Microplastics in sea coastal zone: Lessons learned from the Baltic amber

Irina Chubarenko a, *, Natalia Stepanova a, b

a) P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences, Atlantic Branch, Laboratory for Marine Physics, prospect Mira, 1, Kaliningrad, 236022, Russia
b) P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences, Sea currents Laboratory, Nakhimovski prospect, 36, Moscow, 117997, Russia

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ABSTRACT

Baltic amber, adored for its beauty already in Homer’s Odyssey (ca. 800 B.C.E.), has its material density close to that of wide-spread plastics like polyamide, polystyrene, or acrylic. Migrations of amber stones in the sea and their massive washing ashore have been monitored by Baltic citizens for ages. Based on the collected information, we present the hypothesis on the behaviour of microplastic particles in sea coastal zone. Fresh-to-strong winds generate surface waves, currents and roll-structures, whose joint effect washes ashore from the underwater slope both amber stones and plastics — and carries them back to the sea in a few days. Analysis of underlying hydrophysical processes suggests that sea coastal zone under stormy winds plays a role of a mill for plastics, and negatively buoyant pieces seem to repeatedly migrate between beaches and underwater slopes until they are broken into small enough fragments that can be transported by currents to deeper areas and deposited out of reach of stormy waves. Direct observations on microplastics migrations are urged to prove the hypothesis.

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1. Introduction

Pollution of seas and oceans by macro- and microplastic particles rapidly increases and raises serious concern (Thompson, 2015; Hidalgo-Ruz et al., 2012). Microplastics (MPs) are found nowadays in fish (Lusher et al., 2013) and birds (Trevail et al., 2015), in deep-ocean sediments (Thompson et al., 2004; van Cauwenberghe et al., 2013) and arctic water (Lusher et al., 2015) and ice (Obbard et al., 2014); its surface attracts toxins and chemicals from the environment (Hidalgo-Ruz et al., 2012; Andrady, 2011; Engler, 2012; Mato et al., 2001) and may convey them up the food chain (Hidalgo-Ruz et al., 2012; Andrady, 2011; Ivar do Sul and Monica, 2014). At the same time, various dimensions, shapes and densities of MPs (conventionally, particles smaller than 5 mm (Hidalgo-Ruz et al., 2012; Ivar do Sul and Monica, 2014; Arthur et al., 2008)) make it difficult to predict its behaviour in highly turbulent marine environment. It is suggested (Hidalgo-Ruz et al., 2012) that energetic processes in sea coastal zones under stormy conditions play an important role in mechanical destruction and re-distribution of plastic pieces. However, not any field observations of MPs behaviour in the sea coastal zone have been available up to now, and many basic questions remain still not answered: which physical factors are of primary importance for MPs migrations, where all the marine plastics is and why it is so dispersed everywhere.

Surprisingly, the Baltic amber (sucincte) and impressive stories about its washing out from the sea to the shores of the South-Eastern Baltic (Fig. 1) can shed some light onto these processes. Succinate material density of about 1.05–1.1 g cm$^{-3}$ is close to that of widely used plastics like polyamide (nylon, 1.02–1.05 g cm$^{-3}$), polystyrene (1.04–1.1 g cm$^{-3}$), or acrylic (1.09–1.20 g cm$^{-3}$) (Chubarenko et al., 2016), and nowadays MPs are abundantly found ashore together with amber crumbs (Fig. 1).

Baltic citizens have monitored the behaviour of amber in the sea coastal zone for centuries, hunting for these drops of resin of ancient pine-trees called “tears of Heliades”, the daughters of Helios, the Sun God. Along with great works of literature (like Odyssey by Homer (Heubeck et al., 1988)), myths (e.g., those by Ovid (1997)), and ancient trading documents, there are quite many physically rational observations and facts describing the process of amber migration in the sea and, especially, addressing the phenomenon of “amber washing-out” after severe storms, when sometimes tons of amber pieces are thrown by the Baltic from its bottom to the shore. Contents lists available at ScienceDirect

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E-mail address: irina_chubarenko@mail.ru (I. Chubarenko).

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beaches. These extraordinary events are even especially termed by local citizens — “бросать” — after a Russian word “бросать” (pronounced as “brosat’”), meaning “throw out”.

In this paper, we make an attempt to analyse the collected set of historical and observational facts from the point of view of physical oceanography, trying to (i) deduce physical drivers of the washing-out processes and (ii) project the results onto the problem of transport and fate of plastic particles in the sea coastal zone.

2. Materials, methods and sources of information

Any systematic monitoring or scientific investigation on the Baltic amber migrations and beaching is not yet available. The main method of this study is cross-comparison of the information from historical and local sources — with present-day knowledge on the Baltic Sea oceanography and hydrophysical processes in the sea coastal zone.

Comparisons of material and transport properties of amber crumbs and microplastics are performed as the first step. They refer to both seminal studies on loose-boundary hydraulics by Shields (1936), who by chance dealt also with amber and plastics, and recent publications (e.g., Critchell and Lambrechts, 2016; Ballent et al., 2012, 2013), as well as to our own experience with microplastics particles (Chubarenko et al., 2016; Esiukova, 2017; Khatmullina and Isachenko, 2017; Zobkov and Esiukova, 2017).

