Quasi-tropical cyclone caused anomalous autumn coccolithophore bloom in the Black Sea

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Abstract. A quasi-tropical cyclone observed over the Black Sea on 25-29 September 2005 caused exceptionally strong anomalous autumn coccolithophore bloom lasted for more than 1.5 months. The cyclone induced intense upwelling causing the decrease of surface temperature on 15°C and acceleration of the cyclonic Rim Current up to extreme values of 0.75 m s^{-1}. The Rim Current transported nutrient-rich Danube plume waters from the north-western shelf to the zone of the cyclone action. Baroclinic instabilities on the plume boundary cause intense submesoscale process, accompanied by mixing of the shelf and upwelled waters. These processes trigger the initial growth of remote sensing reflectance (R_{rs}) on the offshore front of the plume indicating the beginning of the coccolithophore bloom. Further, the bloom has shifted to the zone of the strongest upwelling in the western cyclonic gyre, where vertical entrainment of nutrients caused the maximum development of the bloom. Advection by the Rim Current spread the bloom over the entire south part of the Black Sea on more than 1000 km from its initial source. One month after the cyclone action, R_{rs} in these areas reached a value of 0.018 sr^{-1}, corresponding to an estimate of a coccolithophore concentration of 10^7 cells l^{-1}.

1 Introduction

Vertical mixing and upwelling caused by the action of tropical cyclones uplift nutrients to the euphotic layer and induce intense sporadic phytoplankton blooms in the World Ocean (for example, Babin et al., 2004; Chacko, 2017; Han et al., 2012; Kubryakov et al., 2019a; Lin et al., 2003; Miller et al., 2006; Morozov et al., 2015; Tsuchiya et al., 2013). An important tracer of such changes is the chlorophyll-*a* concentration (Chl), which can be determined from satellite measurements. Intense nutrients entrainment leads to the rapid rise of Chl, which can be observed several months after the action of the storm in various ocean areas (for example, Shi et al., 2007; Wu et al., 2008), including the Black sea (Kubryakov et al., 2019a). In some cases, the action of atmospheric cyclones causes the growth of specific groups of phytoplankton. For example, (Zhu et al., 2014) showed that the storm action in Taihu lake led to an intensive growth of potentially toxic cyanobacteria.

At the same time, there is almost no information on the impact of tropical cyclones on the development of coccolithophores. Coccolithophores are one of the dominant phytoplankton groups in the ocean. Their specific feature is the ability to form calcified plates – coccoliths, which play a significant role in the ocean carbon pump (Balch et al., 2011; Hernández et al., 2018, 2020; Krumhardt et al., 2017; Rost and Riebesell, 2004) and formation of calcareous sediment layers (Coolen, 2011; Hay et al., 1990; Honjo, 1976). Coccolithophores cause significant light scattering and increasing the reflectance of the water, which makes it possible to study them using satellite data (Balch et al., 1996; Cokacar et al., 2001, 2004; Holligan et al., 1983; Hopkins et al., 2015; Kopelevich et al., 2014; Krumhardt et al., 2017; Mikaelyan et al., 2011; Shutler et al., 2013; Suslin et al., 2012; Tyrell and Merico, 2004). The Black Sea has one of the strongest coccolithophore blooms in the world (Mikaelyan et al., 2005, 2011, 2015; Cokacar et al., 2001, 2004; Pautova et al., 2007; Yasakova and Stanichny, 2012; Kopelevich et al., 2014; Korchemkina et al., 2014) with cell concentrations that can reach $30 \cdot 10^6$ cells l^{-1} (Mihnea, 1997). The most intense coccolithophore blooms in the Black Sea are observed in the spring and summer (Cokacar et al., 2001, Mikaelyan et al., 2015). Weaker blooms are also observed in the cold period of a year, both from satellite data and measurements of Bio-Argo buoys (Kubryakovet al., 2019a) and *in situ* measurements (Hay et al, 1990; Sorokin, 1983; Stelmakh et al., 2009; Stelmakh, 2013; Sukhanova, 1995; Türkoğlu, 2010; Yasakova et al., 2017).

Tropical cyclones mostly are observed at latitudes less than 30°. However, in September 2005 the anomalous atmospheric cyclone was observed over the Black Sea basin at 40°E (Fig. 1a). This cyclone has all the characteristic features of the tropical cyclones: spiral cloud bands, warm core, pronounced eye of the cyclone, and high wind velocity reaching 25 m s^{-1} (Efimov et al., 2007, 2008). Similar cyclones were documented rarely in the Mediterranean Sea (Pytharoulis et al., 1995; Homar et al., 2003), but never before over the Black Sea. Later, detailed statistics of cyclones of the basin on the base of the regional atmospheric model showed that eddies with similar intensity were detected over the Black Sea only 3 times over 30-year period (Efimov et al., 2009). One of the unique characteristics of the cyclone in September 2005 was its quasi-stationarity. It acted on the Black Sea for more than 4 days, which lead to significant changes in the Black Sea dynamics and ecosystem. This paper documents for the first time the impact of such an anomalous quasi-tropical atmospheric cyclone on the development and evolution of autumn coccolithophore bloom in the Black Sea on the base of the analysis of satellite optical, infrared, and altimetric data.

2 Data and methods

For the analysis of the coccolithophore bloom in the Black Sea, the Level 2 MODIS-Aqua daily maps of remote sensing reflectance at a wavelength of 555 nm (R_{rs}) and Chl for September-November 2005 with a spatial resolution of 1 km and a time of 1 day were used. High R_{rs} values are caused by increased backscattering on particles. In the coastal zone, especially at river mouths, the main reason for the increase in R_{rs} values is terrigenous particles. In the deep part of the Black Sea, the intense growth of R_{rs} values are mainly caused by scattering on coccoliths during the coccolithophore bloom (Cokacar et al., 2001, 2004; Kopelevich et al., 2014).

The equation $N=0.8 \cdot 10^9 \cdot b_{bp}(700)^{1.21}$ and the linear relationship between $R_{rs}(555)$ and $b_{bp}(700)$ $R_{rs}=0.7 \cdot b_{bp}(700)$ obtained on the base of comparison of Bio-Argo and satellite measurements (Kubryakov, et al., 2019b) were used to estimate the coccolithophore cells concentration from R_{rs} values. According to the used parameterization, the concentration value is more than $1.0 \cdot 10^6$ cells l^{-1}, i.e. bloom conditions, corresponds to the value of R_{rs}=0.005 sr^{-1}. The area of coccolithophore bloom was estimated as a total area with values of $R_{rs} \geq 0.005$ sr^{-1}.

Wind velocity measurements of the scatterometer SeaWinds of the satellite QuikSCAT for September-November 2005 with a spatial resolution of 0.25°×0.25° and a time resolution of 1 day was used. The Ekman pumping was defined as $W_{ek} = \frac{1}{\rho_w \cdot f} rot(\vec{\tau})$, where ρ_w=1000 kg m^{-3} is the water density, $\vec{\tau} = c_d \rho_a \cdot |\vec{v}| \cdot \vec{v}$ is the wind stress, $c_d = 1.3 \cdot 10^{-3}$ is the drag coefficient, ρ_a=1.3 kg m^{-3} is the air density, v is the wind velocity.

A regional dataset on altimetry-derived daily mapped sea level anomalies with 1/8° resolution produced by AVISO was downloaded from CMEMS (Copernicus Marine Environment Monitoring Service). Mapped sea level anomalies were added to the mean dynamic topography (Kubryakov and Stanichny, 2011) to compute surface geostrophic velocities in the sea. The obtained dataset was validated in (Kubryakov et al., 2016) with drifters and hydrological data. The analysis of the sea surface temperature (SST) was carried out using measurements of AVHRR (Advanced Very High-Resolution Radiometer) radiometers with a spatial resolution of 1 km.

