	7,3	5,5
Direction (˚)	Direcția (˚)	22	353
$\lvert V \rvert_{mean}$ (m/s)	$\lvert V \rvert_{mediu}$ (m/s)	8,1	11,9

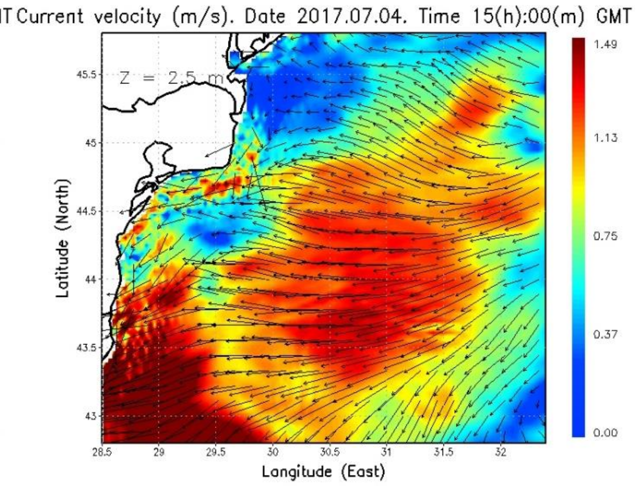


a)

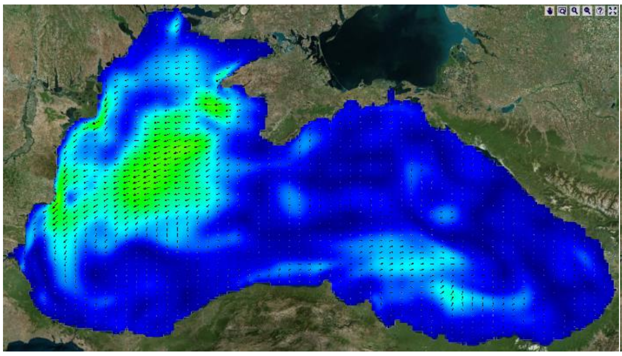

a)



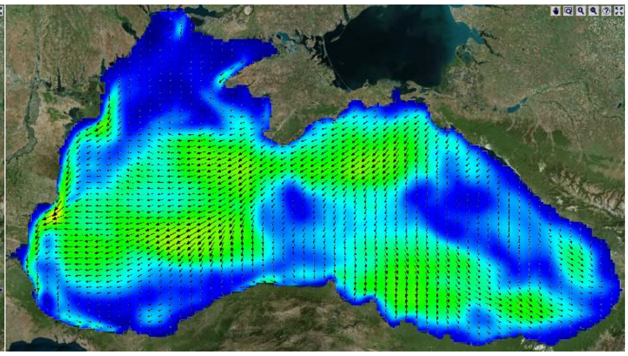
b)



b)



c)



c)

Fig. 3.26 – The model resut 03.07.2017 *Fig. 3.27 – The model resut 04.07.2017*

Although the wind from (Fig. 3.26) changes its direction with +29˚ (Fig. 3.26), currents along the shore (from the Danube mouths and the southern area) are increasing in speed, maintaining direction, except for the Sahalin area, where it moves slightly away from the shore (generated by a return, coherent with the 353˚ direction, presented in (Fig. 3.26a).

POM estimation (Fig. 3.26b) presents, in the central and northern area, changes that were expected at the shoreline and adjacent (although the speed of currents is exaggerated in the center of the sea). The very high speeds in the southern shoreline are, however, inaccurate, so very rarely encountered.

In Fig. 3.26c and Fig. 3.26c, the Black Sea movement is presented using the MOHID program.

Taking into account the general elements presented before the analyzes, as well as the observations from each case, it can be stated that:

- both models do not have success rates high enough to be used in critical or specific situations at well-defined moments; each model correctly estimates the current field for certain areas or situations, however big differences may appear;
- the stability conditions specific to the Black Sea currents system are slowly reachable (probably after storms with speeds above 10 m/s and with long interval times);
- the different sources of data used by the models should not lead to the large differences found between their estimates;
- as with wave modeling, different forecasts are observed, even when using the same data sources. By modifying certain parameters, there may be better results "matches" to the characteristics of the area for which the models were implemented.

It seems obvious that regardless of the implemented model for a particular area, a long period of testing, checking and comparisons with in-situ measurements, followed by modifications of the model's control parameters.

Chapter 4. Unconventional energy in the coastal area

There are currently two major renewable energy sources (excluding hydropower located on rivers), which have reached the level of large-scale deployment and operation, which have comparable electricity production costs to those produced conventionally. In recent years, many studies have been carried out to target the production of energy based on wavs. An energy source that has not been exploited on a large scale, instead many prototypes have been built and are now in operation. These devices have to withstand strong storms that may take place annually, or in some cases once a few years, events that can be devastating in terms of the equipments integrity. It is very difficult to produce a equipment that can withstand the formidable power of the ocean or seas waves. Since waves vary in size and intensity, energy converters need to be calibrated according to the magnitude of the significant wave high from the area of interest. If the wave is too small, it can not move the conversion system, and if it is too high, the energy it supplies exceeds the mechanical parameters that the converter can operate, blocking it and / or causing serious damage.

So, there is a great challenge for engineering to take advantage of the water movement, given that the generators that work in harsh climatic conditions must be designed to be robust, reliable, and efficient. In recent years, many advances have been made to design waves energy conversion devices, some of which are near the final stage at which they can be commercialized on a large scale. However, important technological issues still remain to be solved before wave energy can be commercially exploited.

Although the water mass movement provides an enormous energy source, it is hardly exploited and in low quantety. The ocean's energy potential is fundamentally manifested in four direct forms:

- the energy associated with the thermal difference between different ocean depths (not of interest at the Black Sea)
- tidal energy (not of interest at the Black Sea),
- current energy,
- wave energy.

4.1. Wind energy in Europe

According to the latest WindEurope reports [33], wind power has come second in terms of power capacity in Europe (Fig. 4.1). Gradually exceeding oil production from 2007, nuclear power production in 2013, hydroelectric power production in 2015, and 2016 coal power generation, which is on a steady decline. As wind energy production is steadily rising, it will soon overcome gas production (which is slightly increasing).