Information on historical aspects of an amber collecting process in the south-eastern part of the Baltic Sea, exceptionally massive amber washing-out events, and the largest beached amber pieces was collected from books (Beck and Shennan, 1991; Finlay, 2006) and web sites of museums (Physical and chemical qualities of amber, 2016; Balanga Amber Museum, 2016), jewellery makers (About amber, 2016; About Baltic amber, 2016; Large beaching of amber in Pionerskiy, 2016), hobby/spare time sites (Amber and its gathering, 2015; Catching of amber in the Baltic Sea, 2015).

Observational facts, particular event descriptions, specific features of amber washing-outs were summarised from various dispersed sources, including historical (Finlay, 2006; Beck and Shennan, 1991) and present-day publications (Kireyeva, 1960; Amber and its gathering, 2015), web (Alekseev, 2015; Pushkarskaya, 2015; Nuyakshev, 2014; The storm threw tons of amber and seaweed to the coast of the Baltic Sea, 2013) and TV sources (Treasure hunters attacked the Baltic coast scattered with amber, 2015; Privalov, 2016) as well as direct communications and discussions with local citizens and hobby-hunters. Analysis of those field situations was complemented by meteorological information from regular governmental weather stations (Reliable forecast, 2004).

Geological information on general amber deposit structure and depths of openings of amber-containing layer to the sea bottom came from the geological atlases (Atlas of geological and environmental geological maps of the Russian area of the Baltic Sea, 2010) and amber mining plant site (Geology, 2016).

Oceanography of the Baltic Sea has already been quite well investigated. The referred magnitudes of typical stormy winds speed, direction, and fetch, as well as significant wave height, period, and length of the developed surface waves are based on fundamental investigations published in books (State and Evolution of the Baltic Sea, 2008; Leppärantta and Myrberg, 2008).

Discussions on particular mechanisms of transport and mixing in the coastal zone refer to classical works on the formation of roll-structures in the upper layer mixed layer (Langmuir, 1938; Craik and Leibovich, 1976; Thorpe, 2005; Leibovich, 1983), and wave-induced sediment transport (Dean and Dalrymple, 2001; Van Rijn, 2012).

Finally, the observed behaviour of amber pieces is projected onto that of microplastics particles, and a scheme of migration of plastic pieces in the sea coastal zone is suggested.

3. Results and discussion

3.1. Amber vs microplastics: physical and transport properties

Amber, plastics, and marine flotsam appear together on wrack-lines of the beaches of the south-eastern part of the Baltic Sea after windy weather (e.g., Esiukova, 2017). Before projecting the observed behaviour of amber pieces onto that of plastics in general and MPs in particular, let us compare their physical and dynamical characteristics.

Material density. For both amber and plastics, only the range of material densities has a physical sense. Amber is naturally inhomogeneous, and the stones may also have various inclusions. Amber does not change its density with time in marine waters, and even does not get bio-fouled. On the other hand, plastics may contain various additives, which initially influence their density,
and under environmental conditions plastics change their density due to weathering and bio-fouling, which, correspondingly, decreases or increases their density. Overall, the density of amber measured in our laboratory varied between 1.05 and 1.1 g cm$^{-3}$; some sources mention values up to 2.00 g cm$^{-3}$, which is very rare case (e.g., (About amber, 2016)). Many widely used plastics fit this range, like polyamide (nylon, 1.02–1.05 g cm$^{-3}$), polystyrene (1.04–1.11 g cm$^{-3}$), acrylic (1.09–1.20 g cm$^{-3}$), and some are close, like polyethylene (0.97–1.28 g cm$^{-3}$ with additives), polyester (1.01–1.46 g cm$^{-3}$) (Chubarenko et al., 2016).

Shape. MPs are shown to have various shapes, most common being 3 d regular or irregular beds, flattened wreckage, flakes, films, fibres. Amber pieces (Fig. 2) have rather irregular but definitely volumetric (3 d) shapes; many of them break in parts in stormy waves and have sharp fresh cleavages. Fig. 2 shows MPs and amber crumbs collected on the beach at the same time: it seems that there is no prevalent shape of MPs particles beached together with amber. Note that all of them were beached with lots of seaweed and marine flotsam (see Fig. 1 and photos in Supplement Material), so that plastics were entangled and could not float freely.

Particle principle shape (3 d-particle, or flat flake, or thin fibre) is shown to be very important for its motion (Khatmullina and Isachenko, 2017). However, smaller details seem to be not so important. Shields (1936) in his well-known laboratory investigation of re-suspension threshold for different bed loads did not find “essential influences of the grain shape upon the magnitude of bed-load movement” Shields (1936, p. 28): he used 3 d sharp-edged (amber and granite) and rounded (brown-coal) particles for bedload.

Size, age, and mechanical damages. In the context of this study, important is comparison of sizes and qualities of plastic and amber pieces, beached during the same environmental conditions. Under calm weather and weak winds, no amber is present on the beaches. Weak to moderate winds typically bring (in case the “event” happens) amber crumbs with small wooden pieces (Fig. 1), accompanied by almost exclusively MPs. The stronger winds – the larger plastics and amber pieces are beached, often with wood only (without seaweed), but MPs and small amber crumbs remain as well. Fig. 3 shows such “moderate-winds” beached plastics: it has severe mechanical damages and bio-fouling, and the dates printed on them indicate 3–5 years of residence in the sea. After storms, together with large amber “brosy”, very heavy and large plastic objects can be washed out: large boxes, entangled fishing nets and ropes, etc. Again, amber crumbs and MPs are also present (e.g., Esiukova, 2017).

