Dear Dr. Bagaev,

Thank you for your review of our manuscript. Please find in the following our responses to your comments. We repeated your comments in bold and you can find our response in italic.

1. Please specify what makes it possible to consider your model particles as microplastics. It might also be better to separate the description of the experiments from their interpretation and application to MPs transport prediction.
Our aim of this study is to investigate in how far the uncertainty in the representation of extreme storm events in metocean data for the Baltic Sea affects the uncertainty in the transport of sediment and MP. For this purpose, we simplified the representation of MP in the model. The idea of using a sediment transport model for transport simulations of MP is motivated by the cited studies. As a simplification, we assume that the plastic particles have a spherical shape and a density defined by the two high density plastic types (PVC and PET). Based on these simplifications, there is additional uncertainty in the transport simulation resulting, for example, from non-optimal settling velocities and critical shear-stresses, but this kind of uncertainty was not to be quantified in this study. We show different kinds of experiments, and some of the experiments are motivated by the outcome of another. For this reason, we decided to keep the description of an experiment and its interpretation closely together to allow the reader to follow this logic.

2. The conclusion made in the last sentence in Abstract is poorly linked to the aim of the study and was hard to understand. Please clarify.
If forecasting a storm event with a state-of-the-art weather model, the location and intensity of a storm system is affected by uncertainties which originate from uncertainties in the initial conditions, lateral boundary conditions and the model physics. The purpose of this study is to investigate if these uncertainties also affect the location of areas where material during/after the storm event is eroded/deposited, because in the different representations of the storm (ensemble members), its track varies in its position. The study indicates that the uncertainty in the storm representation is affecting the amount of transported material, but the location of erosional and depositional areas keeps nearly constant <u>in the study area</u> (changes only in size because of more or less erosion). This means that the model chain can be used in forecast mode to predict areas where erosion/deposition takes place. This allows for a strategic planning of measurement campaigns, because the model can be used to identify regions in which we should take samples. We will make this clearer.

3. Introduction, 2nd paragraph: again two poorly linked sentences. It is not clear how the models can complement field measurements.
As explained for the previous comment, the model chain allows for identifying regions in which erosion/deposition should take place. Our aim is not complementing the measurement campaigns, but to have a tool which can be used to identify sample regions beforehand. The proposed model helps to identify regions in which larger amounts of high-density MP is potentially deposited. This allows for a more specific planning of measurement campaigns.

4. 4th paragraph: too many assumptions made unexpectedly for the reader. Maybe there is a need for more references. New assumptions could be formulated in the Methods section. The interest of this study is not mentioned anywhere in Abstract.
We apply a simplification of a MP transport model to study the impact of the metocean uncertainty on the sediment and MP transport. Aim of this study is to investigate, whether this uncertainty affects the location of erosional and depositional areas. The application of the sediment transport model is motivated by the cited articles. We will make it clearer that the parameters for the MP transport are simplified and better motivate the purpose of the study, a decision support tool for measurement campaign planning.

5. Lack of references to existing models. For example: Ballent, A., Pando, S.,Purser, A., Juliano, M. F., and Thomsen, L.: Modelled transport of benthic ma-rine microplastic pollution in the Nazar Canyon, Biogeosciences, 10, 79577970, https://doi.org/10.5194/bg-10-7957-2013, 2013.Nicole Kowalski, Aurelia M. Reichardt, Joanna J. Waniek Sinking rates of microplasticsand potential implications of their alteration by physical, biological, and chemical-factors, Marine Pollution Bulletin, Volume 109, Issue 1, 2016, Pages 310-319, ISSN0025-326X, https://doi.org/10.1016/j.marpolbul.2016.05.064.A. Bagaev, A. Mizyuk, L. Khatmullina, I. Isachenko, I. Chubarenko, Anthropogenicfibres in the Baltic Sea water column: Field data,

laboratory and numerical testingof their motion, Science of The Total Environment, Volumes 599600, 2017, Pages560-571, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2017.04.185.If the transport of the MPs in the marine environment could not be investigated with the existing models, please explain.

The studies that we know so far use a deterministic representation of the metocean conditions for the transport simulations, i.e. they calculate MP transport under the assumption that the wind conditions were exactly known. They focus on parameters like the settling velocity, for example. These parameters for the transport model are simplified in our study, instead we use probabilistic metocean data. We mentioned in the conclusions that for a better prediction of the MP transport, we would have to improve the parameters for the MP transport model. The existing studies would also get an additional source of uncertainty if applying probabilistic instead of deterministc metocean data. We will add references to existing models and make the difference and the different focus to existing studies clearer.

6. Why exactly do you prefer to use the Eulerian approach?

The idea is to apply a sediment transport model, because these models are widely used in coastal engineering for example. The physics described by Eulerian and Lagrangian models is the same, the difference is just the numerical implementation. So when a sufficient spatial resolution / number of particles are used, it shouldn't make a difference which method is applied.

7. Both papers Khatmullina Isachenko and Waldschläger Schüttrumpf report settling velocities for still fresh water. Please explain the applicability of their results to salt (brackish) turbulent marine water. How exactly do you use those formulas for the settling velocity?

We use the Stokes formula as a simplification for the settling velocity. In an improved version of the model, the settling velocity could be represented by the mentioned articles. For example, we could use an ensemble approach based on different parameters to represent the uncertainty in the settling velocity, or define different fractions of the same plastic particle with different settling velocities based on the distribution of the particle shapes. A combination of the ensemble of metocean conditions with a representation of the uncertainty in the parameters for the MP transport (settling velocity, critical shear stress) would improve a forecast of MP transport processes.

8. You have not mentioned the values of critical sedimentation/resuspension shear stress and settling velocity for your particles. It might be useful for the future studies and the experiments reproduction.

These parameters do not have constant values since they depend on sea water viscosity. We, however, give example values for 10° C water in a new appendix section now.

9. It is important to explain why you use 10 and 330 mkm as the size of the particles, which is not common for MPs studies.

These diametres are motivated by a study for the North Sea (Stuparu et al., 2015). In this way we have MP particles which correspond to a relatively fine and coarse sediment fraction. We will include this information in the text.

10. Page 4: final paragraph - is really hard to understand. Please clarify.

The uncertainty of weather forecast originates in uncertainties in the initial conditions, the lateral boundary conditions and the representation of the model physics. For processes which cannot be explicitly resolved by the model resolution, parameterizations are used. We use stochastic perturbations of these parameterizations. The methods applied here are standard methods used at various operational forecast centres. The cited study tested to use initial conditions from an ensemble of data assimilation. In this way, the uncertainty in the initial conditions will lead to differences (spread) between the ensemble members already in the first model time steps. In the presented approach, it needs some time until the stochastic perturbations provoke differences in the members.

11. Page 9, line 19: findings indicate that bathymetry has predominant impact, how exactly do they do this? Is this statement somehow new compared to the results of Enders et al, 2019? I think that Fig. 13 might help you to highlight the new findings.

The motivation of this article is to investigate the impact of metocean uncertainty on the transport behaviour of MP. The finding in the presented study is related to this uncertainty, which is a result of the uncertainty *in the metocean data used to drive the sediment transport model.*

12. The authors found that with the decrease of MP density and size the ability of models to predict their transport decreases. I think this result is sufficiently supported by the experiments and should be stated more clearly! In fact you showed that small and light MPs (so called nanoplastics) are being driven by waves, while MPs (0.5-5mm) are affected by hydrodynamics.

The study focuses on the uncertainty in the MP transport provoked by the uncertainty in the representation of a storm in metocean data. We found a larger uncertainty for smaller and lighter material, which shows that an ensemble approach is getting more important if one is interested in smaller and/or lighter particles. The uncertainty in ocean currents and waves also differs with particle properties. A short-coming of this study is the fact that there are no stochastic perturbations of the model physics of the ocean model. For this reason, the uncertainty in the hydrodynamics might be underestimated.

13. Page 11, lines 1 and 2 seems too obvious.

Our statements show that if one is interested in the modelling of very light and/or very small material, the uncertainty in the metocean forcing of the transport model becomes more important. We do not know any study taking this kind of uncertainty into account.

14. Page 14, budget methods please explain, what do you mean? The whole paragraph looks unclear.

A budget method relates (a) input and (b) output of a quantity to (c) changes in its mass, e.g. inside an area of interest. If two of the three values are known, the third one can be determined. The purpose of our study is a potential support for the planning of measurement campaigns. To be able to create a map of the sea-floor with MP concentrations, a better knowledge of concentrations entering the Baltic Sea is necessary. We assume a homogeneous distribution over the sea-floor. This is sufficient to see where potential erosion and deposition could take place. For a more realistic simulation, knowledge about the amount of material inside the Baltic Sea would be necessary. Then, the model could run for a longer period, and should approximate the distribution on the sea-floor. The error in the approximation will be size- and density dependent.

15. Conclusion section too many repetitions with the Introduction and methods.

We will revise the conclusion section and remove repetitions.

16. Important, but somewhat discussionable is the idea regarding possible future application of the chain of models for MPs sink prediction. Your findings are based on the numerical experiments with the spectral wave model and GCM models with 1 nm grid, which might be ok for the sediments, but MPs distributions show high patchiness and probably high mesoscale variability. Which means that your models might require higher spatial resolution in order to be able to determine possible accumulation zones for the samples collection (since in situ samplings of bottom sediments for MPs are usually sparse and low in volume).

Our interest is a decision support for planning measurement campaigns. This is why we are interested in regions where large amounts of material is potentially deposited after a storm event. We think that for this purpose, the resolutions of the models are sufficient. We are also able to nest specific domains with higher resolutions into the existing models. For the western Baltic Sea, we tested setups with 600 m resolution for the wave and ocean models and 1.4 km for the atmospheric part.

Dear Dr. Pohl,

Thank you for your review of our manuscript. Please find in the following our responses to your comments. We repeated your comments in bold and you can find our response in italic.

1 Main comments:

I missed a discussion on the relevance of storms as a sediment transport mechanism on the seafloor. What about other sediment transport processes such as seafloor currents (e.g. tidal, thermohaline, hyperpycnal flows, river discharges etc.) and sediment gravity flows (e.g. slides or turbidity currents likely to be triggered by storm events)? To which water depth can a storm event affect the seabed? Typically, the storm-weather wave-base is located at 150 200 m, and sediments below this base are unaffected. Could the authors explain how storms can transport sediment across the seafloor? In the rock record, storm deposits (Hummocky cross-stratification) indicate mainly reworking of sediment on the seafloor, rather than lateral transportation.
It is a known issue that during strong storm activity, amber is beach-combed. In this study, we focus on high-density MP particles. We assume for this reason that there should be a comparable behaviour of these MP particles and amber. The cited articles underline this assumption. As there is a source of amber in the Baltic Sea, we assume that there are also locations which accumulate MP. A 3-D ocean model is used here with terrain-following vertical coordinates. It is capable to simulate the mentioned sea-floor currents. River discharges are defined from a climatology, but without MP load, as we are interested in the resuspension of particles from the seabed. A simulation over one month, suggests that only strong wave activity during the storm event produced sufficiently high bed-shear stresses to transport the MP particles. This corresponds to the experiences from the amber hunting community. High shear stresses are neccessary to transport the particles in suspension. The water depth still affected by waves depends on the wave length. The Baltic Sea is relatively shallow with the result that larger parts of the seafloor can be affected by wave activity.

The sediment transport model could be explained clearer. I struggle to understand what this model is doing exactly. How wromas the bed shear stress calculated and what are the assumptions for these calculations? What type of movement is simulated at the seabed (oscillatory water motion by waves or unidirectional flow)? What are the values of the calculated shear stress and do these make sense when comparing to field and laboratory measurements? I think the outreach of the paper would increase significantly if it becomes clearer to non-experts what this model is doing. In particular as this paper will be of high interest and relevance for readers from other research fields. I cannot evaluate the atmospheric models, as this is not my field of expertise.
We will add an appendix to the manuscript explaining the sediment transport model more in detail. It is a 3-D model, which calculates the concentrations in each model grid cell. An empirical formula for the estimation of the combined shear stress of waves and currents at the sea-floor is used. The initiation of motion is calculated by the Shields curve, settling velocity of the particles is simplified and based on the Stokes formula.

The used criterion for the movement or suspension of sediment is not clear. The Shields curve describes the initiation of movement of sediment on the bed, which means transportation as bedload. There exist additional curves to estimate the threshold for suspension of sediment (e.g. (Bagnold, 1966; van Rijn, 1993; Nino et al., 2003)). Could the authors be more specific which criterion they used and why? Also, the Shields criterion describes the movement of particles under unidirectional flow. How would this translate through to oscillatory water motion, as caused by wave movement?
An empirical formulation is used to estimate the combined impact of currents and waves in terms of an effective bottom stress. Details including the formulas can now be found in an added appendix section.

