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Variability of Wind-Driven Coastal Upwelling in the North-Eastern Black Sea in 1979–2016 According to NCEP/CFSR Data

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Abstract—This paper presents the variability of wind-driven upwelling based on results of the coastal upwelling criterion analysis for the Gelendzhik region of the Black Sea for 1979–2016 years. The calculations of the criterion are based on the wind data from reanalysis of NCEP-CFSR. The proposed method is used for the analysis of long-term upwelling variability in the Black Sea for the first time. This method allows detecting both full and incomplete upwelling in contrast to measurements of the sea-surface temperature (SST) on regular coastal weather stations or on satellites. Current study shows more than 100 cases of the upwelling (when upwelling criterion < -1) for 37 years in total, and some of them were confirmed with a satellite images. Comparison of the SST from Gelendzhik meteostation and upwelling criterion revealed that 70% of the upwelling cases are related to decrease of the temperature on sea surface. It is shown that the highest probability of wind upwelling events is detected in the mid-summer period. Interannual variability of the coastal upwelling criterion is very high, there was 1 year (2010) when no upwelling cases were registered, and maximum 8 cases are registered for 1987 year. There are three cases of upwelling on average per year. The process of the coastal upwelling depends on wind impact, but also on direction and strength of the coastal current. Study of the upwelling and its variability is necessary to supplement knowledge about coastal dynamic processes that affect the ecosystem and the recreational potential of the region.

Key words: Coastal upwelling, upwelling criterion, Black Sea, thermistor chain, wind reanalysis.

1. Introduction

One of the most important processes in the coastal ocean is upwelling, the movement of water from deeper layers of the sea to the surface (Tomczak and Godfrey 1994). As a result of upwelling, the upper boundary of the seasonal thermocline in the shelf zone can rise to the sea surface and remain there for several days. Such short-period alteration of the hydrological structure is accompanied by intensive advection of waters and their vertical and horizontal mixing. This has significant influence on local hydrochemical structure, the flow of biogenic and polluting substances, and changes the conditions of the coastal ecosystem. Both Tuzhilkin et al. (2012) and Zatsepin et al. (2016) described specific cases of coastal upwelling in the researched area of the Black Sea. Upwelling in the coastal zone across different parts of this region had been researched by Blatov and Tuzhilkin (1990), Borovskaya et al. (2005) and Novikov and Tuzhilkin (2015). Understanding of the physically processes of coastal upwelling permits more accurate interpretation of results in such different topics of the ocean science as marine ecosystems monitoring or generation and distribution of internal waves.

Interannual variability in coastal upwelling processes is difficult to analyze due to lack of long-term measurements of sea temperature. However, using satellite data permits studying upwelling for the most recent 25 years. An early usage of satellite data for such analysis was presented by Ginzburg et al. (1997), who studied the spatial-time variations and thermohaline characteristic features of upwelling in north-western part of the Black sea. Satellite data, however, are non-regular in its time sampling, and thus, there is no opportunity to capture all events. Novikov and Tuzhilkin (2015) used in situ measurements of the sea-surface temperature (SST) to studying upwelling around meteorological stations of Anapa, Gelendzik, Tuapse, and Sochi. In both cases (satellite and in situ measurements of the SST), it is impossible to detect events of incomplete upwelling. If the under-thermocline water is observed near the sea surface, the process is referred to as full