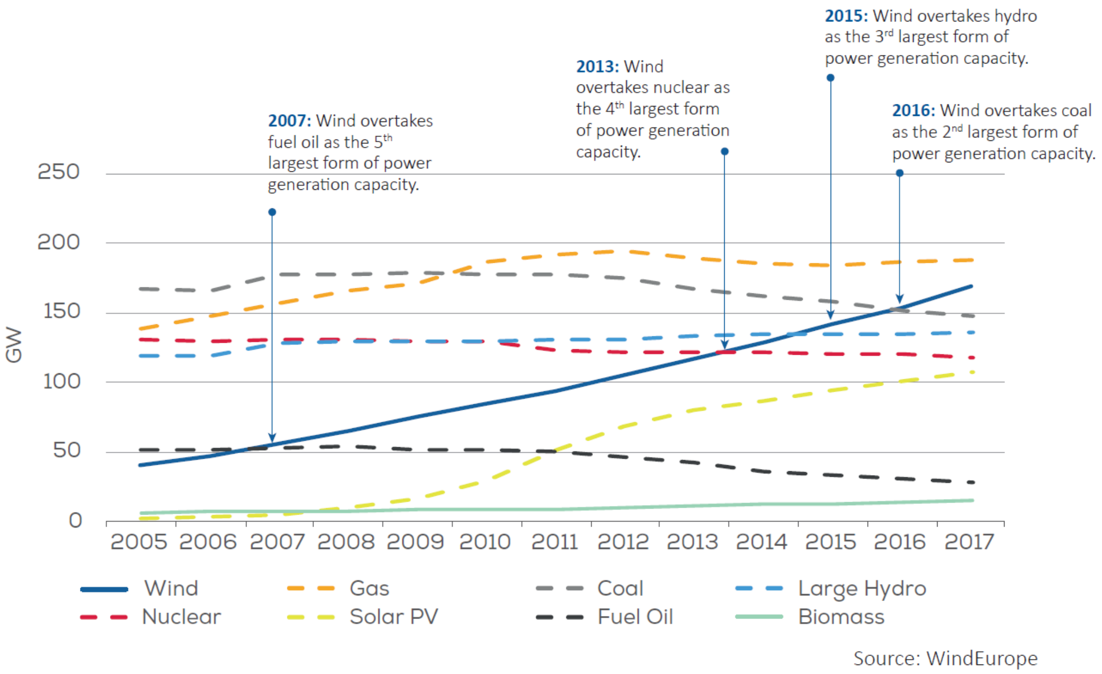


Fig. 4.1 – The European Union's total power capacity [34]

Based on the chart, it can be noticed that in Europe, wind energy dominated in 2017, about 55% of all installed power capacities. Conventional sources of energy, such as fuel and coal, are continuously decreasing, as the uninstalled energy capacity is higher than the installed capacity. In 2017, the uninstalled capacity of the gas oil was almost equal to the installed capacity.

At the end of 2017, offshore wind power capacity was 168.7 GW while about 15.8 GW were installed offshore. Cumulatively, wind power accounts for 18% of all installed capacity in Europe.

Over the last 12 years wind power capacity installed annually increased steadily from 6.6 GW in 2005 to 15.6 GW in 2017 (Fig. 4.2). Offshore installations represent 3.1 GW, approximately 20% of the total installed capacity in 2017.

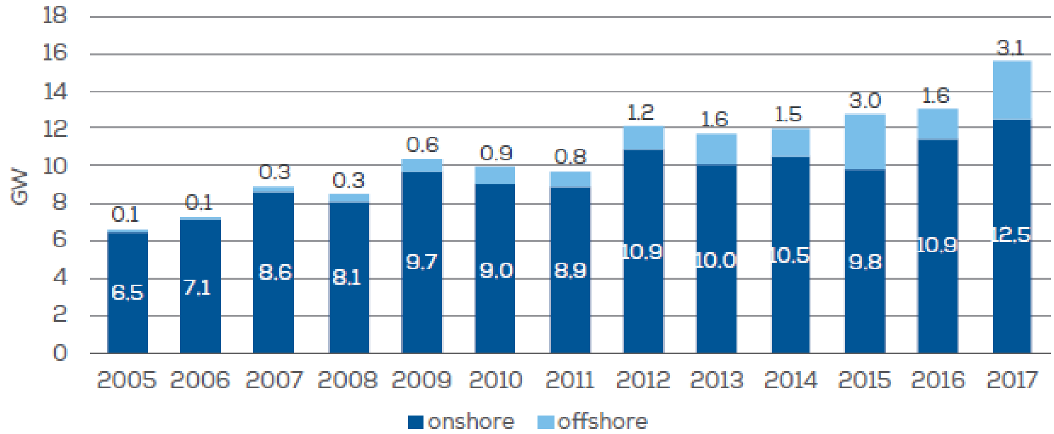


Fig. 4.2 – Wind capacity installed annually on shore and offshore [34]

The total installed wind capacity of 18% equals to 168.7 GW at European level.

More than half (58%) of the wind power capacity is installed in only three countries; Germany (56.1 GW), Spain (23.2 GW) and the United Kingdom (18.9 GW). Romania contributes to this with a 3 GW installed capacity.

Chapter 5. Offshore renewable energy mapping studies

5.1. Wind energy in the Romanian coastal zone

Research has been carried out on wind research on the sea. This study looked at the comparison of data from a meteorological model with data from meteorological stations along the Romanian seashore, namely the Black Sea weather station on the Gloria oil platform.

It should be borne in mind that the two sets of data come from different sources (eg model data and measured data), so they can not be compared simply. Data sets have been analyzed from different perspectives to manage a correlation and contribute little to understanding how wind speed varies when scalable in the model.

Measured data - Wind recorded on shore

Based on the series of data obtained from several weather stations along the shoreline and from one inland, preliminary estimations of the energy potential were made. It should be noted that the M. Kogălniceanu meteorological station is about 16 km distance from the shore, in open field, and because of this the power distribution value is the lowest. The other three stations are on the coast, with higher power densities [35]. For Sulina, Constanta and Mangalia stations, the height at which data is collected is 9m, 14m and 9m, respectively. The height of the M. Kogalniceanu meteorological station is unknown [24].

Measured data - Wind recorded offshore

Offshore data were collected on an oil platform between 1995 and 2007. They are made up of nearly 85000 values, resulting in an average wind speed of 7.97 m/s at a height of about 28 m [24].

Model data

The data used in this study is the result of the "Global Wind Atlas" project, a free-to-use internet access application.

The results of this comparative analysis can be seen below.

The data processing and map editing were made using ArcGIS software. Romania's Exclusive Economic Zone was made taking into account the International Court of Justice's Report on the Black Sea maritime delimitation between Romania and Ukraine in 2009 [36].

The measured data sets were used alongside the models to compare the model's effectiveness along the seashore and offshore. In Fig. 5.1, the red diamond shapes represent the meteorological stations on shore, the black triangle represents the Gloria platform (station), and the green points, the place where the model values were selected.