Assumptions and limitations of the model should be discussed. The authors specifically state all assumptions and simplifications in their calculations, but I was missing a discussion on how these assumptions (e.g. spherical particles) might affect the results and conclusions.

The spherical shape of the particle will influence its settling velocity. Waldschläger and Schüttrumpf (2019) discuss the impact of the shape on the settling velocity. There is also an impact of biofilms, which affect the weight of the particles. Our aim was to quantify in how far the uncertainty from the metocean conditions affect the transport. The simulations showed a strong impact on the amount of transported material, but not on the location where erosion and deposition takes place. This finding should persist if adapting the parameters to more realistic ones, affecting the amount of transported material and the specific location for a specific size class. The uncertainty is taking into account by driving the model chain with an ensemble of the atmospheric model. The uncertainty in the parameters like the settling velocity or critical bed shear stress could also be taken into account, by defining several fractions covering the uncertain range of the specific parameter. This is possible as there is no interaction between the fractions.

2 Comments made while reading the manuscript:

Page 1, line 7: Can you mention to which depth these surface waves would reach down the water column?
Interaction of the wave with the seafloor takes places in depth less than half the wave length. The dominant wavelength is between 20 m and 70 m and can reach up to 130 m (Kriauinien, J., Gailiuis, B. and Kovalenkovien, M. 2006. Peculiarities of sea wave propagation in Klaipeda Strait, Lithuania. BALTICA 19: 20-29.).

Page 1, line 13-15: Would this also depend on the ocean depth? Maybe you mean this with bathymetry? I suggest to specifically mention that the ocean depth plays a major role in whether or not particles on the seafloor can be resuspended due to increased surface wave intensity.
With uncertainty, the uncertainty in the representation of the storm is meant. At a fixed position, the amount of eroded or deposited material is affected differently depending on the particle properties. Ocean depth at this location is important, but also in the vicinity of the location, which influences waves and currents. This is meant by bathymetry.

Page 2, line 2-3: Could you back this up with a reference? At least in deep-marine sedimentology, sediment transport models still have issues and results often do not match observations.
The sediment transport model is based on the work of Sassi et al. (2015), we add this reference. We assume that for the task of identifying areas of interest for empirical quantification of MP accumulation, uncertainties in the transport models are acceptable.

Page 2, line 8-9: Who assumes that? What about other sediment transport processes such as seafloor currents or sediment gravity flows?
We add references which stress the importance of extreme events for sediment erosion.

Page 2, line 16-20: Could you please be more specific here. The Shields curve would give you the critical shear stress at which particles would start to move as bedload. Other curves describe the initiation of suspension (e.g. (Bagnold, 1966; van Rijn,1993; Nino et al., 2003)). Also, this diagram estimated the critical shear stress with a unidirectional flowing current. It is not clear to me how this would translate through to oscillatory water motion, as caused by wave movement.
Details are now given in an added appendix session.

Page 2, line 20: How have you calculated the shear stress exerted on the seabed due to wave motion of the sea surface?
Details are now given in an added appendix session.

Page 7, line 3-7: This needs more explanations. These sentences are difficult to understand.
These sentences describe properties of the GETM model which reduce undesired numerical mixing. Numerical mixing leads to an unrealistically high diffusion of transported concentrations, reducing the peak concentrations and overestimating the area in which tracers spread. We add an explanatory sentence stating this.

Page 7, line 9: What is the difference between wave and current induced bed (shear) stress? I guess this relates back to my comment on page 2, line 16-20.
GETM simulates the ocean currents on a 3-D mesh. The current induced bed shear stress is based on this current. Wave data are externally provided from the simulation done with WAVEWATCHIII. Wave induced bed shear stress is calculated based on theses wave data. Both stresses are added also taking their non-linear interaction into account. Details are now given in the appendix.

Page 7, line 10: Does this mean that the wave induced oscillatory motion of the water at the seafloor is neglected? Looking at ancient storm deposits in the rock record, oscillatory motion appears to be a dominant sedimentary process.
With the latter, the maximum combined wave- and current-induced bed stress is meant. This is based on an empirical formula as mentioned before. So, oscillatory motion is taken into account.

Page 7, line 10-13: It is not clear to me what this means. If this is important, it should be explained. If not, these sentences might be removed from the manuscript.
For the regional ocean model in this study, initial conditions and lateral boundary conditions are needed. Starting from initial conditions which do not agree with the meteorological data will cause adjustment effects at the very beginning which may produce unrealistically high currents. This statement says how the conditions are at the beginning of the simulation and what goes in and out at the border of the model domain. This is a necessary information and citation.

Page 7, line 15: Sea surface elevation = water level?
Correct. In line 16, water level is used.

Page 8, line 9: Why did you chose these particular grain-size range? What about particles between 10 and 200μm?
We used the same sizes as in the study for the North Sea from Stuparu et al. (2015). It is not a range, these are two discrete fractions, and it is computationally expensive to add more fractions. Our purpose is a support for measurement campaigns and particles of above 300μm are easier to sample.

Page 9, line: 17: Please amend to: Figure 7c-f.
Figure a is the deterministic run (without stochastic perturbations of the model physics in the atmospheric part). Figure b serves as a comparison with a publicly available atmospheric dataset.

Page 9, line 19-21: Was there a predominant current direction? Could you indicate this direction in figure 7? Could this current explain the pattern of erosion and deposition (i.e. erosion on northeast and deposition on southwest dipping slopes)? Would this pattern change if the direction of the storm surge is different?
Currents in the Baltic Sea are in long-term driven by a thermohaline circulation leading to cyclonic currents, but intermittently can be changed and even reversed by wind. This also controls transport direction of the suspended material and consequently deposition areas. An entirely different storm realization could therefore also change erosion deposition patterns, but we see that this effect plays a minor role in our simulations, i.e. meteorological uncertainty is not that strong. We state the main current direction in the caption of the figure but do not add it e.g. as arrows not to mix it up with the wind direction shown in other figures.

Page 9, line 22-24: I think it is very important to state that surface waves can only redistribute sediments and plastics to a certain water depth. Storms are important for the MP distribution in coastal areas and shallow seas (e.g. large areas of the Baltic Sea), but apparently play a minor role in the distribution of MPs on the seafloor for most parts of the worlds oceans (below the storm weather wave base). I would think that MPs are frequently remobilized by storms and thus get transported until they are deposited below the storm weather wave base. Here water depth is too deep and plastics cannot longer be remobilized by storms. This would suggest that MP concentrations are probably highest just below the storm weather wave base.
We agree with this speculation but we could not demonstrate this in this model study. As it is known from amber, there must be a stock on the seafloor affected under storm conditions. Our assumption is that there is a comparable behaviour with MP. This assumption is based on other scientific studies, and the identification of potential deposition areas with the model can help to support measurement campaigns whose outcome could

validate the model runs.

Page 9, line 24-26: What about changes in the wind direction?
They are taken into account by the ensemble approach. The stochastic perturbations of the model physics provoke slightly different developments of the storms in the different members, not only in intensity, also in the track of the storm. This was one of the principial ideas of this study, to see if this variability in the location of the storm affects also the location where erosion and deposition appears.

Page 10, line 5: Why is the color scheme in figure 9b c different compared to figure 7 8? This is confusing and makes a comparison difficult.
Figure 9 is for the 10 µm fraction and figures 7 and 8 for the 330 µm fraction. The range of values is different (0 to 1.2) for figure 9 and (0 to 2.5) for figure 7 and 8.

Page 10, line 12: Again, why where these grain-size classes chosen? Wouldnt it make more sense to spread the size classes more evenly in between the two end-members (10 and 300µm)?
Based on the fractions as in Stuparu et al. (2015). The model can simulate only the transport of discrete size fractions. For one measurement method used in the project, 300 µm was the lower limit for the sampling. With 330 µm, we are 10% above of this lower limit.

Page 11, line 5-9: I think I finally understood that you model both, oscillatory motion and unidirectional flow. Is this correct (see my comment on page 7, line 10)? How high are the calculated bed shear stresses ?
These vary between zero and 0.090 N m^{-2}*, strongly depending on water depth.*

Page 12, line 1-2: Does atmospheric forcing mean the generation of a unidirectional current at the seabed? If yes, what is the current velocity and how did you account for interactions with the bathymetry?
The 3-D regional ocean model with 1 n.m. resolution applied in this study simulates the ocean currents close to the seafloor. A 3-D regional ocean model (GETM) is used, which has terrain following vertical coordinates. It calculates the U and V components of the current at each model timestep for each grid cell. The model is driven by the atmospheric data, but also includes river discharges and is driven at the open boundary with the North Sea by lateral boundary conditions of a North Sea ocean model.

Page 14, line 1-2: What about sediment transport mechanism other than storm induced movements? Tidal currents for example. Although tidal currents are not very strong in the Baltic Sea, they play a significant role in the North Sea. Storms may also trigger sediment gravity flows such as turbidity currents which could transport MPs on the seafloor (Pohl et al., 2020). Also seafloor currents due to thermohaline circulation can transport and redistribute MPs (Kane et al., 2020). I think other processes should be discussed.
As figure 12 suggests, strong wave activity plays the pre-dominant role for erosion and though for the transport in suspension. Our aim was not to quantify which are the pre-dominant processes leading to the transport of MP. We wanted to investigate in how far the uncertainty in a weather forecast would affect the transport behaviour of sediment and MP. Tidal currents play a role in the Danish Straits only but the interior of the Baltic Sea is non-tidal. Turbidity currents cannot be represented in our model since the concentration of suspended matter has no influence on seawater density in the model. Thermohaline circulation, on the other hand, is fully taken into account. We add the missing processes to the discussion of the study's limitations.

Page 14, line 2: This is an interesting point. Could the authors be more specific on how these budget methods would work?
The same question was asked by Reviewer 1 so we give the same answer. A budget method relates (a) input and (b) output of a quantity to (c) changes in its mass, e.g. inside an area of interest. If two of the three values are known, the third one can be determined. The purpose of our study is a potential support for the planning of measurement campaigns. To be able to create a map of the sea-floor with MP concentrations, a better knowledge of concentrations entering the Baltic Sea is necessary. We assume a homogeneous distribution over the sea-floor. This is sufficient to see where potential erosion and deposition could take place. For a more realistic simulation, knowledge about the amount of material inside the Baltic Sea would be necessary. Then, the model could run for a longer period, and should approximate the distribution on the sea-floor. The

error in the approximation will be size- and density dependent.

Page 15, line 12-13: The authors use in their model only spherical particles, although most MPs have more complex shapes (angular and oblate fragments, fibers etc.). I fully understand that the simulation of more realistic shapes would add another level of complexity, or might be even impossible to model as we dont fully understand the hydrodynamics for these complex shapes (Khatmullina and Chubarenko, 2019). However, the authors should mention possible deficiencies of the model due to the assumption of spherical particles. Nevertheless, I think these models are crucial for understanding MP distributions and the assumption of spherical particles is a good starting point.
Our aim was to study the effect of the uncertainty in the representation of storms on the transport of MP particles. This kind of uncertainty is, as far as we know, neglected in other studies. The simplifications of the model have of course impacts on the transport behaviour, as unknown particle shapes will add even more uncertainty.

Page 15, line 15-16: I dont understand this sentence. Size difference in what? MPs? Sediment? Could the authors please rephrase and make this clearer?
Will be rephrased.

Page 15, line 18-20: Only because they have the same settling velocity? I think that this is too simple.
The correlations in figure 13 shows the connection between a sediment particle and a ligther but larger MP particle. Enders et al. (2019) showed such a relation based on measurements.

Page 15, line 31-32: This is only valid for shallow waters above the storm weather wave base.
Yes, but the Baltic Sea is relatively shallow.

Page 16, line 10-13: This is very interesting! Could these models predict particular microplastic sinks on the seafloor? To which water depth would storms affect the seafloor distribution of MPs?
Yes, such models should be applicable for this task. The model can predict potential sinks of MP, under the condition that material is available. We assumed a homogeneous distribution of MP over the entire Baltic Sea and we do not have river loads or beach accumulation (as a sink) taken into account. The model predicts areas which are sensitive to a potential deposition. The water depth affected by waves is half of the wavelength, which goes up to 130m in the Baltic Sea, but will strongly dependent on wind direction and especially fetch.

