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Analysis of hydrographic and meteorological data from the N-NW Black Sea necessary for the prediction of drifting floating mine routes in the vicinity of the Romanian coastline

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Abstract. In the context of the armed conflict between Russia and Ukraine, the Russian authorities issued a warning on March 18, 2022, stating that due to severe hydrometeorological conditions in the northern Black Sea basin, more than 400 floating mines, an integral part of Ukraine's port defense system, were torn from their moorings in the ports of Odessa, Ochakov, Chernomorsk and Pivdenny. Due to the dynamics of the hydrographic circulation of the Black Sea, the floating mines moved southwards, reaching the Turkish coast. Obviously, the imminent danger of explosion of these mines makes maritime traffic in the area unsafe. Consequently, an elaborate study of the present hydrometeorological conditions in the western Black Sea and their short-term forecasting, as well as the establishment of hydrometeorological models, are needed to predict the routes of drifting floating mines. Once the mathematical model of the movement trajectory has been established, the safe identification, interception and annihilation of drifting floating mines can be undertaken. This paper aims to analyze the hydrographic and meteorological conditions provided by the Romanian coastal stations in order to establish the model of the movement of water masses and wind along the Romanian coastline necessary to establish the movement routes of drifting sea mines

Keywords: drifting floating mines, hydrometeorological conditions

1. Introduction

The Black Sea, considered as an inland, continental sea, is located between Europe, Anatolia and the Caucasus, covers an extended area of about 423,000 km² and contains a water volume of about 555,000 km³. It has an average depth of 1315 m, with a maximum depth of 2258 m (Fig. 1). The geographical coordinates 40°54'- 46°38' latitude and 27°27'- 41°42' longitude, place it in the northern hemisphere, temperate zone. It communicates to the south-west with the Mediterranean Sea through the Bosphorus and Dardanelles Straits, and to the north with the Sea of Azov through the Kerch Strait [1].

Bordering Romania, Ukraine, Russia, Georgia, Turkey and Bulgaria, the Black Sea is characterized by its irregular shape, with the largest bays, Burgas and Varna, located in the western part (off the coast of Bulgaria), followed by Odessa and Karkinit in the north-west, and Kalamit and Feodora in the north (off the coast of Ukraine). In the east are the bays of Novorossiysk and Gelendzhik (off the coast of Russia) and in the south the bays of Sinop and Samsun (off the coast of Turkey).

The bathymetry of the Black Sea consists of the continental shelf (shallow shelf) with depths of (100...200) m, the continental slope, the continental piedmont and the abyssal plain (Fig. 2) [1], [3].

The configuration of the bathymetric line, as well as the presence of depressions and canyons, substantially influence the distribution of water masses, the direction and velocity of water currents.



Figure 1. Satellite image of the Black Sea [2]



Figure 2. Morphologic zone of the N-W Black Sea [3]

2. The hydrodynamic processes characterization in the Black Sea

The main cause of hydrodynamic processes occurring in any marine environment are the result of complex interaction phenomena between seawater and the atmosphere. The exchange of energy between the two environments is due to the action of the wind, which causes the formation of waves and surface (drift) currents [4]. In addition, the difference in density between the water layers produces surface currents from low-density to high-density areas, called deep (convection) currents [5], which, however, affect the drift motion of floating objects to a minor extent.

For the purpose of the present work it is important to analyze the influence of meteorological wind characteristics influencing the surface dynamics of water bodies.

2.1 Wind conditions

The wind, acting parallel to the water surface, transfers potential energy to the water mass through the frictional force, which generates drift currents. At the same time, the surface of the water is deformed by the wind, producing capillary waves [6].

The western part of the Black Sea has a high energetic potential, the wind reaching average speeds of 6 m/s in summer and 8 m/s in winter (see Fig. 3) in front of the Gloria Platform, which makes the

seasonal aerodynamic variations on the Romanian coast much more pronounced compared to the eastern part of the Black Sea, characterized by a relatively stable dynamic regime of air masses [7].

