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RELATIONS BETWEEN MARINE PLASTIC LITTER AND RIVER PLUMES: FIRST RESULTS OF PLUMPLAS PROJECT

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We report here first and preliminary results of the PLUMPLAS Project – an ongoing international joint research effort between Federal University of Rio Grande (Brazil), Xiamen University (China), and P.P. Shirshov Institute of Oceanology (Russia) developed within science and technology cooperation initiative (STI) between BRICS countries. The studies are focused on specific model regions representing different conditions of river discharges and anthropogenic loads, namely, the areas adjacent to the Kerch Strait in the Black Sea (Russia); the region of the Patos Lagoon mouth in the South Atlantic (Brazil); and Jiulong river estuary in Xiamen (China). The working hypothesis being tested is as follows: the floating plastic litter in the coastal ocean is mainly concentrated in the river plumes associated with continental freshwater discharges, and its dynamics is largely controlled by the dynamics of the plumes. The preliminary results of in situ observations and modeling accomplished to date seem to be in line with this hypothesis.

Keywords: plastic litter, microplastic, river plumes, Kerch strait, Patos lagoon, Jiulong river

Introduction

Plastic pollution is known to significantly affect ecosystems at the sea surface, seabed, water column, and shorelines (e.g., Woodall et al., 2014). Plastic debris impact at least about 700 marine animal species, ranging from small zooplankton to marine mammals (Gall and Thompson, 2015). The impact of plastic on marine life includes entanglement, ingestion and potential contamination by persistent pollutants, and introduction of invading and pathogenic species (Derraik, 2002). Additionally, plastic degradation has been shown to release methane and ethylene, greenhouse gases that can exacerbate climate change (Royer et al., 2018).

Although several studies have investigated ocean plastic pollution, there are still many gaps in our understanding of this environmental problem. For instance, relatively few studies have focused on the origins and pathways of marine plastics. While main sources and pathways have been identified (van der Wal et al., 2015), their individual contributions to worldwide plastic pollution are still largely unknown (Bruge et al., 2018). Rivers are recognized as a major source for plastic litter entering the ocean; however, only a few studies attempted to quantify this source. For example, (Lechner et al., 2014) estimated the mean flux of litter into the Black Sea from the Danube River as 174 kg per hour. On a global scale, the total discharge of plastic waste from rivers into the ocean is estimated to be between 1.1 and 2.4 million metric tons per year (Lebreton et al., 2017). Given that the overall annual land-based discharge of plastics into the ocean is believed to range between 4.8 and 12.7 million tons (Jambeck et al., 2015), this means that the world's river estuaries, which occupy only a small fraction of the global coastline, are likely accountable for up to 50% of all plastic waste in the ocean. This is due to not only the fact that they receive and accumulate waste from extensive watersheds, but also the ability of buoyant river plumes in the ocean to propagate over long distances offshore. While floating litter locally washed away or blown by wind from the coast will in most cases return to land after a short time because of the action of waves and near-shore currents, plastic waste introduced with river discharges can be dispersed far from the shore by the inertial or wind-driven motion of the plume and remain afloat for an indefinitely long time, traveling long distances until reaching land, accumulating at the center of subtropical convergence zones ("great garbage patches"), or sinking due to colonization and/or changes in chemical properties due to photo-oxidation (van Sebille et al., 2015).

Therefore, the dynamics of river plumes and their inter-relations with buoyant or suspended plastic litter under various forcing conditions is key to understanding the pathways of plastic pollution in different regions, identifying critical areas of maximum exposure, and developing prevention and mitigation strategies. However, a review by (Horner-Devine et al., 2015) described the state-of-the-art knowledge on the dynamical features of fluvial plumes as follows: *"..although (recent) studies have clarified many individual processes, a holistic description of the interaction and relative importance of different mixing and transport processes in river plumes has not yet been realized*". This is so partly because of the rarity of observational data at spatial and temporal resolutions sufficient to elucidate the internal structure and variability of plumes, especially those of modest sized rivers.