Model uncertainties of a storm and their influence on microplastics / sediment transport in the Baltic Sea

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Abstract. Microplastics (MP) are omnipresent in the aquatic environment where they pose a risk to ecosystem health and functioning. Little is, however, known about the concentration and transport patterns of this particulate contaminant. Measurement campaigns remain expensive and assessments of regional MP distributions need to rely on a limited number of samples. The prediction of potential MP sink regions in the sea would thus be beneficial for a better estimation of MP concentration levels and a better sampling design. Based on a sediment transport model, this study investigates the transport of different MP model particles, PET and PVC particles with simplified spherical sizes of 10 and 330 µm, under storm conditions. A storm event was chosen because extreme wave heights cause intense sediment erosion down to depths unaffected otherwise, and are therefore critical for determining accumulation regions. The calculation of metocean parameters for such extreme weather events is subject to uncertainties. These uncertainties originate from the unperfect knowledge of the initial conditions and lateral boundary conditions for regional models, which are necessary to be able to run a numerical model. Processes, which can be resolved by the model, are limited by the model's resolution. For those processes for which the model resolution is too coarse, parametrizations are used. This leads to additional uncertainty based on the model physics. This sensitivity study targets the propagation of uncertainty from the atmospheric conditions to MP erosion and deposition, on the basis of freely available models and data. We find that atmospheric conditions have a strong impact on the quantity of eroded and deposited material. Thus, even if the settling and resuspension properties of MP were known, a quantitative transport estimation by ocean models would still show considerable uncertainty due to the imperfect knowledge of atmospheric conditions. The uncertainty in the transport depends on the particle size and density, transport of the larger and denser plastic particles only takes place under storm conditions. Less uncertainty exists in the location of erosional and depositional areas, which seems to be mainly influenced by the bathymetry. We conclude, while quantitative model predictions of sedimentary MP concentrations in marine sediments are hampered by the uncertainty in the wind fields during storms, models can be a valuable tool to select sampling locations for sedimentary MP concentrations to support their empirical quantification. The purpose of this study is a support of the strategic planning of measurement campaigns, as the model predictions can be used to identify regions with larger net deposition after a specific storm event.

1 Introduction

The presence of MP particles has been proven in a variety of different ecosystems (e.g. Huerta Lwanga et al., 2016; Andrady, 2011). MP constitute potential transport vectors for toxic substances, both substituted chemicals during production and adsorbed environmental pollutants, which can be assimilated by aquatic organisms (Besseling et al., 2019). The littering of the environment with these synthetic particles foreign and incompatible to natural cycles is happening at an unprecedented rate and contributes to the degradation of ecosystem services worldwide (Watkins et al., 2017). The relevance of these particulate pollutants for specific ecosystems cannot, however, be assessed when drivers of their distribution are not understood and their current stocks remain unknown.

Currently, MP data collection from various environmental compartments is expensive and time consuming, consequential only small data sets are achievable. Here, numerical models known and vigorously applied in sediment transport studies (e.g. Sassi et al., 2015) can help to complement sparse measurements. For this purpose, an initial dataset is necessary to calibrate and validate the numerical models. The initial model setup can be applied as a support tool for measurement campaign planning, by identifying regions in which net deposition can be expected. This is the major purpose of this study.

Plastic denotes a wide range of different polymer types along with different density ranges. Among the most widely produced (PlasticsEurope, 2019) are polyvinylchloride (PVC) with a density of 1275 $\mathrm{kg\,m^{-3}}$ and polyethylene-terephthalate (PET) with 1400 $\mathrm{kg\,m^{-3}}$(Andrady and Neal, 2009), which were used as model particles in the present study.

During cyclone "‘Xaver"’ in October 2017, mean horizontal bottom water currents exceeded 0.5 $\mathrm{m\,s^{-1}}$ in the bottom water, e.g. in the Arkona Basin (Bunke et al., 2019). ~~It is assumed~~ We expect that significant transport and sorting of larger and denser plastic particles only takes place under such storm conditions. This assumption is justified in this study by a one month model run including storm and calm conditions. The interest of this study is the identification of potential areas of accumulation of MP particles to support the planning of measurement campaigns by identifying potential areas of interest, because we assume that a stock of high-density plastic particles exists in Baltic Sea sediments.

Extreme events have a strong impact on particle transport (e.g. Bartholomä et al., 2009). The idea that storm events determine the relocation of settled MP is supported by old knowledge from the amber hunting community. It is observed that only after strong wave and ocean current activity, amber is beach combed and jewelery hunting becomes profitable. Amber is a naturally occurring polymer with a density range of 1050-1150 $\mathrm{kg\,m^{-3}}$ (similar to MP) and is especially abundant in the Baltic Sea. It was produced a long time ago by the resin of trees which now form a standing stock on the Baltic Sea sea floor. In the laboratory measurements by Shields (Shields, 1936), amber was also taken into account. It was found that the initiation of motion of amber can be described by the Shields curve, comparable to that of sediments.

Chubarenko and Stepanova (2017) compared the transport behaviour of amber with the one of MP and found dimensionless critical bottom shear stresses close to the one represented by the Shields curve. They also found a variation depending on the plastic type and shape. Therefore, the Shields curve is adapted to calculate the critical shear stress.

A sediment transport model is applied in this study to simulate the transport of MP as suspended matter with sizes in the order of sand particles. Certain factors cannot be accounted for, such as plastic type and shape which can influence the critical bottom shear stress (Chubarenko and Stepanova, 2017; Enders et al., 2019) and settling velocity of particles (Khatmullina and Isachenko, 2017). Based on laboratory measurements using MP down to 0.4 mm in size, Waldschläger and Schüttrumpf (2019) calculated a sinking formula depending on the particle shape. For reasons of simplicity, the standard Stokes formula (Stokes, 1851) for spherical particles is used here.

Although the critical bottom shear stress and the settling velocity are assumed to strongly impact the uncertainty in the transport behaviour, this intial study focuses on a quantification of the metocean uncertainty in the transport behaviour. There are several other approaches to estimate the transport of MP, e.g. Ballent et al. (2013); Bagaev et al. (2017). These models are based on deterministic metocean products and models. Our objective is instead to assess whether relocation of MP particles during a single storm event is quantitatively predictable, or whether it is too sensitive to the meteorological uncertainties to allow for a sufficiently precise model estimation. If this uncertainty is too large, even a precise knowledge of a particle's sinking and erosion properties would not allow for an estimation of its transport.

A well-known method to quantify sensitivity to uncertainties in numerical models is the use of an ensemble approach. Ensemble forecasts are used in operational weather prediction since more than 25 years (Buizza, 2018) and were also successfully applied to different areas like, for example, in aviation (e.g. Osinski and Bouttier, 2018), for the energy sector (e.g. Taylor and Buizza, 2003) or in hydrology (e.g. Pappenberger et al., 2008). An application of ensemble forecasts to quantify the uncertainty in the morphological impact of storms was proposed by Baart et al. (2011). Osinski et al. (2016) applied a windstorm tracking algorithm onto the operational ensemble forecasts of the European Centre for Medium-Range Weather Forecasts (ECMWF) and demonstrated a strong variation of the track as well as of the damage potential of the different realizations of historical storm events in the ensemble members. This range of uncertainty should also be reflected in the uncertainty in the transport of suspended matter. An ensemble of 30 members, produced by a mesoscale atmospheric model in non-hydrostatic mode, is applied in the presented study to estimate these uncertainties in the transport behaviour of MP.

Existing studies on the transport of MP in the marine environment are mainly based on a particle tracking approach (e.g. Jalón-Rojas et al., 2019b; Liubartseva et al., 2018). Jalón-Rojas et al. (2019a) showed the importance of applying a 3-d model to estimate MP transports. This is the case in this study. An Eulerian approach was applied in our model, i.e. MP is stored as a concentration in grid cells and a bottom reservoir.

2 Data and Models

For our assessment, we applied a four-step model chain, as illustrated in Figure 1. Firstly, ensemble data based on stochastic perturbations were produced with the atmospheric model WRF-ARW to account for uncertainties in the representation of storm events. Secondly, the atmospheric fields were passed to the wind wave model WAVEWATCH III®. Thirdly, atmospheric and wave ensemble data were then applied to drive the regional ocean model GETM. Finally, a transport module in GETM simulated the transport of PET and PVC with particle sizes of 10 and 330 μm. The atmospheric model WRF-ARW was applied here to produce an ensemble hindcast of a storm surge event in the Baltic Sea and to provide the necessary forcing fields for the wave and the ocean model. The simulation period covered 1 January 2019 to 4 January 2019 UTC. This includes the storm

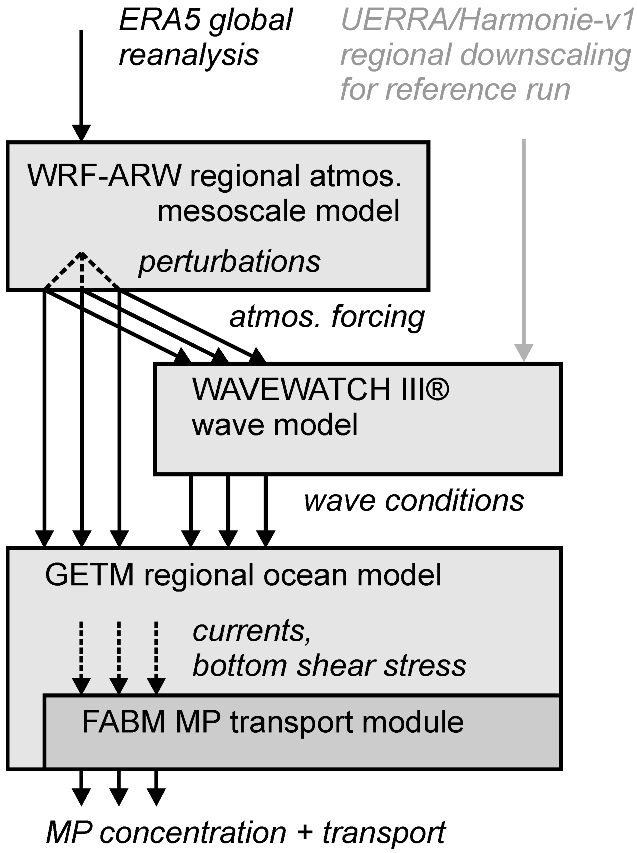

Figure 1. Schematic overview of the model chain used in this study

Alfrida[1] which moved across southern Sweden and especially hit the island of Gotland, where wind speeds of 27.5 $\mathrm{m\,s^{-1}}$ (10 Bft) were reached (The Local, 2019). Storms of this strength occur approximately two to three times per year in the Baltic Sea, but at different locations. WAVEWATCH III® (abbreviated as WWIII) was used to produce ensemble hindcasts of wave parameters based on the WRF-ARW output. GETM was driven by the ensemble hindcasts of the corresponding atmospheric and wave parameters from the unperturbed and perturbed model runs.

2.1 The atmospheric model WRF-ARW

The atmospheric mesoscale model WRF-ARW[2] (Skamarock et al., 2019) in version 4.1.1 was used in this study for ensemble hindcasting. A region slightly larger than the Baltic Sea is used with a horizontal resolution of about 0.063° and output was written every five minutes. Vertically, 89 pressure levels until 50 hPa were applied in accordance to levels 2 to 90 in the ERA5 reanalysis (Copernicus Climate Change Service (C3S), 2017). Initial and lateral boundary conditions originated from the ERA5

[1] e.g. look into the ECMWF Severe Event Catalogue: https://confluence.ecmwf.int/pages/viewpage.action?pageId=129123779 (last access: 02 April 2020)
[2] https://github.com/wrf-model/WRF/releases (last access: 14 March 2020)

reanalysis. Osinski and Radtke (2020) tested different ensemble generation strategies with WRF-ARW driven by ERA5 and compared the outcome with the uncertainty measure provided by the ERA5 reanalysis. As demonstrated in Osinski and Radtke (2020), stochastic perturbations, namely, stochastically perturbed parameterization tendencies (SPPT; Buizza et al., 1999) and stochastic kinetic energy backscatter (SKEB; Shutts, 2005), were used here to produce a small ensemble of 30 members to study the impact of the uncertainty in the atmospheric forcing on the transport patterns, which includes random perturbations of the lateral boundary conditions (Skamarock et al., 2019). Instead of validating the atmospheric data against observations, the wind data were validated indirectly by the wave model output. A visual comparison of the WRF-ARW wind fields against UERRA/HARMONIE-v1 and ERA5 data can be found in Osinski and Radtke (2020).

Sources of uncertainty in atmospheric model predictions originate from the initial conditions, in case of a regional model also from lateral boundary conditions and from the model physics. Osinski and Radtke (2020) compared different ensemble generation methods and proposed to use the ERA5 data from the Ensemble of Data Assimilations as initial conditions to allow for a spread already from the start of the simulation. The initial conditions in the presented study are based on the high resolution ERA5 reanalysis and the model approach includes perturbations of the model physics and the lateral boundary conditions. In contrast, the desired spread needs to develop in the model ensemble in the method chosen here. We chose this method to keep our results comparable to a potential future application in forecast mode. While we ran the model for a storm event in the past, the same could be done for a predicted storm, possibly based on a deterministic forecast product.