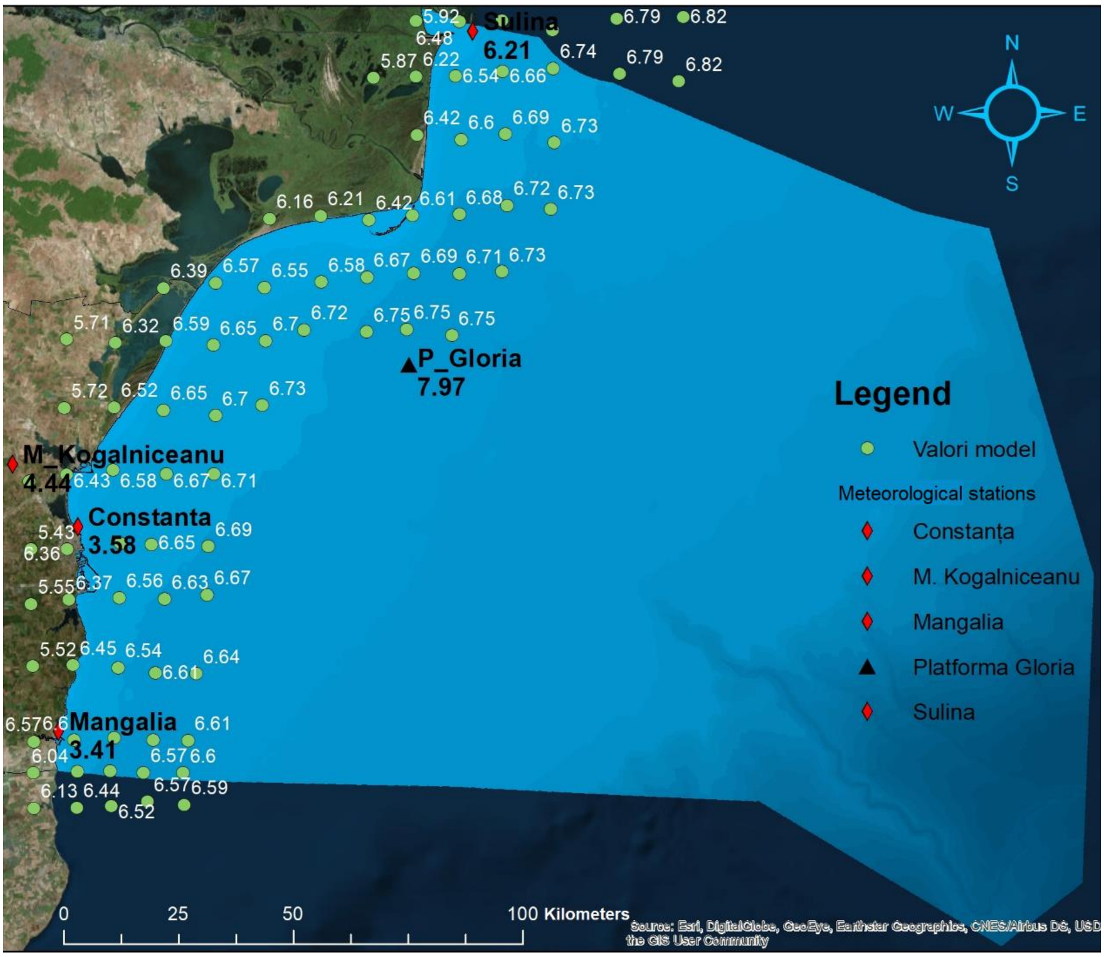
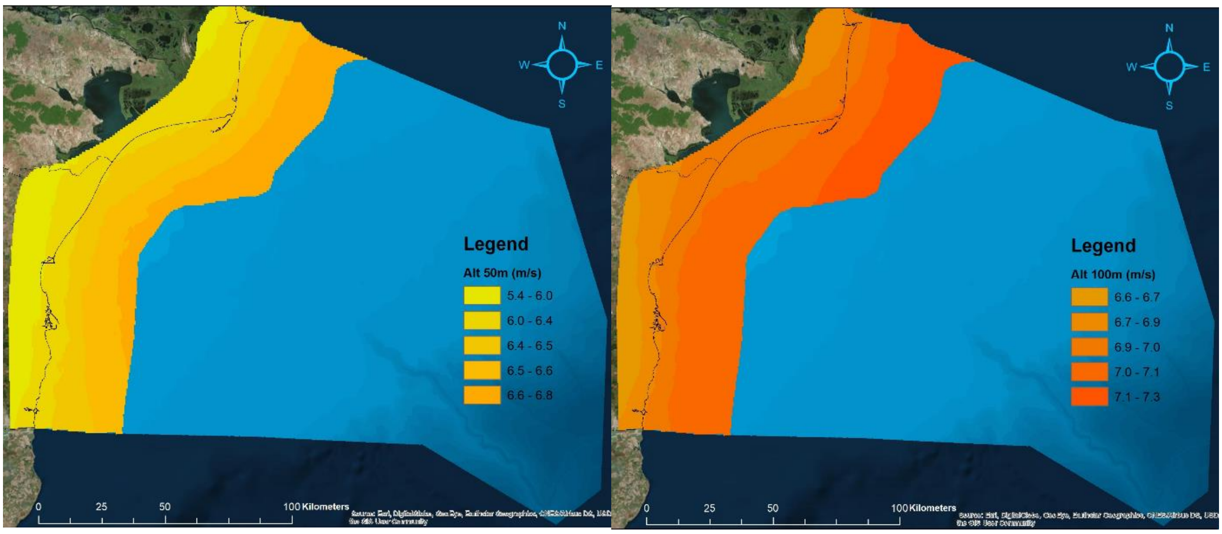
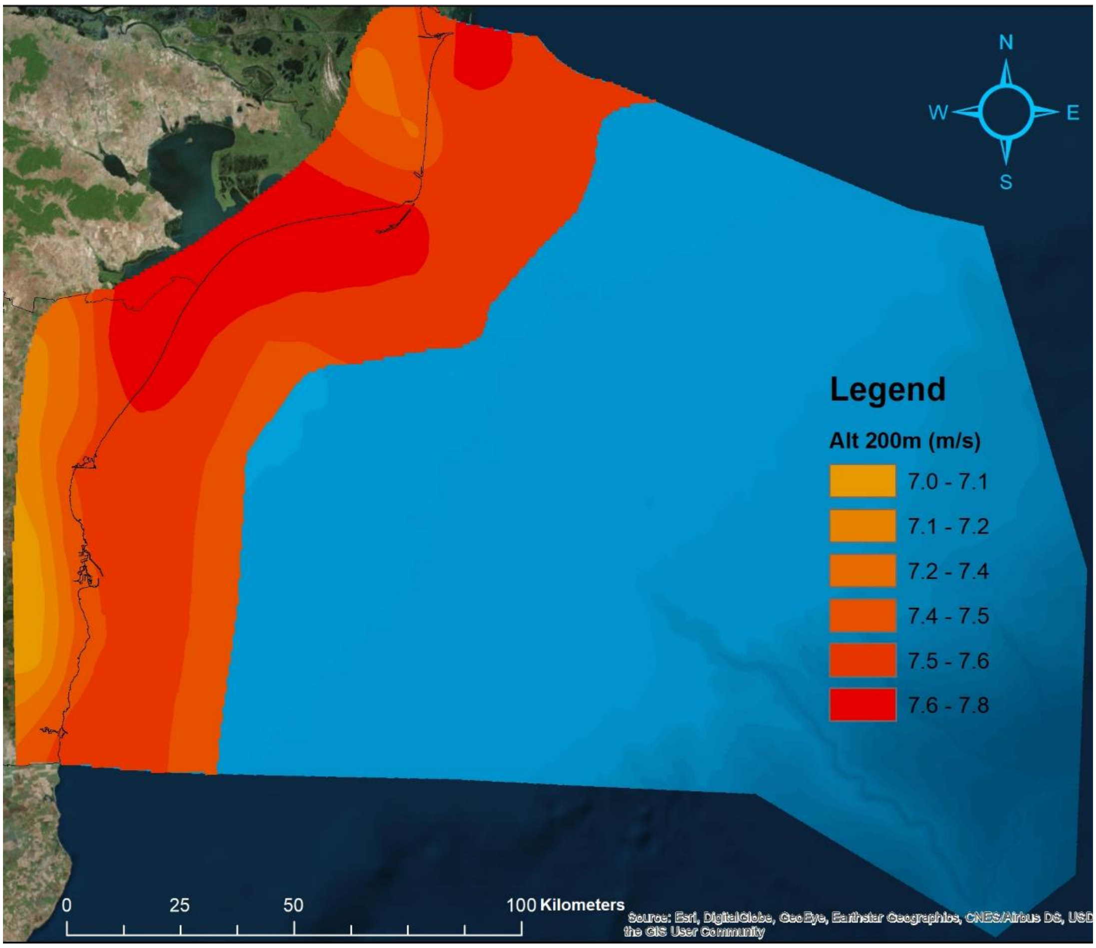