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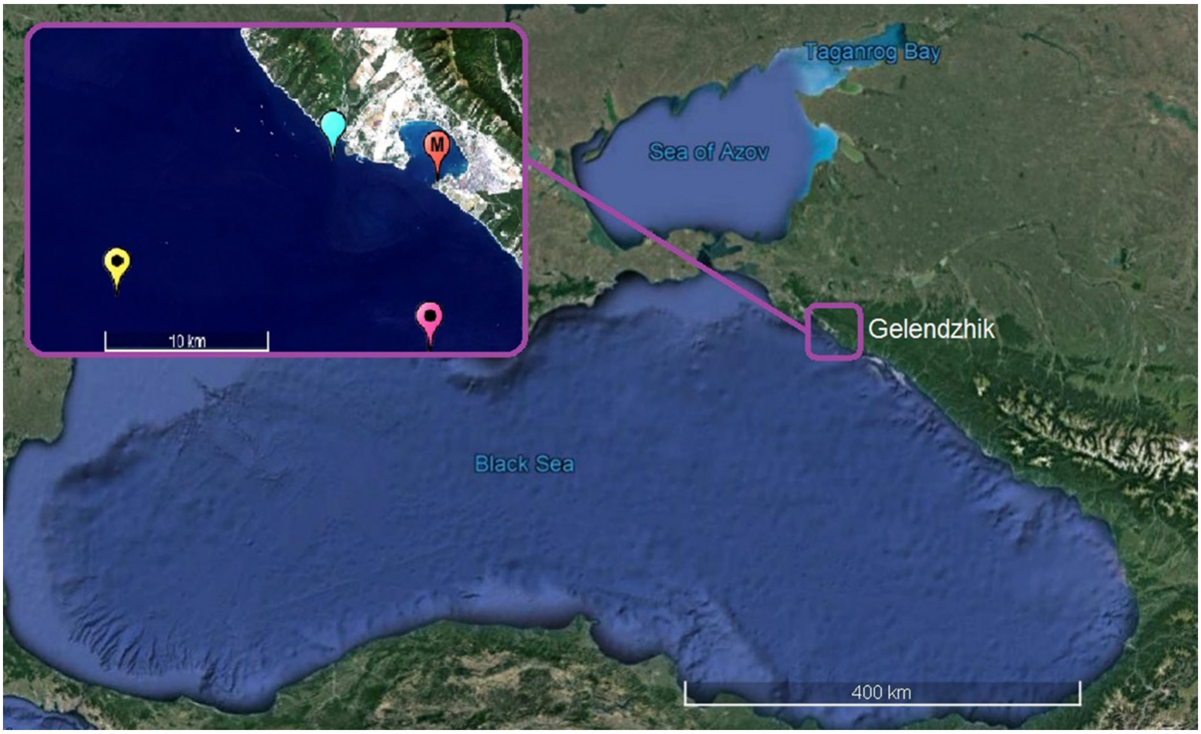

Figure 1
Overview over the research area: blue mark indicates thermochain deployment location, M-mark—Gelendzhik meteorological station, yellow, and pink marks—reanalysis points of 0.3°/0.2° resolution, respectively

upwelling; otherwise, it is incomplete. Intensive wind stress can lead to either full or incomplete upwelling depending on local water dynamics and stratification. The frequency of incomplete upwellings is higher than the complete cases and these processes also have a significant impact on coastal ecosystems. Such events were observed by Silvestrova et al. (2017) in thermal water structure and measured by the moored thermochain.

The temperature difference between the zone of upwelling and the surrounding waters at the sea surface is 5–10 °C (Silvestrova et al. 2017). Ginzburg et al. (1997) observed such a temperature difference in the coastal zone with a characteristic width ranging from 10 km to over 100 km in the Black sea. The present study is about climatology of wind-driven upwelling possibility of occurrence in the north-eastern Black Sea based on calculation of the upwelling criterion (1) for 1979–2016 years. Comparison of the upwelling criterion and data from the thermochain (for 2013–2015 years) shows that the criterion for the Ekman upwelling is a useful predictor of its occurrence (Silvestrova et al. 2017). The bioproductivity of the Black Sea shelf zones would be much lower in the absence of local upwelling and downwelling. These processes lead to a transformation of hydrological structure and mixing processes, which would maintain a sufficiently high concentration of biogenic elements in the upper euphotic layer.

1.1. Data Description

The study area for the present analysis is located in the north-eastern part of the Black Sea near Gelendzhik city, Russia. Nowadays, a sub-satellite hydrophysical testing site is operating in this coastal zone of the Black Sea (Zatsepin et al. 2014), the purpose of which is long-term monitoring of water dynamics with a sub-mesoscale spatial resolution, including cycles of upwelling and downwelling. The region is characterized by a narrow shelf with active water dynamics, influenced by the Rim Current and mesoscale eddies with typical diameters from 40 to

100 km (Zatsepin et al. 2012). The location of the research area is shown in Fig. 1.

Surface wind velocity (*u*, *v*), temperature and salinity of water, and thickness of upper mixed layer (UML) were used as input data for calculating the upwelling criterion and Ekman transport. Wind forcing determined by the NCEP Climate Forecast System Reanalysis high-resolution data set (1979–2010) is used. This reanalysis described by Saha et al. 2010. The spatial resolution of the reanalysis data is ∼ 0.3°, while temporal resolution is 1 h. An updated version (Climate Forecast System Version 2, described by Saha et al. (2014)) with spatial resolution ∼ 0.2° is used for the period 2011–2016. The nearest reanalysis points to Gelendzhik are located 10–15 km offshore (Fig. 1).