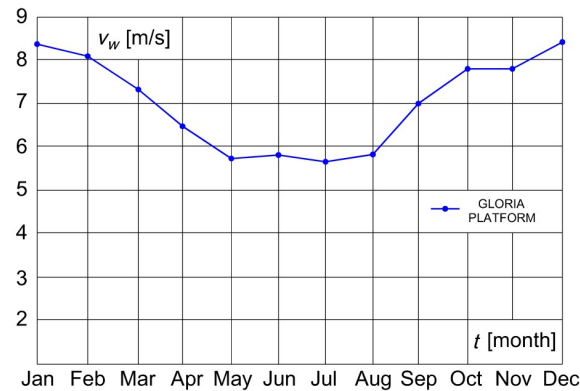


Figure 3. Monthly average wind speed values for the North-Western sector of the Black Sea based on meteorological data from the Gloria Platform, 1999-2009 [7]

The atmospheric circulation regime has a pronounced variability, the winds of record having a high degree of instability, both in terms of direction and speed, with no regular winds. The winds along the Romanian Black Sea coast are generally light to moderate and storms in the area are rare.

The data provided by the National Research and Development Institute for Marine Geology and Geocology (GeoEcoMar) are used to determine the average annual wind speeds off the Romanian coasts for the period 2015-2020 (Fig. 4).

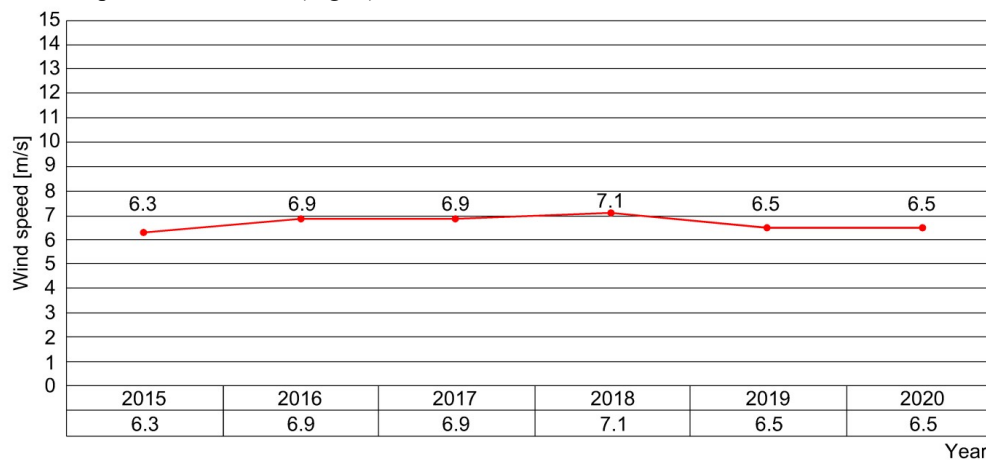


Figure 4. Annual average wind speed off the Romanian coasts, 2015-2020 (GeoEcoMar) [8]

The data come from autonomous marine monitoring stations that are part of the EUXIN network, part of the Black Sea security system. EMSO-EUXIN is the regional security system for the western Black Sea to alert authorities in real time in case of marine geo-threats (underwater earthquakes, submarine landslides, active fault movements, tsunami waves, etc.). The three complex EuxRO buoys are located on the Romanian continental shelf at a distance of about 160 km from the coast (Fig. 5), with the agreement of the Ministry of National Defense, through the Romanian Naval Forces, represented by the Marine Hydrographic Directorate (MHD).



Figure 5. Positioning of EuxRo autonomous marine monitoring stations on the Romanian continental platform [8]

The influence of topography plays a crucial role on wind distribution. The meteorological station located offshore, on the Gloria Platform, provides the most realistic wind distribution along the Romanian coastline, the wind rose being based on the daily wind vector (see Fig. 6).

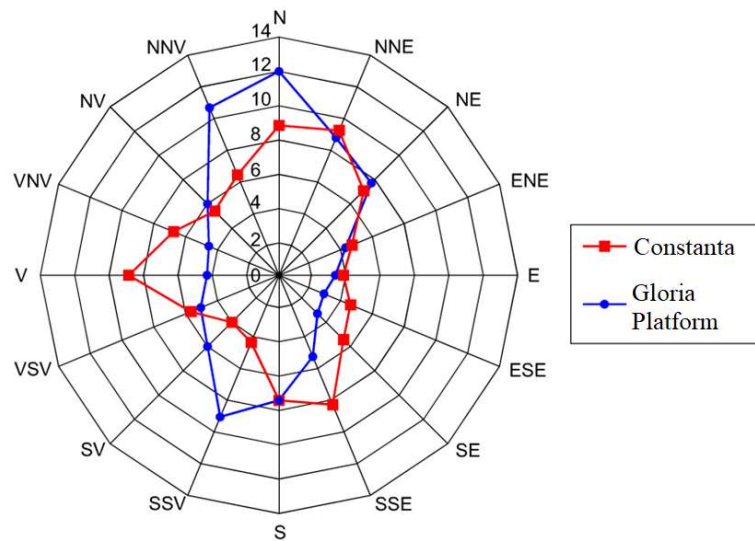


Figure 6. Wind direction distribution measured by the meteorological station on the Gloria Platform, interval 1952-2020, respectively Constanța, interval 1965-2000 [8]

