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Model estimates of microplastic potential contamination pattern of the eastern Gulf of Finland in 2018

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Abstract The work is focused on the assessment of microplastics transport and distribution in the eastern part of the Gulf of Finland by means of numerical modeling. In the present study only the riverine sources of microplastics are taken into account. The presented model also accounts for possible sink of suspended microplastic particles into sediments due to simple parameterization of biogeochemical processes such as biofouling and ingestion by zooplankton. Two basic scenarios with different initial fall velocities of suspended microplastic particles, 0.2 m/day and 1.2 m/day, are discussed. The distribution of microplastics coming with the riverine waters of the Neva, Luga, and Narva rivers has been investigated, based on a numerical hydrodynamical hindcast of the year 2018. Model simulations show that the transport of suspended microplastics occurs along the northern coast of the considered area more intensively compared to the southern coast, especially in the easternmost shallow part of the gulf. The results are in a good agreement with other studies focused on the microplastic pollution of the Neva Bay, and with available observational data. The presented results and developed model can be useful tools aimed to assess the intensity and mechanisms of microplastic pollution of the eastern Gulf of Finland. The results can be used in the selection of areas for future environmental monitoring of microplastics pollution of the eastern part of the Gulf of Finland.

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1. Introduction

Microplastics can be defined as plastic particles and fibers smaller than 5 mm (Cole et al., 2011; Thompson et al., 2004). Still, the range of sizes of microplastic particles is of several orders of magnitude. A good review of microplastics' characteristics and processes involved in its transport can be found in (Zhang, 2017).

Microplastic particles are considered to be pollutants for the environment and biota (e.g., Karbalaei et al., 2018). Microplastic particles released into the environment are bioavailable in the food chain and can ultimately enter human food (Kolandhasamy et al., 2018). To identify potential measures to reduce the release of microplastics into the environment, it is necessary to identify the main sources and distribution of microplastics on land, in the atmosphere and in the hydrosphere. It is customary to distinguish between primary and secondary sources of microplastics (Cole et al., 2011). The former are plastics, originally produced by industry on a micro scale. Secondary sources of microplastic arise as a result of the destruction of macroplastic objects (both in the ocean and on land) under the influence of mechanical, chemical and biological processes.

Recently, a large number of studies concerning the problem of the entry and distribution of microplastics in the World Ocean have been published. The transport, spatial distribution and accumulation of microplastics were studied by means of numerical modeling (e.g., Lebreton et al., 2012; Sterl et al., 2020), drifters (e.g., Maximenko et al., 2012), as well as by direct observations (e.g., Eriksen et al., 2014). Q2 (Clark et al., 2016) fulfilled a good review of the phenomenon of the microplastics distribution in the ocean and discussed its interaction with biological processes, primarily with the entry of micro- and nanoplastic particles (<300 μm) into the food web of marine organisms and migration within it. It is important to note that many studies focused on the distribution of microplastics in the World Ocean (e.g., Lebreton et al., 2012; Maximenko et al.; 2012) do not consider gravitational settling of microplastic particles or the influence of biological processes upon it due to the lack of observational data to parameterize such effects. On the other hand, there exist rather detailed studies, but focused on relatively limited areas. For instance, (Besseling et al., 2017) used a detailed model of microplastic particles' transport in freshwater basins (Quik et al., 2015), which describes aggregation, sedimentation, degradation, resuspension and burial for 25 different particle diameters ranging from 100 nm to 10 mm. (Berezina et al., 2021) investigated the impact of biological productivity upon the microplastics presence and transportation throughout the year by means of numerical modeling and confirmed that the biological factor plays a significant role in microplastic distribution in water. Biological impact upon the microplastics sinking rate and distribution was also recently investigated in (Fischer et al., 2021; Lobelle et al., 2021).

Microplastics entering the marine environment are transported by currents and turbulent mixing and are removed from the water due to gravitational settling (Kaiser et al., 2017; Karlsson et al., 2017), ingestion by marine organisms (Frias et al., 2014; Lusher et al., 2015; Rochman et al., 2015; Tanaka and Takada, 2016), removal to the shore during storms (Herrera et al., 2017; Imhof et al., 2018; Naji et al., 2017; Turra et al., 2014) and freezing into sea ice (Obbard et al., 2014). A large number of studies focused on the pollution of the marine environment with microplastics emphasizes the urgency of this problem and the great concern of not only the scientific community, but also of general public and political decision-makers.

In estuarine-type bays, such as the Gulf of Finland located in the Baltic Sea, rivers with large industrial and populated cities located on the banks may be the main source of microplastics. The Neva, Luga and Narva are the largest rivers flowing into the eastern part of the Gulf of Finland. Also, the close vicinity of St. Petersburg with a population over five million people adds municipal wastewaters as potential source of microplastics (e.g., Murphy et al., 2016; Ziajahromi et al., 2016). The influx of microplastics into the waters of the Neva Bay (the easternmost part of the Gulf of Finland) from the surrounding beaches can hardly be large since they are constantly being cleaned, although for other beaches of the Gulf of Finland the situation may be different. A significant role in microplastics' transport can be played by air transport from urban dumpsites to the water area during storms. Finally, microplastics can enter the water from one-year sea ice after its melting in spring, though the origin of such microplastics may be difficult to determine (e.g., Obbard, 2018; Obbard et al., 2014).

For the Baltic Sea region, the input and distribution of microplastics were investigated in (Bagaev et al., 2017, 2018; Beer et al., 2018; Chubarenko and Stepanova, 2017; Stolte et al., 2015; Talvitie et al., 2015). Recently, (Schernewski et al., 2020) analyzed wastewater sources for the entire Baltic Sea, compiled microplastics emission data, developed emission scenarios and simulated transport and deposition of microplastics in the Baltic Sea environment. The removal of microplastic particles from the water coming from the Viikinmäki wastewater treatment plant located in the Gulf of Finland (Helsinki archipelago region) was investigated in (Talvitie et al., 2015), where authors emphasized the need to study the sources of microplastics and its routes into water environment.

Detailed studies of the microplastics distribution in the eastern part of the Gulf of Finland began only in 2018 (Eremina et al., 2018) and consisted of monitoring the microplastic content along the coasts of the Neva Bay. Results of survey aimed to investigate the content of microplastics and its characteristics in water and sediments in the Neva Bay were also reported in (Pozdnyakov et al., 2020).