NCEP/CFSR data were finally selected after a consideration of a number of such products. This product offers the highest spatial and temporal resolutions in comparison with such reanalysis as MERRA, JRA, and ERA-Interim (Lindsay et al. 2014). A comparison between wind speeds from reanalysis and from the meteorological stations of Anapa and Novorossiysk showed good agreement in the regular speed range 5–10 m/s, but NCEP/CFSR underestimates higher wind speeds (Myslenkov and Chernyshova 2016). Van Vledder and Akpinar (2015) compared wind speeds from the reanalysis to satellite data and found BIAS is –0.5 m/s and RMSE is 2 m/s. Several different wind reanalyses were used for the Black Sea wave modelling and minimal errors in the wave fields occured using NCEP/CFSR (Akpinar and Ponce de León 2016).

We use SST data series from Gelendzhik meteorological station, located in the Gelendzhik bay, and time series of the vertical temperature distribution in the sea from the thermochain. For the SST measurement, the time step is 6 h, more information about meteostation data described by Moskalenko et al. (2016). The thermistor chain (thermochain) consists of 17 temperature-sensing elements deployed on a buoy station with subsurface buoyancy. It was moored about 1 km offshore at a depth of 22 m at the satellite-covered hydrophysical test site of the Shirshov Institute of Oceanology, Russian Academy of Sciences (Zatsepin et al. 2014, Ocherednik et al. 2018), across from the Golubaya Bay near the city of Gelendzhik. The sensors were placed on a wire at an equal distance (0.8 m) between them in the 6–20 m depth range. The sampling rate was 30–60 s, and the accuracy was ± 0.05 °C.

In addition, for confirming some subset of the observed upwelling cases, we use satellite images from NOAA with SST data.

1.2. Upwelling Criterion Calculation

Zatsepin et al. (2016) and Silvestrova et al. (2017) described and verified wind upwelling criterion *Ru* for the investigated area as

$$Ru = \frac{w \cdot t}{H} < -1 \tag{1}$$

$$w \approx \frac{\tau y}{f \cdot \rho \cdot Rd}. \tag{2}$$

It is calculated as a ratio of the vertical water velocity (w), determined by the Ekman transport (1), and the upwelling wind action time (t) to the thickness of the upper mixed layer (H). The alongshore wind stress (τ_y), the baroclinic Rossby radius (Rd), water density (ρ), and the Coriolis parameter (f) are used for the Ekman transport calculation. The upwelling criterion was calculated for all months, except winter (December, January, February, and March) when seasonal cooling of the upper layer and the weak winter stratification made identifying *Ru* impossible.

The determining factor for the wind upwelling development is the integral wind force, which is comprised of wind stress and the time of upwelling wind action, because all other parameters are fixed or presented as an average monthly values. For the alongshore wind stress calculation, the wind components were rotated for 50° counterclockwise according to direction of the coast in the studied area. Therefore, the τy positive direction corresponds to the south-eastern wind and the threshold value for the upwelling criterion is -1. The physical meaning of the threshold value is showing moments of time when the Ekman transport is strong enough for the under-thermocline waters to reach the sea surface.

The monthly averaged UML thickness is determined from the earlier observations of water structure

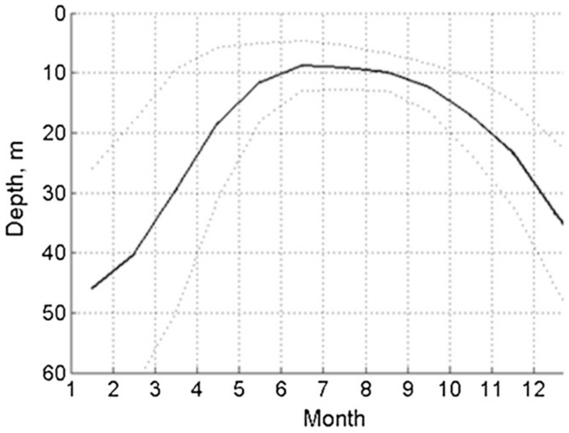

Figure 2
Average thickness of the UML for the research area

on testing site described by Zatsepin et al. (2014). The UML thickness is presented in Fig. 2.

2. Results

The upwelling criterion was calculated at a 1 hourly temporal resolution, then values of one sign are summed up until sign changes, and every value of *Ru* is assigned to the final time of the case. We found ∼ 120 cases when $Ru < -1$. In addition to calculation of the criterion for 37-year period, we try to compare all the cases with SST data series from Gelendzhik meteostation. Figure 3 presents the joint graph of the meteostation SST and the upwelling criterion for 2012 year.

Comparison of the SST and *Ru* reveals that 88 cases (∼ 70%) are related to a decrease of the temperature of the sea surface, 51 of them reflect a decrease of more than 5 °C. For example, a temperature changes from 24.4 to 18.6 °C on June 20, 2012. This case was confirmed by satellite data—see Fig. 4. The validity of the upwelling criterion (*Ru* was − 0.73) was also confirmed for the full upwelling on June 17–19, 2009. The temperature decreased for 5 °C at the sea surface.