2.2 The wind wave model WAVEWATCH III®

Wave-induced bottom shear stress is an important driver for the resuspension of bottom sediments and potentially of high-density MP on the seafloor, as investigated in this study. To be able to prescribe wave parameters in high spatial and temporal resolution, the third generation spectral wind wave model WAVEWATCH III v6.07®[3] (Tolman, 1991; The WAVEWATCH III® Development Group (WW3DG), 2019) was applied in a 3-level one-way nested configuration. The model domain with the highest resolution is based on the same grid as in the GETM model (Gräwe et al., 2019). Dissipation and wind input were based on the formulation of Ardhuin et al. (2010) and the SHOWEX bottom friction scheme after Ardhuin et al. (2003) was applied. For the latter, a map of the D50 sediment grain size was prescribed based on EMODnet[4] data. The wave spectrum was discretized in the same way as in the ERA5 reanalysis with 24 directions starting at 7.5° with a 15° direction increment and 30 frequencies starting at 0.03453 Hz geometrically distributed with a step of 1.1. A setup with 0.1° resolution covering the North Sea and a small part of the eastern Atlantic ocean was used to produce boundary conditions for the Baltic Sea setup at the border with the North Sea. The 0.1° model was nested into a setup for the Atlantic ocean with 0.5° resolution. The GEBCO_2014 Grid in version 20150318[5] was used as bathymetry for the Atlantic and North Sea setups. The Baltic Sea setup had a resolution of one nautical mile with a bathymetry based on the work of Seifert et al. (2001). The 0.5° setup is driven by ERA5 winds and the ERA5 sea-ice cover fraction. For the 0.1° setup, UERRA/HARMONIE-v1 (Ridal et al., 2017) winds and the ERA5 sea

[3]https://github.com/NOAA-EMC/WW3 (last access: 14 March 2020)
[4]http://www.emodnet-geology.eu/ (last access: 14 March 2020)
[5]http://www.gebco.net (last access: 14 March 2020)

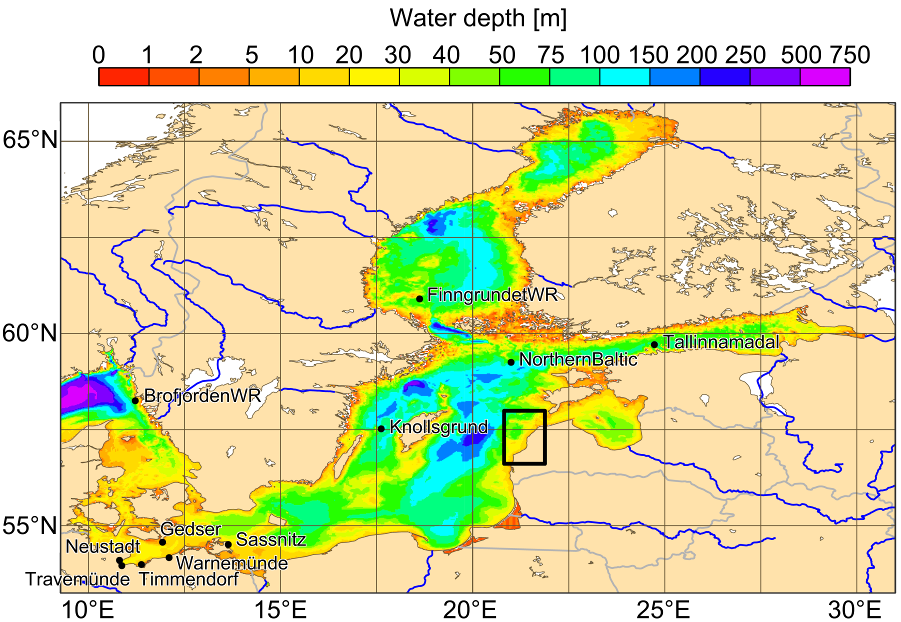

Figure 2. Bathymetry [m] of the 1 nautical mile WAVEWATCH III® setup. Black dots show stations for the validation of water level and significant wave height. The black rectangle shows the sub-region for plots of the transport simulation results.

ice cover fraction were used because of their higher spatial resolution. The Baltic Sea setup was driven by two datasets, the UERRA/HARMONIE-v1 wind for a reference simulation and the wind produced with the WRF-ARW wind ensemble for the MP ensemble simulations. Sea ice was taken from the Ostia reanalysis[6]. An obstruction grid based on the GSHHS (Wessel and Smith, 1996) coastline dataset has been generated with the gridgen software[7] to take unresolved orography into account.

Observation data from buoys available from the Copernicus Marine environment monitoring service[8] (CMEMS) were used for validation and calibration. A comparison with station data in Figure 3 shows a good agreement in the significant wave height as well as verification scores over January 2019 (Table 1). The spread in the ensemble is visible at all stations and is expected to provoke differences in the bottom shear stress leading to differences in the resuspension.

Waves affect the seafloor until a water depth of about half the wave length. The dominant wavelength in the Baltic Sea is between 20 m and 70 m and can reach up to 130 m (Kriaučiūnienė et al., 1961).

[6]http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001

[7]https://github.com/NOAA-EMC/gridgen (last access: 14 March 2020)

[8]http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=INSITU_BAL_NRT_OBSERVATIONS_013_032 (last access: 14 March 2020)

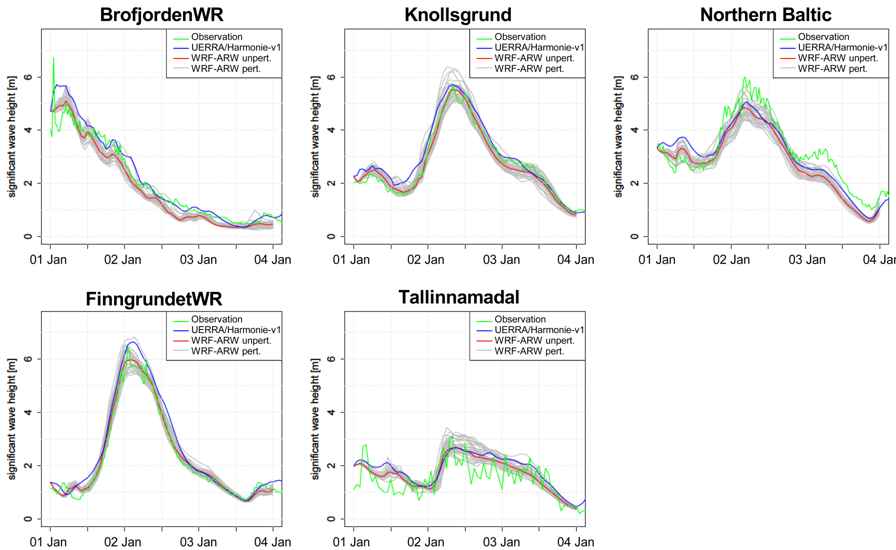

Figure 3. Significant wave height at five stations from the 1 nautical mile WAVEWATCH III® model run; wind data from UERRA/HARMONIE-v1, WRF-ARW unperturbed and thirty WRF-ARW members generated with stochastic perturbations.

Table 1. Verification scores – root mean square error (RMSE), scatter index (SI, Zambresky, 1989) and correlation (COR) – for significant wave height simulated by WAVEWATCH III® driven by UERRA/HARMONIE-v1 for January 2019

Station	Bias [m]	RMSE	SI [%]	COR
BrofjordenWR	0.08	0.26	22.64	0.96
Knollsgrund	-0.02	0.20	15.25	0.98
Northern Baltic	-0.11	0.29	18.33	0.96
FinngrundetWR	0.01	0.24	18.05	0.98
Tallinnamadal	0.22	0.41	61.75	0.85

2.3 The regional ocean model GETM

GETM (General Estuarine Transport Model; Burchard and Bolding, 2002; Hofmeister et al., 2010; Klingbeil and Burchard, 2013) is an ocean model specifically designed for the coastal ocean (see review by Klingbeil et al. (2018)). For the present study, GETM was applied to the Baltic Sea with the model setup of Gräwe et al. (2019), on the same 1 nautical mile grid as the innermost WAVEWATCH III® nest. The model domain is shown in Figure 2. The original setup was extended by a coupling to FABM (Framework for Aquatic Biogeochemical Models; Bruggeman and Bolding, 2014) to consider sediment and MP. For an accurate 3-d transport of these quantities, GETM provides high-order advection schemes with reduced spu-

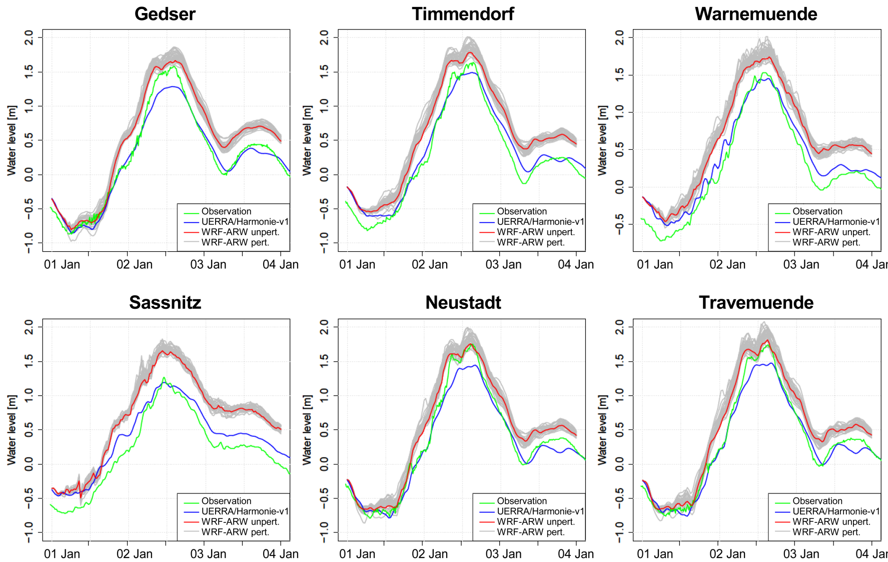

Figure 4. Water level at six stations with the 1 nautical mile GETM model; atmospheric data from UERRA/HARMONIE-v1, WRF-ARW unperturbed and thirty WRF-ARW members generated with stochastic perturbations.

rious mixing (Klingbeil et al., 2014), a state-of-the-art second-moment turbulence closure for vertical mixing from GOTM (General Ocean Turbulence Model; Burchard et al., 1999; Umlauf and Burchard, 2005) and flow-dependent lateral mixing (Smagorinsky, 1963). Numerical mixing leads to an unrealistically high diffusion of transported concentrations, reducing the peak concentrations and overestimating the area in which tracers spread. The accuracy of the model is further increased by adaptive vertical coordinates that guarantee an optimal vertical mesh aligned to the dynamic boundary layers and to the stratified interior (Gräwe et al., 2015). Air-sea fluxes were calculated from the meteorological data provided by the atmospheric model according to the bulk formulas of Kondo (1975). Based on the data provided by the wave model, GETM calculated the mean and maximum combined wave- and current-induced bed stress during a wave cycle. The latter was used in FABM for the erosion of sediment and MP from the bottom pool (see next section). ~~The initial state of the hydrodynamic model used for this study~~ A realistic initial state as starting condition for the hydrodynamical model was obtained by prolonging the simulations from Gräwe et al. (2019) with the atmospheric dataset UERRA/HARMONIE-v1. Further details about open boundary conditions and river discharge can be found in Gräwe et al. (2019).

A detailed validation of the model setup can be found in Gräwe et al. (2019) and Radtke et al. (submitted). For demonstration purposes, only the spread in sea surface elevation due to the different atmospheric forcing sets is shown here (Figure 4). A verification of the water level at different stations from EMODnet[9] showed a satisfactory performance for both forcing datasets, WRF-ARW and UERRA/HARMONIE-v1. A large spread is also visible in the water level, especially at the peak of the surge.

[9]https://www.emodnet-physics.eu/ (last access: 14 March 2020)

The ensemble generation in the GETM model in this study is only based on the ensemble hindcasts of the atmospheric and wave parameters driving the model runs. Brankart et al. (2015) showed that stochastic perturbations in the ocean model are also important for uncertainty estimation. The uncertainty in the ocean currents could therefore be underestimated.

2.4 Microplastics representation

In GETM and FABM sediment and MP are represented as Eulerian concentration fields. GETM simulated the 3-d transport of the pelagic concentrations, whereas the FABM model calculated the interaction with the corresponding bottom pools due to erosion and deposition and provides settling velocities to GETM. In FABM, a model for non-cohesive sediments (see Sassi et al., 2015) was used to calculate erosion, settling and deposition of both sediment and MP. The different transport was caused by the lower densities of MP, which, however, exceed that of the ambient water, i.e. we only considered sinking particles. This study focuses on model MP of sizes and densities as reported by Stuparu et al. (2015): 10 and 330 μm for both PVC with a density of 1275 $kg\,m^{-3}$ and PET with 1400 $kg\,m^{-3}$. To study the impact of density and particle size on the uncertainty in the transport, additional densities of 1100, 1200 and 1300 $kg\,m^{-3}$ and particle sizes of 200, 250, 300 and 350 μm were tested. As our main focus is a support of measurement campaigns, and larger particles are easier to sample, our major foucs is on particles above 300 μm.