3 Results and Discussion

3.1 Impact of a quasi-tropical cyclone on physical processes in the Black Sea

From 25 to 29 September 2005, an anomalous intense quasi-tropical cyclone was observed in the atmosphere over the Black Sea from satellite images (Fig. 1a). It had a cloud-free eye and distinct spiral cloud bands and was no more than 300 km in diameter. Wind velocity in the cyclone reaches 20–25 m s^{-1} according to the QuikSCAT satellite data (Fig. 1c). Its development occurred after weak wind conditions and was associated with overheating of the sea surface and increased moisture fluxes over the western part of the Black Sea. Importantly, this cyclone was observed over the western part of the Black Sea for more than 4 days. A detailed analysis of the dynamics of this cyclone and the reasons for its formation was carried out in (Efimov et al., 2007, 2008).

Cyclonic wind vorticity led to strong Ekman pumping and divergence in the upper mixed sea layer. Particularly, Ekman pumping, on 26 September in the zone of cyclone action exceeds $4 \cdot 10^{-5}$ m s^{-1} (Fig. 1d), while in (Efimov et al., 2008) authors document absolute maximum reaching $20 \cdot 10^{-5}$ m s^{-1}. The atmospheric cyclone was situated over the western cyclonic gyre of the Black Sea circulation. The center of the western cyclonic gyre was observed in altimetry maps as an area of a decreased sea level reflecting the uplift of isopycnals (Fig. 2a). On average the pycnocline and nitrocline in the centers of the western cyclonic gyre in the Black Sea are elevated by 20 m relative to the periphery of the sea (Ivanov and Belokopytov, 2013). A quasi-tropical atmospheric cyclone caused additional intense upwelling in this area, accompanied by strong mechanical mixing. The action of Ekman pumping pushed the waters from the central part of the basin to its periphery strongly increasing the sea level gradients over the Black Sea continental slope. Particularly, the sea level on the western shelf of the basin rose on 20 cm from 0.2 to 0.4 cm (Fig. 2a, c). At the same time in the west-central part of the basin, the sea level dropped on 20 cm (Fig. 2a, c). Such a divergence causes the compensating upward vertical motions and intense entrainment of cold waters from deep layers to the surface. According to the AVHRR radiometer data, on 29 September, the SST in the central-western part decreased by more than 10°C (Fig. 1b), reaching an exceptionally low value for the September about 10°C. The maximum cooling was observed in the center of the cyclonic gyre in the south-western part of the sea, where SST fell to 10°C which was on 13-15°C lower than in surrounding waters (23-25°C). The isotherm 10°C in the Black Sea in September are located under the seasonal thermocline at depths of 30-40 m. Thus, the action of the atmospheric cyclone led to the rise of isopycnic surfaces by 30-40 m and the outcropping of deep isopycnals layers on the sea surface. Taking into account the active thermal mixing of waters due to the action of the cyclone and intense solar heating in this period of a year, it can be assumed that the waters were uplifted from even larger depths. Nitroclyne in the Black Sea is relatively shallow and its upper border is located at the depth of 40-50 m (Konovalov and Murray, 2001; Tuğrul et al., 2015). The upwelling and mixing during such a strong vorticity in the Black Sea may cause significant entrainment of the nutrients in the upper layers, and occasionally trigger intense blooms of phytoplankton in the warm period of a year (Kubryakov et al., 2019a).

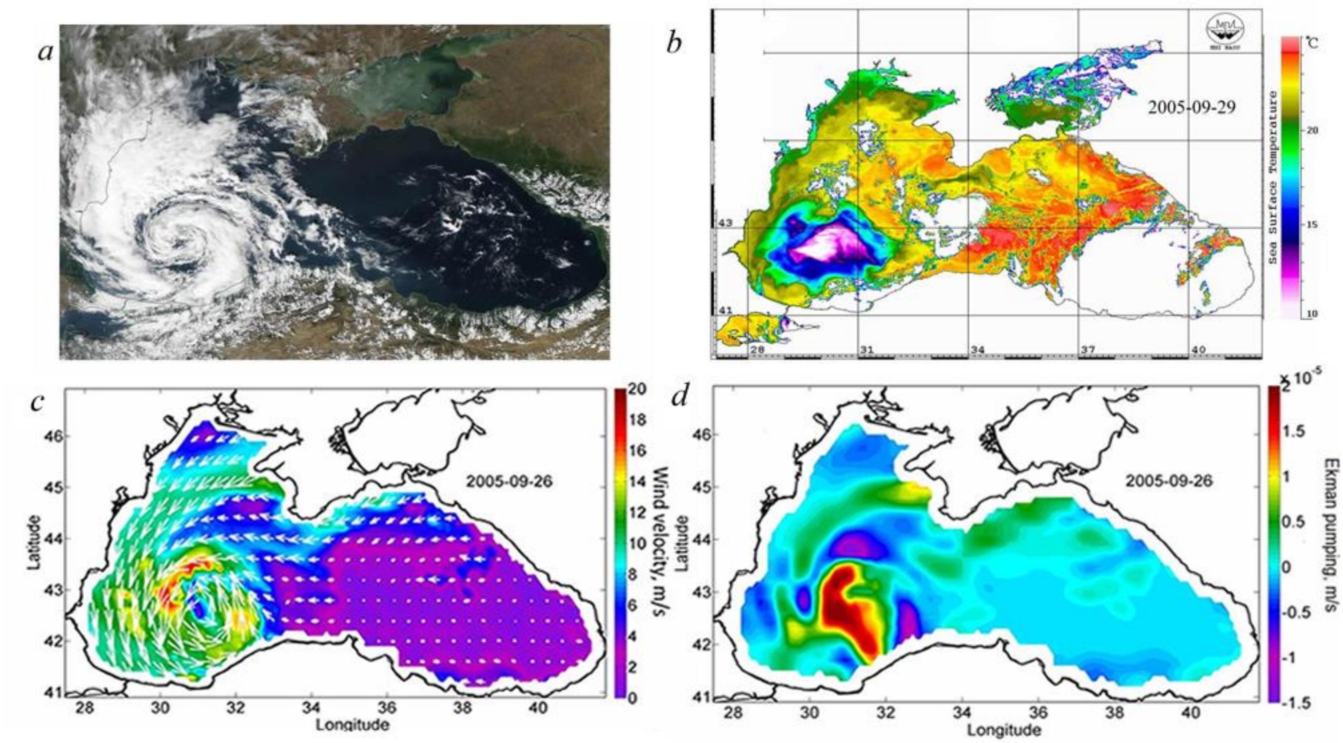

Figure 1: (a) – satellite image of MODIS-Aqua in the visible range for 27 September 2005 (data obtained from the Worldview portal); **(b)** – SST (°C) for 29 September 2005, according to the AVHRR radiometer; **(c)** – wind velocity (m s^{-1}) of the scatterometer SeaWinds of the satellite QuikSCAT on 26 September 2005; **(d)** – Ekman pumping velocity (m s^{-1}) on 26 September 2005, calculated from the scatterometer SeaWinds of the satellite QuikSCAT.

Upwelling and the rise of the sea level caused a significant intensification of the large-scale cyclonic circulation of the Black Sea – Rim Current. Its velocity over the continental slope increased on average twofold from the values of 0.25 to 0.45 m s^{-1} (Fig. 2b, d). The highest values of geostrophic velocity were recorded in the south-western part of the sea, where they reached extremely high values for the Black Sea exceeding 0.6 m s^{-1} with a maximum of 0.75 m s^{-1} in the southwest part of the basin (Fig. 2d). The maximum intensity of the geostrophic velocity was observed about 2 weeks after the action of the cyclone on 6-10 October (Fig. 3, black line) The currents response on the rise of the wind curl in the Black Sea is delayed, as it is shown (Grayek et al., 2010; Kubryakov et al., 2016). This delay is related to the mechanism of the intensification of the Black Sea geostrophic circulation. Wind curl cause induces the onshore Ekman transport to the coast of the Black Sea. This transport further causes an increase in sea level and downwelling near the coast. Rising gradients drive the Black Sea cyclonic geostrophic circulation. The time needed for the sea level and currents to adjust to the changes in the wind curl estimated on the base of altimetry data in several previous studies as about 1-2 weeks (Grayek et al., 2010; Kubryakov et al., 2016), which is in close agreement with the delay observed in the present case.