Tuzhilkin et al. (2012) described this case, and it was observed by the contact measurements.

Is there a temperature response to upwelling winds in other cases? For further analysis, we visualize the vertical distribution of water temperature from the thermochain for the period from July 15 to September 23, 2012 (Fig. 5). There were few events when thermocline upwelled to the depth of 10 m. For one event on September 1, 2012 *Ru* reached − 1.14; for others, *Ru* was around − 0.75. The criterion was − 1.19 on July 20, but thermocline water did not upwell neither to the surface nor even to 10 m below

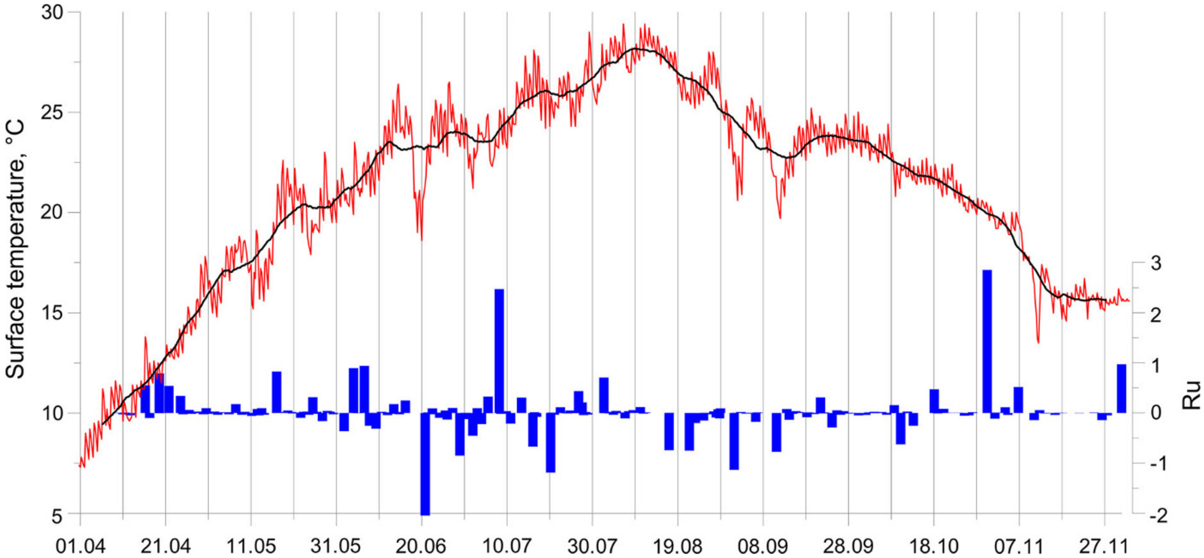

Figure 3
Meteostation SST and the upwelling criterion for 2012 year. Blue bar chart—upwelling criterion, red line—SST, black line—SST running average for 11 days