Sink or float? Amber (density 1.05–1.11 g cm$^{-3}$) cannot float in Baltic water (1.006–1.014 g cm$^{-3}$); its density does not change with time in the sea, and it does not get bio-fouled. Concerning plastics, beached together with it, the answer is not so obvious: plastic density may change due to weathering or bio-fouling, relatively light PE films may catch sand, while heavier PET bottles may contain air bubbles, etc. The direct checking of plastic objects from the wrackline shows (see Supplement Video “Sink”), however, that most of them are sinking almost immediately. Measured density of beached wet wooden sticks is about 1.02 g cm$^{-3}$, i.e., they also sink in water. In accord with this we are observations by (Ballent et al., 2012, 2013): they report that their collection of high-density MPs is made from objects stranded after a high tide on sandy beaches of the North Sea. High-density pellets, used for laboratory experiments in (Ballent et al., 2012, 2013), were collected on sandy beaches in California.

Thus, an essential part of the beached plastics is heavier than water. This is true for both tidal (like the North Sea) and non-tidal (like the Baltic Sea) beaches; at least for the latter ones - presence of weakening surface waves is important.

Critical shear stress for amber and MPs. Some information on direct measurements of re-suspension threshold (initiation of motion) in water current can be found from both amber and MPs side, as well as from investigations of other bed-load materials of the “plastic” density range (Table 1).

In seminal work by Shields (1936) on sediment re-suspension and transport by water currents, along with barite, granite and brown coal, amber crumbs were occasionally used as one of the investigated bed loads. Amber fragments with grain size from 0.3 to 3 mm (mean diameter $d = 1.56$ mm) and density 1.06 g cm$^{-3}$, resulting from the cutting of larger amber pieces, are incorporated in sediment research as “easily movable ... sharp edged” bed-load particles. Critical shear stress for such particles, re-calculated from the amber-points on the Shields (1936) diagram (Fig. 4), is about $\tau = 0.03–0.04$ N m$^{-2}$, and critical velocity $u_c = 4-6$ mm s$^{-1}$.

From MPs side, only very limited information is still available. Ballent and co-authors (2012; 2013) reported measured in

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Fig. 2. Plastic and amber pieces beached after 7–8 m s$^{-1}$ wind episode: (a) various microplastics: fragments, folded and stretched films, foam; (b) amber typical-size crumbs; (c) amber pieces found at the same time but rare for such wind speed (photo by I. Chubarenko).

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laboratory dynamical characteristics for three kinds of industrial pre-production high-density plastic pellets collected on sandy beaches of Los Angeles County (California), see Table 1. They were of rounded shape and somewhat larger than the Shields amber particles (3.3–5.1 mm), with densities from 1.06 to 1.13 g cm$^{-3}$. In a view of inter-comparison, one should have in mind that there are three differences in the (Shields, 1936) and (Ballent et al., 2012) experiments. Firstly, the working fluid in (Shields, 1936) was fresh water, whilst (Ballent et al., 2012) worked with saltwater with density 1.03 g cm$^{-3}$; for our analysis, in Table 1 both real and “effective” densities are shown for (Ballent et al., 2012) experiments. Secondly, different experimental techniques were used: in (Shields, 1936), bed-load material was re-suspended by unidirectional flow in an open channel, whilst in (Ballent et al., 2012) a rotating re-suspension chamber was used. While comparing these methods (Tolhurst et al., 2000), found the calculated threshold values “relatively comparable”, but affected by the “device size”; thus, in our case, some deviations are anticipated. And the third difference lies in the principal difficulty to define what exactly (formally) is “the beginning of motion”; (Shields, 1936) defines the threshold by “extrapolating the bed-load transport curve to the time bed-load movement ceases” (Shields, 1936, p. 10), and (Ballent et al., 2012) report the bed-load shear/velocity “at which 50% of the particles rolled, slid or saltated on the chamber floor” (Ballent et al., 2012, p. 18761). Nonetheless, the experimental points for both amber crumbs and plastic pellets fit quite well in the classical “Shields curve” (Fig. 4), which expresses in dimensionless form the border between regimes of “motion” and “no motion” of the bed-load material under action of fluid flow.