The aim of this work is to assess the distribution of the microplastics in the eastern part of the Gulf of Finland, entering with river waters, taking into account the possible sink of suspended microplastic particles into bottom sediments due to biogeochemical processes. A similar study was recently performed by (Martyanov et al., 2019), where the propagation of microplastic particles in the Neva Bay, presumably coming from the Neva River runoff, was studied under conditions of realistic hydrodynamic and meteorological forcing using a high-resolution numerical model described in (Martyanov and Ryabchenko, 2016; Ryabchenko et al., 2018). The main differences between the current work and the study by (Martyanov et al., 2019) include using another hydrodynamic model with grid covering most of the Gulf of Finland, and setting the rate of gravitational settling of

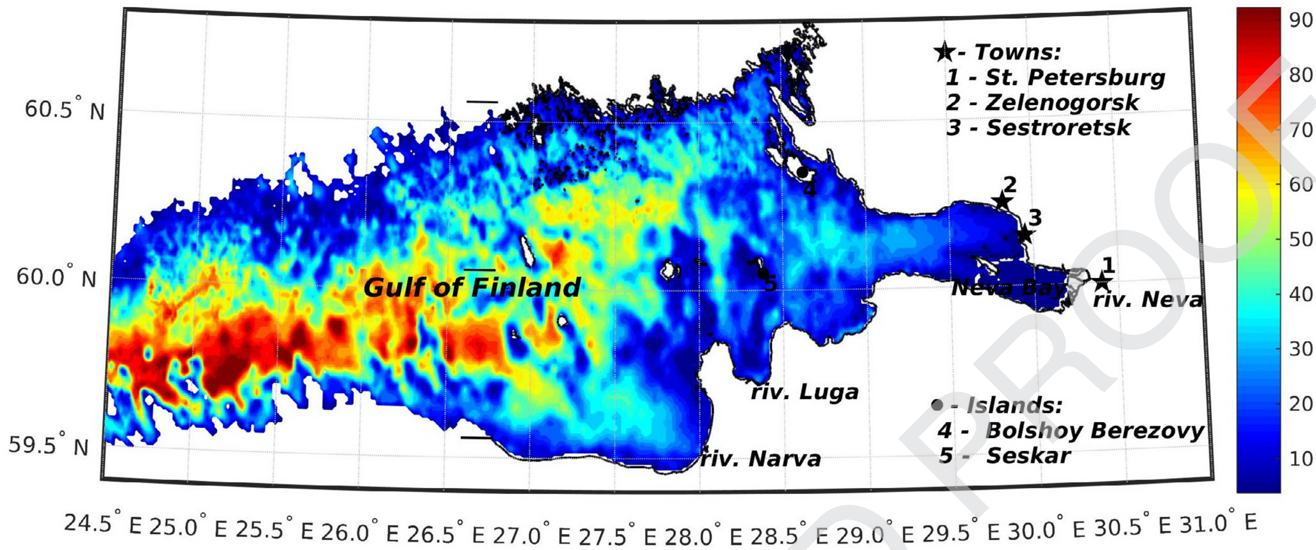

Figure 1 Model's domain and bathymetry (m).

microplastic particles which takes into account its possible change due to biofouling (Leiser et al., 2020) and ingestion by zooplankton. We also discuss the potential release of microplastics ashore from the water during stormy events in the eastern part of the Gulf of Finland. The findings of our study may be useful in understanding the results of field surveys focused on microplastic pollution of the eastern part of the Gulf of Finland, and also in locating possible areas of increased microplastics concentration in the coastal zone and planning future monitoring campaigns.

2. Methods

2.1. Hydrodynamic model, forcing and boundary conditions

The study area covers almost the entire Gulf of Finland from the mouth of the Neva River in the east up to the meridian 24.08 E in the west (Figure 1). We use the Massachusetts Institute of Technology general circulation model — MITgcm (Marshall et al., 1997) to simulate the thermohydrodynamics of the gulf. The model is run in the hydrostatic regime. The TKE closure scheme based on (Gaspar et al., 1990) is used to parameterize the vertical turbulent mixing of momentum and scalar fields. The horizontal viscosity and diffusivity coefficients are set constant and equal to 75 m^2/s and 10 m^2/s, respectively. Here the coefficients of horizontal viscosity and diffusivity are taken equal to their minimum possible values ensuring the computational stability of the difference methods used. Thus, horizontal viscosity and diffusivity play a secondary role in our model, so that the transport of momentum, temperature, salinity and tracers along the horizontal is carried out mainly by currents. This approach is in accordance with a number of studies (e.g., Vankevich et al., 2016; Westerlund et al., 2018; Westerlund et al., 2019), where the dynamics of the Gulf of Finland were successfully simulated using the NEMO model with constant coefficients of horizontal viscosity and diffusivity. The sea ice module is based on the viscous-plastic rheology and sea ice thermodynamics described in (Losch et al., 2010). The model is implemented on a spherical horizontal grid covering the specified area with resolution of 0.5′ in latitude and 1.0′ in longitude, which approximately corresponds to 1 km horizontal resolution in both directions at the mean latitude of the Gulf of Finland. The model's vertical resolution in the upper 20 meters is 2 m, in the 20—50 m — 3 m, and deeper 50 m — 4 m. The time step of model integration is 100 seconds.

The boundary conditions for temperature, salinity and sea level at the open western boundary are taken from the reanalysis data of the Swedish Meteorological and Hydrological Institute (SMHI) available at the COPERNICUS website (http://marine.copernicus.eu, product BALTICSEA_REANALYSIS_PHY_003_011). To calculate the model's current velocity components at this open boundary we use a modified Stevens scheme (Stevens, 1990), according to which barotropic velocity components are calculated using sea level data, whereas baroclinic velocity components are taken from the computational domain. The atmospheric pressure, wind speed components, air temperature and humidity, precipitation, short-wave and long-wave incoming radiation are specified based on the ERA-Interim reanalysis (https://www.ecmwf.int) with the time step of atmospheric data equal to 3 hours. The monthly-mean runoff of the rivers Neva, Luga and Narva, flowing into the model's domain, are taken from the Baltic Environmental Database (BED) of the Stockholm University (http://nest.su.se/helcom_plc/).

The initial distributions of temperature and salinity are set based on the results of previous simulations on a coarser grid reported in (Vladimirova et al., 2018). Initial fields of current velocity and sea level are set to zero.

Simulations have been carried out for the period 2015—2018. The period 2015—2017 is considered to be an adaptation time to initial conditions. The model solution obtained for the year 2018 is considered to be a quasi-equilibrium solution and is used for further analysis.

2.2. Microplastics transport model

The model operates with microplastic particles whose buoyancy varies based on the involvement of these particles in biogeochemical processes. The buoyancy is neutral in the absence of biogeochemical processes, which is assumed for water temperatures less than 4°C. It is assumed that microplastics enter the Gulf of Finland with the waters of the Neva, Luga and Narva rivers, i.e. only riverine source of microplastics is taken into account in the present study. The supply of microplastics to the Gulf of Finland is determined by the river discharge and the content of microplastics in the river water. The real content of microplastics in the discharge waters of the rivers considered is not known. An attempt to take into account the differences in the content of microplastics in different rivers would require some functional dependence, like content is a function of population, industry, etc. Such information is currently absent for the Neva Bay and the eastern Gulf of Finland region. That is why we assumed a simplest approach and prescribed microplastics concentration C in rivers equal to 1000 conventional units (c.u.) in a cubic meter. This concentration is not related to any actual concentration of microplastic particles in the Neva Bay or in the Gulf of Finland due to lack of such data, and is simply used to indicate the external source of these particles in the model. Additionally, with the microplastic concentration being determined by the model in the entire domain, it can be easily rescaled if the actual content in the river waters becomes known.