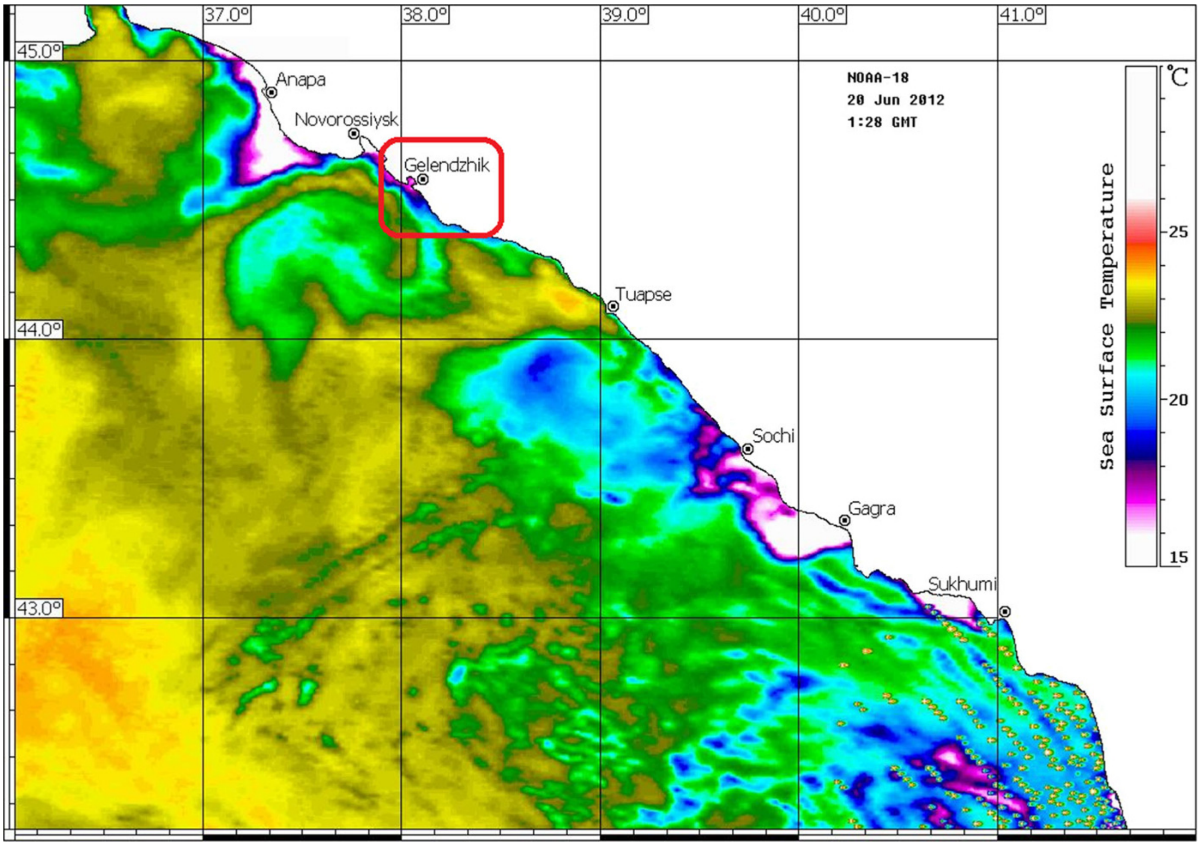

Figure 4
SST from NOAA satellite image for June 20, 2012. Red square indicates researched area

the surface. Nevertheless, such data show that oscillation of *Ru* leads to vertical movements of water, although they are not always observable at the surface. Silvestrova et al. (2017) compared the upwelling criterion and data from the thermochain. According to this work, all cases when the criterion was close to –1 are connected with temperature changes, but do not always lead to the full upwelling.

We find some cases when *Ru* was sufficiently high, but there was no coincident evidence of the upwelling at the sea surface. We also find the inverse to be true. This could be due to several reasons. Upwelling in this region is not solely triggered by wind stress. Local water dynamics (the system of the alongshore currents and eddies) has a strong impact on the processes of upwelling and downwelling (Silvestrova et al. 2017). An absence of the upwelling trace at the sea surface demonstrates the interaction between local dynamics and wind stress. There could be strong wind forcing, but if it is not intensified by the south-eastern current or it is counteracted by the north-western current, the cold water will never ascend to the surface. However, there could be incomplete upwelling at some depth. There were few cases with a strong water temperature decrease without high upwelling criterion, which were connected with offshore winds or with water dynamics.

The seasonal distribution of local upwelling events, when $Ru < -1$, is presented in Fig. 6. A clear peak of the number of events observed in July (appr. 38%). Although there were many cases with high integral Ekman transport in April and November, this did not lead to a high number of events when $Ru < -1$, because average thickness of the UML in these months is more than 20 m. The thickness of UML can vary significantly depending on the water dynamics and other factors. For example, if in April/