One more example can be incorporated in the present analysis. Brown coal (ignite) particles from (Shields, 1936) experiments, with their density of 1.27 g cm$^{-3}$, can be considered as a model for MPs like that from Plexiglas (density 1.24 g cm$^{-3}$), polyurethane (1.17–1.28 g cm$^{-3}$), or polyvinylchloride (1.16–1.58 g cm$^{-3}$). The particles used in three runs in (Shields, 1936) were characterized by the mean diameters 1.77, 1.88 and 2.53 mm, and described as “angular, with rounded corners”. Again, using the corresponding points from the (Shields, 1936) diagram, one obtains the values for critical shear stress to be about $\tau^* \approx 0.13–0.35$ N m$^{-2}$, and critical velocity 5–20 mm s$^{-1}$.
Fig. 4 illustrates conditions of “initiation of motion” of particles in the fluid flow (Shields, 1936): the dependence of the dimensionless Shields critical shear, $\theta = \frac{\tau^*}{\frac{1}{2} \rho g d^2}$, from the dimensionless particle Reynolds number, $Re^* = \frac{u^* d}{\nu}$, Here, $\tau^*$ is dimensional critical shear stress, $\rho_p$ - particle density, $\rho_w$ - water density, $g$ - acceleration due to gravity, $u^*$ - critical velocity, $d$ - diameter of the particle and $\nu$ - water kinematic viscosity. We highlighted the Shields (1936) data points for amber and lignite (density 1.27 g cm$^{-3}$), and added points for three kinds of plastic pellets from (Ballent et al., 2012). Points for coarse sand (Casey, 1935; cited after Shields, 1936) are also shown for comparison. Thus, small particles of similar to plastics density are used in sedimentology research, and both amber crumbs and “MPs” (with both sharp-edged and rounded particles) obey the initiation-of-motion dependencies obtained for natural loose bed-load materials.

Physically, amber, sands and (used in the above experiments quite large and 3 d-shaped) MP particles have similar critical Shields dimensionless shear of about $\theta = 0.03 - 0.04$, which means the analogous re-suspension threshold in unidirectional current for the particles with the same $Re^*$. It could be expected that films, flakes and fibres, in contrast to 3 d-fragments and rounded pellets, hardly obey this dependency. At the same time the observations show that, in the case of “broisy”, MPs of various shapes are beached together, see Fig. 2 for example. This indicates contribution of other transport mechanisms for amber/plastics migrations and beaching; most probably these are wave-induced motions.

It is important to note for future experiments on MPs transport that the re-suspension threshold measurements in sedimentology usually follow a unified (Shields, 1936) technique: bed-load (loose sand, amber or MPs) is exposed to the flow moving above it. Hence, such experiments characterize the initiation of motion of MPs over the bed, entirely covered by the analogous (MP) particles. Under real-sea conditions, MPs seem generally to be re-suspended from natural bottom materials, which means at least influence of another bed roughness (i.e., another boundary layer thickness) and use of the particle $Re^*$ number based on dimensions of both MP particle and bottom material. Additional laboratory experiments on MPs re-suspension from bottoms covered by silt, sand, cobbles, etc. Are very desirable to obtain re-suspension threshold more applicable to in-situ conditions for MPs. In addition, along with the re-suspension by water flow, the oscillatory wave motions seem to be valuable for easy-moveable plastic particles.

### 3.2. Baltic amber: appearance and migrations in sea coastal zone

Appearance of amber on the beach is quite a typical phenomenon for the south-eastern part of the Baltic Sea, from Poland to Lithuania, and is very attractive for both local citizens and tourists. As a consequence, the conditions when it happens are well known and rather characteristic of this region: after wind episodes of more than 7–10 m s$^{-1}$, the wrackline of the beaches – here or there – is often delineated with amber crumbs. Just windy episodes bring numerous but small crumbs of amber (2–5 mm), like those shown in Fig. 1: the photo was taken on 25 September 2015 on the beach of the Vistula spit during a very calm weather period - but right after the transient 4-h episode of gentle breeze up to 6 m s$^{-1}$ from the north-west (frontally to this shore). Heavier winds and especially severe winter storms may present amber samples up to 12 kg - the largest known piece, found on the Baltic shore of Prussia in the 19th century (Baltic Countries Mineral Industry Handbook, 2016). The other two giant beached amber samples, reported in historical texts, were about 9.7 and 7 kg. Such washed out stones are extremely rare: all the history knows less than 10 stones heavier than 5 kg (Baltic Countries Mineral Industry Handbook, 2016). The largest amber piece in the present-day collections, exhibited nowadays in the Berlin Natural Science Museum (Germany), is 47 cm long and weighs 9.8 kg (About amber, 2016). Concerning the maximum total volume of the beached amber, local legends mention the autumnal event in 1862, when almost 2 tons of amber were beached near Yantarny (former Palmniken, Fig. 5) during one storm (Finlay, 2006; Beck and Shennan, 1991). After a storm of 1914, people collected about 870 kg of amber on the northern beaches of the Sambian peninsula (Beck and Shennan, 1991). Along with amber, the wrackline after storms contains seaweed, shells, and wet wooden pieces; and nowadays they are always mixed with some plastic garbage and microplastics particles.

Baltic amber is fossil resin produced by pine trees which grew in Northern Europe about 50 million years ago. In the course of time,
by polymerization and oxidation, the resin was transformed into amber (About amber, 2016). The world largest deposit (about 90%) of amber (Baltic Countries Mineral Industry Handbook, 2016) is located in Kaliningrad region (Russia) near the city of Yantarny (Fig. 5), with open mining on land. Meanwhile, the underground distribution of layers of the amber-containing “blue clay” and their openings to underwater slope are poorly known. Within the open mining site, the layer of the blue clay is located approximately between 10 and 20 m below the sea level (Geology, 2016), and has a slight inclination towards the land, suggesting that its opening to the underwater slope might be within the depth range of 8–15 m.

Until the 13th century, the seacoast inhabitants collected amber directly from the seashore, and later they learned how to obtain amber by combing the seabed from small boats with nets and long sticks (Finlay, 2006). With the appearance of the diving suit, the direct collection from the bottom became also popular. Amber pieces can often be found on the bottom of slight depressions at the depths of 5–15 m, or stuck in-between boulders in areas with stony bottom.