The simulations in this study started from homogenous bottom pools of 1 $kg\,m^{-2}$ as a purely hypothetical reference value and zero suspended material in the water column. Rivers and open boundaries were assumed to not import material into the model domain. MP transport in the model is affected by wave activity and different types of currents. Tidal currents are represented, but play a role in the Danish Straits only but the interior of the Baltic Sea is non-tidal. Turbidity currents cannot be represented in our model since the concentration of suspended matter has no influence on seawater density in the model. Thermohaline circulation, on the other hand, is fully taken into account.

3 Results and discussion

3.1 MP relocation and its uncertainty

After a 2-days storm surge event, a rearrangement of particles could be observed in the model with some locations dominated by erosion and others by deposition. This can be seen in the change of amount of MP stored in the bottom pool (PET and PVC with a diameter of 330 μm). To demonstrate the range of uncertainty in the transported amount of MP, two different grid cells in the Gotland basin were selected (Figure 5), 57.69°N 21.35°E (Figure 6a–b) as a net erosion location and 57.66°N 21.32°E (Figure 6c–d) as a net deposition location. Relative to the initial concentration, net erosion varied in the range of 39–72% for PVC and 16–45% for PET. Net accumulation varied between -13–38% for PVC and 22–34% for PET. That is, for PVC in the deposition grid cell (Figure 6c) , in some ensemble members weak erosion is visible while the majority of the ensemble members show net deposition at this location. For the denser PET, the uncertainty range is smaller than for PVC, implying that its transport is less sensitive to uncertainties in the wind fields and more predictable. Still, the transported amount even in this particle class varies by around a factor of two between realizations, showing that a realistic quantitative estimation of MP transport is impossible in ocean circulation models even if the precise sinking, settling and resuspension properties of the MP particles were perfectly known.

3.2 Erosion and deposition areas

Now we consider the spatial patterns where erosion and sedimentation take place. The spatial pattern in four selected ensemble members and the deterministic runs is shown in Figure 7. We chose four members with a considerable spread in the simulated wave height (Fig. 7g). The overall spatial pattern is very similar between the different realizations. The main impact of the metocean uncertainty lies in the amount of the transported material. The perturbations of the atmospheric model also produces deviations in the track of the storm between ensemble members which is impacting the direction of ocean waves and currents and in this way the direction into which the bottom shear stresses are directed. These findings indicate that the bathymetry has a predominant impact on the region where erosion and deposition take place, as the locations are insensitive to changes in the track of the storm. For this specific storm surge event and selected region, net deposition took place on the south western sides, net erosion on the north eastern sides of ridges. Model MP of 330 μm in deeper regions, below 50 m, stayed completely unaffected. It is well known that water depth plays a major role for sediment erosion by waves, since deep-water waves (wavelength much shorter than the water depth) show an exponential attenuation in their velocity amplitude with depth (e.g., Kundu and Cohen, 2001). Our findings suggest that this causes stability in spatial patterns of MP transport against changes in the wind forcing and makes the areas where erosion and deposition take place during a specific storm event predictable.

The uncertainty ranges of the spatial pattern of the model results were further investigated by means of the ensemble statistics composed of the mean, minimum and maximum of each individual grid cell of all ensemble members (Figure 8). The net effect, whether the location was charaterized by deposition or erosion, appeared largely consistent for the entire uncertainty range. Only few locations showed deviations from this finding where some ensemble members shifted between weak erosional and depositional net effects. The larger extent of the erosional areas was due to more severe representations of the storm event in some ensemble members. Overall, these findings suggest stability in spatial patterns of MP transport against changes in the wind forcing. Areas of erosion and deposition during a specific storm event are predictable.

3.3 Effect of particle size on transport uncertainty

Next, we investigate the effect of particle size on the uncertainty in the transport, reducing the size of the particles to 10 μm. The small PET particles show a net erosion almost across the whole model domain due to slower resettlement. That is, they are kept in the water column even after 1.5 days after the storm, at the end of the simulation. This partly explains the large difference between the ensemble minimum and maximum (Figure 9b,c): When sedimentation takes longer, quantitative differences in erosion strength will result in larger transport deviations, since the material can be advected further. This finding is also supported by theory on sediment transport: smaller particles (if unconsolidated) go into suspension under lower shear stress levels and respectively require calmer metocean conditions to deposit. Thus, the uncertainty in MP transport appears to strongly depend on particle diameter and density.

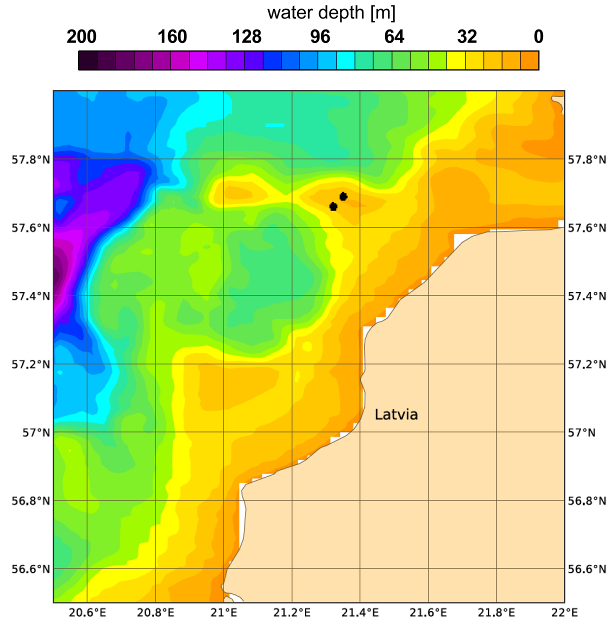

Figure 5. Bathymetry [m] of the subregion for which the model results are presented. Black dots indicate the location of two selected grid cells for later reference.

To find out whether this is a systematic effect, the uncertainties in the amount of transported material dependent on the particle properties size and density were investigated in more detail. These relationships were studied based on sensitivity runs with thirty ensemble members for (1) PVC with grain sizes of 200, 250, 300 and 350 μm as well as (2) 330 μm MP of different densities of 1100, 1200, 1300 and 1400 $kg\,m^{-3}$ (Figure 10a,b). The seafloor concentrations at the end of the model run deviate between the ensemble members. Relative deviations from the ensemble mean were calculated. Figure 10c,d shows that with decreasing density and/or particle diameter, the relative uncertainty is increasing, with the exception of the 1100 μm MP class showing a smaller uncertainty since it is almost completely resuspended at the chosen location. We conclude, that the uncertainty of the amount of transported material on the seafloor at a specific time depends strongly on the properties of the transported material. The application of an ensemble approach (using more than one model realization to predict transport pathways) is therefore especially important if finer and lighter material shall be represented in future model applications.

3.4 Pathways of atmospheric uncertainty propagation

In the following, the mechanism by which the atmospheric uncertainty affects the MP transport is identified. In our model, this can be caused (a) by influencing the wave height, which changes the bottom shear stress and therefore MP mobilization or (b) by directly affecting the ocean circulation through e.g. momentum input, thereby influencing both mobilization and transport. We focused on these two major pathways and attempted to distinguish their influence. The possibility of interlinkage by wave-current interaction is neglected in the present model cascade. To estimate the respective uncertainties of MP transport of the two

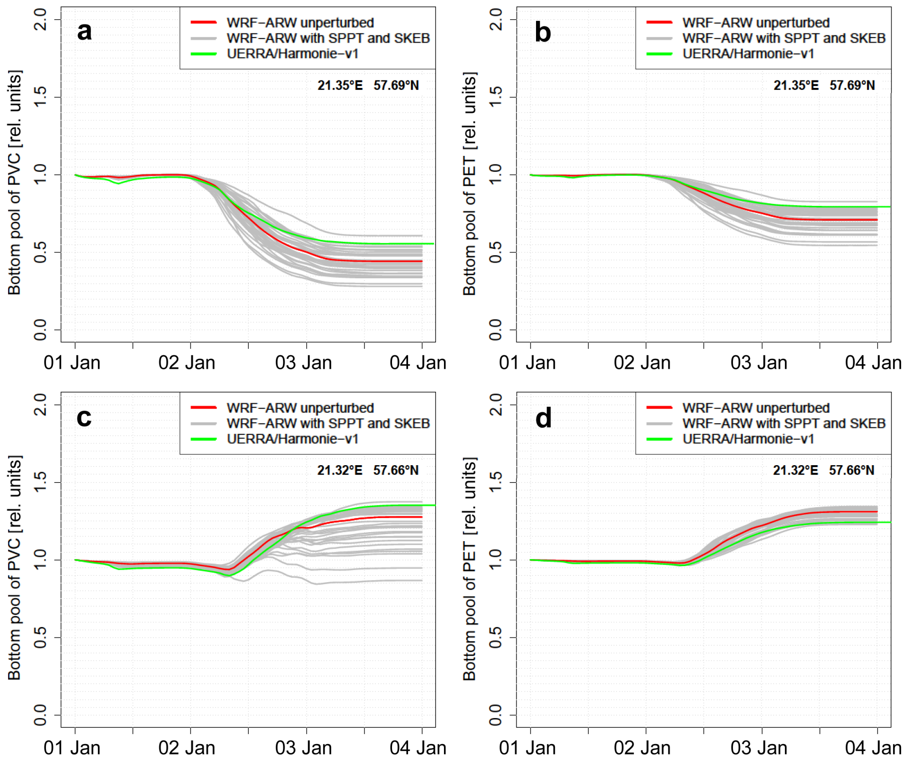

Figure 6. Changing bottom concentration of PVC (left panels) and PET (right panels) particles with 330 µm diameter in two grid cells indicated in Figure 5, relative to the initial concentration. The different curves show thirty perturbed runs and one unperturbed run with WRF atmospheric forcing and another simulation with UERRA/HARMONIE-v1 forcing. Panels (a) and (b) show a grid cell predominated by processes of net erosion, whereas (c) and (d) show a cell with net sedimentation.

mentioned pathways, an ensemble driven with the wave data from the unperturbed WRF-ARW run with the perturbed WRF-ARW atmospheric forcing and vice-versa with perturbed wave data and unperturbed atmospheric data has been conducted. By comparing (Figure 11) the outcome with the original ensemble, where both perturbed atmospheric and wave data were used, it can be seen that the impact of the wave field depends on the properties of the transported material. The lighter or smaller MP, the more important is the impact of the wave uncertainty on the amount of transported material. For denser and larger MP, the uncertainty in the direct effect of atmospheric uncertainty on hydrodynamics is predominant.

3.5 Importance of storms for MP transport

Higher-density MP of about 300 µm diameter were only transported under severe storm conditions as demonstrated in Figure 12. The continuation of the simulation for the rest of January 2019 caused nearly no further erosion or deposition. This confirms the assumption of the importance of extreme events for MP transport, which complicates its direct empirical determination. Budget methods will be required to empirically determine quantities of transported MP. A budget method relates

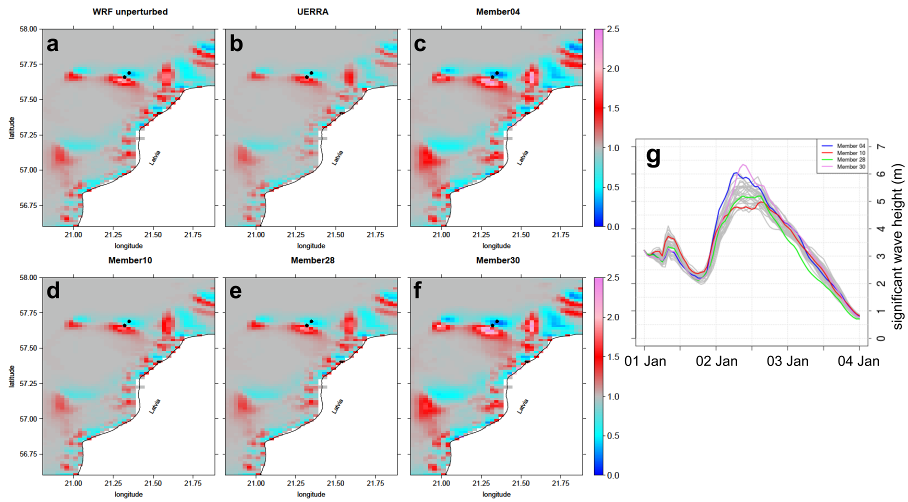

Figure 7. Seabed concentration of PVC with 330 µm at 2019-01-03 12UTC, i.e. after the storm surge event in the model, relative to the homogenous initial concentration. Individual panels show the unperturbed WRF run (a), the model driven by UERRA/HARMONIE-v1 (b) and four selected WRF ensemble members (c–f). Dots show the location of the grid cells selected in Figure 6. (g) Timeseries of the significant wave height [m] at the position of the dot in the other figures with net erosion.