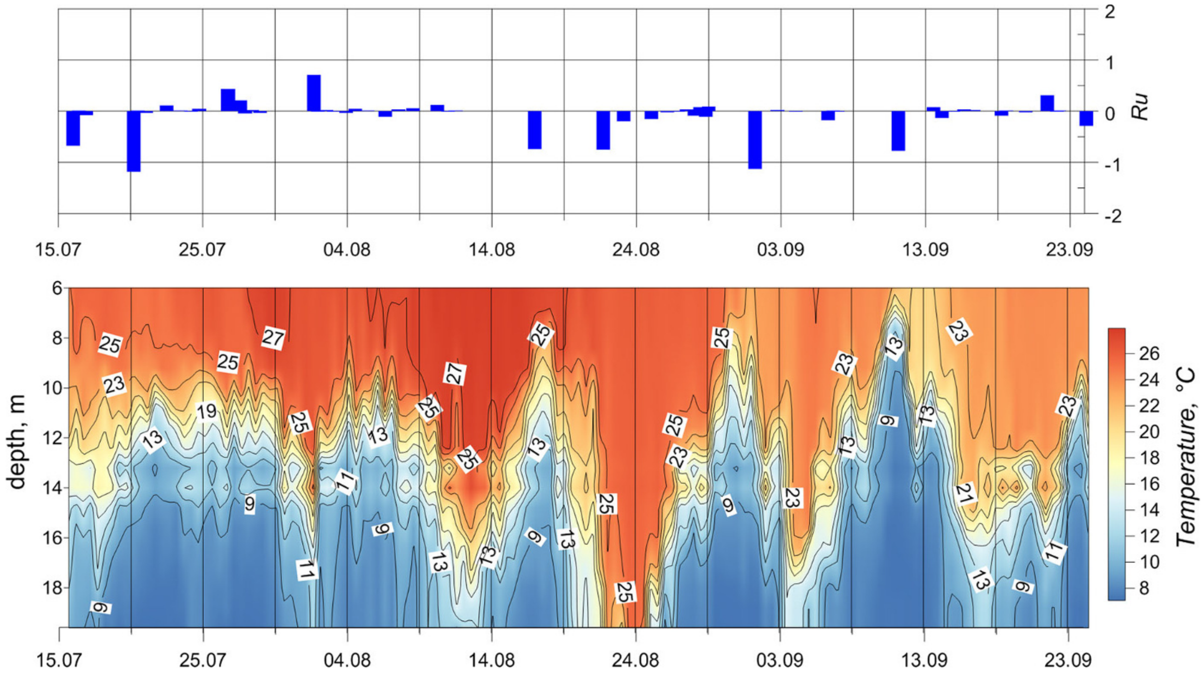

Figure 5
Upwelling criterion Ru (above) and vertical distribution of temperature (below) from July 15 to September 23, 2012

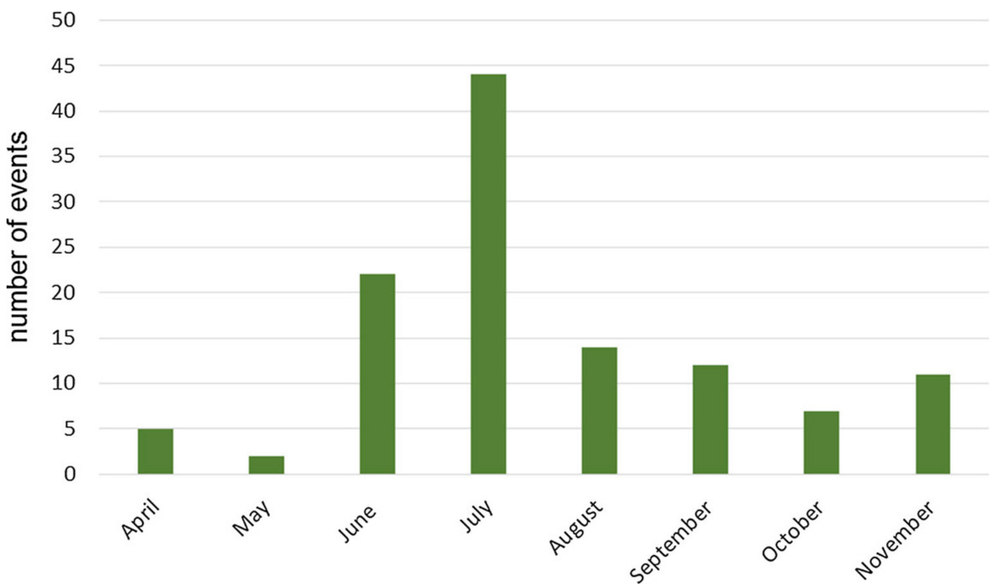

Figure 6
Seasonal distribution of upwelling events for 1979 to 2016 year

November, there is a shallow UML, due to intensive heating, there will be a correspondingly high probability of the occurence wind-driven upwelling, though the real values of *Ru* could differ from calculations.