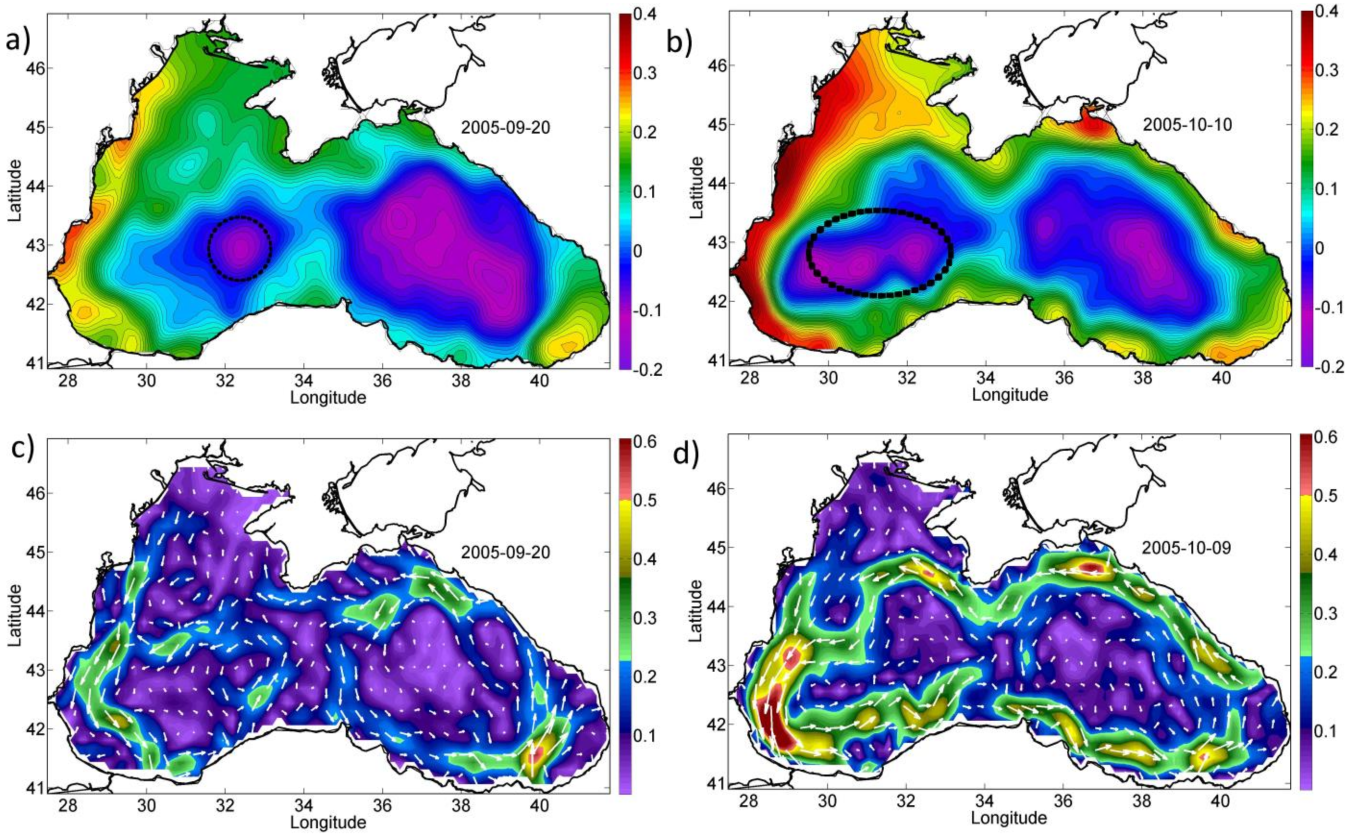

Figure 2. Altimetry-derived map of sea level and geostrophic velocity before **(a, c)** and after **(b, d)** the action of the cyclone. Sea level (m) at: **(a)** – September 20, 2005, **(b)** – October 10, 2005; geostrophic velocity (m s^{-1}) at: **(c)** – September 20, 2005, **(d)** – October 9, 2005. Black circles show the position of the western cyclonic gyre.

As horizontal and vertical circulation are coupled, the same delay would be observed between the time of cyclone action and the maximum upwelling. Thus, we might suggest that the vertical entrainment of nutrient-rich waters from deep layers also reaches its maximum after 2 weeks from the cyclone.

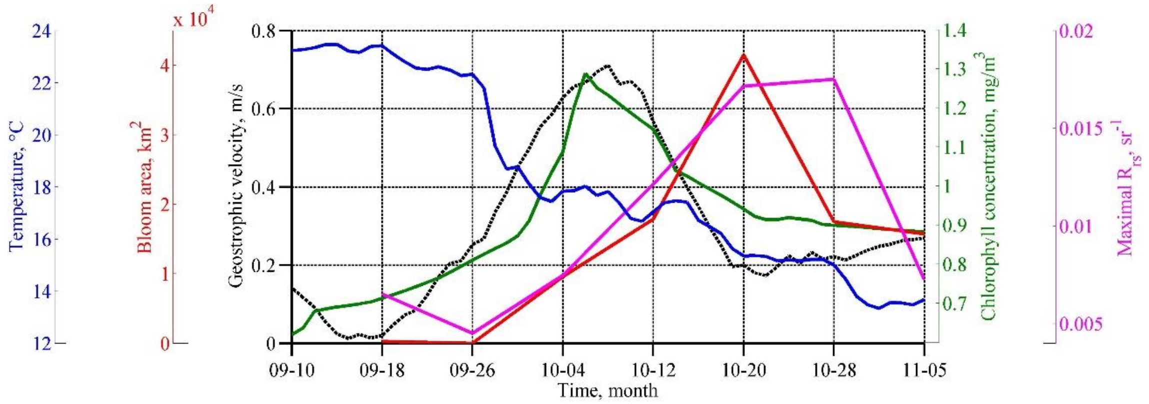

Figure 3: Time variability of SST (blue line), R_{rs} (purple), Chl (green) averaged in the center of the western cyclonic cycle; area of coccolithophore bloom (red); geostrophic velocity over the south continental slope (black), m s^{-1}.

3.2 Impact of quasi-tropical cyclone on chlorophyll A

Satellite measurements show that such changes in the basin dynamics significantly affected the bio-optical characteristics of the Black Sea. Before the passage of an atmospheric cyclone, the values of Chl in the central part of the basin were relatively low, less than 0.7-0.8 mg m^{-3} (see Fig. 3, 4). High values of Chl at this time were observed over the north-west shelf of the basin (Fig. 4a). Here values of Chl exceed 3 mg m^{-3}, which in this area is associated with the spread of a plume of Danube (Yankovsky et al., 2004; Karageorgis et al., 2014). It should be noted that the Danube plume and shelf waters of the Black sea correspond to turbid Case 2 waters. The determination of the Chl in Case 2 waters is a difficult task and it is likely overestimated mainly due to the presence of CDOM. At the same time, they can be successfully used as a tracer of plume waters (Sur et al., 1994, 1996; Kubryakov et al., 2018). At the beginning of September 2005, rich in Chl Danube waters occupy all western shelf and its southern border was located in the southwestern part of the basin near 42°N.

