

We want to thank the three referees for the interest in our work and the effort spent on reviewing our manuscript. The insightful comments are highly appreciated. We have considered all their suggestions and comments, and we have made the modifications/corrections. We have detailed the replies when necessary in the letter. The manuscript with the marked correction is uploaded with this letter.

REFeree #1

Comment 1. What is the spatial and temporal resolution of POM? What is more or less the size of the first sigma layer for the 2D approach and how does it compare to the mentioned 5m layer thickness (page 2, line 7)? Assuming the layer is narrow(<5m), do the results differ if you average over the first two or three surface near layers? How does the 2D layer thickness compare to the average particle depth from the 3D approaches (0.7 and 2.5 m, page 3, line 17/18)?

The spatial resolution of POM is 500 m around the bay and the temporal resolution is 12 s. All the model details are described in the mentioned reference [Sun et al. \(2017\)](#), but we have included these details in the revised version (page 3, lines 2-3)¹.

The model uses a total of 21 sigma layers, so the depth represented by a given sigma layer changes significantly over the space as a function of bottom depth. This can be observed in Figure 1 for the fifth and twelfth sigma layers (depths higher than 20 m has not been detailed for a clearer representation inside the bay). We can see that the 5m surface layer thickness is represented by the layers 1-5 near the mouth while it is represented by layers 1-12 in the inner bay. So, we cannot average a given number of layers to represent the 0-5m layer thickness, especially if we also take into account the outer bay. In this paper, we are comparing the 3D approach with the typical 2D approach used in many previous papers that considers particles floating in surface water and only uses surface currents. The only realistic way to represent the surface waters in the 2D approach for a shallow system as Jervis Bay is using the first layer. In the revised version, we have included the number of sigma layer and the 2D layer thickness (0.08 m in the inner bay and 0.3 m at the mouth) (page 3, line 18).

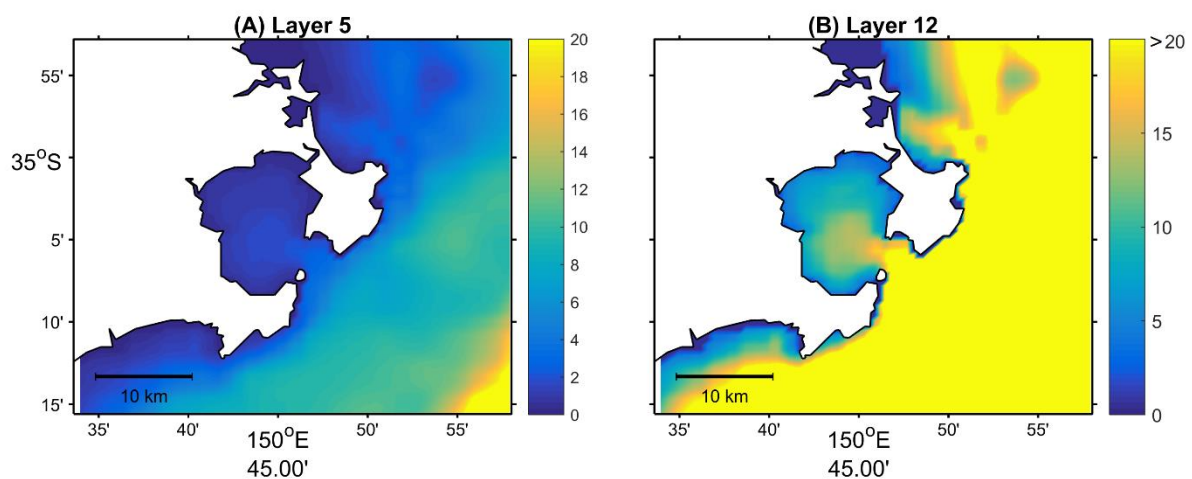


Figure 1. Depths at sigma layers 5 (A) and 12 (B).

¹ Page and line numbers refer to the manuscript with the marked changes.

Comment 2. On page 3, line 4 it is written that your aim is not to discuss typical patterns of the microplastic transport and sinking in Jervis Bay. To which extent are your findings transferable to other regions? Do you think that under certain circumstances a 2D approach could be sufficient?

We agree that we can be more specific. In the revised version, we have detailed that our study focuses on coastal shallow waters when relevant (page 2, line 11; page 3, line 9). For example, the mentioned statement will be modified as (bold): *“the aim of this work is not to discuss the typical patterns of microplastics transport and sinking in Jervis Bay; it is a case study to explore the implications of a 2D approach on the simulation accuracy of neustic-microplastics transport **in coastal shallow waters**”*