The PLUMPLAS project is an ongoing international joint research effort between Federal University of Rio Grande (Brazil), Xiamen University (China), and P.P. Shirshov Institute of Oceanology (Russia) developed within science and technology cooperation initiative (STI) between BRICS countries. The scope of this project embraces two different but interconnected subjects identified as the priority topics; namely, marine plastic litter and river plumes. The studies are focused on specific model regions representing different conditions of river discharges and anthropogenic loads, namely, the areas adjacent to the Kerch Strait and the Mzymta River mouth in the Black Sea (Russia), as well as some selected coastal areas of the Russian Arctic seas; the region north of the La Plata estuary and the Patos Lagoon mouth in the South Atlantic (Brazil); and Jiulong River Estuary in Xiamen and Pearl River Estuary near Hong Kong (China). The principal working hypothesis being tested is as follows: the floating plastic litter in the coastal ocean is mainly concentrated in the river plumes associated with continental freshwater discharges, and its dynamics is largely controlled by the dynamics of the plumes. The latter can be traced based on their reduced salinity and high content of suspended matter by means of in situ measurements, remote sensing, and hydrodynamic modeling.

The three teams of the project consortium complement each other with respect to their fields of their primary expertise, as well as the oceanographic and socio-economic conditions of the focal regions of their research. Although the COVID-19 pandemic greatly impeded field work and international cooperation in 2020. Nevertheless, the consortium kept working on the project trying to maintain the implementation plan. In this information note, we present the first results obtained within the PLUMPLAS project by national teams in the selected study regions.

Results

In situ data on plastic debris originating from Patos Lagoon

Situated in southern Brazil between 30°S and 32°S, Patos Lagoon (hereinafter, PL, Fig. 1), the world largest choked coastal (surface area around 10.000 km²), drains the waters from its hydrological basin of 200.000 km² to the South Atlantic Ocean through a very narrow channel. Part of this basin is within Rio Grande do Sul State (RS, 67%) and the remaining area is in Uruguay with the main tributaries contributing to the Mirim Lagoon (Fig. 1) that is connected to PL by the São Gonçalo Channel. Several important cities are situated along the main tributary rivers and the coastline of these lagoons, forming a population of circa 7,500,000 inhabitants in RS with sewage treatment reaching only about 50% of human disposal. Industrial, agricultural, fisheries and harbor activities are highly developed in this region.

The mean continental discharge rate from the lagoon is 2,400 m³/s (Vaz et al., 2006) but in high river discharge periods or El Niño events it can reach values in excess of 10,000 m³/s. Main wind regimes are from NE (spring and summer) and SW (autumn and winter) oriented parallel to the longitudinal axis of the lagoon. Tides are not important because of the proximity of an amphidromic point for the M2 component (Möller et al., 2007).

The circulation of the lagoon has been described by Möller and Castaing (1999), Möller et al. (2001, 2007), Fernandes et al. (2002, 2005) and Möller and Fernandes (2010). These authors have pointed out that this is a river-dominated system. During high river discharge periods, a seaward flow is established, and the estuarine area is reduced to the entrance channel. In this situation, a large plume is developed in the area and can be embedded with the plume derived from the La Plata River (Zavialov et al., 2003; Burrage et al., 2008; Marques et al., 2010; Zavialov et al., 2016) and, in this case, an area of convergence of plastic material can be formed.

The main objective of this part of the PLUMPLAS project is to study the dynamics of the plastic plume of Patos Lagoon through data sampling and mathematical modeling. Plastic litter was collected using a fishing net (9 m x 1.80 m, mesh sizes 13 mm in the