Immediately after the action of an atmospheric cyclone in late September, Chl increased significantly throughout the western part of the sea and on 4 October Chl reached its maximum values (1.3 mg m^{-3}) in the western central part of the basin (green line in Fig. 3). This zone of fast increase of Chl in the north and central-western part of the sea is marked by a red ellipse in Fig. 4b. Such rapid bloom can be related both to the entrainment of Chl from its summer subsurface maximum and the growth of phytoplankton. However, this first rise of Chl in the western central part of the Sea rapidly ended, and on the next 8-daily map (Fig. 4c) Chl in this zone decreased to the background values, which suggests the mainly mechanical nature of its increase. Another feature well-seen in the Chl maps after the cyclone is the propagation of the Danube plume waters in the cyclonic direction (see black arrow in Fig. 4b). The Rim Current accelerated after the cyclone action transport the plume water along the sea coast from the south-western part to the south-central coast (marked as the black arrow in Fig. 4b). On 5 October (Fig.

4b) the zone with high Chl ((>3 mg m^{-3}) reaches 34°E. At this time this zone looks like a band with about 50 km width extending from the Danube mouth in the cyclonic direction. Similar action of the Rim current transport on the transfer of Danube plume to the southern part of the basin was documented in several previous studies (see e.g. Özsoy and Ünlüata, 1997; Yankovsky et al., 2004; Kubryakov et al., 2018).

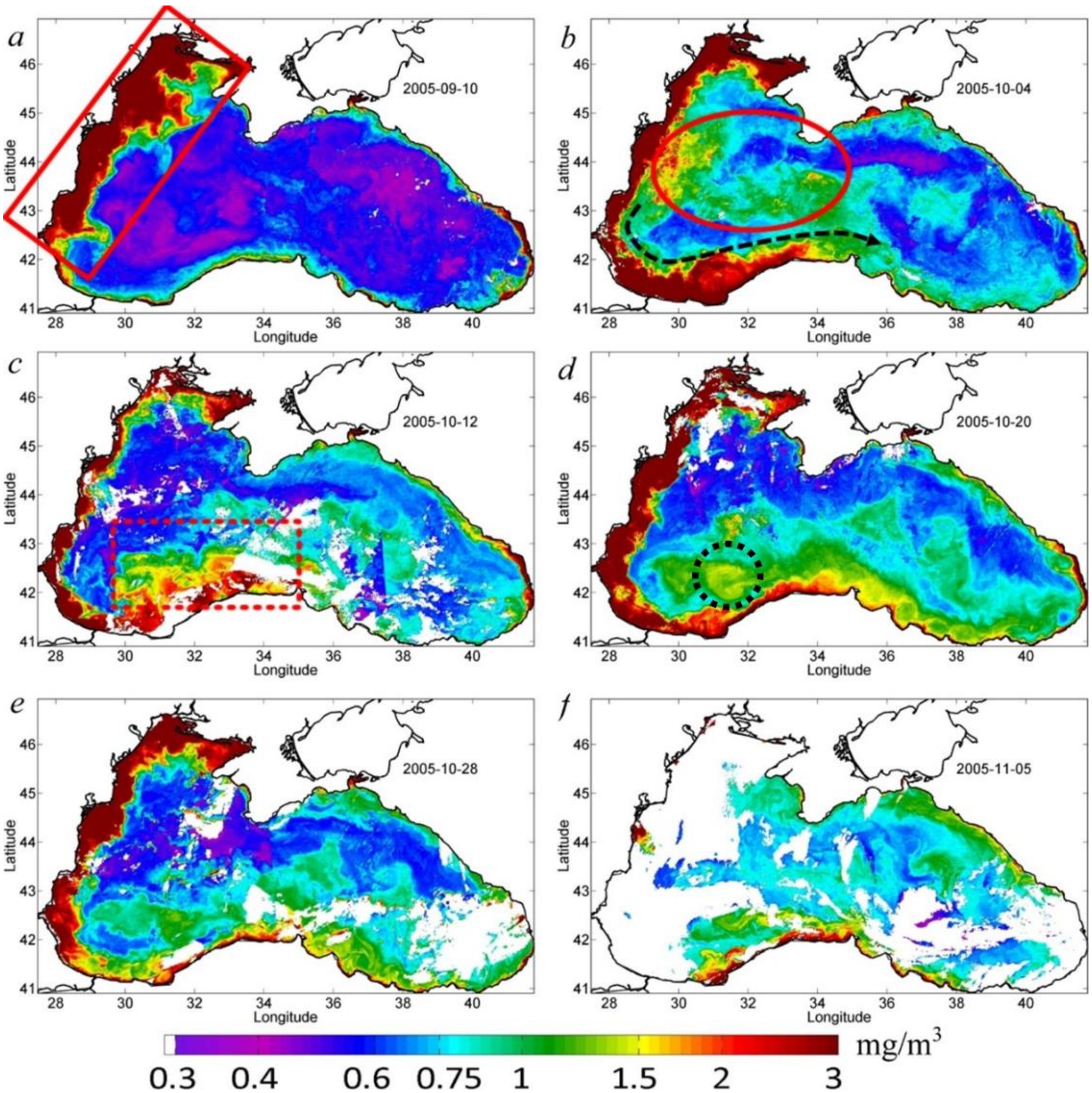

Figure 4: 8-day maps of chlorophyll-a concentration, mg m^{-3}, centered at **(a)** 10 September 2005, the red rectangle (solid line) shows the position of the Danube plume; **(b)** 4 October 2005, the red oval shows the rapid phytoplankton bloom area in the center of the sea; **(c)** 12 October 2005, the red dashed rectangle show the position of the mixing area; **(d)** 20 October 2005, black dashed circle show the maximum of Chl corresponded to the position of the western cyclonic gyre; **(e)** 28 October 2005; **(f)** – 5 November 2005.

Significant intensification of the Rim Current in the southwest Black Sea up to extreme values of 0.75 m s^{-1} cause its baroclinic instability related to strong horizontal shear. The offshore boundary of the front of turbid waters was characterized by several mesoscale features – eddies and filaments, well-seen on the zoomed MODIS map in Fig. 5a, which intensifies the horizontal exchange in this part of the basin. As a result, on 12 October 2005, the area of the high Chl values in the southeastern part of the sea significantly widens and reaches a width of 100-150 km (see red dashed rectangle in Fig. 4c) The observed difference between the Chl maps in Fig. 4b, c shows that near the coast (in the area of the red dashed rectangle) Chl decreased, while to the north increased. This evidence about the dilution of the plume due to its horizontal mixing with offshore waters with relatively low values of Chl (Chl<0.75 mg m^{-3}). Such distribution indicates that a significant part of the brackish and nutrient-rich plume water moved across the isobaths and penetrated in the southwest central part of the sea.