As can be observed, the offshore wind distribution shows the highest values in the N, NNV and SSV directions, while on the coast, at the Constanța station, the winds with the highest frequency are oriented in the V direction, the measured data in this case, however, having a high degree of uncertainty due to the nearby buildings blocking the airflow.

The predominant frequency of the offshore winds on the N-S-S and NNE-SSV axes explains the movement of drifting objects along the Romanian coast from Ukraine towards Turkey.

2.2 Wave conditions

Waves are gravity-driven oscillatory motions produced in free-surfaced water by some disturbance [9].

The main causes of the occurrence and manifestation of sea waves are wind action, the attraction of the Moon and the Sun, seismic movements of the seabed, volcanic eruptions or the movement of partially submerged bodies through the water.

Sea waves generated by wind action are regular or random and can be classified as follows [4], [9]:

- Wind waves, i.e. oscillatory motions generated by frictional forces between moving air and liquid particles on the water surface;
- swell waves, i.e. oscillatory motions remaining after the wind ceases due to the inertia of the water masses;
- break waves, i.e. oscillatory motions formed close to the shore when, due to shallow depths, the wave crest rises, bends forward, bends and then collapses (breaking).

In practice, the assessment of wave characteristics is based on the force of the wind that causes the waves (see Table 1) and the local characteristics of the catchment. Thus, for the Black Sea, the maximum values of wave parameters are: significant height, $H_s = 3$ m; length, $L_v = 43$ m; apparent speed, $c = 8.2$ m/s [8].

Table 1. Sea state scale as a function of wind [8]

Wind characteristics		Wave created characteristics				Sea conditions
Force F_v [Bft]	Speed v_v [km/h]	Length L_v [m]	Height h_v [m]	Speed v_v [m/s]	Period T_v [s]	
I	II	III	IV	V	VI	VII
0	< 1	-	-	-	-	Quiet. Smooth sea
1	1...5	-	-	-	-	Light breeze. foam-free waves
2	6...11	-	-	-	-	Light breeze. Pronounced waves that don't break
3	12...19	-	-	-	-	Light wind. Small waves with glassy breaking crests
4	20...28	-	-	-	-	Small waves up to 1.5m high with rolling crests
5	29...38	25	1,2	6,2	4,0	Strong wind. Medium waves with breaking crests
6	39...49	39	2,16	7,8	5,0	Very strong wind. High waves with crests breaking and splashing
7	50...61	87	4,0	11,8	7,0	Strong wind. Big waves, and the sea is foamy
8	62...74	85	5,0	11,5	7,4	Very strong wind. Large waves with arched crests
9	75...88	138	8,4	14,7	9,4	Storm. Big, rolling waves
10	89...102	180	11,5	16,8	10,7	Strong storm. Violent waves, the sea is white and rough, low visibility
11	103...117	285	12,6	21,1	13,5	Severe thunderstorm. Exceptionally high waves, reduced visibility
12	> 118	376	14,5	24,4	15,5	Hurricane. Huge waves, the air is full of foam and water, visibility near zero

The distribution of waves along the direction of propagation is determined by the distribution of the prevailing winds and the general orientation of the shore. In coastal areas, where the water depth is shallow, the wave distribution becomes non-symmetric due to the limitation of fetches (areas on the water surface where the wind has constant characteristics) on the one hand and, on the other hand, due to the refraction phenomenon that determines the orientation of wave crests parallel to the shoreline [6].

The direction of wave propagation along the Romanian coast, according to the data of the National Research and Development Institute "Grigore Antipa" (INCDM), is predominantly NE-E-E-SE, and the average annual wave height, calculated by several authors, is (0.8...0.98) m [10] (Fig. 7).