Fig. 5.1 – Representation of the weather stations and data extracted from the model (power density values)

Analyzing the map above (Fig. 5.1) in which the data from the meteorological model are represented besides the measured ones, some particularities can be observed. It should be taken into account that the data provided by the meteorological stations are measured at different heights from the height at which the model produces the results. The value of the wind speed at Sulina is quite close to the the values corresponding to the model around it .The value of the station is lower (as expected), due to the altitude of 9m at which the weather station is measuring.



(a) – 50 m altitude (b) – 100 m altitude



(c) – 200 m altitude

Fig. 5.2 – Wind speed at different heights 50 m, 100 m and 200 m

The values for Constanta and Mangalia stations are significantly lower, a possible explanation being that the respective meteorological stations are located in areas where there are shading effects due to different constructions in their immediate vicinity.

Following the analysis of the three maps resulting from the interpolation of the data obtained from the above mentioned model, one can observe the variation of the wind speed along the seaside, depending on the altitude. In the third image (height of 200 m, Fig. 5.2), the interpolation result shows two areas where the wind speed is between 7.6 and 7.8 m/s.

5.1.1. Estimates of power density at various heights

To calculate the power density, the fallowing equation was used (Ec. 5.1).

$$P_{wind} = \frac{\rho_{air} \cdot U_x^3}{2} \quad \text{Ec. 5.1}$$

ρ_{air} – air density (≈ 1,22 kg / m^3),

U_x – wind speed reported by the weather station

In Fig. 5.3 we can observe the power density values extracted from the model along with the recorded values of the weather stations. The same situation as above can be observed, where the values recorded at P. Gloria station are higher than the values extracted from the model.

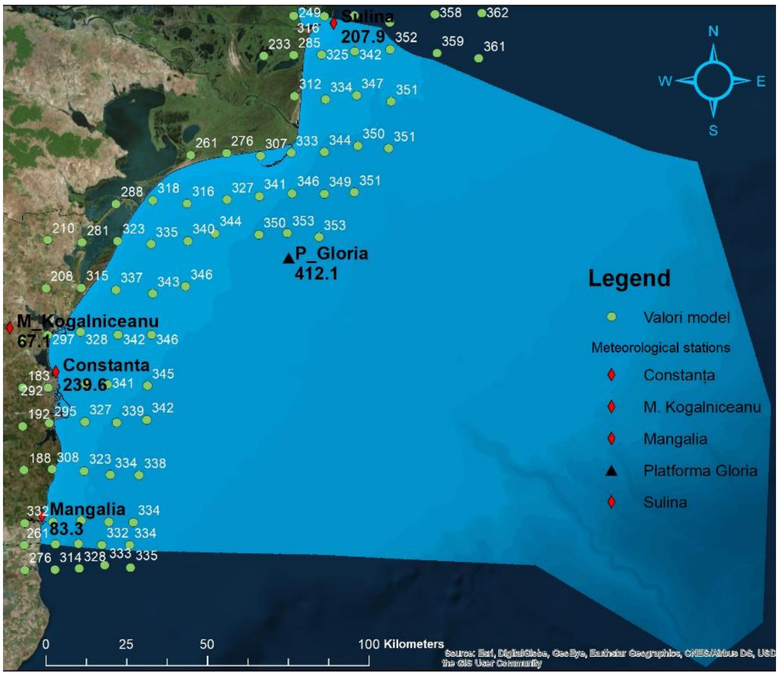
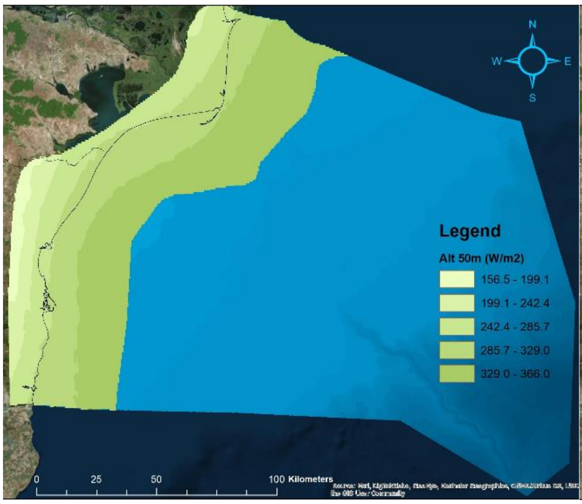
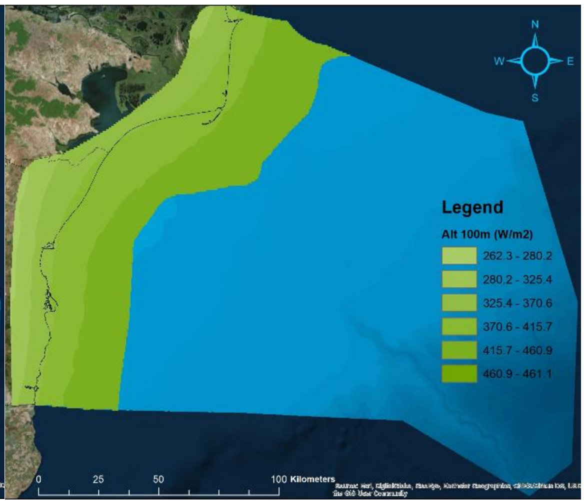