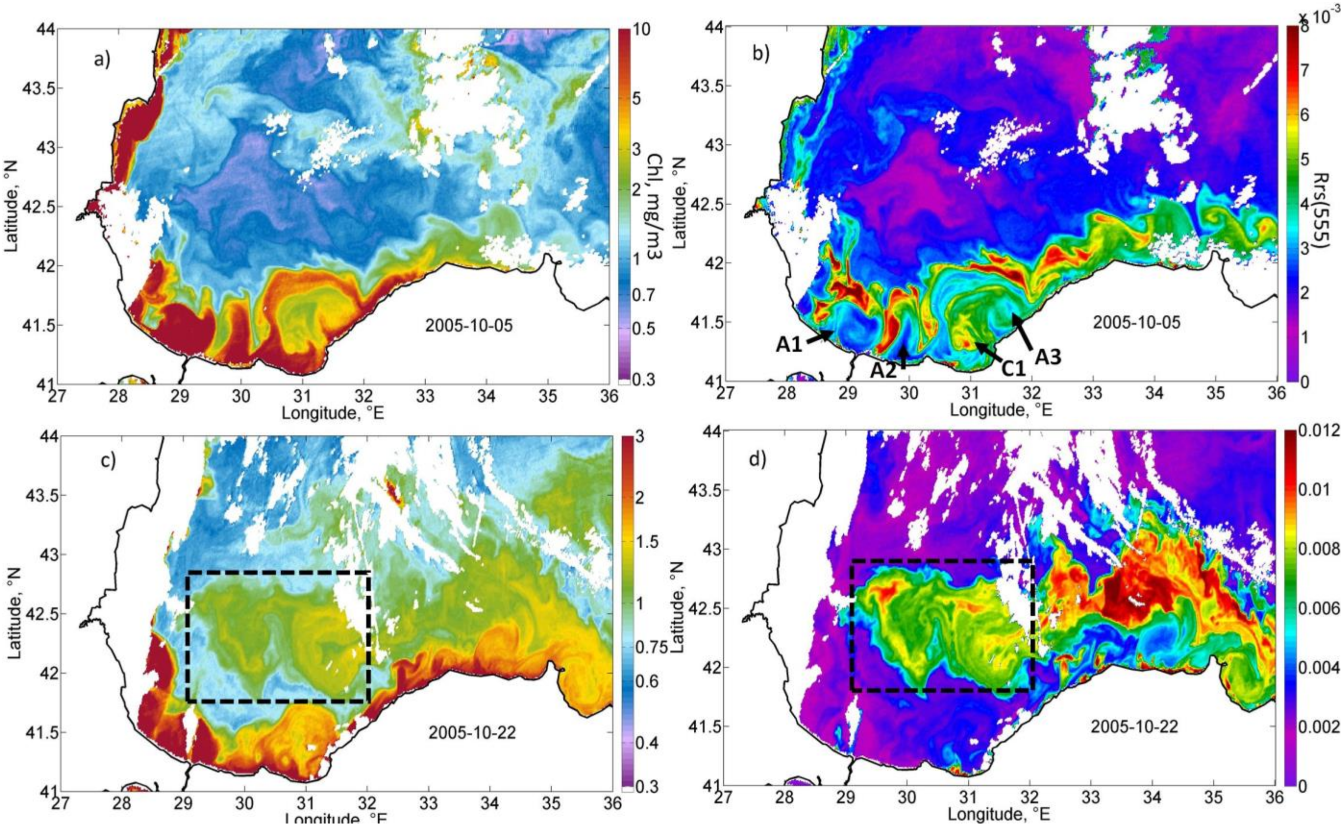

Figure 5. Zoomed daily MODIS maps demonstrating two stages of coccolithophore blooms development: MODIS daily map of Chl **(a)** and R_{rs} **(b)** on 5 October 2005 demonstrating the initial rise of R_{rs} on the offshore periphery of the Danube plume; MODIS daily map of Chl **(c)** and R_{rs} **(d)** on 22 October 2005 demonstrating the strong rise of R_{rs} in the central-western gyre of the Black Sea (black dashed circles).

A week later, at 16-24 October this wide zone of increased Chl (Chl>1.5 mg m^{-3}) disappears and the width of the plume decreases significantly (see zoomed Fig. 5c). In this time high values of Chl shifted to the central-western part of the sea (Fig. 4d, 5c). The position of the local maximum of Chl (black circle in Fig. 4d, 5c) corresponded to the position of the zone of maximum upwelling in the western cyclonic gyre, i.e. zone of minimal temperature in Fig. 1b. Waters with high Chl values were transported from this area by intense Rim Current to the east. As a result, the region of high values of the Chl extended eastward along the continental slope up to the eastern coast of the basin – 41.5°E (Fig. 4d, e, 5c). In these areas, Chl increased to a value of 1-1.3 mg m^{-3}, which was two times higher than in early September (Fig. 4d). To the end of October, Chl in the areas affected by the cyclone action began to decrease. It fell about twofold to the values of 0.75 mg m^{-3} (Fig. 4e).

At the beginning of the November Chl in the whole central part of the Black Sea rise to these values (Fig. 4f). This rise probably indicates the beginning of late-autumn phytoplankton bloom, which is associated with the deepening of a mixed layer to the upper border of nitrocline (Mikaelyan et al., 2018).

3.3 Impact of quasi-tropical cyclone on coccolithophores bloom

However, the most significant impact of the cyclone was observed in the field of R_{rs}. Exceptionally high rise of R_{rs} was observed in the western cyclonic gyre and south deep part of the basin (Fig. 6a). The comparison of the R_{rs} map on 28 October 2005 with the climatic-averaged map for 2003-2019 (Fig. 6a, b) demonstrates this anomalous event. In the usual year R_{rs} in the Black Sea in October does not exceed 0.001 sr^{-1}, except the area located near Danube mouth, the Kerch strait, the most coastal areas near Caucasian rivers, and shallow north-western shelf (see black rectangles in Fig. 6b). These areas are the source of lithogenous particles in the Black Sea caused by riverine or the Azov Sea inflow, resuspension of bottom sediments, and coastal erosion (see Constantin et al., 2017; Aleskerova et al., 2017, 2019).

After the action of the cyclone, we observed significantly different patterns. R_{rs} was highest not near the coast or river mouths, but in the deep western part of the basin with depths more than 1500 m and the south over the continental slope. In this area, R_{rs} reach very high values (more than 0.01 sr^{-1}), which is 10 times higher than climatic values. In this south part of the basin, there are several small rivers, but their plumes usually do not extend on more than 10 km from their mouth (Kostianoy et al., 2019). In the considered cases in Fig. 6a the width of high R_{rs} values near the south part of the basin was about 100 km and it was not located near a specific river mouth, but extended over the whole periphery of the basin.

An additional possible source of the particles in the Black Sea is a deep maximum of suspended matter (Yakushev et al., 2007; Pakhomova et al., 2009; Stanev et al., 2017) which is located on the suboxic boundary in the Black Sea (100-150 m). However, the study based on Bio-Argo data (Kubryakov et al., 2019b) shows that high values of particles backscattering in the surface layers in winter usually occupy only the upper 0-50 m and are not connected to this deep maximum. In-situ data (Oztrovskii and Zatsepin, 2016) show that even during extreme events vertical mixing does not reach the suboxic interface on 100-150 m depth, which may cause the entrainment of anoxic waters to the surface layers of the basin. Therefore, the observed rise of R_{rs} should have a biological origin. In the Black Sea, such a rise of R_{rs} is often observed during coccolithophores bloom (Cokacar et al., 2001). The above arguments suggest that in the presented case we observe unusual coccolithophores bloom in October in the Black Sea.