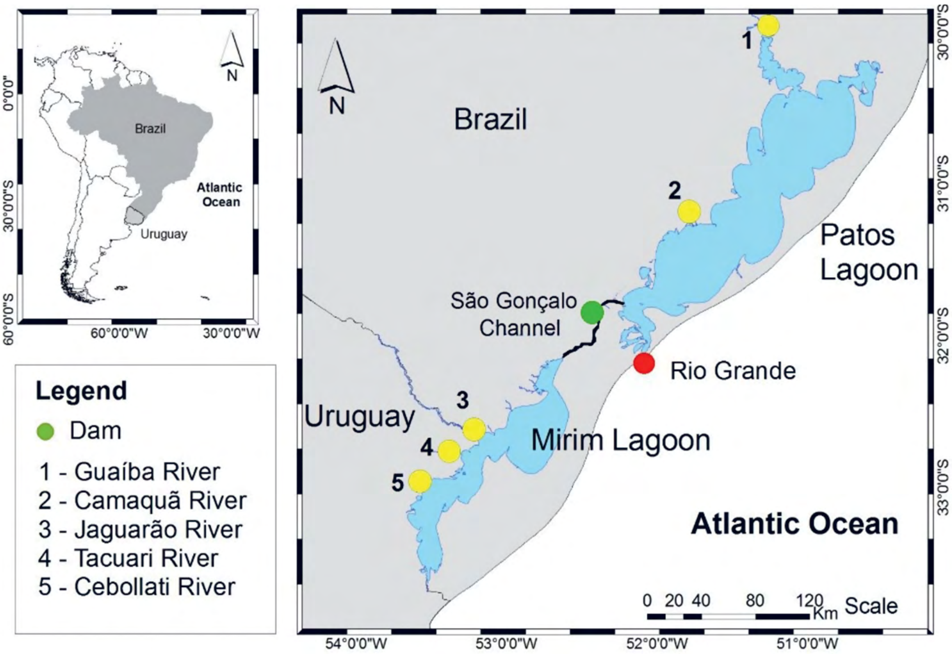

Fig. 1. The Patos-Mirim lagoon complex with the tributaries of Patos Lagoon (1 – Guaíba River with 5 tributaries; 2 – Camaquã River; São Gonçalo Channel where a dam was built in 1977 (green circle) and those of Mirim Lagoon; 3 – Jaguarão River; 4 – Tacuari River; 5 – Cebollati River).

wings and 5 mm in the center) at five stations within the estuary and two stations in the adjacent coast. Sampling was carried out monthly between August, 2019, and February, 2020. The collected items were counted, weighed and classified according to type, color and probable source according to the procedure described in (UNEP, 2016). A total of 2,784 items (weighing 4496 g) were collected, with plastic representing 99% of the materials. Most plastics were fragments (78%) and lines (19%). Transparent (51%), white (22%) and blue (17%) were the dominant colors of items. From the total, 311 items were sampled in estuarine waters, while 2,443 were from the coastal region immediately adjacent to the access jetty of the estuary, i.e., within the lagoon's plume. This suggests that the jetty could act as a barrier accumulating litter at this portion. The dominance of fragments in transparent/white colors suggests the breakdown of larger items in the environment, and the high amounts of nylon lines indicate contamination caused by fishing activities. Monitoring the types and sources of plastics is essential for mitigating its impacts.

Modeling Patos Lagoon plastic dispersion

The methodology based on modeling the plastic fluxes using data of production, consumption and waste management was applied to estimate the amount of plastic debris that reaches Patos Lagoon's waters between the years of 2010 to 2017 (Santos et al., submitted). The main types of plastic debris encountered in the PL are Polyethylene (PE), Polypropylene (PP) and Polyvinyl Chloride (PVC), which could also reflect as the main composition of plastic debris. The amount of plastic waste generated in the Patos

Lagoon basin was estimated to be in the range of 144.76 Kton to 261.29 Kton per year, which meant that an average of 8% to 14% of the consumed plastics in the basin ends up as mismanaged waste. From that, the range of plastics possibly entering this water body as plastic debris is 21.67 Kton to 108.76 Kton per year translating to an average of 6.54 grams/person/day to 32.82 grams/person/day, the equivalent of 2 to 11 plastic bottle caps/person/day. It was also possible to identify the main activities associated with the consumption of plastics in the basin which could reflect the possible sources of plastic waste and debris entering the Lagoon as textiles and clothing and food-related activities. A part of this plastic debris is deposited throughout the lagoon as governed by its hydrodynamics, while a part of it reaches the coastal zone through the Patos Lagoon coastal plume. At the next stage of the project implementation, in situ data collected in this region will be used to validate the results given by the model.