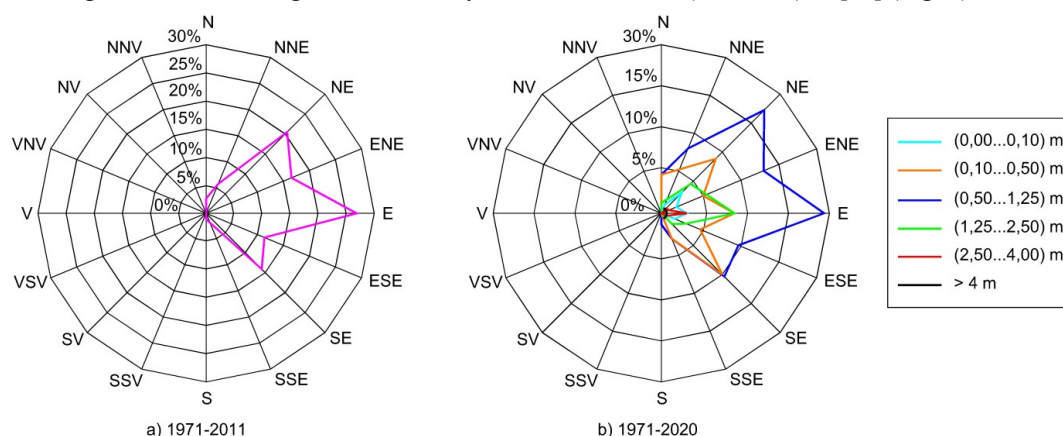


Figure 7. Distribution of wave propagation direction frequencies in the Constanta area, 1971-2011 [4], a); Wave height frequency in cardinal directions at Constanța station, 1971-2020, b) [8]

The predominant frequency of the direction of wave movement on the NE, E, SE axes explains the movement of drifting floating objects along the Romanian coast, from the open sea towards the coast.

2.3 Marine current conditions

The horizontal displacement of water masses under the action of a combination of forces due, in general, to wind action, inhomogeneity of water volume, accumulation of runoff in the area of the spill and the slope of the sea surface due to the variation of atmospheric pressure, lead to the formation of marine currents.

The main current of the Black Sea (Rim) is of a peripheral type and encircles the entire basin at the edge of the continental shelf in a cyclonic direction. Within it, two other cyclonic loops (West and East) form in each half of the basin. Medium-scale anticyclonic loops are formed at the periphery of the main current (Batumi area, permanent character; to the SW of Sevastopol and to the E of Kali-Akra, semi-permanent character; W continental shelf, transient character [12]) (Fig. 8).

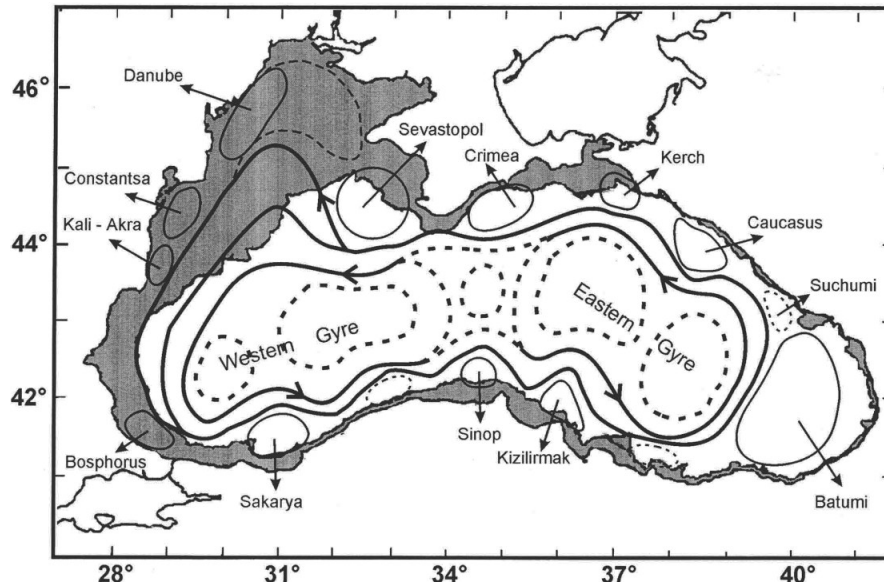


Figure 8. General circulation of main currents in the Black Sea [11]

The circulation of marine currents in the coastal area of the north-western Black Sea has specific characteristics due to higher wind speeds compared to the inland areas of the basin.