It is assumed in the model that microplastic particles can be ingested by zooplankton and/or adhere to individual organisms in the upper water layer. When zooplankton die off and/or when microplastic particles become heavier due to the biofouling process, they sink and, ultimately, reach the bottom as part of detritus. It is well known that biogeochemical processes in the sea, including those mentioned above, strongly depend on the ambient temperature, and their intensity increases during the growing season (spring, summer and autumn) at higher temperatures, and is negligible in winter at low temperatures. Since the ecosystem model is not used here, the temperature remains the only predictive variable in the model by which these seasonal variations in biogeochemical processes can be tracked. Using the results of an ecosystem model (Isaev et al., 2020; Vladimirova et al., 2018), we estimated that the temperature 'boundary' between the vegetation and winter periods, when the content of phytoplankton, zooplankton and detritus and, hence, the detritus fall velocity in the Gulf of Finland is close to zero, can be assumed to be about 4°C. Following the model developed in (Savchuk, 2002 and references therein), the detritus fall velocity W_g depends on water temperature T. Summarizing the above, we parameterize the fall velocity of microplastic particles in the following idealized form:

$$\begin{aligned} &W_g = \gamma \times W_{g0} \times \exp(kT), \qquad \text{if } T \geq 4^\circ\text{C} \\ &W_g = 0, \qquad \text{if } T < 4^\circ\text{C}, \end{aligned} \tag{1}$$

where $0 < \gamma < 1$ – part of microplastic particles captured by zooplankton and subject to biofouling; W_{g0} is basic constant gravitational fall velocity of microplastic particles; $k = 0.08$ 1/°C. According to Eq. (1), where T is the instant water temperature, at the beginning of the growing season, upon reaching the temperature of 4°C, the formation of detritus instantly begins, with the corresponding sinking of microplastics with it. In (Berezina et al., 2021), based on the model of the marine ecosystem combined with the model of microplastic transport, it was shown that the time during which microplastic with initially neutral buoyancy acquires its own fall velocity by means of interacting with biota, is from several days to several weeks. Due to such uncertainty of this period, in the current study we do not use any time lag associated with biota growth. This simplification can be considered as one of the limitations of the model used in our study. It also should be emphasized that the model does not describe the resuspension of the microplastic particles from the bottom. In this study, we estimate the maximum potential influence of biota on microplastics and assume that all microplastic particles at water temperatures above 4°C are ingested by zooplankton (and then get into detritus) or subject to biofouling, followed by the sinking of heavier particles into the bottom layer. This means that γ is taken equal to 1 in the current study. The exact value of W_{g0} is not well known. To assess the sensitivity of the model solution to this constant, its values are taken equal to 0.2 m/day as in (Martyanov et al., 2019) and 1.2 m/day as in (Vladimirova et al., 2018). Thus, two scenarios with different initial constant fall velocities W_{g0} are implemented and discussed in this study.

The parametrization (1) is original in relation to microplastics, because we assume that microplastics captured by zooplankton or subjected to biofouling sink in the water column with the fall velocity of gravitational sinking of dead organic matter (detritus). As for the parametrization of the detritus fall velocity, the parametrization is not original, but taken from (Savchuk, 2002) with some modification. The new element is the introduction of zero fall velocity at water temperatures less than 4°C. As follows from the Eq. (1), there is a large discontinuity at T = 4°C. This is an obvious flaw in our parameterization.

Converting the microplastic's fall velocity into microplastic particles' size is a complicated problem. The fall velocity and particle size are linked through the particle's density and shape, which in case of microplastics can both vary in a wide range (e.g., Kaiser et al., 2019; Khatmullina and Chubarenko, 2016; Kowalski et al., 2016). For example, polystyrene's density is about 1005 kg/m3, polycaprolactone density is about 1131 kg/m3, while polypropylene is more lightweight than water. Unfortunately, the exact type of suspended microplastics is not known in the Neva Bay. In these circumstances we decided not to specify any particular type of microplastic particles and their size in our simplified model.

When discussing the selected values of the fall velocities of microplastics, it should be remembered that in our model the particles entering the basin have neutral buoyancy, and the fall velocity acquired by them is a certain average fall velocity of detritus particles containing microplastics, and therefore it should not be associated with the fall velocities of the microplastics itself. Therefore, the selected range of the fall velocities of microplastics reflects the range of fall velocities for detritus of different origins known from the literature.

A three-dimensional equation of the passive tracer transport is used to simulate the spatio-temporal distribution