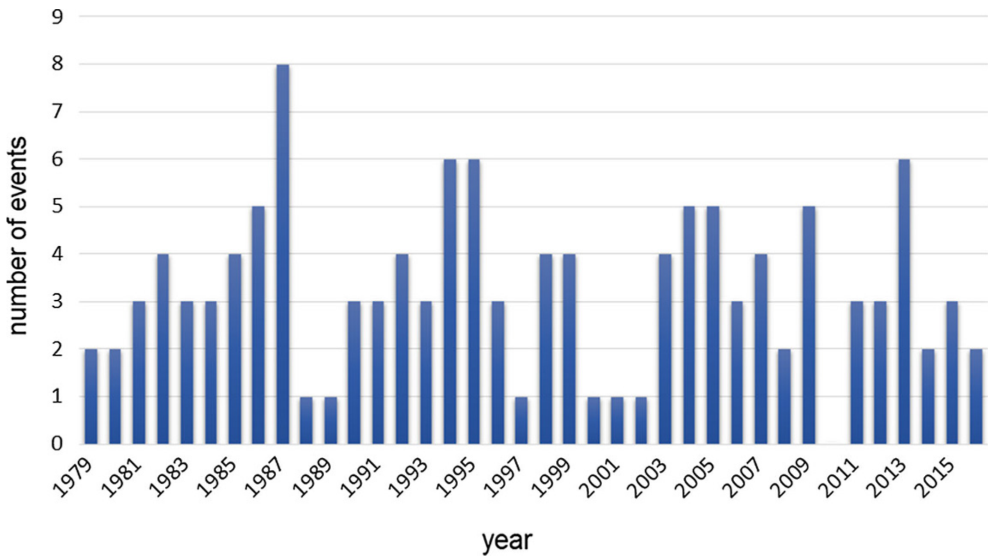

Figure 7
Interannual variability of the upwelling cases when $Ru < -1$

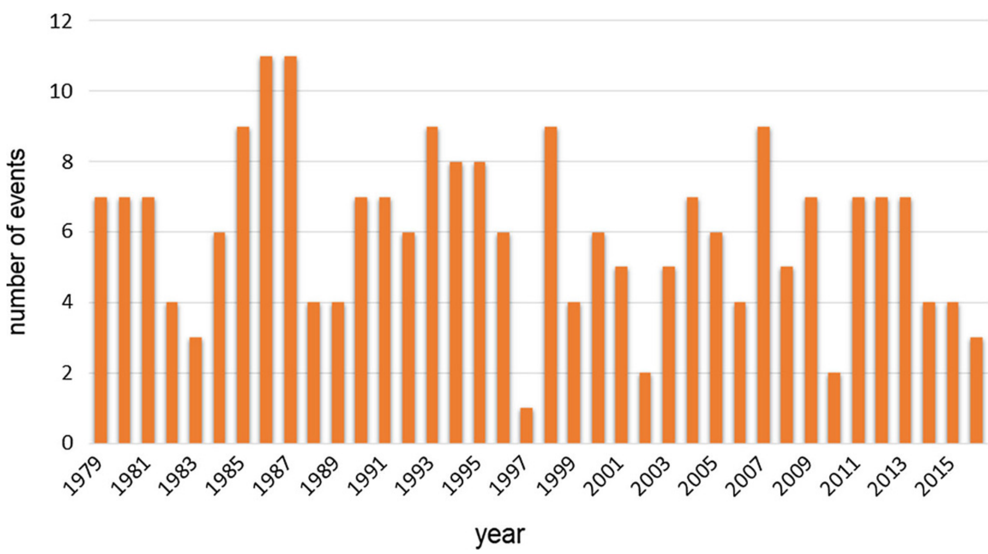

Figure 8
Interannual variability of the upwelling cases when $Ru <- 0.7$

Interannual variability of the wind-driven coastal upwelling cases is presented in Fig. 7. The average number of the wind-driven coastal upwelling events is 3 cases per year. There was only 1 year (2010) when no cases with $Ru < -1$ were registered. The minimum number of cases—once a year—is registered for 1988, 1989, 1997, 2000, 2001, and 2002. Maximum 8 cases are registered for 1987, and 6 cases for 1995, 1996, 2004, 2005, 2009. Lowering the threshold for Ru to -0.7 yields a fairly comparable distribution of upwelling events to the -1 threshold value (Fig. 8). However, the interannual number of the upwelling cases variessignificantly.

Time series data for the NAO from National Oceanic and Atmospheric Administration were averaged for the period from April through November. In addition, time series for the NCP (North Sea—Caspian Pattern) from Climatic Research Unit, University of East Anglia were used for comparison until 2005 year. Correlation between the NAO, the NCP, and the wind-driven upwelling events is very low, because upwelling winds apparently are not associated with the global atmospheric circulation. In the studied area, there are two main atmospheric processes types that determine wind conditions—north-eastern and south-eastern (Moskalenko et al. 2016). The wind-driven upwelling near Gelendzhik is caused by the north-western winds, which are infrequent. We had analyzed wind charts for the years when there were a maximum and minimum number of the upwelling cases. Connection with different prevailing atmospheric processes was not found.

3. Conclusions

Analysis of the upwelling criterion variability showed that wind-induced upwelling occurs on average three times during the warm season (April–November). However, the strong interannual variability of the wind upwelling criterion is observed. This interannual variability is not directly related to the North Atlantic Oscillation Index, or to the prevailing types of atmospheric circulation in the studied area. When the coastal upwelling criterion reaches the threshold value, it is not necessarily accompanied by development of the full upwelling when cold waters reach the sea surface. The process of the coastal upwelling depends on wind impact, but also on direction and strength of the coastal current. The obtained results supplement the knowledge about this phenomenon in studied area. The extension of the criterion for coastal upwelling that will take into account both the wind impact and the dynamics of water as well as problem of upwelling prediction are the subject of ongoing research. The upwelling strongly changes the hydrological and hydrochemical structures of the coastal waters and has a direct impact on the ecosystem-making prediction of these phenomena and studying of this variability is a relevant task.