Also, the freshwater inflow in the area, due to the overflow of rivers and streams into the sea, leads to the emergence of a quasi-stationary current system. Thus, in the area of Romania's continental shelf, in front of the Danube Gorges, there are two currents, one from north to south and the other from south to north.

The north-south current flows in the littoral zone, right next to the shore, over the entire depth, with velocities of (0.33...0.47) m/s. The south to north current flows in a compact mass over a width of 40 Mm, up to a depth of 10 m, with an average velocity of 0.47 m/s and tends to keep the north to south current near the coast [12].

Along the Romanian Black Sea coastline, the marine currents are highly unstable, both in terms of direction and speed, mainly due to the variable wind regime, which can change direction and intensity several times, even during the same day.

As in the area of the Romanian Black Sea coastline the prevailing winds are from the North and North-West, much stronger than the others, the long-term average result of the surface marine currents is oriented approximately from N-E to S-V.

3. Research methodology

3.1 Determining the area of analysis and data sources for the research

The area subject to the analysis of surface circulation in the Black Sea refers to the Romanian continental shelf of the Black Sea, as removed by the decision of the International Court of Justice (ICJ) in The Hague on February 3, 2009 (Fig. 9).

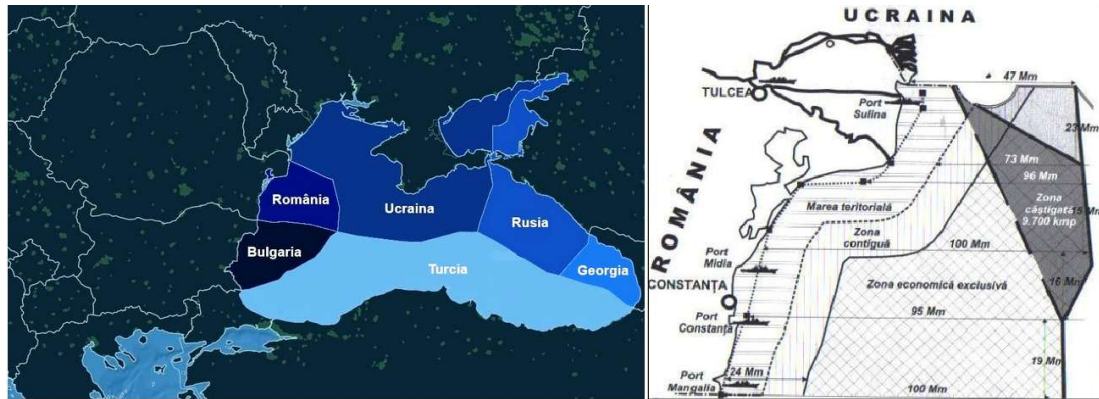


Figure 9. Romanian continental platform of the Black Sea delimited by the ICJ decision [13]

The National Administration of Meteorology (ANM) is the Romanian meteorological institution whose field of activity is meteorological and climatological observations on the Romanian territory.

The national network of meteorological observations and measurements consists of 160 automatic meteorological stations (SMA), 8 Doppler radar systems, 1 satellite data reception system (MSG) and 64 rain gauges.

On the Romanian coastline there are 5 permanent stations for monitoring and collecting environmental information (Sulina, Sfântu Gheorghe, Gura Portiței, Constanța, Mangalia), 3 autonomous marine monitoring stations (EuxRo1, EuxRo2, EuxRo3) and the hydrometeorological station on the Gloria Platform, as can be seen in Fig. 10.