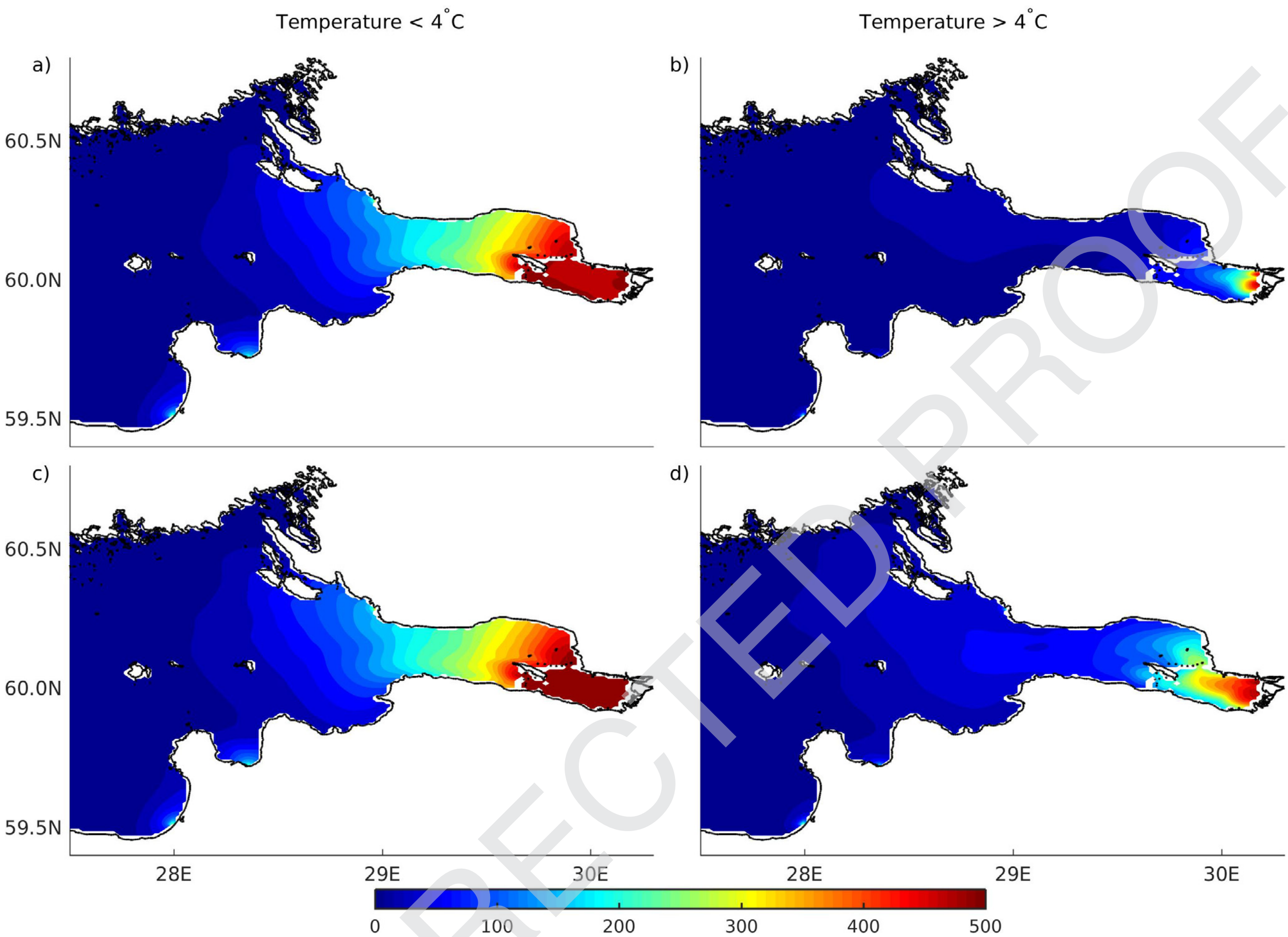

Figure 2 Modeled microplastics concentration in the top model layer (0–2 m) in 2018 with $W_{g0} = 1.2$ m/day (a, b) and 0.2 m/day (c, d) averaged for the autumn–winter period (T < 4°C, left figures) and spring–summer period (T > 4°C, right figures).

of microplastics particles concentration in the eastern part of the Gulf of Finland. A basic advection-diffusion equation for the passive tracer has been modified to take into account the gravitational settling of microplastics particles under certain conditions described above in accordance with Eq. (1). The vertical diffusivity coefficient for microplastic is parameterized using the TKE closure scheme by (Gaspar et al., 1990), and the horizontal diffusivity coefficient for microplastic is considered to be constant and equal to 10 m^2/s.

At the open western boundary, a radiation condition is set for the outgoing flow and a zero concentration of suspended microplastic particles is set for incoming flow. At the solid lateral boundaries and at the upper boundary (sea surface) the flux of microplastic particles is set to zero, while at the lower boundary it is set equal to $C \times W_g$.

3. Results

3.1. Spatial-temporal distribution of microplastics in water and sediments

According to the model configuration, microplastic particles do not settle in the water column down to the bottom in the autumn-winter period when water temperature is less than 4°C. Analysis of the results shows that during the transport process, microplastics are concentrated mainly in the upper mixed layer. Below we present the patterns of its distribution in the uppermost layer of the model. In particular, Figures 2a and 2c show the modeled microplastics concentration in the top model layer (0–2 m) averaged over the autumn-winter period. It demonstrates that microplastics concentration decreases from the source at the river mouth towards the western boundary of the model area. Transport of suspended microplastic particles into the Gulf of Finland occurs more intensively along its northern coast, especially in its easternmost narrow part, which is explained by the general circulation scheme in gulfs and bays located in the northern hemisphere.

With the beginning of the intense heating of the water column, the mechanism of settling of microplastic particles starts to work, and its rate increases with an increase of water temperature (Eq. 1). Therefore, in the spring-summer period the main part of microplastics coming with the river waters settles in the estuarine areas. This process is seen in the distribution of suspended microplastic particles in surface waters. Figure 2 also demonstrates that in the spring-summer period, a 10-fold decrease of the surface concentration of suspended particles occurs already in the Neva

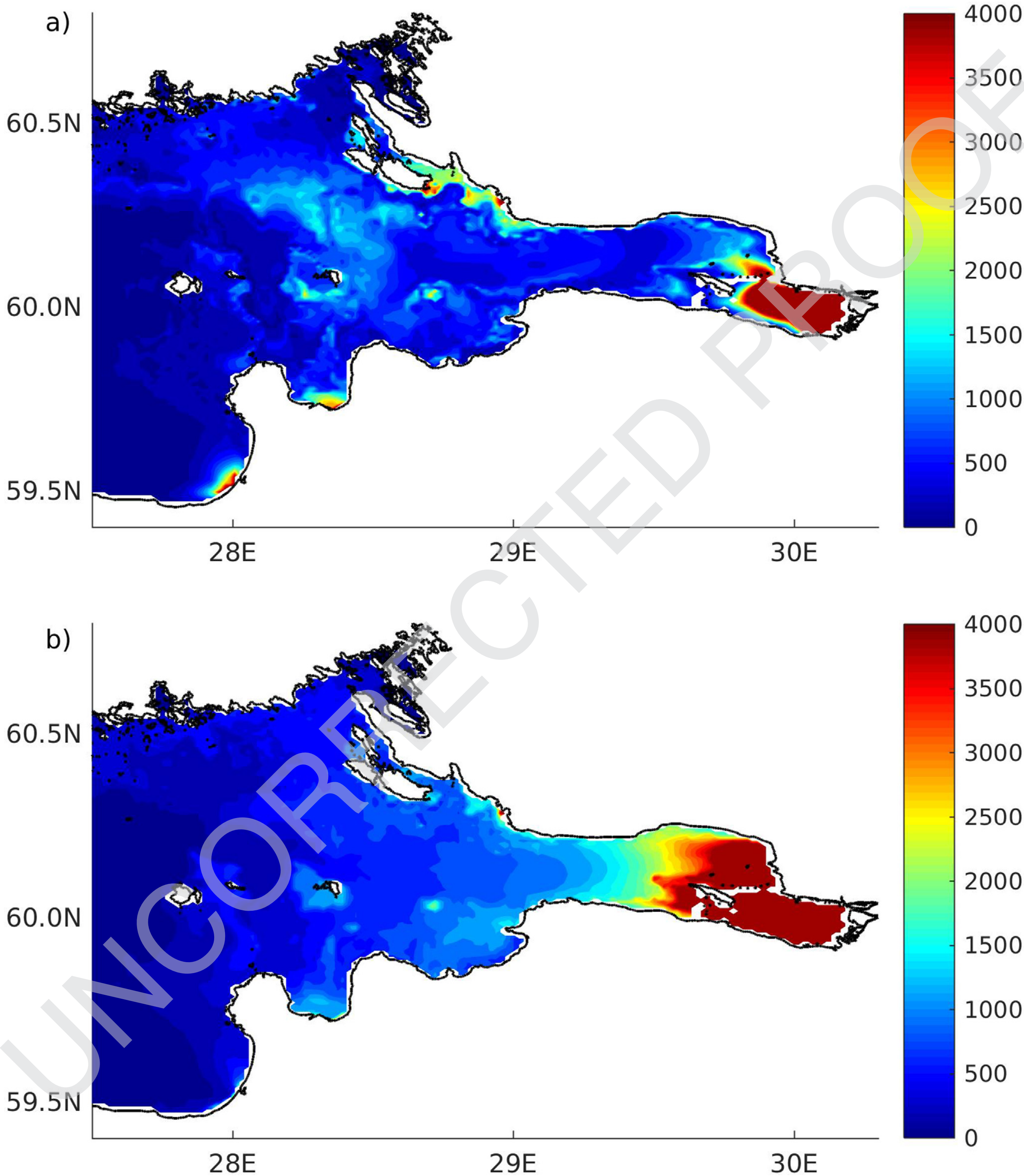

Figure 3 Modeled annual-mean content of microplastic particles in the sediments in 2018 (c.u./m^2). a) $W_{g0} = 1.2$ m/day; b) $W_{g0} = 0.2$ m/day.