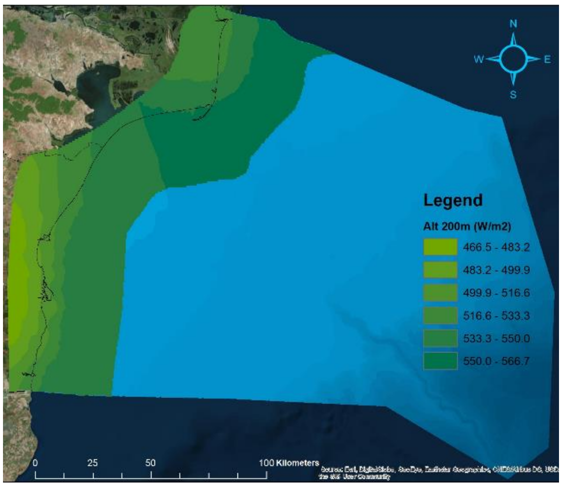
Fig. 5.3 – Power density values (model data and measured)



(a) – 50 m altitude



(b) – 100 m altitude



(c) – 200m altitude

Fig. 5.4 – Power density at different heights

A brief comparison of the three images in Fig. 5.4, shows how the result of the interpolation follows more or less the shore line in the first two images (for 50 m and 100 m respectively) and how the maximum power density moves towards the north in the third image (200 m height). Also in the third picture the influence of the Razim - Sinoe Lagoon Complex can be noticed, which, by its low roughness index, affects the power density (Gura Portita area). The green tinge band (533.3-550.0 W/m^2) enters inland.

The output data of the models and the measured data could suggest that in the northern part of the Romanian seaside, the power density is much higher than in the south.

Research is still ongoing, with new data collection studies and campaigns being required to validate the numerical models.

5.2. Wave Energy

One of the main characteristic propertie of waves is their ability to move at great distances, almost without energy loss. Due to this, the energy generated in any part of the sea can reach a faraway shore where it can be used or absorbed.

Depending on the state of the sea, the average energy density (per square meter) at the surface of the water is proportional to the square of the wave height.

$$E = \frac{1}{8}\rho \cdot g \cdot H^2 \qquad \text{Ec. 5.2}$$

The wave power is described by the following formula:

$$P = \frac{\rho g^2}{64\pi} H^2 \cdot T \qquad \text{Ec. 5.3}$$

The equation offers power in W/m^2 and varies with the height and wave period.
The value of the significant wave height is a mediation of a number of waves. The approximate value of this notion is known as 1/3 of the height of the highest wave ($H_{1/3}$). More precisely, the height of 120 waves is recorded for a few minutes (depending on their period, the measurement time may be higher or lower), then the highest 40 values are selected and their average is calculated [11].

5.2.1. Estimates of power per linear meter of wave

Wind and wave data from the Gloria Platform station were analyzed to determine the values on which to resolve the wave (T) and significant wave (Hs) equations, parameters that are included in the power equation per linear meter of wave [37].

$$\frac{g \cdot Hs}{U_A^2} = 0{,}283 \tanh\left[0.53\left(\frac{gd}{U_A^2}\right)^{\frac{3}{4}}\right] tanh\left\{\frac{0{,}00565\left(\frac{gF}{U_A^2}\right)^{\frac{1}{2}}}{tanh\left[0{,}53\left(\frac{gd}{U_A^2}\right)^{\frac{3}{4}}\right]}\right\} \qquad \text{Ec. 5.4}$$

$$\frac{g \cdot T}{U_A} = 7{,}54 \tanh\left[0.833\left(\frac{gd}{U_A^2}\right)^{\frac{3}{8}}\right] tanh\left\{\frac{0{,}0379\left(\frac{gF}{U_A^2}\right)^{\frac{1}{3}}}{tanh\left[0{,}833\left(\frac{gd}{U_A^2}\right)^{\frac{3}{8}}\right]}\right\} \quad \text{Ec. 5.5}$$

The wave data from the Gloria Oil Platform was chosen as it is offshore and reflects the actual state of wave distribution or height. The values are not affected by the shore or bt shallow depth as in the case of the other points in which the measurements were made (Constanta and Mangalia stations).

The aim was to produce maps on which the power per linear meter of wave could be analyzed, depending on the depth. This can be estimated for concrete cases (even in this case the approximations are realistic) where speed, wind direction, storm duration, sea depth, and fetch length are known, and as the wind is constantly changing, these approximations can only be done individually depending on the storm. For the present simulations, the equations that descrie the significant wave height and period were used. Based on the equations results, the wave power was calculated up to a depth of 100 m. It should be noted that the equations describing the significant wave height and its period can be used to describe the values up to the 90 m isobot.

Three situations have been chosen (when the wind direction spreads from northeast, east and south) where the waves would have a greater impact from an energy point of view in the coastal area. A more frequent situation has been chosen, where the wind blows from the northwest. The fetch was different in all four cases (depending on the direction of wind propagation), taking into account the distance from the Crimean peninsula to the Romanian shore (for the northeast direction), respectively the distance from the shore east of the Black Sea in the east direction and in the south-east direction from the Turkish shore. And for the wind speed a single value of 40 m/s was considered. The value is at the upper limit, and it would represent the wind speed in a storm situation. The interpolation of the power values was performed using the Kriging method.