At the bottom of the sea, amber is usually found around the Sambian peninsula at the depths from 3 to 12 m, maximum 15 m. One reason for this could be that the layer of the ancient Litorina Sea “blue clay” is located at the depths of 4–15 m below the sea level. It stretches from the Vistula Spit to the Curonean Spit and further north (Atlas of geological and environmental geological maps of the Russian area of the Baltic Sea, 2010), but opens to the sea bottom only off the Yantarny deposit (Fig. 5). At the same time, amber is never washed ashore without plenty of seaweed, wooden sticks, and natural marine litter. This suggests that the beached amber pieces are not directly washed out from the bottom sediments, but are caught by seaweed clouds during their underwater migrations, just like other slightly negatively buoyant wooden (or plastic) pieces. An important observation is that - after stormy weather - amber is typically washed ashore together with red algae Furcellaria lumbricalis, which are abundant in the eastern part of the Baltic Proper and compose a belt along the shore, dominating on submerged rocks at 6–15 m depth (Kireyeva, 1960). Furcellaria can

Fig. 5. Map of the south-eastern part of the Baltic Sea, showing the location of open amber mining near the city of Yantarny. The isobath 20 m (in blue) is the offshore limit of probable openings of amber-containing blue clay to the underwater slope (Geology, 2016). The moraine outcrops (thick black lines) are a potential trap of amber (Atlas of geological and environmental geological maps of the Russian area of the Baltic Sea, 2010). An effective wind fetch for the given region (State and Evolution of the Baltic Sea, 2008) and typical sites of amber ‘brosy’ (Atlas of geological and environmental geological maps of the Russian area of the Baltic Sea, 2010), the scheme initially compiled by S. Isachenko after enquiry of miners) are shown by red and yellow points, with the colour corresponding to wind direction. Map of Europe: http://www.freeworldmaps.net; the map in background was drafted in open software Quantum GIS (ver. 2.0) www.qgis.org/ru/site/forusers/download.html, with final production in CorelDraw X4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
also grow in large floating mats (Kireyeva, 1960; Furcellaria, 2015), and such mats are also mentioned quite often as washed ashore together with amber during the “brosy” events. One way or another, it is quite obvious that amber pieces, which are heavier than water, are washed out of the sea during storms from the depths down to 6–15 m.

3.2.1. The events of “brosy”

As observations show, amber pieces are able to move up-slope and small pieces appear at the shoreline even at moderate winds (see Fig. 1 and photos in the Supplement Material); we are not aware of any systematic monitoring of such cases. The major part of observational facts describes the cases after severe storms, when amber “brosy” are large and impressive indeed. Amber hunting in the sea has a long historical trace, and is at present quite a popular spare time activity in Kalingrind region. It is regarded under the Russian law as hobby-fishing or collecting berries in nature, and many hunters enjoy extreme fishing for amber stones in the stormy surf. As a consequence, general signs indicating favourable conditions for the “brosy” are well known - but the exact place and the very moment are still almost unpredictable. These signs and characteristic features of the “brosy” events, the specific weather conditions are repeatedly mentioned in various sources including books (Baltic Countries Mineral Industry Handbook, 2016; Finlay, 2006; Beck and Shennan, 1991; Atlas of geological and environmental geological maps of the Russian area of the Baltic Sea, 2010), web-sites (About amber, 2016; About Baltic amber, 2016; Amber and its gathering, 2015), news (Alekseev, 2015; Pushkarskaya, 2015; Nuyakshev, 2014; Large beaching of amber in Pionerskiy, 2016; The storm threw tons of amber and seaweed to Pushkarskaya, 2015; Nuyakshev, 2014; Large beaching of amber in the Sea, 2010), and show that exactly these directional winds may be accompanied by 1–2 smaller ones, 400–500 m apart, which contain mainly seaweed, almost without amber.

(VII) “The Baltic withdraws its treasures”: usual/every-day experience shows that no amber is present on/in the beach sands. A stormy seaweed patch in the swash zone may begin drifting off-shore already in an hour or two; the shoaled seaweed cloud may stay on the beach up to several days; small (3–4 mm) amber crumbs washed out after moderate-wind events can be found on the beach for about one day. In accord with these time scales are investigations of agar-containing Furcellaria lumbricalis: its beached mats are shown to be carried back to the sea in 1–2 days (Kireyeva, 1960).

Here are selected only those specific features of meteorological, hydrophysical, and topographical conditions corresponding to the cases of “brosy” that are mentioned in several independent sources. Below, we examine them from the point of view of physical oceanography, aiming at prediction of the behaviour of plastic litter and microplastic particles in the sea coastal zone.

3.3. Oceanographic analysis

Behaviour of particles in the sea coastal zone is one of the most challenging problems in marine sciences, being both highly complicated and utterly needed for a great variety of applications. This way, analysis of the “natural case study” of amber “brosy” is illuminating and informative. The authors are not aware of any systematic investigation or interpretation of physical conditions driving the amber migrations in the coastal zone. At the same time, the collected information allows for suggestion of some answers on why, how and from which depths the negatively-buoyant amber stones are washed ashore.