Bay if the basic fall velocity of microplastic particles is set $W_{g0} = 1.2$ m/day (Figure 2b), and to the west of the St. Petersburg's Flood Protection Barrier (FPB) if $W_{g0} = 0.2$ m/day (Figure 2d).

Figure 3a shows the modeled annual-mean content of microplastic particles (expressed in c.u./m^2) deposited in the sediments in the eastern part of the Gulf of Finland in 2018 with basic fall velocity $W_{g0} = 1.2$ m/day. The patterns of microplastics in Figure 3 represent the accumulation of mi-

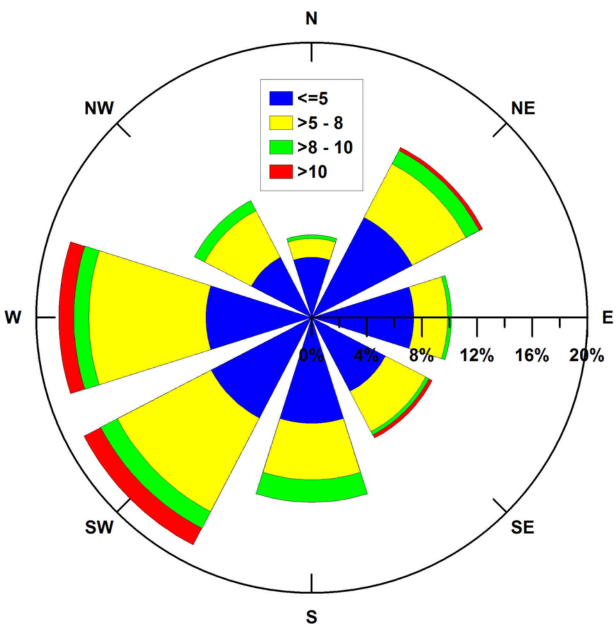

Figure 4 Distribution of daily-mean wind speed and direction over the eastern part of the Gulf of Finland in 2018 based on ERA-Interim reanalysis. The wind rose is plotted under the traditional convention for wind (wind blows from the given direction).

croplastics in bottom sediments, starting from 2018, excluding the part accumulated during the spin-up of the model. The main part of the particles entering the bay with riverine waters is deposited in the Neva Bay (Figure 3a). There is also an increase in the microplastics content in sediments in the southern coastal zone of the gulf near the mouths of the Luga and Narva rivers. All these regions of increased microplastics deposition are obviously associated with the proximity of the source of microplastics (river mouths) and the pathways of river water transport. The transport of river waters with an increased concentration of microplastics along the northern coast of the gulf leads to the formation of increased microplastics deposition region between 28.5° and 29.2°E. The shallowness of the region also contributes to the formation of this area, which leads to a faster deposition of microplastic particles due to both shallower depths and higher values of the fall velocity due to better heating and higher water temperatures (Eq. 1). Another area with microplastics content in sediments significantly exceeding background values is seen between the Seskar Island and Bolshoy Berezovy Island with the center at the point (60.25°N, 28.25°E). This area is characterized by noticeably weaker currents than the currents along the northern coast of the gulf, which gives microplastic particles more time for settling and, to some extent, compensates for their lower (compared to the northern coastal zone) concentrations in the upper layer. In addition, the existence of a shallow water area between these two islands and a seamount on the southern coast of the Seskar Island contribute to a more rapid deposition of microplastics into the sediments.

In the case of the basic fall velocity $W_{g0} = 0.2$ m/day (Figure 3b), the annual-mean content of microplastic particles deposited in the sediments turns out to be relatively high not only in the Neva Bay bounded by the FPB, but also outside the shallow Neva Bay area. Compared to the case of more rapid sedimentation of the suspended microplastic particles (when $W_{g0} = 1.2$ m/day), the distribution of microplastics content in the sediment layer now looks much smoother and demonstrates a more uniform decrease when moving from the sources.

Table 1 Frequency of daily-mean wind speed over the eastern part of the Gulf of Finland in 2018 based on ERA-Interim reanalysis.

Speed, m/s Direction	0–5	5–8	8–10	>10
S	28	15	6	0
SW	30	28	5	5
W	28	31	4	4
NW	18	14	3	0
N	16	5	1	0
NE	30	16	4	1
E	27	9	1	0
SE	22	12	1	1

3.2. Influence of stormy events on the microplastics distribution

Wind regime in 2018. The generally accepted definition of storm wind and the Beaufort scale are based on wind speeds averaged over a 10-minute interval. To avoid confusion, we will classify the daily-mean wind speed used below as fresh breeze (with wind speed 8–10 m/s) and strong breeze (with wind speed > 10 m/s). Since at such daily-mean wind speeds, its 10-minute averaged values during the period of its action (more than 1 day) can reach stormy values exceeding 20.8 m/s, we will conventionally call these periods stormy events. Analysis of the atmospheric circulation carried out according to the daily-mean wind speed and direction data, retrieved from the ERA-Interim reanalysis, shows that western and southwestern winds prevailed over the eastern part of the Gulf of Finland in 2018 (Figure 4). The number of days with winds in these directions was 135. The number of days with the daily-mean wind speed exceeding 8 m/s, was 10 for the southwest, and 8 for the west winds. Strong breeze (with wind speed > 10 m/s), during which the microplastics release from the water to the beach is most likely, occurred 5 and 4 times for southwestern and western winds, respectively. Though the release of microplastics from the water to beach is not included in the model, this process is very likely to occur in real natural conditions. Storms may generate specific circulation patterns in the domain and may lead to increased microplastic concentrations near the northern coasts. This process is simulated by the current model, while the release of microplastic onto the beaches during stormy weather is not. Still, according to (Chubarenko et al., 2018), the peaking levels of contamination of the beach by microplastics (one order of magnitude higher than the background values) can be attributed to certain stormy events. Thus, in our point of view, proving that the enhanced microplastic concen-

Table 2 Dates of stormy events (based on daily-mean wind speed) over the eastern part of the Gulf of Finland in 2018 based on ERA-Interim reanalysis (autumn—winter stormy events are marked with bold).