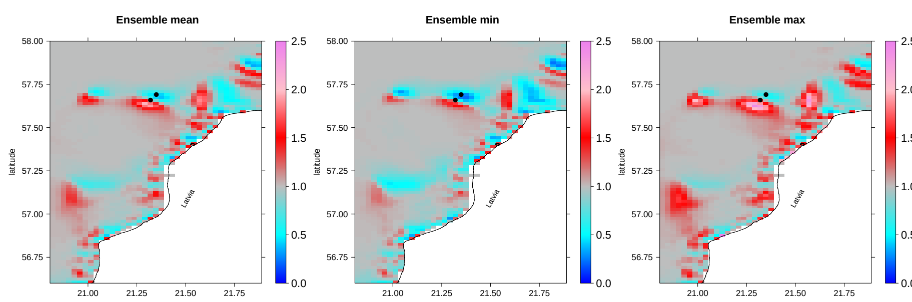

Figure 8. Ensemble mean, minimum and maximum of the seabed concentration of PVC with 330 µm at 2019-01-03 12UTC, i.e. after the storm surge event in the model, relative to the homogenous initial concentration. Dots show the location of the grid cells selected in Figure 6.

(a) input and (b) output of a quantity to (c) changes in its mass, e.g. inside an area of interest. If two of the three values are known, the third one can be determined. That is, transport rates might be more reliably derived from observed amounts before and after storm events than by multiplying abundances of suspended MP with instantaneous volume transports, both of which might show strong temporal variation during extreme weather conditions.

3.6 Similarities between MP and sediment transport

The finding that spatial patterns of MP can be reliably predicted by ocean models, while the quantitative estimation of MP was prone to considerable uncertainties shows that additional approaches are required for a more reliable estimation of large-scale

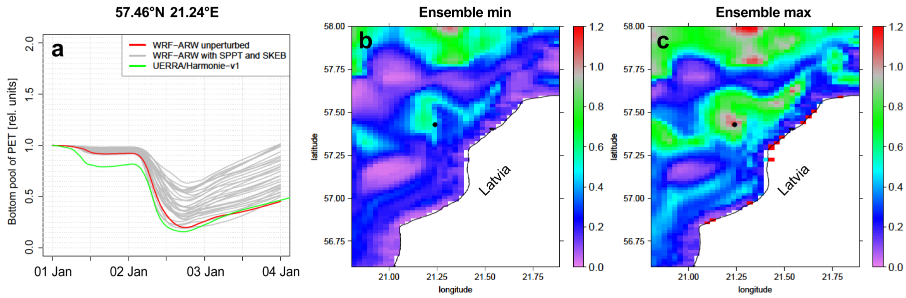

Figure 9. (a) Change of the seafloor concentration of PET particles with 10 µm diameter in one selected grid cell in thirty perturbed runs and one unperturbed run with WRF forcing and one run with UERRA/HARMONIE-v1 forcing. (b) Ensemble minimum and (c) ensemble maximum at 2019-01-04 00UTC (at the end of the simulation). All concentrations relative to the homogenous initial concentration. The black dots show the location for the time series plots.

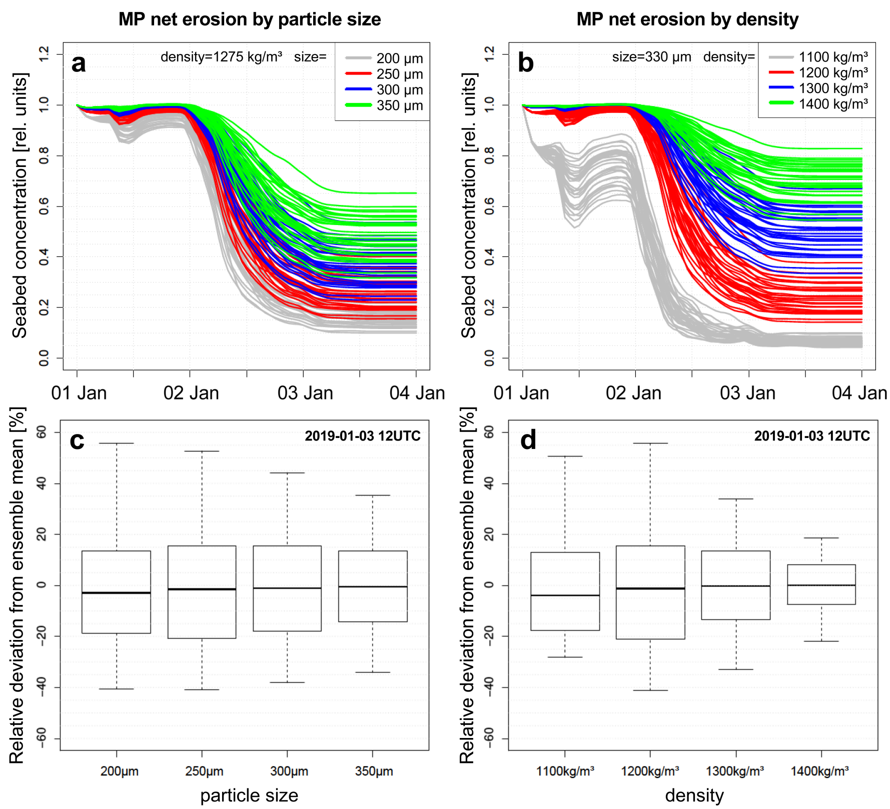

Figure 10. Time series of thirty ensemble members at 57.69°N 21.35°E for (a) different MP sizes and (b) different MP densities. (c,d) Box-and-whisker plots show the uncertainty in the concentration of material on the seabed, expressed as a relative deviation of the individual ensemble members from the ensemble mean.

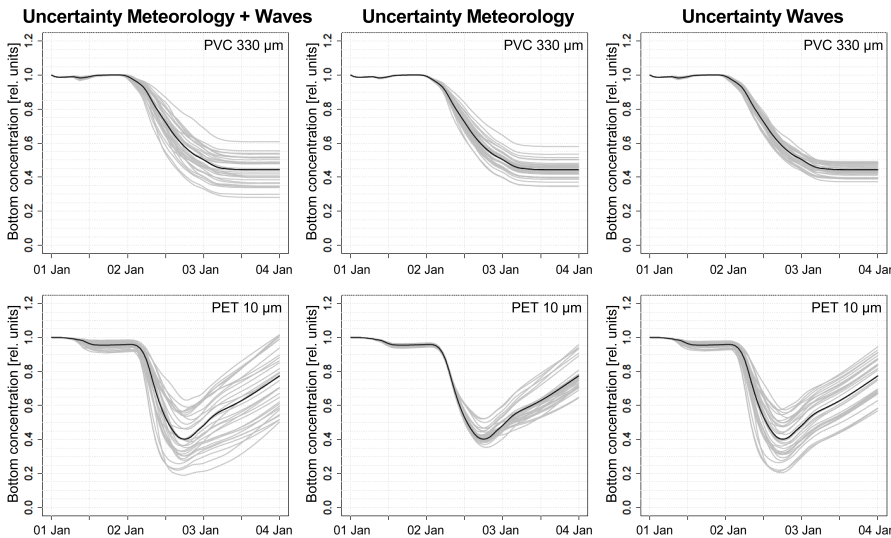

Figure 11. Spread of runs with varying atmospheric forcing and/or varying wave forcing, for PVC with 330 µm size (upper panels) and PET with 10 µm size (lower panels). Bottom concentration at 57.69°N 21.35°E (see Figure 9) relative to the initial value.

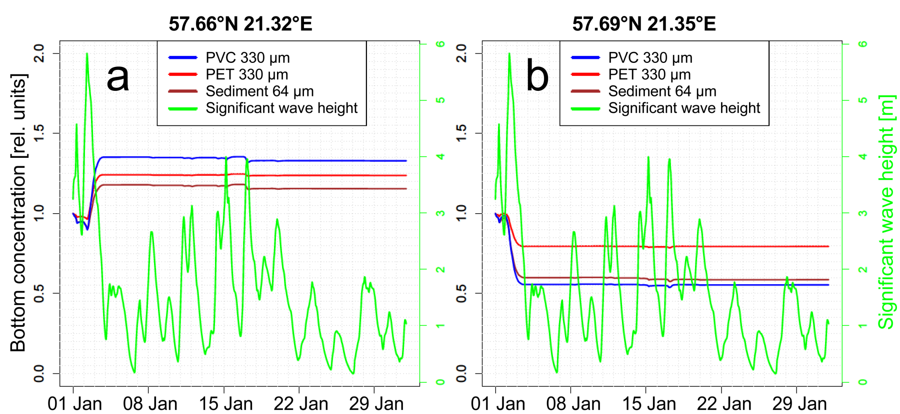

Figure 12. Evolution of the amount of PET and PVC with 330 µm and sediment with 64 µm on the sea floor during January 2019, starting from initial amount of 1 $\mathrm{kg\,m^{-2}}$, at two grid cells, a) with net deposition and b) with net erosion.

MP concentration levels. Here, the recently found MP-sediment proxy postulated by Enders et al. (2019) which is based on correlations between certain high-density polymer size fractions ($> 1000\ \mathrm{kg\,m^{-3}}$, $> 500\ \mathrm{\mu m}$) and sediment grain size fractions, would be an achievable method. Estimations of MP levels can be based on a relatively small in-situ data set and extrapolated to larger spatial scales by using the MP-sediment correlates. Lower densities of MP (1000 - 1600 $\mathrm{kg\,m^{-3}}$) compared to sediments (quartz: 2650 $\mathrm{kg\,m^{-3}}$) are offset by a larger size. This relationship was explained by comparable threshold bed shear stresses, and thus erosion rates, between these size fractions, which appeared to be the predominant mechanism determining the sorting

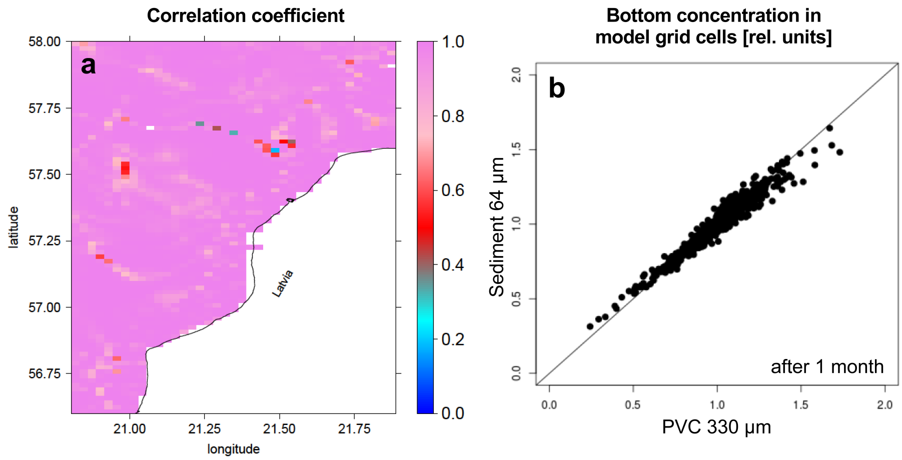

Figure 13. (a) Pearson correlation between the time series of bottom concentrations of PVC with 330 µm and sediment with 64 µm for January 2019. (b) Scatter plot of bottom concentrations after the 1-month simulation. Concentrations are given relative to the homogenous initial concentration.

in the described study area (Warnow estuary, Baltic Sea, Germany, (Enders et al., 2019)). Although the MP size ranges covered in the present study were below the ones investigated by Enders et al. (2019), it is assumed that similar patterns can be found for smaller size ranges. Indeed, in the present study, after the storm surge event, model PVC of 330 µm co-occurred with sediment grains of 64 µm in size, as apparent by the high correlation coefficient shown in Figure 13. This correlation is found to be largely explained by similar erosion rates (Figure 12b), whereas bottom concentrations predominantly determined by deposition are also influenced by the settling velocity of particles and thus slightly differ (higher amounts of PVC). It is thus expected that areas largely influenced by the settling of MP show a larger difference in ~~size~~ the expected MP-sediment size relation than described by the current MP-sediment proxy. For instance, larger (and/ or heavier, such as PET) MP particles than 330 µm PVC would be closer to the deposition rate of sediment grains of 64 µm (Figure 12a). Existing maps of sediment substrate type, which typically differentiate between median grain sizes above and below 63 µm (e.g., EMODnet, 2020), may therefore also provide information about MP concentrations to be expected. However, as this investigation is purely based on our model results with the above-discussed uncertainties, in-situ measurements are inevitable to further research the influences on this MP-sediment proxy.