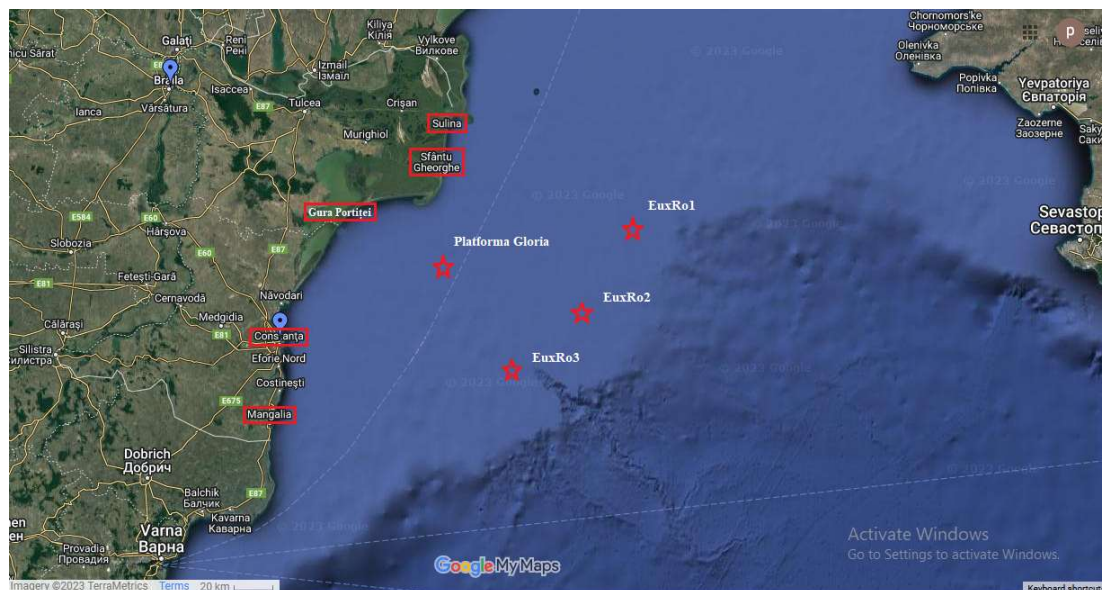


Figure 10. Location of permanent stations for hydrometeorological monitoring of the Romanian coasts [14]

In order to collect the hydrometeorological data necessary for the present study, it is necessary to query the wind, waves and currents databases provided by at least 3 permanent stations, the one in Sulina, which represents the entrance into the Romanian area, the one in Mangalia, which represents the exit from the Romanian area and the one on the Gloria Platform, in order to establish a triangulation of the determinations. Of course, for a high accuracy of the determinations, it is necessary to have access to the databases provided by all the permanent stations listed above.

The data collected from the measurement points must cover a period of at least 20 years in order to be able to establish a mathematical model to establish the general trend of the circulation dynamics in the N-NW Black Sea. Due to the unpredictability of environmental parameters, which can change even within a few hours, only seasonal motion models can be established, which provide general drift trends of floating objects under the action of environmental factors. Once the drift sector of the floating object is established at a given point in time, search and interception vessels can much more usefully manage and focus their search routes and search patterns at sea.

Based on the databases provided by hydrometeorological stations over the last 20 years, seasonal data necessary to determine the direction and intensity of wind, wave and current vectors are obtained, leading to the establishment of the analytical relationship of motion of a drifting object.

3.2 Determining the general seasonal circulation pattern in the N-NW Black Sea

In order to determine the general trend of seasonal circulation in the N-NNW Black Sea it is necessary to determine the vector of the resultant force acting on a point on the sea surface.

The expression of the elementary force due to environmental factors acting on the unit mass, in unit time, is:

$$F_1 = m \cdot a = m \cdot \frac{v}{t} = v, \quad (1)$$

where:

m - the mass of the floating object in kg, a - the acceleration of the floating object's motion in m/s², v - the speed of the floating object's motion in m/s, t - the time interval in which the floating object's motion takes place in s.

The vector equation of the resultant force acting on a buoyant object, as a function of the dominant environmental vectors, is written as:

$$\vec{R} = \vec{F}_a + \vec{F}_c + \vec{F}_v, \quad (2)$$

where:

$\vec{F}_a$ - wind force vector, $\vec{F}_c$ - force vector due to surface currents, $\vec{F}_v$ - force vector due to waves.

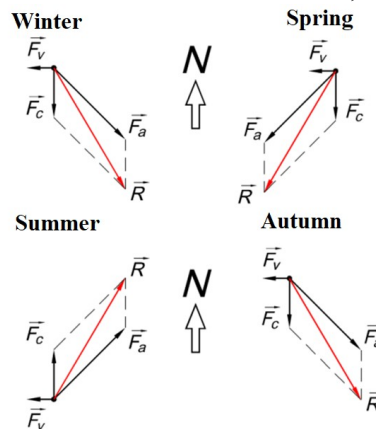


Figure 11. Seasonal estimation of the resultant vector acting on the floating object

Considering that waves are vertical oscillatory movements of water particles and that the average annual wave height in the vicinity of the Romanian coastline does not exceed 1 m, they affect the direction of movement of drifting floating objects to a small extent. Thus, depending on the available general seasonal average data for wind and surface currents, the resultant vector acting on the drifting object has the orientation shown in Fig. 11.

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