Speed, m/s Direction	8—10	>10
S	**16.01; 24.01; 31.10; 11.11; 12.11; 08.12**	—
SW	22.06; **20.09; 22.09; 16.11; 29.11**	**25.01; 12.09; 30.09; 09.10; 30.11**
W	18.03; 19.06; 20.06; 06.08	**07.01; 13.09; 26.09; 27.09**
NW	**08.01**; 05.06; 21.08	—
N	30.06	—
NE	**04.02; 05.02; 27.02; 18.11**	01.06
E	**27.10**	—
SE	**17.01**	**30.10**

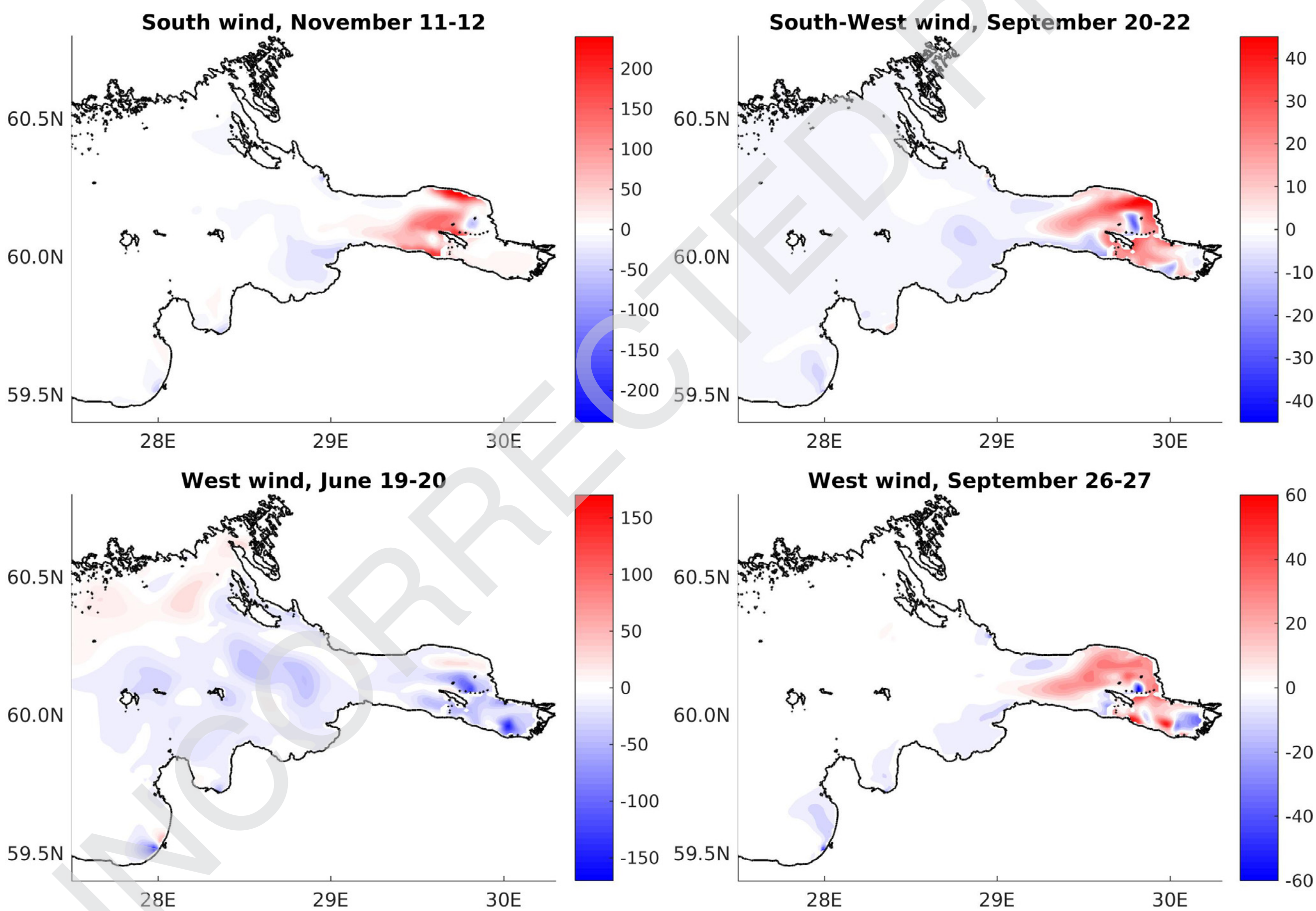

Figure 5 Distribution of the difference ΔC of the suspended microplastics in the surface layer (c.u./m^3) for $W_{g0} = 0.2$ m/day. Note the different scales. See the text for the definition of ΔC. Positive values of ΔC mean an increase in concentration due to the stormy event.

trations in the water are produced near a beach during a stormy event, is a key factor for understanding and explanation why and where the microplastic litter may be found and accumulated on the beaches. Table 1 summarizes the wind statistics. Based on these data, it can be concluded that the number of days with fresh breeze (strong breeze) with western and southwestern winds over the eastern part of the Gulf of Finland in 2018 was at least 50% (>80%) of the total number of days with stormy events in this area. In other words, strong breeze with western and southwestern wind directions occurred much more frequently than strong breeze with other wind directions. The intra-annual distribution of stormy events occurred in 2018 and presented in Table 2 shows that 75% of stormy events happened in the autumn-winter period, and only one out of eleven strong breeze events occurred in summer.

Influence of stormy events on microplastics distribution in coastal zones. Let us now consider the distribution of microplastics in case of prolonged (at least two days) stormy events observed in summer and autumn of 2018:

1) June 19—20, west wind 8—10 m/s,

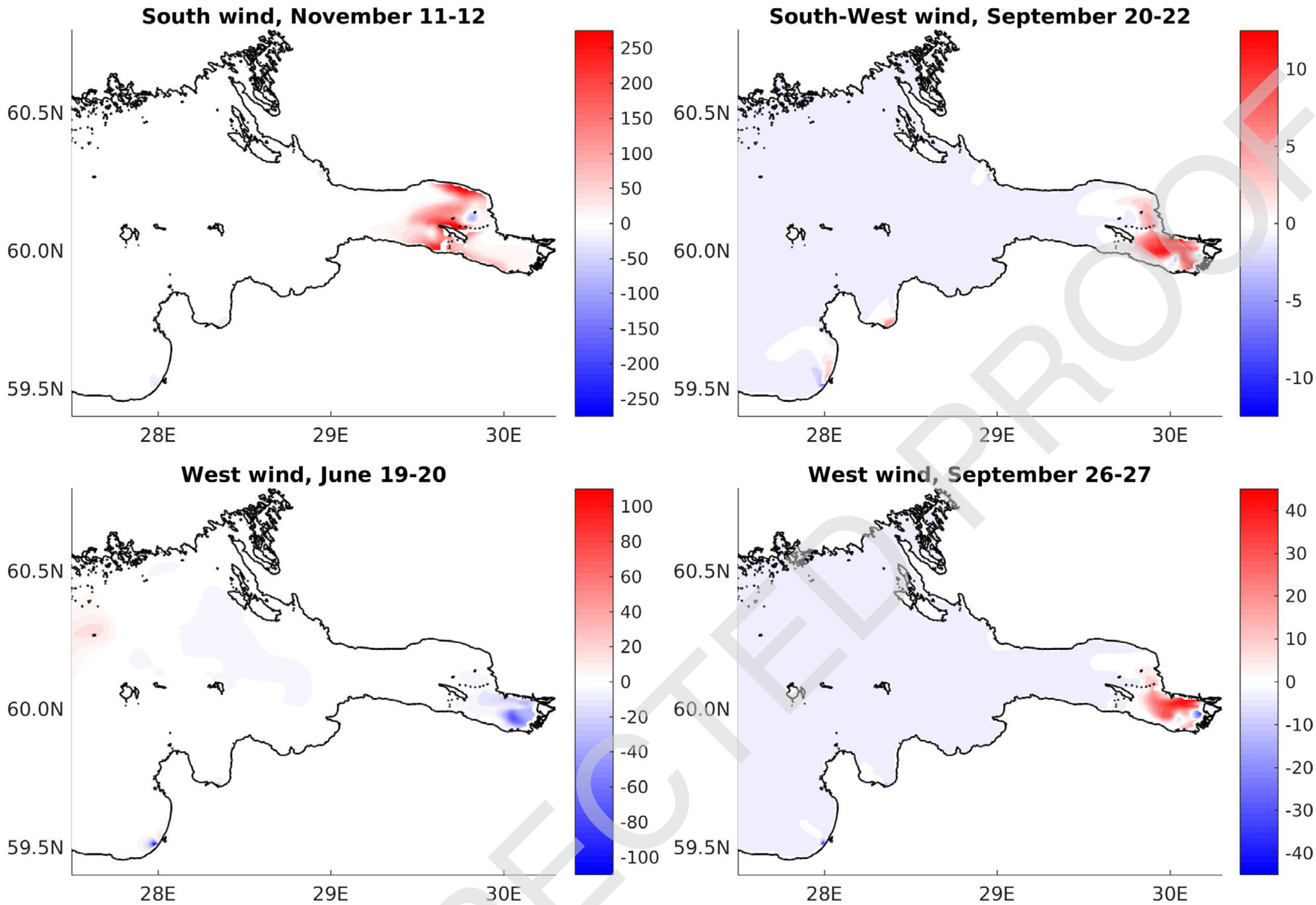

Figure 6 Distribution of the difference ΔC of the suspended microplastics in the surface layer (c.u./m^3) for $W_{g0} = 1.2$ m/day. Note the different scales. See the text for the definition of ΔC. Positive values of ΔC mean an increase in concentration due to the stormy event.

2) September 20–22, southwest wind 8–10 m/s,
3) September 26–27, west wind >10 m/s,
4) November 11–12, south wind 8–10 m/s.

Figures 5 and 6 show the distributions of the difference $\Delta C = C_1 - C_2$ of the suspended microplastics concentration in the surface layer for four above-mentioned situations and different settling velocities W_{g0}. Here C_1 and C_2 are suspended microplastics concentrations in the surface layer, averaged over the fresh/strong breeze period and over 7 days of calm weather before this period, respectively. Positive values of ΔC mean an increase in concentration due to the stormy event. We note that the time-interval of calm weather between stormy events occurred on September 20–22 and on September 26–27 was less than 7 days. In this case, C_2 for the event occurred on September 26–27 is calculated by averaging the suspended microplastics concentration for the period September 12–19.

The most striking feature of the presented distributions for $W_{g0} = 0.2$ m/day (Figure 5) is an increase of the coastal suspended microplastics concentration along the northern coast near the Zelenogorsk region compared to the southern coast. This pattern holds for all considered wind directions (south, south-west and west). An increased concentration is also located in the coastal area near the Sestroretsk region for the southwestern and western winds, but it decreases in the case of the southern wind.

The above-mentioned features of suspended microplastics' spatial distribution for different stormy events generally occur for $W_{g0} = 1.2$ m/day as well (Figure 6). Much more homogeneous horizontal distribution of ΔC outside the Neva Bay, compared to the case with $W_{g0} = 0.2$ m/day, may be associated with insignificant suspended microplastics concentrations in summer (see Figure 2b).

4. Discussion and conclusions

The distribution of microplastics in the eastern part of the Gulf of Finland, coming with the riverine waters of the Neva, Luga, and Narva rivers, has been investigated for realistic conditions of 2018 by means of numerical modeling. The model takes into account a possible sink of suspended microplastic particles into sediments due to biogeochemical processes such as biofouling and ingestion by zooplankton. We assume that microplastics captured by zooplankton or subjected to biofouling sink in the water column with the fall velocity of gravitational sinking of dead organic matter (detritus).

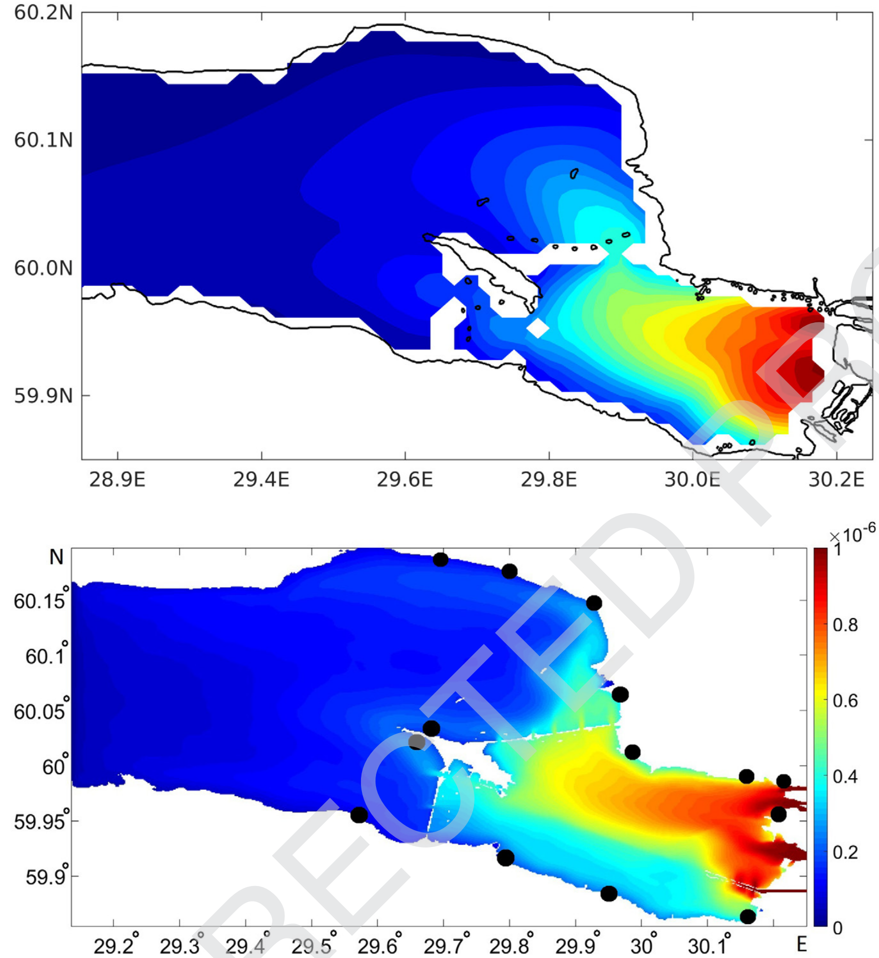

Figure 7 Top: modeled microplastics volume concentration in the top model layer (0–2 m) with $W_{g0} = 0.2$ m/day, time-averaged for the period June–August 2018 as obtained in this study; Bottom: the same, but obtained by (Martyanov et al., 2019), black dots show the locations of field observations.