3.3.1. Surface wave field

As follows from the items (I)–(III) listed above, the main physical driver for massive “brosy” of large amber stones is a long-lasting stormy wind of proper direction — perpendicular to the shoreline: westerly/northerly winds for western/northern Sambian shore, correspondingly (see Fig. 5). Characteristics of winds and wave field in the Baltic Sea are well investigated (State and Evolution of the Baltic Sea, 2008), and show that exactly these directions offer the longest wind & wave fetch in the given area — as long as 240–250 km (State and Evolution of the Baltic Sea, 2008) (Fig. 5). So it is not surprising that especially high waves (II) are developed. After several days of storm (III), surface waves in open sea can be assumed already well-developed, and their length and height can be estimated from their fetch. For the Baltic Sea, the strongest stormy winds (wind speed more than 30 m s\(^{-1}\)) generate the highest (significant wave height \(H\) up to 7–8 m) and the longest (wave length \(L\) up to 100–120–140 m) surface waves possible for this...
let us assume

... stormy situations begins from the depths of about 50–70 m. Further shore-wards, water motions under propagating waves become ellipsoidal, with longer and longer horizontal axis, until they are transformed into reciprocating motion on the fore-beach (Fig. 6). In particular, they suspend bottom material and cut the branches of Furcellaria off the bottom boulders.

While approaching the shore, surface waves become shorter and then break in the surf zone. The surf zone (Fig. 6) begins at the depth of about $d - 2H$, which is about 15 m for the longest waves in the considered case. Other stormy waves are breaking over depths from $2H$ to (1–1.5) $H$, or from 15 to 2–3 m for various $H$ (State and Evolution of the Baltic Sea, 2008).

Thus, from the shore and to the 15 m-isobath, water is stirred by breaking stormy waves, so that bottom sediments, growing at these very depths tangles of Furcellaria lumbricalis, and marine flotsam experience these energetic motions. The 15 m-isobath is only 3–5 km off-shore, while the amber-containing patches are said to arise “a few kilometers” off-shore (VI). Overall, several independent features – the breaking depth of the highest stormy waves, the areal of growth of Furcellaria lumbricalis, the estimative distance to the rising flotsam patches - point at the same depth range of 10–15 m from which the largest pieces of amber can be washed ashore by exceptionally strong storms of proper direction.

Patchiness

Patchiness is quite a usual feature of hydrophysical, sedimentological, biological and many other natural fields, and its spatial and temporal characteristics may shed some light onto the underlying processes. In the case of amber “brosy”, an obvious compact flotsam patch is invariably described as the only source of amber: amber is never washed ashore without seaweed or wet wood. Large “brosy” (after severe storms) bring red Furcellaria; in intermediate-scale events, the patch contains green algae (i.e., it comes from shallower areas), and sometimes the Fucus vesiculosus (which is nowadays absent in the area and is observed in “brosy” patches only (Volodina and Gerb, 2013)). In the smallest cases of washing-outs (like the one shown in Fig. 1) amber crumbs are accompanied only by very small wet wooden sticks. This does not directly suggest, however, that larger amber stones are washed from deeper areas. This rather shows that stronger storms bring the algae from deeper parts - while amber could, in principle, be entrained on the way, from any part of the underwater slope. With weaker winds (and waves), there are no currents strong enough to transport larger pieces, even if they are not far from the shore.

In order to disclose the physical background, it is important to grasp spatial scale of patches and their evolution with time. Observations show that sometimes during one storm several patches can arrive to the shore (here or there, now or later). However usually there is one patch at a time on the shore, which stays in the swash zone for an hour or so – and then drifts back off-shore. The location of amber “brosy” is not permanent even within one stormy event, and is thus not related to bathymetry or peculiarities of the coastline. The length of the shore face, where seaweed and amber are left on the beach, has a scale up to several hundreds of metres, however the very patch in water is much smaller in diameter – a few dozens of metres only, see, e.g., photos on the web sites news (Alekseev, 2015; Catching of amber in the Baltic Sea, 2015) and in Supplement material. Video “The Patch” (in Supplement material) and photo in Fig. 7, taken at the shore of the Vistula Spit on 1 October 2016, show a quite typical episode after fresh western winds of about 7–10 m s$^{-1}$ and give an impression of these scales. The very patch in water is ca. 15–20 m in diameter only, which can be identified by the behaviour of birds: they are hunting for fish, attracted by the cloud of seaweed, wood, and other bottom material. At the same time, suspended algae of much lesser, but still considerable amount are present in the swash zone on both sides of the patch (over about 200 m along the shore in the given case), what can be seen on the video: the foam on the wave crests in swash zone over these 200 m has a greenish shade, being white farther to the right and farther to the left. This is a proxy of the scale of the beached flotsam patch, which will be left on the shore after the event and may often contain many small amber stones and crumbs. Such a scale of the patchiness says in favour of two things: (i) since the rest of the beach line is (relatively) clean, this is not just an overall wind–wave mixing which is responsible for the flotsam washing-out, and (ii) there is some mesoscale (not a large-scale) process at work, which lifts the material from the bottom and pushes it on-shore.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.01.085

Roll structures

The next set of observational facts (IV-VI) says that the material is washed ashore not during the storm – but right after it, and is not just uniformly distributed along the shore, but gathered in quite compact patches (see photos in Supplement Material, Fig. 7 and video “The Patch” for example). What a mechanism could compact (at 10–15 m depth) and lift from the bottom a cloud of (usually sinking) amber stones, wooden sticks and algae, and then carry it...
onshore while stormy wind is weakening, but waves are still well developed? Noteworthy details, not mentioned by observers or publications, but grasped by the photo in Fig. 7 and in the video “The Patch”, are also the flattened rows on the sea surface (the so-called slicks), stretching from the area of the patch shoaling towards the sea, and in deeper sea area. Near the shore, this damping of small-scale surface waves is obviously due to the floating algae. Farther in the sea, the slick rows may also indicate just a water divergence at the surface, not necessarily containing any floating material. (No oil spills, which potentially could look alike, were detected in this area.)