Microplastic and plastic litter in Kerch Strait of the Black Sea

In situ measurements and sampling of microplastic debris and floating plastic litter in the Kerch Strait connecting the Black Sea and the Sea of Azov were conducted from R/V «Peleng» on July 16–18, 2020, along with CTD and ADCP profiling in the cross-section of the strait. It is well-known that the shallow Sea of Azov can be thought of as a large estuary receiving discharges from the Don and the Kuban rivers, therefore, the flow through the Kerch Strait towards the Black Sea usually carries a variety of pollutants, however, the flux of plastic waste through the strait has never been quantified.

The microplastic debris were sampled using a Manta trawl net with mesh size 300 μm towed behind the vessel cruising at 4 kts and taking material from the upper 1 m of the water column. As a result, a large set of plastic particles, fibers and films were collected. All sampled items were measured, weighted, and sorted by composition using Micro NIR 1700 spectrometer instrument. The particle sizes ranged from 0.4 to

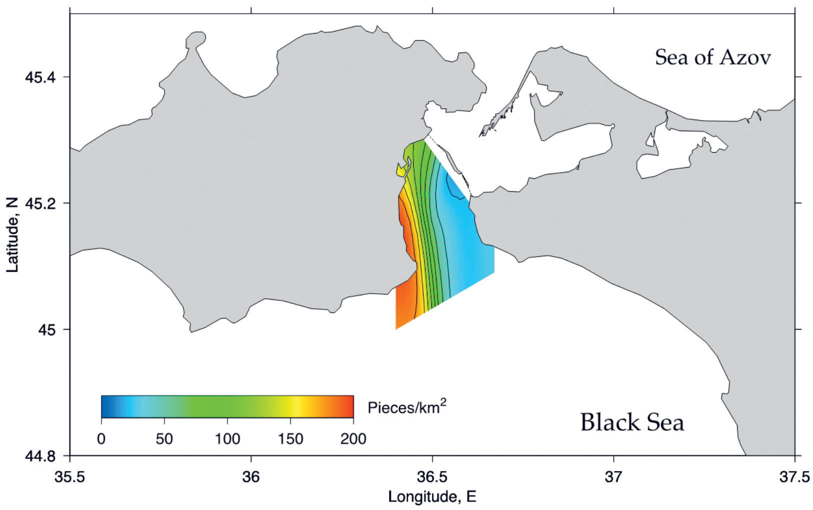

Fig. 2. Distribution of floating plastic litter in the Kerch Strait inferred from visual observations on 16–18 July, 2020.

25.0 mm and weights varied between 0.05 and 7.72 mg. With respect to the chemical composition, about 63% of the collected particles were identified as HDPE (high-density polyethylene), 21% as PP (polypropylene), 5% as PET (polyethylene terephthalate), 4% as PA (polyamide), 4% as PC (polycarbonate), and 3% as all other types of plastic.

The visual observations of the floating plastic litter in the Kerch Strait were organized as follows. As the vessel was moving along the track at 6 kts, two dedicated observers equipped with binoculars constantly visually controlled the 50 m wide stripe space adjacent to the moving ship, one from the starboard and the other from the port side. During these observations, the ship's track included two complete transects across the strait, one along the Crimean bridge at the distance of about 2 km south of it and the other one at the southern outlet of the strait, from Takil Cape in the west to the Iron Horn Cape in the east, plus one 3 miles long meridional section from Takil Cape southward. Once a floating object was detected and identified as plastic, its coordinate was promptly registered by GPS recorder. Afterwards, the surface concentration of plastic litter was inferred by interpolation based on the observed distances between the neighboring pieces.