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References

Akpinar, A., & Ponce de León, S. (2016). An assessment of the wind re-analyses in the modelling of an extreme sea state in the Black Sea. *Dynamics of Atmospheres and Oceans, 73,* 61–75.

Blatov A. S. and Tuzhilkin V. S. (1990). Medium-scale eddies and synoptic variability in the World Ocean. Itogi Nauki Tekh., Ser.: Okeanologiya, 8.

Borovskaya, R. V., Panov, B. N., Spiridonova, E. O., et al. (2005). Coastal Black Sea upwelling and interannual intensity dynamics. *Ecological Safety of the Coastal and Shelf Zones and Complex Use of Shelf Resources (Sevastopol), 12,* 42–48.

Ginzburg, A. I., Kostyanoy, A. G., Soloviev, D. M., & Stanichny, S. V. (1997). Coastal upwelling in the north-west Black sea. *Earth Observation and Remote Sensing, 6,* 61–72.

Lindsay, R., Wensnahan, M., Schweiger, A., & Zhang, J. (2014). Evaluation of seven different atmospheric reanalysis products in the Arctic. *Journal of Climate, 27,* 2588–2606.

Moskalenko, L. V., Melnikov, V. A., Kuzevanova, N. I., & Podymov, O. I. (2016). Peculiarities of multiscale wind regime variability at coastal water area of the north-eastern black sea. *Izvestiya Rossiiskoi Akademii Nauk. Seriya Geograficheskaya, 1,* 74–86.

Myslenkov, S., & Chernyshova, A. (2016). Comparing wave heights simulated in the Black sea by the SWAN model with satellite data and direct wave measurements. *Russian Journal of Earth sciences, 16*(5), 1–12.

NAO index http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml.

NCP index https://crudata.uea.ac.uk/cru/data/ncp/.

Novikov, A. A., & Tuzhilkin, V. S. (2015). Seasonal and regional variations of water temperature synoptic anomalies in the northeastern coastal zone of the Black Sea. *Physical Oceanography, 1,* 39–48.

Ocherednik, V. V., Baranov, V. I., Zatsepin, A. G., & Kuklev, S. B. (2018). Thermochains in the Southern Branch Shirshov Institute of Oceanology RAS: design, methods and results of the sensors metrological investigation. *Oceanology, 2,* 1–9. **(in press)**.

Saha, S., Moorthi, S., Wu, X., et al. (2014). The NCEP Climate Forecast System version 2. *Journal of Climate, 27*(6), 2185–2208.

Silvestrova, K. P., Zatsepin, A. G., & Myslenkov, S. A. (2017). Coastal upwelling in the Gelendzhik area of the Black Sea: Effect of wind and dynamics. *Oceanology, 57*(4), 521–530.

Tomczak, M., & Godfrey, J. S. (1994). *Regional Oceanography: an Introduction*. Oxford: Pergamon.

Tuzhilkin, V. S., Arkhipkin, V. S., Myslenkov, S. A., & Samborsky, T. V. (2012). Synoptic variability of thermohaline conditions in the Russian part of the Black Sea coastal zone. *Vestnik Moskovskogo Universiteta, Ser. 5. Geography, 6,* 46–53.

Van Vledder, G Ph, & Akpinar, A. (2015). Wave model predictions in the Black Sea: Sensitivity to wind fields. *Applied Ocean Research, 53,* 161–178.

Zatsepin, A. G., Ostrovskii, A. G., Kremenetskiy, V. V., et al. (2014). Subsatellite polygon for studying hydrophysical processes in the Black Sea shelf-slope zone. *Izvestiya Atmospheric and Oceanic Physics., 50,* 13–25.

Zatsepin, A. G., Piotouh, V. B., Korzh, A. O., Kukleva, O. N., & Soloviev, D. M. (2012). Variability of currents in the coastal zone of the Black Sea from long-term measurements with a bottom mounted ADCP. *Oceanology, 52*(2), 579–592.

Zatsepin, A. G., Silvestrova, K. P., Piotoukh, V. B., Kuklev, S. B., & Podymov, O. I. (2016). Observation of a cycle of intense coastal upwelling and downwelling at the research site of the Shirshov Institute of Oceanology in the Black sea. *Oceanology, 56*(2), 188–199.

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