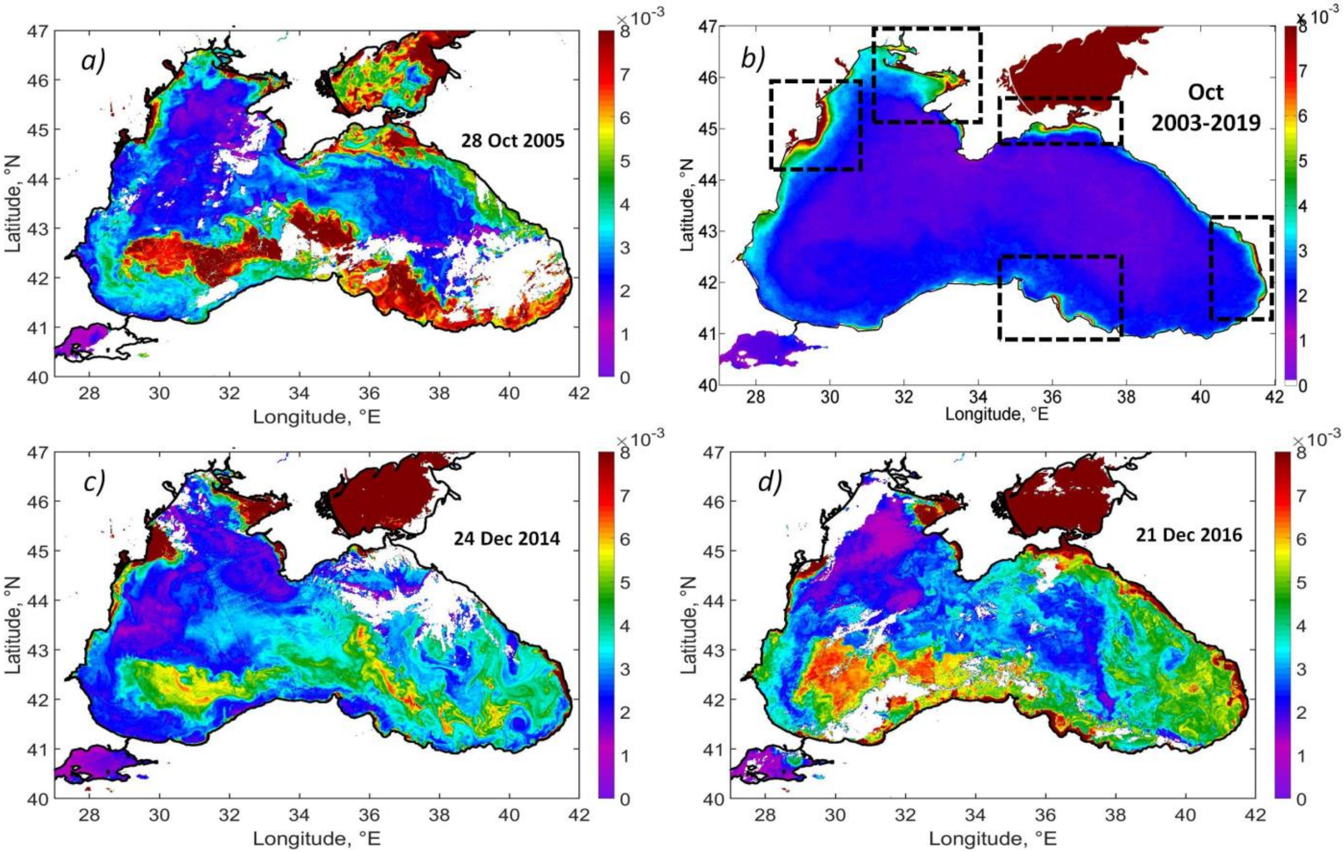

Figure 6. (a) MODIS RRS map on 28 October 2005 showing the intense coccolithophore bloom developed after the action of quasi-tropical cyclone; **(b)** climatic R_{rs} map for October of 2003-2019 (black rectangles show the main sources of the lithogenous articles in the Black Sea); similar to the case of October 2005 coccolithophore blooms observed on the maps of R_{rs} on 24 December 2014 **(c)** and 21 December 2016 **(d)**.

The detailed evolution of R_{rs} in September-October 2005 is demonstrated in Fig. 7. Before the passage of an atmospheric cyclone, R_{rs} in the Black Sea was less than 0.004 sr^{-1} (Fig. 7a), except the north-western shelf affected by the discharge of the major rivers. This value is typical for this season and indicates that the surface layer of the sea central part contains low concentrations of particles that cause backscattering. R_{rs} in the western central part was low until the action of the quasi-tropical cyclone at the end of September (see the purple line in Fig. 3).

After the action of the cyclone at the beginning of October 2005, the rise of R_{rs} was first observed in the south-western part of the sea (red rectangles in Fig. 7b), where it increased to the values of $5\text{-}6{\cdot}10^{-3}$ sr^{-1}, corresponding to the level of coccolithophore bloom. The increase of R_{rs} was detected only in a limited area located over the south continental slope of the basin. An increase of R_{rs} was only observed on the shelf/slope boundary in the intermediate zone between the shelf and the central part of the sea and was absent near the coast. Similar, but smaller rise of R_{rs} was also observed in the shelf/slope boundary in the western part of the sea.

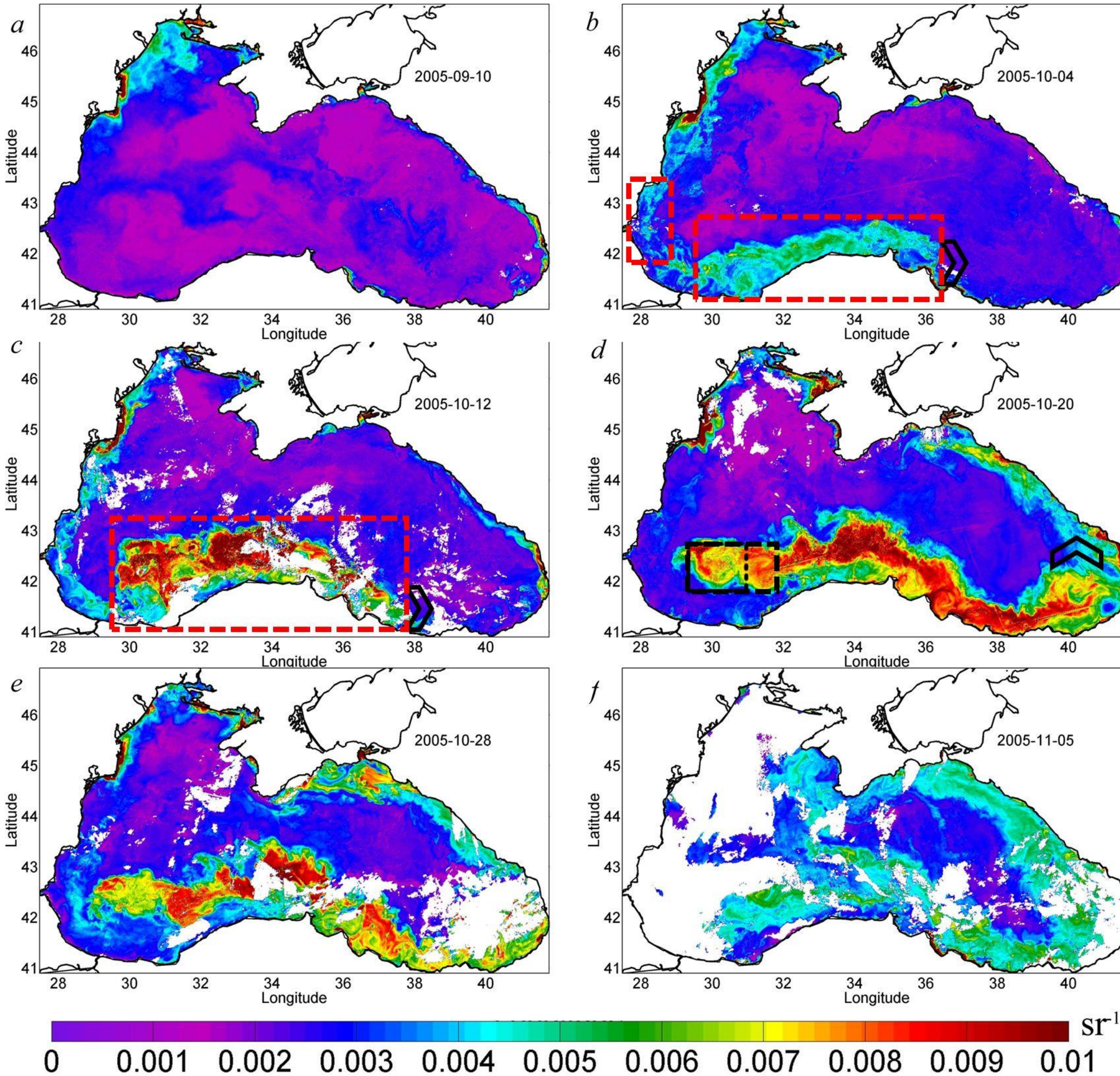

Figure 7: 8-day maps of remote sensing reflectance R_{rs}, sr^{-1}, centered at **(a)** 10 September 2005; **(b)** 4 October 2005 the red rectangle shows the area of the initial start of the bloom; **(c)** 12 October 2005, the red rectangle shows a mixing area; **(d)** 20 October 2005, the black rectangle shows the center of the deep bloom in the western cyclonic gyre **(e)** 28 October 2005, **(f)** – 5 November 2005. The black arrow shows the position of the eastern boundary of the bloom.