The resulting distribution of visually identifiable plastic litter in the Kerch Strait is shown in Fig. 2. Overall, the concentration varied between about 10 and 200 pieces per km^2, with the average value close to 100 pieces/km^2. However, it is noteworthy that the distribution is far from homogeneous – the litter is mainly concentrated in the western part of the Strait, where the principal stream carrying the Sea of Azov water into the Black Sea is usually localized.

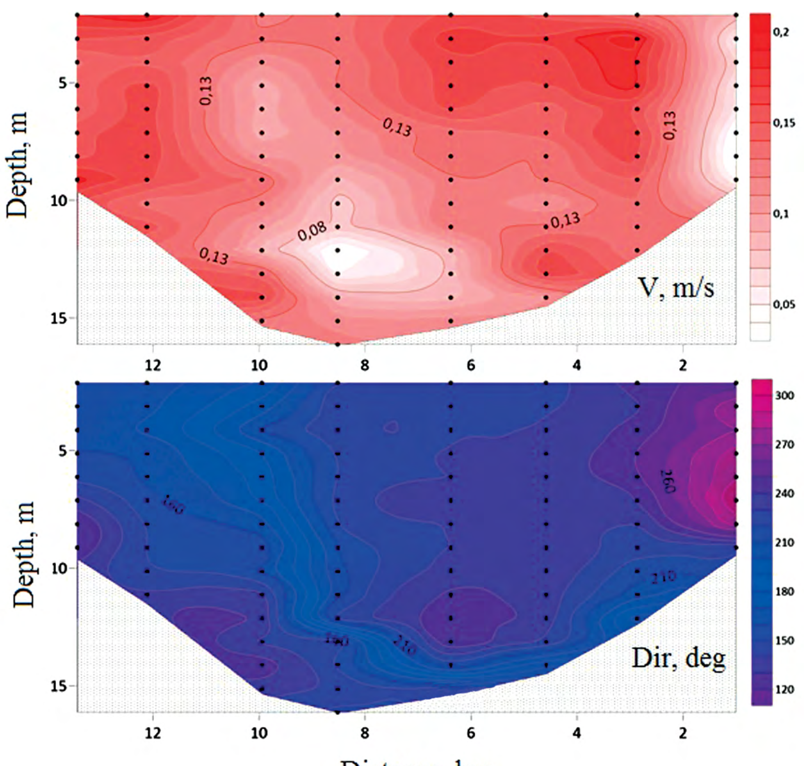

Fig. 3. Velocity (m/s, upper panel) and direction (degrees, lower panel) of current in the cross-section of Kerch Strait on July 17, 2020, as registered by ADCP measurements.

The newly obtained data of plastic litter concentration together with the current velocity data collected in ADCP profiling (Fig. 3) enabled us to estimate for the first time the flux of plastic through the Kerch Strait from the Sea of Azov into the Black Sea. This can be done by simply multiplying the plastic concentration by the velocity and then integrating it over the width of the Strait. This procedure yields an estimate of 14,700 major pieces of plastic such as bottles, bags, etc., passing through the Strait per day. Assuming the average weight of a plastic litter piece 15 g (which is the weight of a standard plastic bag, many pieces may be lighter, but others may be heavier, e.g., plastic bottles weighting around 40 g), this leads to 220 kg/day, or about 9 kg/hour. This is quite a considerable mass of plastic, although it is about 20 times smaller than the amount brought to the Black Sea by the Danube according to (Lechner et al., 2014). It must be kept in mind, however, that our estimate for the Kerch Strait is based on instantaneous one-time measurements, and cannot represent long-term average values.

Riverine plastic debris and microplastics in Jiulong river estuary

The Jiulong River is the second-longest river in Fujian province of China with a watershed area of 14,740 km^2. The Jiulong River estuary (JRE) is characterized by intense agricultural activities with macro-tidal influence (an average tidal range of 4.95 m), and intensely impacted by rapid industrial and urban development of Xiamen city. Xiamen coast receives large amounts of waste from the Jiulong River.