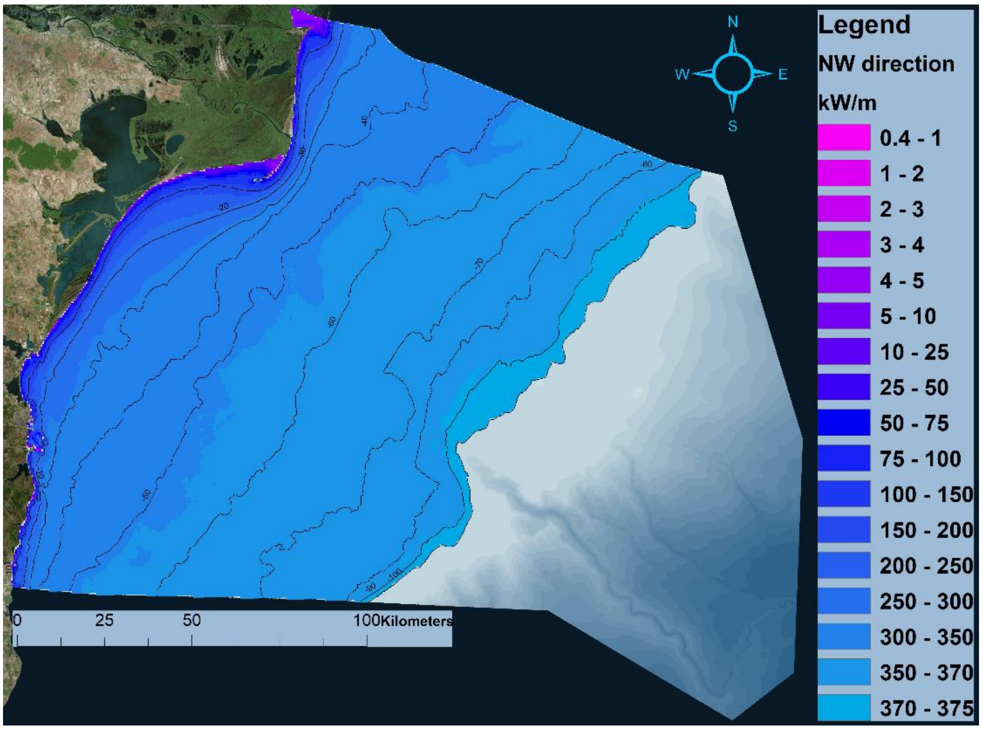


Fig. 5.5 – The interpolation result of power values when the wind blows from the northwest direction

In the case of figure Fig. 5.5, when the wind blows from the northwest direction, the fetch distance (from the shore to the sea) is low (about 30 km), resulting in a net inferior power than the other NE and E situations.

When the wind spreads from the east (Fig. 5.6) the power is between 22 kW/m and 6500 kW/m.

The differences in power when the wind is running from NE or E are small. The smallest distance (15 km) from the shore to the area where the wave power is between 4000 kW/m and 4500 kW/m is in the south of the coast.

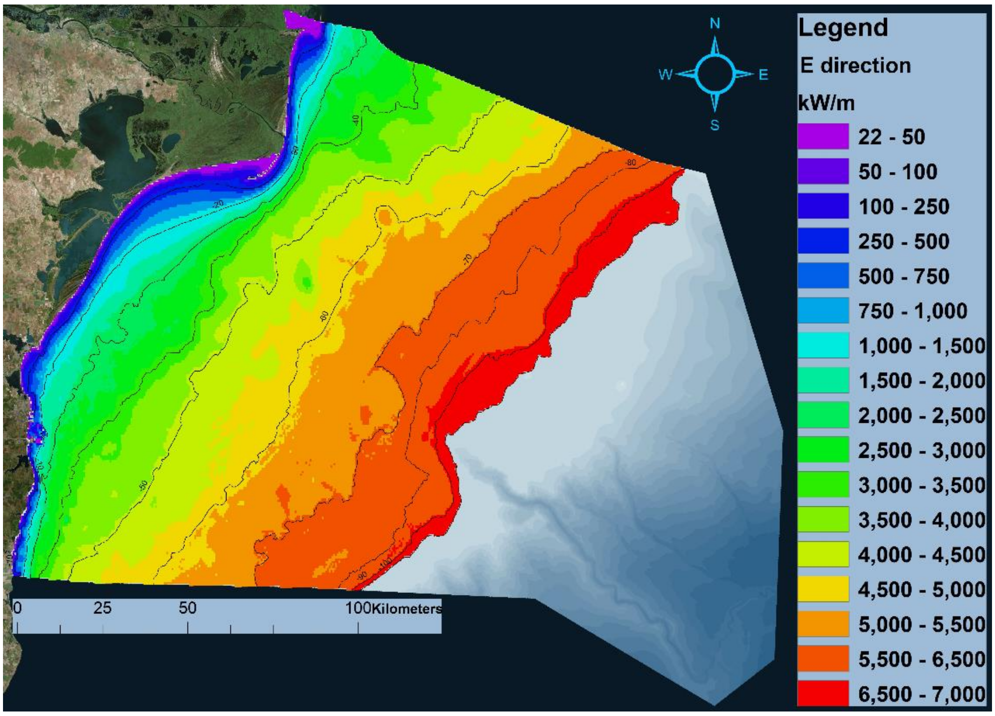


Fig. 5.6 – The interpolation result of the power values when wind blows from the east

Another map was created to illustrate how the wind from the south-east direction affects the wave field, but due to the fact that after a certain distance the influence of the fetch on the wave height is gone, and that it's result was similar to the one from the east it was shown.