The presented model accounts only for biologically-relevant additions to the initial suspended microplastics fall velocity, ignoring other possible factors and effects. They include a wide range of particles' sizes, shapes, initial density of microplastic particles, and variations of all these properties with time spent in the marine environment, as well as the wave-induced transport of suspended particles, their mechanical fragmentation, resuspension of microplastic particles from the bottom, etc. It is important to emphasize that the presented model takes into account the potential influence of biological processes on the distribution of microplastics in a very simplified form. In fact, it just distinguishes between cold and warm seasons depending on the water temperature, which reflects the absence and presence of active biological processes related to phytoplankton and zooplankton functioning.

Simulations have shown that the transport of suspended microplastics in 2018 occurred along the northern coast more intensively, especially in the easternmost narrow part of the gulf near the Neva Bay. At the same time, we know that circulation patterns in the Gulf of Finland are complex and vary from season to season and from year to year, and sometimes circulation under southwesterly winds can rapidly change from normal estuarine circulation to reverse estuarine circulation (Westerlund et al., 2018). This means that the patterns of the microplastic distribution presented in the current study may differ markedly in other years, especially outside the Neva Bay and the easternmost narrow part of the gulf where the circulation is determined by the river runoff.

The microplastics propagation is regulated not only by currents and turbulence, but also and to a large extent by the fall velocity of suspended particles. The model assumes that this fall velocity is equal to zero during the cold autumn-winter period (T < 4°C) and exponentially depends on the water temperature T during the spring-summer period (T ≥ 4°C) with proportionality constant W_{g0}. Currently, this constant is not well known. To assess the sensitivity of the model solution to this constant, its values are taken equal to 0.2 m/day as in (Martyanov et al., 2019) and 1.2 m/day as in (Vladimirova et al., 2018). In the spring-summer period, the main part of microplastics coming with the river waters settles in the estuarine areas. A tenfold decrease of the surface concentration of suspended particles occurs already in the Neva Bay if the basic fall velocity of microplastic particles is set $W_{g0} = 1.2$ m/day, and to the west of the

St. Petersburg's Flood Protection Barrier (FPB) if $W_{g0} = 0.2$ m/day.

In the case of $W_{g0} = 1.2$ m/day, the main part of the suspended microplastics coming into water through the Neva River enters the bottom sediments mainly in the Neva Bay. A noticeably smaller amount sinks in the coastal zone along the northern coast immediately behind the FPB, in the Zelenogorsk region and in the coastal band between the Bolshoy Berezovy Island and Ozerki village. In the case of $W_{g0} = 0.2$ m/day, the content of microplastic particles deposited in the sediments turns out to be significant not only in the Neva Bay bounded by the FPB, but also outside the shallow Neva Bay area. Compared to the case of more rapid sedimentation of the suspended microplastic particles, the distribution of the microplastics content in the sediment layer now looks much smoother and demonstrates a more uniform decrease when moving from the sources.

Environmental monitoring fulfilled in 2018 in locations shown at Figure 7 and aimed on collecting and analyzing plastic wastes on the coasts of the Neva Bay and the eastern Gulf of Finland, showed that the amount of microplastic found on the northern beaches is 5–10 times larger than that found on the southern beaches (Martyanov et al., 2019). During that survey, different methods of microplastic sampling were used: a frame-method and a rake-method. Each of them is focused on monitoring in different conditions: type of coasts, whether a beach is clean by local city services or not, etc. In (Martyanov et al., 2019) the charts with observational distribution of marine litter on the beaches of the study area measured by these two methods were presented, with corresponding discussion and details. The charts showed the concentration of marine litter (in pieces/m^2 units) on the beaches of the Neva Bay and the outer part of the estuary. The results of simulations presented in our study, which demonstrate increased surface concentrations of microplastics along the northern coast, both suspended in the water and accumulated in the bottom sediments, are in qualitative good agreement with those observational data. Additionally, in spite of completely different models used in the current study and in (Martyanov et al., 2019), the spatial distribution of suspended microplastics obtained for the summer period and $W_{g0} = 0.2$ m/day is very similar (Figure 7). The model used in (Martyanov et al., 2019) is based on the Princeton Ocean Model (Blumberg and Mellor, 1987) with σ-coordinate in vertical and original module of suspended particles dynamics. That model has proven itself well for simulating the general circulation and suspended matter transport (Martyanov et al., 2011; Martyanov, 2014; Martyanov and Ryabchenko, 2013; Martyanov and Ryabchenko, 2016) and coastal erosion (Martyanov et al., 2019b; Ryabchenko et al., 2018) in the Baltic Sea. The model used in (Martyanov et al., 2019), compared to one used herein, has much higher horizontal resolution equal to 100 m aimed to represent the coastline and FPB structure in detail. Both models, despite different resolutions, catch the main path of suspended microplastic's transport in the Neva Bay and further into the Gulf of Finland: the higher concentrations along the northern coast compared to the southern one, and the relatively same rate of concentration's decrease to the west off the FPB. The main difference between the two patterns is smoother concentration fields and a detailed description of the penetration of microplastics into the gulf through the FPB in its immediate vicinity in the finer resolution model. In the current study, we were interested in what happens with suspended microplastic farther to the west, away from the direct riverine input. Due to the lack of enough computational resources to cover the whole Gulf of Finland with the grid of very high horizontal resolution, we use a coarser resolution model in the current study. Unfortunately, both models deal with suspended microplastic's concentration expressed in conventional units because the actual microplastics concentration in the sources is completely unknown. Nevertheless, further studies focused on this problem should deal with this issue. Hopefully, the presented results and developed models will be useful tools to assess the intensity and mechanisms of microplastic pollution of the eastern Gulf of Finland.

The analysis of stormy events statistics made for 2018 gives additional confirmation about the above-mentioned pattern of microplastics distribution, according to which microplastics emissions from the water to the shore are much larger on the northern coast than on the opposite southern coast. According to this analysis, stormy events with western and southwestern winds significantly contribute to an increase in the microplastics concentration near the northern coast from the FPB to Zelenogorsk. Taking into account the longer duration and severity of storms with western and southwestern winds in this area, this means that the microplastics release from the water to the northern beaches should be greater.

Considering the above-mentioned limitations of the model used in the study, the presented results can be considered only as a preliminary assessment of the impact of biogeochemical processes on microplastics distribution. For a more detailed study it is necessary to use complete biogeochemical models that explicitly simulate the growth of phytoplankton and zooplankton. But even in this case, difficulties related to the description of microplastic particles transfer in the trophic chain will inevitably arise.

The results of the present study can be used in the selection of areas for future environmental monitoring of microplastics pollution of the eastern part of the Gulf of Finland. Indeed, the operational data of the hydrometeorological service can be used to determine the prevailing wind speed and direction during a storm. Using maps similar to those shown in Fig. 5, it is possible to determine the areas of the predominant release of microplastics from the water to the coast and mark such locations for further environmental survey focused on microplastics pollution.

Uncited References

Q3

Copernicus 2021, ERA-Interim, reanalysis dataset 2021, Baltic Environmental Database 2021

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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