Summarizing these two features — stage of wind weakening (IV) and slick rows (Fig. 7) — we suggest that the most probable physical mechanism could be the Langmuir circulation (LC): the coherent system of large longitudinal rolls with their axes directed downwind, which arise due to instability of wind-induced current in presence of the Stokes wave drift (Langmuir, 1938; Craik and Leibovich, 1976; Thorpe, 2005) (Fig. 8). Other considered possible alternative mechanisms, such as coastal fronts (for the Baltic Sea - Leppäranta and Myrberg, 2008), rip currents (State and Evolution of the Baltic Sea, 2008), convective exchange flows (Chubarenko, 2010; Chubarenko and Demchenko, 2010), do not provide proper conditions for the observed features (I)-(VII). Indeed, commonly formed longshore fronts are surface convergence/downwelling zones, thus they cannot lift the material from the bottom; stormy rip currents carry the material offshore, i.e., in the opposite direction; topography-originated currents would be associated with certain permanent locations, but this is not observed.

The LC is a quite common phenomenon observed in large lakes, seas, and oceans during windy weather. It is manifested by long “windrows” of foam and algae at the water surface, associated with the surface convergence zones, and slick lines in-between them, indicating the surface water divergence (Langmuir, 1938; Craik and Leibovich, 1976; Thorpe, 2005; Chubarenko et al., 2010; Dethleff et al., 2009). It is known that rolls of the LC arise readily at wind speeds of more than 5 m s⁻¹ and persist at higher and higher winds — until stormy wind destroys their coherent structure (at more than ca. 25 m s⁻¹) (Thorpe, 2005; Leibovich, 1983). With the “brosy”, we have an opposite case: stormy wind ceases (IV) — so that still strong down-wind currents and complicated wave-induced motions are now able to join in the 3D-roll-shaped circulation, embracing the entire mixed-layer depth. Along with the surface windrows and slick rows, this circulation implies convergence/upwelling zones in the lower portion of the mixed layer (see Fig. 8), where the flotsam, suspended by waves from the underwater coastal slope, can be gathered and up-welled (V-VI).

Are the LC-associated upwellings physically able to lift amber stones or microplastic particles from the bottom? The settling velocity of microplastics (0.5–5 mm long) particles with close-to-amber density of 1.05 g cm⁻³ varies between 1 and 5 cm s⁻¹ (Chubarenko et al., 2016), while the maximum upwelling velocity in LC under moderate winds is reported (Leibovich, 1983) to be 1–1.5 cm s⁻¹. In a highly turbulent sea after the storm the currents are obviously much stronger. Large-scale horizontal water transport within the LC-upwelling zones is directed down-wind, so that the lifted patch is to be beached at the shore directly exposed to it (V). Thus, the LC is physically able to compact a seaweed cloud with amber and plastics, lift it from the bottom and transport to the shore line. Assuming the LC-nature of the observed flotsam patchiness and knowing the separation between the upwelling zones in-between Langmuir rolls for the given situation, one can estimate the distance between the slick rows. Taking the depth-to-width ratio of an individual cell (Leibovich, 1983) as about D/W=1.3±3, noting from the above analysis that D should be at least 15–20 m in order to lift the seaweed/amber from the bottom, we arrive at the minimum spacing between upwelling zones of order of 100 m. Since (i) these zones, resulting from instability of wind-induced current in the presence of surface wave transport, are inherently different in intensity and (ii) regions of stony bottoms favourable for the Furcellaria grows and amber settling are dispersed — the patchiness of the beached clouds (VI) looks just natural. By geometrical reasons, the re-suspension of the bottom material by the LC-mechanism should take place at some distance from the shore, which agrees well with field evidence (V-VI). Shoaling of the LC may modify the row spacing; however, this process has not been yet investigated.

In general, either instability of currents due to wind-wave interaction or other generating mechanism is at work, the roll structures in the upper layer of the sea seem to be responsible for the observed phenomenon.

4. Conclusions: Projection to microplastics behaviour

Annoying presence of microplastics everywhere in nature...
causes much anxiety, which is multiplied due to severe lack of knowledge on its behaviour, especially in marine environment. Unexpectedly, an impressive natural "case study" — the phenomenon of "brosy" of Baltic amber after severe storms — provides a unique source of valuable information to this end: it allows to point out the most important physical factors and to suggest the mechanisms driving migrations of plastics in the sea coastal zone.