4 Conclusions

A storm surge event in the Baltic Sea in January 2019 has been hindcasted by a four-step ~~model chain. A homogeneous distribution over the entire Baltic Sea was assumed due to a lack of knowledge about the real initial distribution. The model chain~~ probabilistic model chain started from an homogeneous initial MP distribution. The model validation showed a good performance in water level and significant wave height compared to different station data.

~~The ensemble approach showed a~~ A strong variation in the amount of transported MP between ensemble members ~~. This was found.~~ It illustrates that quantitative modelling of MP transport during storm events exhibits substantial uncertainty already because ~~the~~ of uncertainties in meteorological forcing fields (e.g. wind speeds)~~are imprecisely known~~. A test with different particle sizes and densities showed a dependence of the uncertainty in the transport on the particle properties. The impact of the metocean uncertainty on sediment and MP transport increases with decreasing particle density and/or size.

The spatial distribution pattern where material was eroded or accumulated in the model runs was stable against the atmospheric perturbations~~. This illustrates~~ , illustrating the capability of a numerical model to identify regions of interest where seafloor samplings of MP concentrations are promising~~after the occurrence of a storm~~.

The demonstrated procedure could also be applied in forecast mode, by exchanging the ERA5 reanalysis data used in this study by, for example, the freely availabe GFS forecasts[10]. As a synoptic scale winter storm event is well predictable in the medium-range (3-5 days), this would allow to produce ensemble simulations of MP transport a couple of days in advance to identify sampling regions, as a strategic support tool for measurement campaigns. ~~As strong storm events occur infrequently, there is a good chance to provide them to sampling campaign planners in time, which means before the next event that could be able to perturb the relocation patterns again.~~ The impact of the uncertainty from the lack of knowledge of settling velocities and critical bottom shear stresses would then have to be taken into account. One idea to reduce the necessary computational resources is a clustering of the atmospheric ensemble data and by driving the rest of the model chain (wave and ocean model) by a reduced set of representative ensemble members.

As ~~the spatial pattern under severe storm conditions is not strongly affected by~~ a consequence of the insensitive of the location of erosional and depositional areas to the uncertainty in the metocean forcing ~~, and~~ and a substantially smaller transport during moderate conditions~~can be assumed to be substantially smaller~~, this study indicates that it would be in principle possible to construct a map of the spatial distribution of high density MP particles in the Baltic Sea using long model runs containing several storm events. ~~The presented study investigates the effect of~~ Differences between storm events might be larger than the uncertainty in ~~the representation of a single storm~~ a single event. To get a more general picture of erosional and depositional regions in the Baltic Sea, other storm events with different tracks have also to be taken into account. ~~Also, the spatial pattern and the quantities of MP input, e.g. from river discharge, would need to be known.~~

The demonstrated ensemble approach can also be useful for other applications like, e.g., in the maritime transport sector. It could help to predict after a strong storm event whether a safe entering of a harbour by big vessels is still possible or whether the morphodynamic changes are so strong that dredging would be necessary.

Code and data availability. The WRF source code is available from https://github.com/wrf-model/WRF/releases, the WAVEWATCH III® from https://github.com/NOAA-EMC/WW3 and the GETM code from https://www.io-warnemuende.de/getm.html. ERA5 and the UERRA/HARMONIE-v1 reanalysis can be retrieved from the Climate data store at https://cds.climate.copernicus.eu.

[10]https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php (last access: 14 March 2020)

Sample availability. The demonstrated model results can be requested by contacting the corresponding author.

Appendix A: Mathematical description of the particle sinking and erosion model

Sinking velocity of the particles is initially calculated by the Stokes formula,

$$w_{Stokes} = \frac{gD^2}{18\nu}\frac{\rho_p - \rho_w}{\rho_w}, \tag{A1}$$

where g is the gravitational acceleration, D is the particle diameter, ν is the kinematic viscosity of water, and ρ_p and ρ_w are the densities of the particle and the water. To correct for larger particles whose sinking velocity would be overestimated by the Stokes formula, a Newtonian correction is applied by an iterative algorithm:

- A Reynolds number is calculated as $Re = 0.64 w_{sink} D/\nu$.
- A relative drag coefficient is derived from this Reynolds number as $C_D = 18.5/Re^{0.6}$ following Perry and Chilton as cited by Khalaf (2009).
- The updated velocity is calculated as $w_{sink} = \sqrt{\frac{4gD}{3C_D}\frac{\rho_p-\rho_w}{\rho_w}}$

which can be understood as a weighted geometric mean between the two velocities w_{Stokes} and ν/D. This correction makes large particles sink slower than the Stokes formula suggests. We, however, erroneously applied the correction also to the small particles where it resulted in an undesired upward correction. This has no effect on particle erosion but accelerates redeposition, which may even lead to an underestimation of the influence of meteorological uncertainty for the small particles in our study.

Erosion takes place when the actual shear stress exceeds the critical shear stress. To determine the critical shear stress, we follow the Shields curve in its version which was corrected by Soulsby (1997). First, we calculate the dimensionless particle diameter D_*, which relates the particle diameter D to a viscosity-determined length scale, following Rijn (1984):

$$D_* = \sqrt{3}\frac{g}{\nu^2}\frac{\rho_p - \rho_w}{\rho_w}D, \tag{A2}$$

where ν is the kinematic viscosity of water, ρ_p is the particle density and ρ_w is the water density. Then we calculate the critical shields parameter for non-cohesive grains, θ_{cr} (also dimensionless), following Soulsby (1997) as cited by Ziervogel and Bohling (2003),

$$\theta_{cr} = \frac{0.3}{1+1.2D_*} + 0.055 * (1 - e^{-0.02D_*}). \tag{A3}$$

The critical shear stress can then be calculated as

$$\tau_{cr} = gD(\rho_p - \rho_w)\theta_{cr}. \tag{A4}$$

diameter (μm)	density (kg m^{-3})	sinking velocity (mm s^{-1})	critical shear stress (N m^{-2})
10	1275	0.15	0.006210895
330	1275	8.14	0.045142586
10	1400	0.20	0.009277999
330	1400	10.98	0.062337737

Table A1. Sinking velocities and critical shear stress in the model at 10°C.

The actual shear stress is calculated from the wave-induced and the current-induced shear stress, τ_w and τ_c. The current-induced shear stress itself, however, is also modified by the wave field, as it changes the bottom drag coefficient according to the DATA2 formula given by Soulsby (1997),

$$\tau_m = \left(1 + 1.2\left(\frac{\tau_w}{\tau_c + \tau_w}\right)^{3.2}\right)\tau_c\,, \tag{A5}$$

where τ_c is the shear stress induced by the current in the absence of waves. Both of them are combined depending on the angle α between currents and waves,

$$\tau^2 = \tau_w^2 + \tau_m^2 + 2\tau_w\tau_m\cos(\alpha)\,. \tag{A6}$$

If the actual shear stress exceeds the critical one, the deposited material gets resuspended with first-order kinetics, i.e. proportional to its mass in the sediment pool.

The actual values for sinking velocities and critical stresses depend on temperature since it influences sea water viscosity. Values for 10°C are presented in Table A1.

Competing interests. The authors declare that there is no conflict of interest.

Acknowledgements. This study was financed by the Bonus Micropoll project, which has received funding from BONUS (Art 185), funded jointly by the EU and Baltic Sea national funding institutions. K. Klingbeil acknowledges project M5 (Reducing spurious diapycnal mixing in ocean models) of the Collaborative Research Centre TRR 181 "Energy Transfer in Atmosphere and Ocean" (project 274762653) funded by the German Research Foundation (DFG). For the simulations, computing resources at the North German Supercomputing Alliance (HLRN) were consumed. Observational data originate from the E.U. Copernicus Marine Service Information. The simulations in this study were generated using Copernicus Climate Change Service Information (2018/2019). The research and work leading to the UERRA data set used in this study has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement № 607193. We would like to thank the WRF and WAVEWATCH III® developers for providing their models over Github.

References

Andrady, A. L.: Microplastics in the marine environment, Marine Pollution Bulletin, 62, 1596 – 1605, https://doi.org/https://doi.org/10.1016/j.marpolbul.2011.05.030, http://www.sciencedirect.com/science/article/pii/S0025326X11003055, 2011.

Andrady, A. L. and Neal, M. A.: Applications and societal benefits of plastics., Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 364, 1977–84, 2009.

Ardhuin, F., H C Herbers, T., O'Reilly, W., and Jessen, P.: Swell Transformation across the Continental Shelf. Part I: Attenuation and Directional Broadening, Journal of Physical Oceanography, 33, 1921, https://doi.org/10.1175/1520-0485(2003)033<1921:STATCS>2.0.CO;2, 2003.

Ardhuin, F., Rogers, E., Babanin, A. V., Filipot, J.-F., Magne, R., Roland, A., van der Westhuysen, A., Queffeulou, P., Lefevre, J.-M., Aouf, L., and Collard, F.: Semiempirical Dissipation Source Functions for Ocean Waves. Part I: Definition, Calibration, and Validation, Journal of Physical Oceanography, 40, 1917–1941, https://doi.org/10.1175/2010JPO4324.1, https://doi.org/10.1175/2010JPO4324.1, 2010.

Baart, F., van Gelder, P. H. A. J. M., and van Koningsveld, M.: Confidence in real-time forecasting of morphological storm impacts, Journal of Coastal Research, pp. 1835–1839, http://www.jstor.org/stable/26482494, 2011.

Bagaev, A., Mizyuk, A., Khatmullina, L., Isachenko, I., and Chubarenko, I.: Anthropogenic fibres in the Baltic Sea water column: Field data, laboratory and numerical testing of their motion, Science of The Total Environment, 599–600, 560 – 571, https://doi.org/10.1016/j.scitotenv.2017.04.185, 2017.

Ballent, A., Pando, S., Purser, A., Juliano, M. F., and Thomsen, L.: Modelled transport of benthic marine microplastic pollution in the Nazaré Canyon, Biogeosciences, 10, 7957–7970, https://doi.org/10.5194/bg-10-7957-2013, https://bg.copernicus.org/articles/10/7957/2013/, 2013.

Bartholomä, A., Kubicki, A., Badewien, T. H., and Flemming, B. W.: Suspended sediment transport in the German Wadden Sea–seasonal variations and extreme events, Ocean Dynamics, 59, 213–225, https://doi.org/10.1007/s10236-009-0193-6, 2009.

Besseling, E., Redondo-Hasselerharm, P., Foekema, E. M., and Koelmans, A. A.: Quantifying ecological risks of aquatic micro- and nanoplastic, Critical Reviews in Environmental Science and Technology, 49, 32–80, https://doi.org/10.1080/10643389.2018.1531688, https://doi.org/10.1080/10643389.2018.1531688, 2019.

Brankart, J.-M., Candille, G., Garnier, F., Calone, C., Melet, A., Bouttier, P.-A., Brasseur, P., and Verron, J.: A generic approach to explicit simulation of uncertainty in the NEMO ocean model, Geoscientific Model Development, 8, 1285–1297, https://doi.org/10.5194/gmd-8-1285-2015, https://www.geosci-model-dev.net/8/1285/2015/, 2015.

Bruggeman, J. and Bolding, K.: A general framework for aquatic biogeochemical models, Environmental Modelling & Software, 61, 249–265, https://doi.org/10.1016/j.envsoft.2014.04.002, 2014.

Buizza, R.: Introduction to the special issue on "25 years of ensemble forecasting", Quarterly Journal of the Royal Meteorological Society, 0, https://doi.org/10.1002/qj.3370, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.3370, 2018.

Buizza, R., Milleer, M., and Palmer, T. N.: Stochastic representation of model uncertainties in the ECMWF ensemble prediction system, Quarterly Journal of the Royal Meteorological Society, 125, 2887–2908, https://doi.org/10.1002/qj.49712556006, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.49712556006, 1999.

Bunke, D., Leipe, T., Moros, M., Morys, C., Tauber, F., Virtasalo, J. J., Forster, S., and Arz, H. W.: Natural and Anthropogenic Sediment Mixing Processes in the South-Western Baltic Sea, Frontiers in Marine Science, 6, https://doi.org/10.3389/fmars.2019.00677, https://www.frontiersin.org/articles/10.3389/fmars.2019.00677/full, 2019.

Burchard, H. and Bolding, K.: GETM – a General Estuarine Transport Model. Scientific Documentation, Tech. Rep. EUR 20253 EN, JRC23237, European Commission, http://publications.jrc.ec.europa.eu/repository/handle/JRC23237, 2002.