Most previous studies have focused on the distribution of microplastics (MPs) with size of 0.33 to 5 mm, but MPs with smaller volumes are more likely to become carriers of other pollutants and microorganisms in the environment. In this study, the abundance, characteristics and transport of plastic debris and MPs from 45 μm to 300 μm were investigated in the context of the river plume influence on the land-sea transport.

In September 2020, plastic debris and MPs in Jiulong river estuary-Xiamen Bay were investigated by in-situ large-area sampling collection (Fig. 4). Surface seawater

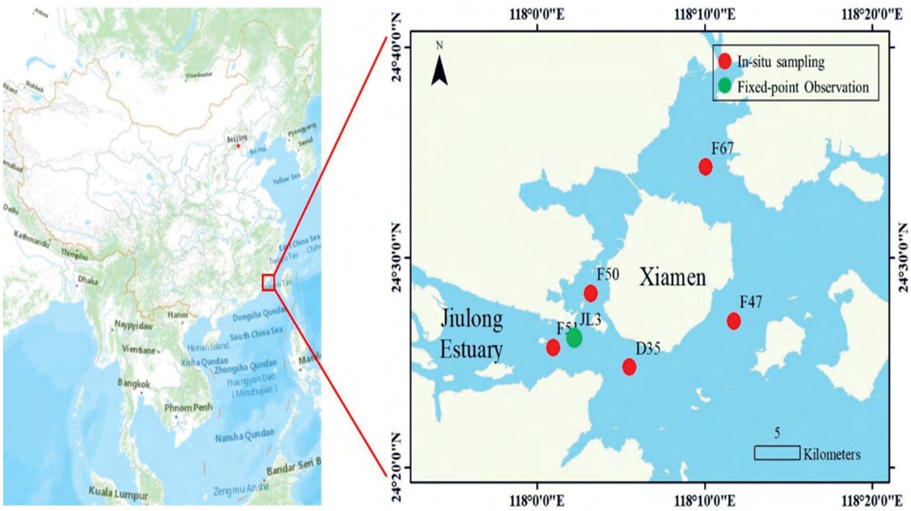

Fig. 4. Sampling stations in and near Jiulong River estuary.

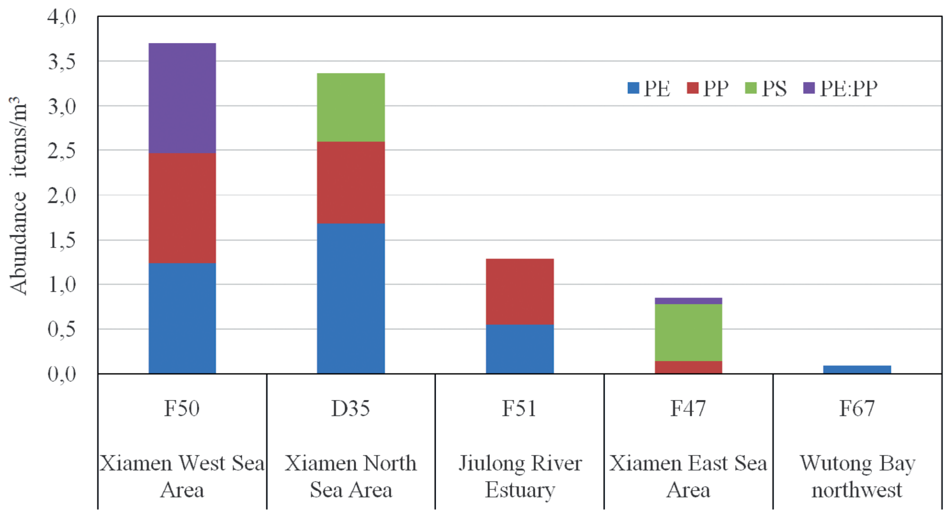

Fig. 5. Composition and abundance of microplastics in Jiulong river estuary, Xiamen Bay. PE is polyethylene, PP is polypropylene, PS is polysterene.

samples were collected using a manta trawl with 0.33 mm mesh. The net was towed a straight line with the vessel speed being kept at an average of 2 knots for 10 min. A calibrated flow meter (HYDRO-BIOS, Germany) was attached to the mouth of the net to allow for volume calculation of the water filtered.