Even though the sources of amber and plastics are different — amber enters water body from the "blue clay layer" of bottom sediments, and plastics mainly arrive from the coasts — they have similar densities and analogous transport properties. With present-day limited experience on MPs behaviour in the sea (Thompson, 2015; Hidalgo-Ruz et al., 2012; Andrady, 2011; Ivar do Sul and Monica, 2014; Chubarenko et al., 2016; Ivar do Sul et al., 2009; Woodall et al., 2014), we, nevertheless, have already found some common features with those of amber. Being slightly heavier than water, both amber and plastics are able to migrate quite easily in marine environment, and in both cases the location of initial source is proved to be not too important. Both kinds of particles are washed ashore: the largest pieces — only after most vivid storms, whilst MPs and few-mm-long amber crumbs begin beaching after just fresh gales (Fig. 1).

One more similarity follows from the examination of state of the beached plastic wreckage: plastic pieces on (soft) sandy beaches have severe mechanical damages and bio-fouling that suggests their long residence among stones in deep sea (i.e., relatively far from these beaches, at depths more than 5–7 m), see Fig. 3. Another physically based argument may have some value here. The main sources of plastics seem to be located at the coastlines (Thompson, 2015; Hidalgo-Ruz et al., 2012; Andrady, 2011). In deep-sea bottom silts only tiny fibres — of all the kinds of plastic pollution — are commonly reported to be in abundance (Thompson, 2015; Hidalgo-Ruz et al., 2012; van Cauwenbergh et al., 2013; Lusher et al., 2015; Obbard et al., 2014; Andrady, 2011; Woodall et al., 2014). This is again in line with the behaviour of amber: we did not meet any information that amber pieces were ever found below 50–60 m depth in the Baltic Sea. When integrated with the analysis of the features (I-VII) above, this means that amber and non-buoyant plastics migrate between the coastline and certain depth on underwater slope, driven by surface waves action and stronger currents in coastal zone. During calm weather periods, they are deposited there since — as long as they are still large - there are no bottom currents to carry them farther off-shore. This suggests an existence of a “plastic rim” around the deeper sea area.

Considering the behaviour of amber pieces as a physically equivalent example for negatively buoyant plastic fragments and pellets, we may conclude that the MPs have a long and complicated “afterlife” within quite a limited depths range in-between coasts and the deep sea, being retained in the area of surface wave transformation and coastal currents which are able to transport and re-deposit them (Fig. 9). Thrown on the beach, non-buoyant plastics are soon captured by waves and carried seaward (and along the coast) as far as stormy currents can retain and carry them. Since non-buoyant macro-pieces tend to sink faster than smaller ones, and wind-wave currents weaken with the distance from the shore — they settle at some (hydrodynamically prescribed) depth, still in the area of deformation of surface waves. Later, with some other storm, they seem to be further damaged and re-deposited within the sea coastal zone. They are also able to come back upslope (to the swash zone and the shore line) with some ceasing storm — to be further mechanically destroyed and UV-degraded, and washed to the sea again and again during the next wind event — until microplastic pieces will be small and light enough to leave the coastal zone with stormy currents and be deposited in the deeper sea, out of reach of stormy waves. Synthetic fibres, found everywhere in deep sea sediments, seem to be an example of such easily-transported MPs. Fig. 9 illustrates the described cycle in more detail, showing also bottom deformations in coastal zone due to the storm action: equilibrium sandy bottom profiles (Dean and Dalrymple, 2001; Van Rijn, 2012; Chardón-Maldonado et al., 2015) during fair-weather conditions, under developing and under weakening stormy waves. This way, negatively buoyant plastic objects should repeatedly migrate up- and down-slope within the coastal zone, composing the “plastic rim” along the shore and exporting only very small particles (from our experience — fibres and small film flakes (Zobkov and Esiukova, 2017)) towards the deep-sea area.

The overall conclusion is that the main, critical factors for plastics migrations in the sea coastal zone are the wind speed and direction (fetch), wave heights, the exposure of the shore to the

Fig. 8. Probable mechanism of formation and on-shore transport of subsurface patches of slightly negatively buoyant seaweed, amber and marine litter: compaction and lift of floating near-bottom material and Furcellaria, cut off from sparse rocks by stormy wave motions, is due to upwellings in-between the cells of the Langmuir circulation.
wind, and the phase of wind development/attenuation. It is important to note that the presented analysis points on physical factors which are applicable to any kind of the shore in any sea/ocean, while amber stones and sandy sediments of the Baltic “case study” only illuminate the results of wind&wave forcing.

An ecological point is also worth noting here. The red algae Furcellaria lumbricalis, which seems to be directly involved in the plastics migration process in the Baltic Sea, is also an important habitat-forming seaweed: its underwater “belts” provide spawning habitat for many fish species, and for this reason some governments even place regulations on the harvesting of this seaweed. This danger of presence in marine environment of plastics in general and microplastics in particular had not been disclosed before the presented analysis. May “amber tears of Heliades” help us to cope with “plastic tears” of our civilization.

Author contributions

NS collected historical and web information, prepared illustrations and videos. ICh performed the analysis and wrote the paper. The authors discussed and agreed on the results.

Author information

The authors declare no competing financial interests.

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Appendix A. Supplementary data

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References


Fig. 9. Scheme of migrations of beach plastics in the sea coastal zone, driven by windy/stormy events: fragmentation, suspension and off-shore transport under developing stormy conditions versus deposition and on-shore move when wind weakens.


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