A detailed daily map of R_{rs} for 5 October 2005 (Fig. 5b) shows that the maximum R_{rs} was observed in the thin zone on the offshore periphery of the Danube plume. At the same time near the coast and in the western central part in the epicenter of cyclone action R_{rs} rise was absent. This frontal zone is a subject of the intense horizontal mixing between brackish nutrient-rich plume waters and saline waters of the central part, which may be one of the possible triggers of coccolithophore bloom. High R_{rs} values were located mainly in the frontal instabilities formed on the boundary of the plume, possibly due to the impact of strong horizontal shear on the periphery of the intensified Rim Current. Mixing between plume and saline waters can significantly intensify buoyancy gradients, which possibly cause the rise of baroclinic submesoscale instabilities observed in Fig. 5a, 5b. Submesoscale motions can induce very strong vertical velocities reaching more than 10-100 cm s^{-1} (Mahadevan, 2016), which can provide upward nutrient fluxes for coccolithophores. For example, we can observe a strong rise of R_{rs} on the periphery of anticyclones A1 and A2 (Fig. 5b), where vertical velocities are probably directed upward. At the same time in the center of anticyclones, where vertical motions are downward R_{rs} is low. Another prominent feature in Fig. 5b is the mushroom structure consists of cyclone C1 and anticyclone A3. The cyclonic part of this structure have significantly higher R_{rs} than its anticyclonic part. These observations suggest the important impact of submesoscale vertical fluxes on the initial rise of R_{rs}. Analysis of MODIS daily maps shows that in this area from 5 to 7 October of 2005 R_{rs} valued almost doubled. We note that R_{rs} was lower near the coast, which indicates that its rise was not related to the terrigenous particles caused by river discharge or storm-driven coastal erosion.

A week later, at 8-15 October R_{rs} value rapidly increased (Fig. 7c) and the bloom area has doubled (Fig. 3, red line). The maximum R_{rs} increased to 0.012 sr^{-1}, which corresponded to $5.8 \cdot 10^6$ cells l^{-1}. The area of most intense bloom was observed in the continental slope south of the western gyre and the regions west of it (see red rectangle in Fig. 7c). This distribution was very similar to the one observed in Chl (Fig. 4c, d). As it is discussed in Section 4 the rise of Chl in this area was related to the horizontal mixing and penetration of the Danube plume to the central part of the basin. The most intense rise of R_{rs} was first observed in the area of mixing of saline waters of the central Black Sea with brackish Danube waters. At the same time, R_{rs} was relatively low near the Danube mouth indicating that riverine waters can not be the reason for such R_{rs} rise.

In the next week (from 16 to 23 October), the bloom position shifted from the coast to the center of the western gyre (Fig. 5d, 7d). The position of this gyre can be observed as an area of decreased SST (Fig. 1b) and sea level (black ellipse in Fig.2b) in satellite measurements. This area corresponded to the zone of maximal vertical mixing and intense entrainment of nutrients from deep isopycnals layers. Here stable bloom area with a diameter of about 100 km developed (see black rectangles in Fig. 5d, 7d). The advection by the Rim Current transport both raised nutrients and already formed phytoplankton cells from this zone to the east. The region of high values of the R_{rs} extended from this area eastward along the continental slope up to the eastern coast of the basin up to 41.5°E (Fig. 7d, e). The propagation of the eastward boundary of the plume is marked by the black arrow in Fig. 7. At the velocity of 0.45 m s^{-1} (Fig. 2d), the particles will be transported on 1000 km in 3 weeks, which causes the extension of the bloom up to the eastern coast of the Black Sea in agreement with satellite optical measurements (Fig. 7e). As a result, the total length of the bloom area was more than 1200 km (Fig. 7d).

At the same time, despite intense cyclonic currents, the western boundary of the bloom was continuously observed in the same location in the center of the western cyclonic gyre (black rectangle in Fig. 7d). This indicates that the upwelling in the center of the west cyclonic gyre was a continuous source of nutrients for phytoplankton, from which the bloom stretched to the eastern shore. Indeed, decreased SST in this area was observed until the end of October, which also indicates the stability of upwelling. If this source was not permanent, the process of advection would cause the decrease of R_{rs} in the west cyclonic gyre. Therefore, the vertical transport of nutrients probably compensates these losses, in the zone of the maximal upwelling in the western cyclonic gyre. The prolonged action of upwelling (2-3 weeks) can be related to, first, the delay between the action of Ekman pumping and upwelling and, second, the time needed for the relaxation of the upwelling after the wind action.

After 2-3 weeks after the cyclone's action, the average and maximum values of the R_{rs} parameter reached the highest values (Fig. 3, purple line). In some areas, the R_{rs} was higher than 0.018 sr^{-1}, which corresponds to an estimate of $9\text{-}10 \cdot 10^6$ cells l^{-1}. Bloom area at this time reached a maximum of about $40 \cdot 10^3$ km^2 (Fig. 3, red line).

At the end of October, the intensity of coccolithophore bloom in the western cyclonic cycle weakened (Fig. 7e) indicating the depletion of nitrates. In this period, the maximum value of R_{rs} decreased to 0.007 sr^{-1}. The highest R_{rs} values started to displace from the eastern cyclonic gyre and shifted to the east to 31-32°E (Fig. 7e). At the beginning of November, R_{rs} fell to 0.005-0.006 sr^{-1}, indicating the termination of the bloom (Fig. 7f). The termination occurs at the time of the beginning of late-autumn phytoplankton bloom, reflected in the rise of Chl over the whole central part of the basin (Fig. 4f).

4 Discussion

The action of an anomalous atmospheric quasi-tropical cyclone caused a strong coccolithophore bloom, which lasted for more than a 1.5 months and covered the entire southern part of the Black Sea. Very similar blooms were observed in satellite data in 2014 and 2016 in Fig. 6c, d. These figures demonstrate similar spatial patterns of R_{rs} extending from the western cyclonic gyre over the south continental slope. Our analysis shows that these blooms were also triggered by intense western storms over the western cyclonic gyre. These illustrations show that the discussed in these paper processes may be also important in defining the biological characteristics of the basin in other years. However, in both of these cases, R_{rs} was significantly smaller than in 2005 and usually does not exceed 0.007, compare to 0.1 in 2005. Also, such blooms in these years was observed later in winter – in December and not in October. This shows that the extremely strong tropical cyclone in 2005 definitely caused strongly anomalous biological processes in the Black Sea – October bloom of coccolithophores with estimated cell concentrations exceeding 10 mln cells l^{-1}.

The natural cause of phytoplankton bloom is the entrainment of nutrients in the euphotic layer caused by rapid changes in basin dynamics. Usually the entrainment of nutrients, particularly, in autumn-winter causes a rapid growth of diatoms (Sorokin, 1983; Mikaelyan et al., 2017), which have the highest growth rate that the coccolithophores (Goldman, 1993; Lomas and Glibert, 1999). Definitely, several authors demonstrated the rapid increase of Chl in the Black Sea after strong storm events (Nezlin, 2006; Kubryakov et al., 2019a). However, in October 2005 we observed another case: the atmospheric cyclone causes the domination of the coccolithophores manifested in the strong rise of R_{rs}, accompanied by only a slight rise of Chl.