Purified MPs were accumulated on a PTFE membrane and analyzed automatically by Micro FTIR spectroscopy. The MPs with similarity more than 60 percentage were identified. We obtained the following data about MPs as summarized in Fig. 5.

MPs were observed in the surface water at all stations in Jiulong river estuary-Xiamen Bay, and their abundance ranged from 0.1 to 3.7 items/m^3, with an average of 1.9±1.6 items/m^3. These content values are relatively low as compared to those found in the literature for Yangtze estuary and Minjiang estuary in China (Zhao et al., 2015; Zhao et al., 2014). In all samples, PE, PP, PS and the mixture of PE and PP were dominant (Fig. 5). The most popular plastics of PE and PP in industry and our daily life, and the low specific densities contribute to their large abundance (Klein et al., 2015).

The size range of MPs in these areas was found to be between 244 and 2625.5 μm, with the average of 1079±537 μm. In the Jiulong river estuary, followed with Xiamen west sea area, the size distribution was dominated by relatively fine particles with sizes below 1000 μm accounting for more than 60% of all items. Xiamen west sea area is a semi-enclosed bay strongly exposed to industrial and urban pollution and limited seawater exchanges, so the fine plastic particles delivered by river discharges are trapped and accumulate in this area.

Conclusion

Preliminary results obtained during the first year of the research within the PLUMP-LAS Project, focused on different geographic objects in distant parts of the World but united by common hypothesis and approaches, generally confirmed the existence of intimate connection between plastic pollution of the ocean and river plumes. Modeling studies and observation conducted near very different sources of continental discharges pointed on similar properties, such as accumulation of plastic litter not in the river mouths proper, but at some distance from them, in the inner parts of the river plumes in the ocean, where streams carrying river discharges lose their momentum and become dynamically «trapped», gradually mixing with the surrounding sea waters. This situation is equally evident for the Kerch Strait behind the Takil Cape in Russia, the Patos Lagoon jetties in Brazil, and the western Xiamen Bay near Jiulong river estuary in China. A similar pattern has been previously reported for river-borne suspended matter discharged into the sea (Zavialov et al., 2018). New characteristics of plastic pollution in connection with river discharges were already obtained within the PLUMPLAS. However, many quantitative details and physical processes behind the plastic-plume interactions are yet to be investigated in the next years.

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СВЯЗЬ МЕЖДУ МОРСКИМ ПЛАСТИКОВЫМ МУСОРОМ И РЕЧНЫМИ ПЛЮМАМИ: ПЕРВЫЕ РЕЗУЛЬТАТЫ ПРОЕКТА PLUMPLAS

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В статье представлены первые предварительные результаты международного проекта PLUMPLAS, предусматривающего совместные исследования Федерального университета Рио-Гранде (Бразилия), Сямэньского университета (Китай) и Института океанологии им. П.П. Ширшова РАН (Россия) в рамках инициативы научно-технического сотрудничества (STI) между странами БРИКС. Исследования сосредоточены на конкретных модельных регионах, представляющих различные условия речного стока и антропогенных нагрузок, а именно на морских территориях, прилегающих к Керченскому проливу в Черном море (Россия); районах устья лагуны Патос в Южной Атлантике (Бразилия) и устья реки Цзюлун (Китай). Основная рабочая гипотеза проекта заключается в следующем: плавающий пластиковый мусор в прибрежных водах океана в основном сосредоточен в речных плюмах, связанных с пресноводным материковым стоком, и его динамика в значительной степени определяется динамикой плюмов. Предварительные результаты натурных наблюдений и моделирования, полученные на сегодняшний день, по-видимому, вполне соответствуют этой гипотезе.

Ключевые слова: пластиковый мусор, микропластик, речные плюмы, Керченский пролив, лагуна Патус, река Жиулонг

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