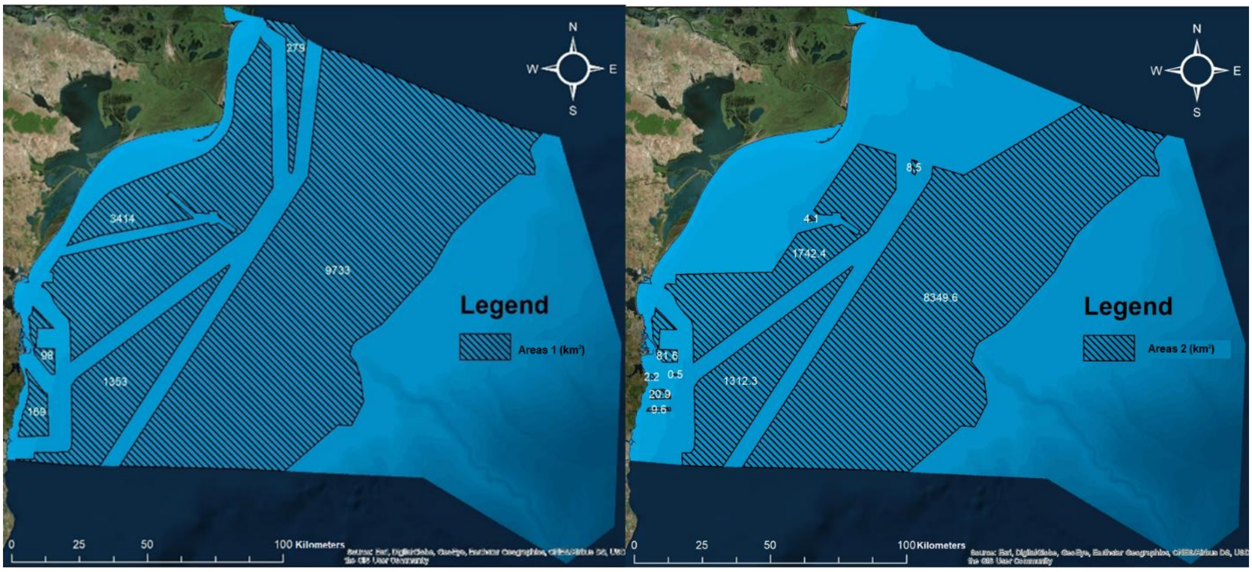
It should be noted that these results represent only one idealized situation. The resulting values take into account a fully developed wave regime, with a rarely encountered wind force (only a few storms over the years). For a more realistic estimation, simulations and calculations should be made for every minute of each day of a year to be able to accurately show the wave / wave values over the time frame.

5.3. Estimates of power per linear meter of wave

To provide insight on the renewable energy potential of the Black Sea, the available sea surface on which different converters can be installed should be evaluated. Therefore, this analysis takes into account the Marine Protected Areas, 2 Mai - Vama Veche Reservation, the shipping lines, the anchorage areas and the forbidden area of the oil platforms.

Two situations have been created, one in which all prohibited areas are taken into account, and a second one in which the protected natural areas, of community interest (SCIs - Sites of Community Importance) are left out [38].

It should be noted that on the basis of art. 28 from NGO no. 57/2007, the activities carried out within the protected natural areas of community interest are prohibited if they cause pollution, damage the habitats or disrupt the species for which they were created. In order to carry out a project or a plan in a protected natural area of community interest, an appropriate assessment of the potential impacts on these areas should be made in accordance with their conservation objectives [39] [40] [41] [42]. Based on the above considerations, several maps were elaborated to illustrate the potential areas of the continental shelf (to a depth of 100 m) to install energy converters and overlapping them with the power density values (for wind and wave) that resulted from the equations.



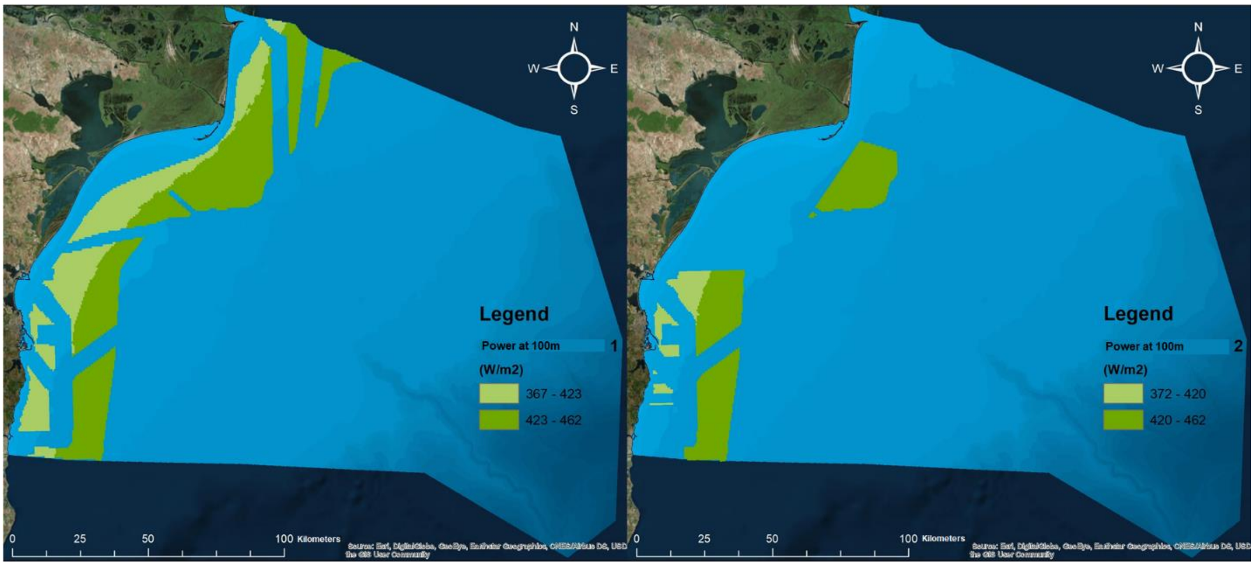
a) b)

Fig. 5.7 – Possible areas for installing energy converters

For this assessment, it was considered that the area near the coast (distance from shore to the 20 m isobath) would remain unused for the instalment of energy converters, as it would spoil the landscape, especially as the coastal area is used for tourism.

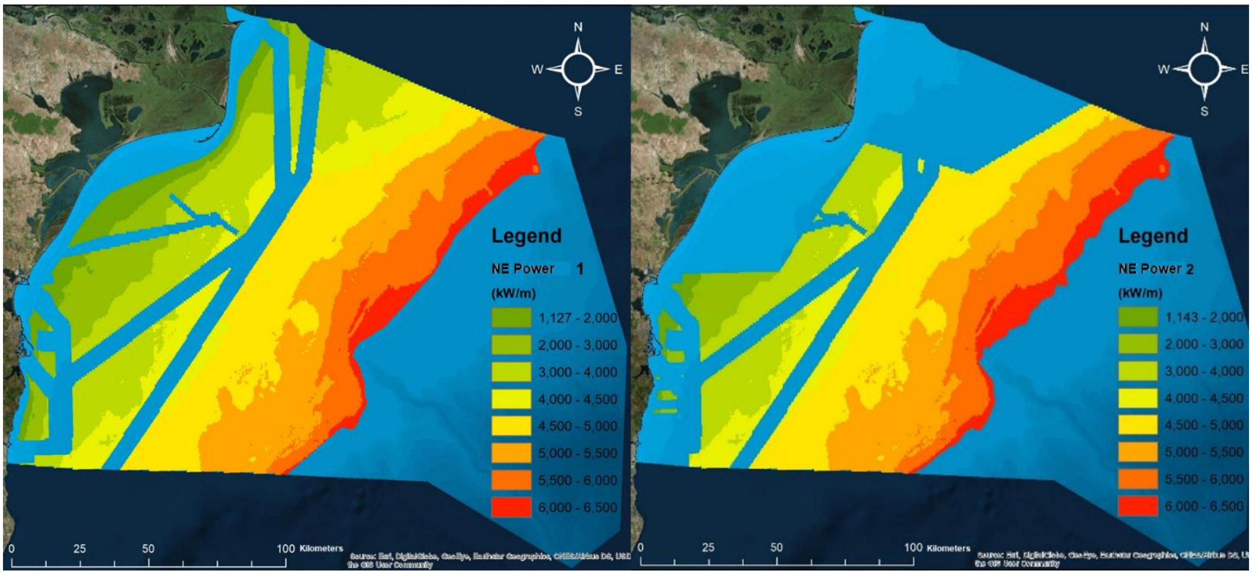
Therefore, by removing from the map the area from the shore to the 20 m isobath, the navigation routes, the oil platform area and the marine reserve areas, the remaining space (Fig. 5.7a) could theoretically be used to install energy converters. To get the map from Fig. 5.7b the areas belonging to the protected areas of community interest have also been eliminated.