Burchard, H., Bolding, K., and Villarreal, M. R.: GOTM – a General Ocean Turbulence Model. Theory, implementation and test cases, Tech. Rep. EUR 18745 EN, European Commission, 1999.

Chubarenko, I. and Stepanova, N.: Microplastics in sea coastal zone: Lessons learned from the Baltic amber, Environmental Pollution, 224, 243 – 254, https://doi.org/https://doi.org/10.1016/j.envpol.2017.01.085, http://www.sciencedirect.com/science/article/pii/S0269749116316402, 2017.

Copernicus Climate Change Service (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), accessed on 26th march 2019, https://cds.climate.copernicus.eu/cdsapp#!/home, 2017.

EMODnet: Map viewer | Geology - seabed substrate, https://www.emodnet-geology.eu/map-viewer/?p=seabed_substrate, 2020.

Enders, K., Käppler, A., Biniasch, O., Feldens, P., Stollberg, N., Lange, X., Fischer, D., Eichhorn, K.-J., Pollehne, F., Oberbeckmann, S., and Labrenz, M.: Tracing microplastics in aquatic environments based on sediment analogies, Scientific Reports, 9, 15 207–, https://doi.org/10.1038/s41598-019-50508-2, 2019.

Gräwe, U., Holtermann, P. L., Klingbeil, K., and Burchard, H.: Advantages of vertically adaptive coordinates in numerical models of stratified shelf seas, Ocean Modelling, 92, 56–68, https://doi.org/10.1016/j.ocemod.2015.05.008, 2015.

Gräwe, U., Klingbeil, K., Kelln, J., and Dangendorf, S.: Decomposing Mean Sea Level Rise in a Semi-Enclosed Basin, the Baltic Sea, Journal of Climate, 32, 3089–3108, https://doi.org/10.1175/JCLI-D-18-0174.1, https://doi.org/10.1175/JCLI-D-18-0174.1, 2019.

Hofmeister, R., Burchard, H., and Beckers, J.-M.: Non-uniform adaptive vertical grids for 3D numerical ocean models, Ocean Modelling, 33, 70–86, https://doi.org/10.1016/j.ocemod.2009.12.003, 2010.

Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salánki, T., van der Ploeg, M., Besseling, E., Koelmans, A. A., and Geissen, V.: Microplastics in the Terrestrial Ecosystem: Implications for Lumbricus terrestris (Oligochaeta, Lumbricidae), Environ. Sci. Technol., 50, 2685–2691, https://doi.org/10.1021/acs.est.5b05478, https://doi.org/10.1021/acs.est.5b05478, 2016.

Jalón-Rojas, I., Wang, X.-H., and Fredj, E.: Technical note: On the importance of a three-dimensional approach for modelling the transport of neustic microplastics, Ocean Science, 15, 717–724, https://doi.org/10.5194/os-15-717-2019, https://www.ocean-sci.net/15/717/2019/, 2019a.

Jalón-Rojas, I., Wang, X. H., and Fredj, E.: A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes, Marine Pollution Bulletin, 141, 256 – 272, https://doi.org/https://doi.org/10.1016/j.marpolbul.2019.02.052, http://www.sciencedirect.com/science/article/pii/S0025326X19301523, 2019b.

Khalaf, H. K.: The theoretical investigation of drag coefficient and settling velocity correlations, Ph.D. thesis, Nahrain University, Nahrain, Iraq, http://nahrainuniv.edu.iq/sites/default/files/thesis_25.pdf, 2009.

Khatmullina, L. and Isachenko, I.: Settling velocity of microplastic particles of regular shapes, Marine Pollution Bulletin, 114, 871 – 880, https://doi.org/https://doi.org/10.1016/j.marpolbul.2016.11.024, http://www.sciencedirect.com/science/article/pii/S0025326X16309201, 2017.

Klingbeil, K. and Burchard, H.: Implementation of a direct nonhydrostatic pressure gradient discretisation into a layered ocean model, Ocean Modelling, 65, 64–77, https://doi.org/10.1016/j.ocemod.2013.02.002, 2013.

Klingbeil, K., Mohammadi-Aragh, M., Gräwe, U., and Burchard, H.: Quantification of spurious dissipation and mixing – Discrete Variance Decay in a Finite-Volume framework, Ocean Modelling, 81, 49–64, https://doi.org/10.1016/j.ocemod.2014.06.001, 2014.

Klingbeil, K., Lemarié, F., Debreu, L., and Burchard, H.: The numerics of hydrostatic structured-grid coastal ocean models: state of the art and future perspectives, Ocean Modelling, 125, 80–105, https://doi.org/10.1016/j.ocemod.2018.01.007, 2018.

Kondo, J.: Air-sea bulk transfer coefficients in diabatic conditions, Boundary-Layer Meteorology, 9, 91–112, https://doi.org/10.1007/BF00232256, 1975.

Kriaučiūnienė, J., Gailiušis, B., and Kovalenkovienė, M.: Peculiarities of sea wave propagation in the Klaipėda Strait, Lithuania, http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=D6B2487835980E6828B2FD6D4D63DB9D?doi=10.1.1.133.7480&rep=rep1&type=pdf, 1961.

Kundu, P. K. and Cohen, I. M.: Fluid Mechanics, Academic Press, San Diego, 2nd edn., 2001.

Liubartseva, S., Coppini, G., Lecci, R., and Clementi, E.: Tracking plastics in the Mediterranean: 2D Lagrangian model, Marine Pollution Bulletin, 129, 151 – 162, https://doi.org/https://doi.org/10.1016/j.marpolbul.2018.02.019, http://www.sciencedirect.com/science/article/pii/S0025326X18301000, 2018.

Osinski, R. and Bouttier, F.: Short-range probabilistic forecasting of convective risks for aviation based on a lagged-average-forecast ensemble approach, Meteorological Applications, 25, 105–118, https://doi.org/10.1002/met.1674, 2018.

Osinski, R., Lorenz, P., Kruschke, T., Voigt, M., Ulbrich, U., Leckebusch, G. C., Faust, E., Hofherr, T., and Majewski, D.: An approach to build an event set of European windstorms based on ECMWF EPS, Natural Hazards and Earth System Sciences, 16, 255–268, https://doi.org/10.5194/nhess-16-255-2016, https://www.nat-hazards-earth-syst-sci.net/16/255/2016/, 2016.

Osinski, R. D. and Radtke, H.: Ensemble hindcasting of wind and wave conditions with WRF and WAVEWATCH III® driven by ERA5, Ocean Science, 16, 355–371, https://doi.org/10.5194/os-16-355-2020, https://www.ocean-sci.net/16/355/2020/, 2020.

Pappenberger, F., Bartholmes, J., Thielen, J., Cloke, H. L., Buizza, R., and de Roo, A.: New dimensions in early flood warning across the globe using grand-ensemble weather predictions, Geophysical Research Letters, 35, https://doi.org/10.1029/2008GL033837, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008GL033837, 2008.

PlasticsEurope: Plastics – the Facts 2019, Tech. rep., PlasticsEurope Deutschland e. V., https://www.plasticseurope.org/application/files/6015/7908/8734/Plastics_the_facts_2019.pdf, 2019.

Radtke, H., Brunnabend, S.-E., Gräwe, U., and Meier, H. E. M.: Explaining interdecadal salinity changes in the Baltic Sea in a 1850-2008 hindcast simulation, Climate of the Past, submitted.

Ridal, M., Olsson, E., Unden, P., Zimmermann, K., and Ohlsson, A.: Uncertainties in Ensembles of Regional Re-Analyses - Deliverable D2.7 HARMONIE reanalysis report of results and dataset, http://www.uerra.eu/component/dpattachments/?task=attachment.download&id=296, 2017.

Rijn, L. C. v.: Sediment transport, part II: suspended load transport, Journal of hydraulic engineering, 110, 1613–1641, publisher: American Society of Civil Engineers, 1984.

Sassi, M., Duran-Matute, M., van Kessel, T., and Gerkema, T.: Variability of residual fluxes of suspended sediment in a multiple tidal-inlet system: the Dutch Wadden Sea, Ocean Dynamics, 65, 1321–1333, https://doi.org/10.1007/s10236-015-0866-2, https://doi.org/10.1007/s10236-015-0866-2, 2015.

Seifert, T., Tauber, F., and Kayser, B.: A high resolution spherical grid topography of the Baltic Sea - 2nd edition, in: Baltic Sea Science Congress, Stockholm, 25–29 November 2001, Poster No. 147, available at: https://www.io-warnemuende.de/topography-of-the-baltic-sea.html (last access: 10 March 2020), www.io-warnemuende.de/iowtopo, 2001.

Shields, A. R.: Application of similarity principles and turbulence research to bed-load movement, 1936.

Shutts, G.: A kinetic energy backscatter algorithm for use in ensemble prediction systems, Quarterly Journal of the Royal Meteorological Society, 131, 3079–3102, https://doi.org/10.1256/qj.04.106, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1256/qj.04.106, 2005.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., Wang, W., Powers, J. G., Duda, M. G., Barker, D., and yu Huang, X.: A Description of the Advanced Research WRF Model Version 4, Tech. rep., NCAR/TN-556+STR, https://doi.org/doi:10.5065/1dfh-6p97, 2019.

Smagorinsky, J.: General Circulation Experiments with the Primitive Equations, Monthly Weather Review, 91, 99–164, https://doi.org/10.1175/1520-0493(1963)091%3C0099:GCEWTP%3E2.3.CO;2, 1963.

Soulsby, R.: Dynamics of Marine Sands, Thomas Telford Publishing, London, 1997.

Stokes, G. G.: On the Effect of the Internal Friction of Fluids on the Motion of Pendulums, Transactions of the Cambridge Philosophical Society, 9, 8, 1851.

Stuparu, D., der Meulen, M. V., Kleissen, F., Vethaak, D., and el Serafy, G.: Developing a transport model for plastic distribution in the North Sea, 36th IAHR World Congress, 28 June – 3 July, 2015, The Hague, the Netherlands, 2015.

Taylor, J. W. and Buizza, R.: Using weather ensemble predictions in electricity demand forecasting, International Journal of Forecasting, 19, 57 – 70, https://doi.org/https://doi.org/10.1016/S0169-2070(01)00123-6, http://www.sciencedirect.com/science/article/pii/S0169207001001236, 2003.

The Local: Thousands without power and traffic disrupted as 2019's first storm hits Sweden, The Local, https://www.thelocal.se/20190102/thousands-without-power-and-traffic-disrupted-as-2019s-first-storm-hits-sweden, 2019.

The WAVEWATCH III® Development Group (WW3DG): User manual and system documentation of WAVEWATCH III® version 6.07. Tech. Note 333, 2019.

Tolman, H. L.: A Third-Generation Model for Wind Waves on Slowly Varying, Unsteady, and Inhomogeneous Depths and Currents, Journal of Physical Oceanography, 21, 782–797, https://doi.org/10.1175/1520-0485(1991)021<0782:ATGMFW>2.0.CO;2, https://doi.org/10.1175/1520-0485(1991)021<0782:ATGMFW>2.0.CO;2, 1991.

Umlauf, L. and Burchard, H.: Second-order turbulence closure models for geophysical boundary layers. A review of recent work, Continental Shelf Research, 25, 795–827, https://doi.org/10.1016/j.csr.2004.08.004, 2005.

Waldschläger, K. and Schüttrumpf, H.: Effects of Particle Properties on the Settling and Rise Velocities of Microplastics in Freshwater under Laboratory Conditions, Environmental Science & Technology, 53, 1958–1966, https://doi.org/10.1021/acs.est.8b06794, https://doi.org/10.1021/acs.est.8b06794, 2019.

Watkins, E., ten Brink, P., Sirini Withana, M. K., Daniela Russi, K. M., Schweitzer, J.-P., and Gitti, G.: The socio-economic impacts of marine litter, including the costs of policy inaction and action, in: Handbook on the Economics and Management of Sustainable Oceans, edited by Nunes, P. A., Svensson, L. E., and Markandya, A., Chapters, chap. 14, pp. 296–319, Edward Elgar Publishing, https://ideas.repec.org/h/elg/eechap/17310_14.html, 2017.

Wessel, P. and Smith, W. H. F.: A global, self-consistent, hierarchical, high-resolution shoreline database, Journal of Geophysical Research: Solid Earth, 101, 8741–8743, https://doi.org/10.1029/96JB00104, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/96JB00104, 1996.

Zambresky, L.: A verification study of the global WAM model December 1987 - November 1988, p. 86, https://www.ecmwf.int/node/13201, 1989.

Ziervogel, K. and Bohling, B.: Sedimentological parameters and erosion behaviour of submarine coastal sediments in the south-western Baltic Sea, Geo-Marine Letters, 23, 43–52, https://doi.org/10.1007/s00367-003-0123-4, 2003.