There are several possibilities of this dominance. First, coccolithophores can use mixotrophy and utilize dissolved organic matter (Benner and Passow, 2010; Poulton et al., 2017; Balch, 2018) formed after diatom blooms, which, particularly, explain the observed in the Black Sea in the spring diatom-coccolithophores sequence (Mikaelyan et al., 2011, 2015). Because of this, coccolithophores have an advantage in low nitrogen and high phosphate conditions. Particularly, several studies show that amount of phosphates largely determines the interannual variability of the intensity of coccolithophore blooms in the Black

Sea (Mikaelyan et al., 2011, 2015; Silkin et al., 2009, 2014). The phosphates are remained in the upper layer of the Black Sea, as the N/P ratio in the deep part of the basin is very low 2-6 (Konovalov et al., 2005; Tuğrul et al., 2014). This is related to the removal of nitrates from the sea in the form of free nitrogen due to the intense chemical in the suboxic layer of the basin (Konovalov et al., 2008; Tuğrul et al., 2014). After mixing events, diatoms, which have a higher growth rate than coccolithophores (Goldman, 1993), rapidly consume inorganic nitrogen and phosphate, but since the N/P ratio is low, part of the phosphate is not consumed in the upper layer. These environmental conditions are favorable for coccolithophores which can grow rapidly under low inorganic nitrogen (Eppely et al., 1969) and relatively high phosphate (Silkin et al., 2009) concentrations.

Second, coccoliths defend cells from photoinhibition, which give coccolithophores an advantage in the shallow mixed layer (Tyrell and Merico, 2004) and also can explain their domination in the summer.

Third, the grazing pressure on the diatoms of dinoflagellates usually is significantly higher than on coccolithophores (Nejstgaard, 1997; Stelmakh, 2013), which may give them an advantage during high concentrations of predators. Stelmakh (2013) showed that in the Black Sea grazing in diatom-dominated regions was about 90%, while in coccolithophore-dominated it was three times lower (30%) in agreement with estimates obtained in (Olson and Strom, 2002).

Satellite data in our study allow us to observe two different phases of the bloom development, which indicates that at least two processes were driving the bloom. The initial rise of R_{rs} was observed at the frontal zone separating the brackish, nutrient-waters of the Danube plume, and saline waters of the central Black Sea (stage 1). Acceleration of the Rim Current up to extreme velocities of 0.75 m s^{-1} significantly intensify horizontal shear, which triggers the formation of several submesoscale eddies (see Fig. 5) in the coastal zone of the Black Sea (Zatsepin et al., 2019) and strongly intensify vertical mixing (Podymov et al., 2020). These eddies first, intensify cross-shelf flow and the horizontal transport of Danube plume waters in the deep part of the basin. The mixing zone became the first area, where coccolithophores started to grow up to bloom conditions. The overflow of the brackish plume on the saline waters additionally increase the baroclinic instabilities (Luo et al., 2016) and intensify submesoscale motions. Recent studies demonstrate that such processes can cause very intense vertical motions, which may be the important reason for the rise of the primary productivity on the fronts (Oguz et al., 2015; Mahadevan, 2016). Such submesoscale vertical fluxes can explain the spatial distribution of R_{rs} in Fig. 5a and also help to explain its earlier growth compare to the central part of the basin at Stage 2.

Therefore, a cross-frontal mixing may cause the growth of coccolithophores due to several reasons: 1) vertical fluxes of nutrients caused by baroclinic submesoscale instabilities; 2) the rise of stratification caused by the overflow of brackish waters on saline waters; 3) penetration of nutrient or dissolved organics from brackish plume waters in the deep saline part of the basin, which can cause the growth of coccolithophores preferring more saline waters (see Brand, 1984).

Additionally, shelf waters of the Black Sea are characterized by a high concentration of zooplankton, which can exceed its concentrations in the deep part of the basin 10 times (Kovalev et al., 1999). The intense penetration of the zooplankton with shelf waters to the central part of the basin may suppress the rise of diatoms despite the strong vertical fluxes of nutrients at the initial stage of cyclone action.

Stage 2 of the bloom begins after about two weeks from the cyclone action on 10-20 October. At the time the bloom shifted to the central-western cyclonic gyre – the zone of maximal upwelling, which is expected. Of particular interest, is the time delay between the cyclone and the bloom in the central part of the basin. This time lag can be attributed both to the delayed response of the basin geostrophic circulation on the changes in Ekman pumping (Grayek et al, 2010; Kubryakov et al., 2016) and the biological process, e.g. growth time, the concurrence between coccolithophore and other types of phytoplankton. However, as the nutrient fluxes were the most intense in this area, the bloom was observed here continuously for more than 2 weeks after 15 October and rich maximal intensity.

Satellite data also showed that the rise of coccolithophores was observed simultaneously with the increase of Chl. Such simultaneous bloom was observed earlier in May-June by in situ measurements in the Black Sea (Mikaelyan et al., 2018; Pautova et al., 2011; Silkin et al., 2011, 2019) and other ocean areas (Balch, 2018) and can be related to the huge amount of nutrients entrained in the central part of the basin both with horizontal and vertical advection

5. Conclusions

The action of an atmospheric cyclone in September 2005 caused an intense bloom of calcified phytoplankton – coccolithophore in the Black Sea basin with satellite-estimated concentration reaching 10 mln cells l^{-1}. The bloom was observed in October-November and lasted for more than 1.5 months. Satellite data shows that there were two important reasons of the bloom: 1) cross-shelf mixing of Danube plume and waters of the central part of the basin and related submesoscale instabilities, which cause the initial growth of R_{rs} on the offshore frontal zone of the plume; 2) intense upwelling in the central-western cyclonic gyre, where R_{rs} reaches maximal values. Intense cyclonic Rim Current spread the bloom over the entire south part of the Black Sea up to its eastern coast.

Coccolithophores plays an important role in the ecosystem of the North Atlantic, Barents Sea, Southern Ocean, and other ocean areas (Balch et al., 1996, 2019; Hopkins et al., 2015; Krumhardt et al., 2016; Moore et al., 2012; Shutler et al., 2013; Tyrrell and Merico, 2004). Studied in this manuscript extreme atmospheric events can play an important role in the observed interannual variability of the coccolithophores in these regions. Such coccolithophore blooms may significantly impact on the seasonal succession of marine phytoplankton. Particularly, they can trigger the following microbial loop – the transition of trophic energy to small species and subsequent changes in the entire trophic structure of the region (Brussaard, 2004; Kubryakov et al., 2019b). Detailed information about the response of the phytoplankton community to short-term physical processes is necessary for understanding the functioning of marine ecosystems. Such information can be provided only on the base of continuous monitoring of the taxonomic composition of phytoplankton, based, e.g. on the measurements of flow cytometers.

Data availability

We acknowledge the use of (1) moderate-resolution Imaging Spectroradiometer (MODIS) Aqua Ocean Color Data produced by NASA Goddard Space Flight Center. DOI: data/10.5067/AQUA/MODIS/L2/OC/2018; (2) DUACS delayed-time altimeter gridded maps of sea level anomalies over the Black Sea (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sea-level-daily-gridded-data-for-the-black-sea-from-1993-to-present?tab=overview produced and distributed by the Copernicus Climate Change Service; (3) QuikScat (or SeaWinds) data are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team and are available at http://www.remss.com/missions/qscat/; (4) AVHHR data were received and reprocessed at Marine Hydrophysical Institute, Russia, and are available from http://dvs.net.ru/mp/data/200509bs_sst.shtml.

Author contribution

Sergey Stanichny and Arseny Kubryakov were involved in planning and supervised the work, Elena Kubryakova and Arseny Kubryakov processed the satellite data, performed the analysis, Elena Kubryakova drafted the manuscript and designed the figures. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest, no competing financial interests.

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