A wind farm of the size considered above in the subchapter 3.2., that covers an area of approximately 64 km^2 (consisting of 72 wind turbines, with a 154 m rotor diameter and a 1.08 km turbine spacing) would find its place anywhere along the seashore in the green polygons, where the power would be between 420 W/m^2 and 460 W/m^2 (Fig. 5.8).



a) b)

Fig. 5.8 – Remaining areas and wind power density



a) b)

Fig. 5.9 – The remaining areas and wave power

With regard to the area where energy would be extracted from the waves, it must be as close as possible to the shore to be connected to an electrical grid and the wave power flux over a year should be as high as possible.

Following Fig. 5.9, it can be understood that the area closest to the shore where the wave power is between 4 MW and 4.5 MW is in the south of the coast, about 40 km offshore. However, it is possible to construct converters that would operate at a lower wave power (1 MW - 2 MW), specific to the area near the shore (Constanta Port area or more to the south) if it is desired to protect the shore and not only.

Chapter 6. General Conclusions Original Contributions and Perspectives

6.1. Conclusions

Analyzing wind and sea level data over a long period of time, it results that the variation of sea level is closely related to the wind direction, having a much more important contribution than seishes generated by sudden changes in atmospheric pressure or heavy rain. An analysis of the 1933-1968 level data shows that the mean and minimum values of May-June are higher than the rest of the average and minimum values of the other months, due to the predominance of the NE and E wind, which "inflate" the sea near the shoreline. And in January the high level is due to strong winter storms.

Based on the analysis of the wind roses and the correlation with the related photographs, the buildings' influence on the air mass movement at the hight of the instruments can clearly be observed. Thus, the Sulina station is the most reliable source in terms of wind data.

From the analysis of the wind speed distribution at Constanta station, namely the 0-3 m/s class variations, it results that during the period 1952-2005 this class had a contribution generally below 40%, exceeding the limit only seven times, in the area of 40-50%. Since 2006, the contribution of low values has exceeded 45-50% of the wind speed distribution and in the last seven years the values have fluctuated around a 65-70% contribution; over the same period the contribution of values above 6 m/s was reduced to 0-2% so it can be said that there is a significant change of the wind regime in the studied area.

Analyzing the data sets from the Romanian and Ukrainian weather stations, it results that the wind speed is higher at the end of the Danube Delta. This is due to the topography and the slighter roughness of the terrain. It is concluded that in the northern part of the Romanian coastline the wind energy potential highest is the highest, a matter that needs to be further investigated, but with an emphasis on the offshore area at altitudes of 50 m, 100 m and 150 m respectively, as this are the heights at which large wind turbines are being built.

From the storm data the analysis, it appears that the power, duration and number of storms has decreased over the last 10 years.

The establishment and use of technologies (taking into account aspects such as corrosive environment, extreme weather conditions, force variability and low wave frequency) has rendered them still in development / refinement. Over the past 25 years the efforts to construct devices that would convert the wave energy have been multiplied.

The maximum measured sea current velocity values during the experiment period were 0.36 - 0.39 m/s. These values were recorded south of Mangalia port, where the seabed topography plays a very important role in increasing the velocity of the sea current. It should be noted that during the experiment, the sea condition was good, the maximum wave height at sea being 0.5 m. In terms of the power density the marine current does not offer much, with a value of 0.198 kW/m^2.

6.2. Original contributions

The specific contributions of this study are listed below:

- assessing the wind conditions, characterizing the northwest Black Sea area, using large series of long-term data,
- carrying out a comparative wind surveys recorded by the meteorological stations along the Romanian seaside in relation to those recorded offshore,
- comparative analysis of the two models results (Mohid and POM) with wind data measured at the Sulina meteorological station in order to gain a better understanding of how the two models perform the simulations in order to help improve the simulations, for the northwest Black Sea area,
- estimating wind power density at different heights based on GWA data compared to the measured weather data,
- identifying areas of interest regarding the wind energy potential,
- evaluating wave power based on depth, wind speed, fetch, significant wave height value, wave period and main propagation directions,
- identifying areas of interest regarding the wave potential,
- assessing the hydrodynamic conditions of the marine current field based on field measurements recorded during a three-day experiment and identifying areas where the current is changing due to bathymetry and shoreline configuration,
- producing maps containing possible locations regarding the installation of renewable energy converters and at the same time eliminating the possibility to overlap with the functional and prohibited areas of the marine space.
- simulations made with SWAN concerning the impact of a wind farm on the wave field have not been accomplished so far at a high resolution
- the power per linear meter of wave correlation between the significant wave and period considering the bathimetry was approached although it is a difficult process.

6.3. Perspective

Below are some research directions and suggestions.

- Monitoring and collection of wind, wave and marine current data by installing multiple multiparameter buoys in the Black Sea (at various points of interest) to conduct studies concerning the power of these parameters in multiple weather situations (including storm situations) over the years.
- Coupling direct measurements from buoys with marine current patterns and waves (Mohid, SWAN and POM respectively) to perform improved simulations and forecasts.
- A future direction to be considered is the design of energy converters in a form that integrates the three energy sources (wind, wave and sea current) into a single "island" of renewable energy. They could be built in a matrix form specially designed to better fit the environmental conditions in the locations where they will be installed. This would increase the efficiency of energy conversion from the three sources, relative to the covered / developed area.
- A plan on how to collect marine current data

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