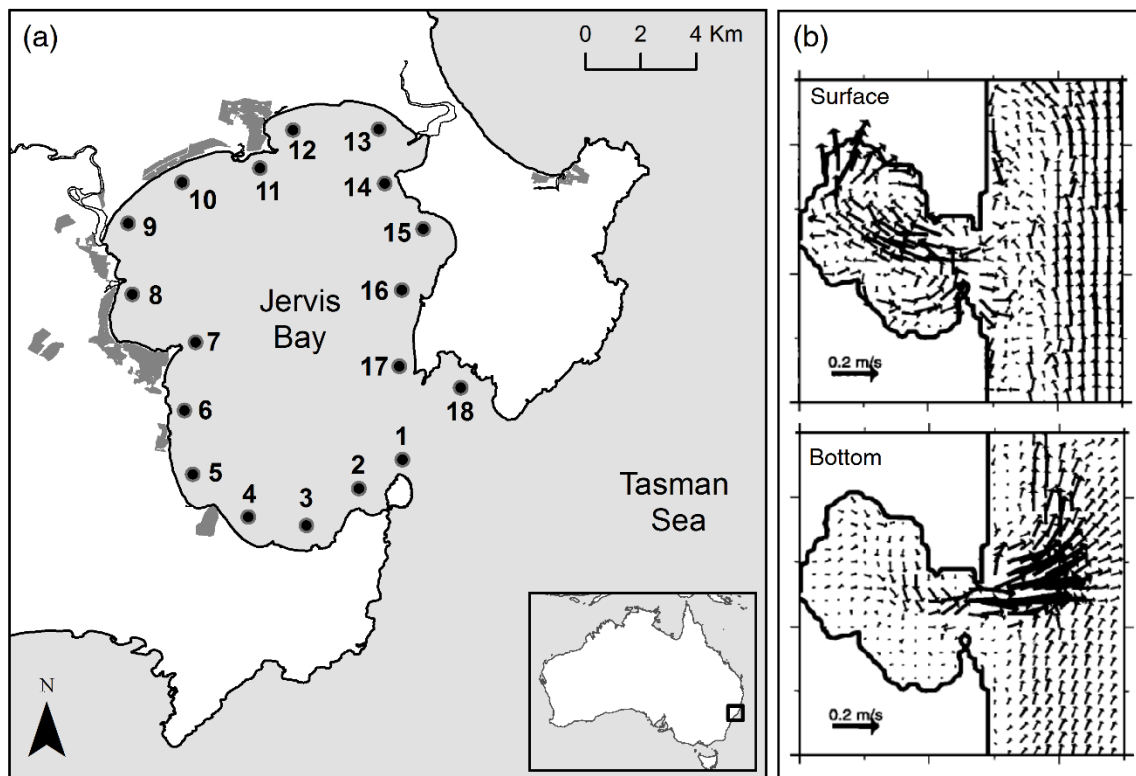
We already discussed under which main circumstances our findings would be transferable and a 3D approach would be recommended: stratified systems, high turbulence, under upwelling and downwelling conditions, when simulating non-buoyant particles.

However, we have elongated this discussion and give more details in the revised version (page 6, lines 1-16):

- Our results can be transferable to other stratified coastal systems such as estuaries characterized by a density circulation.
- Even if our study focuses on coastal shallow water, surface oceanic water are also characterized by vertical current shear (e.g. wind and wave-driven Ekman flow, density-driven processes, [Lund et al., 2015](#); [Lanotte et al., 2016](#)) that could influence the trajectories and final fate of microplastics. Only a 3D approach can consider vertical current shear. A 2D approach could be sufficient when vertical current shear is negligible.

Comment 3. How are the hydrodynamic conditions inside the Bay? Is it possible to find different periods with different hydrodynamic conditions (stratified, mixed) to generalize more the findings?

The hydrodynamic conditions inside the bay were described in page 3: *“During this simulation period, Jervis Bay was characterized by its typical circulation pattern: clockwise and anticlockwise circulation in the northern and southern regions, respectively. The flow exchange through the entrance was highly stratified, with near-surface inflow on the southern side and deeper outflow on the northern side”*. In the revised version, we have included a subplot showing the hydrodynamic conditions in surface and bottom waters:



This is thus the typical circulation of the bay. Conditions can change (coastal trapped waves, upwelling, cooling events) but all these processes are baroclinic (e.g. [Wang and Symonds, 1999](#); [Sun et al., 2017](#); [Liao and Wang, 2018](#)), so the 2D approach is not suitable in coastal systems such as Jervis Bay. We have included this information in the reviewed version (page 6, lines 1-3). Our conclusions are transferable as articulated in the previous question.

Comment 4. Do you have information about the turbulence from POM? How does it compare to the vertical diffusivity coefficients used for the transport model?

The model uses the turbulence closure scheme described by [Mellor and Yamada \(1982\)](#) for vertical mixing coefficients, which is a time variable. The transport model uses the typical constant diffusivity coefficients typically used in the literature because our objective is not evaluating the real conditions of Jervis Bay but the potential range of conditions that can occur in these environments (page 3, lines 18-20).

Comment 5. The density, the size, the shape and the buoyancy of the particles do not go into the study. Can you discuss this point in how far this influences the results? Microplastics contains a large variety of substances and shapes?

The objective of this technical note is to compare the 2D and 3D approaches just for low-dense positive-buoyant neustic microplastics. The motivation is that previous works only modelled the transport of this type of microplastics using a 2D approach. As discussed in the manuscript, our results suggest that *“the vertical movement of particles induced by other physical processes, such as **particle sinking (in the case of non-buoyant particles)**, upwelling and downwelling, could also affect the horizontal transport of microplastics, even in a higher degree, and a 3D approach could be mandatory”* (page 6, lines 8-11). So we already mentioned that we expect that buoyancy has even a higher impact on microplastics trajectories, but we cannot give more details at this point.

However, we also pointed that “Further progress on microplastics modelling requires thus the development of three-dimensional models that consider the particle sinking, which in turn depends on particle physical properties (density, size, shape, Chubarenko et al., 2016)” (page 6, lines 13-15). And this is effectively what we have done. Based on the conclusions of this technical note, we have developed a 3D model that considers the influence of these three physical properties, but also of biofilm properties and other physical processes such as washing off from the beach. The model description and the discussion of the relative impact of each property/process are the objectives of our next paper that has been recently published (Jalon-Rojas et al. A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastics trajectories and fates to particle dynamical properties and physical processes, *Marine Pollution Bulletin*). We have included this reference in the technical note (page 6, lines 15-16).

Comment 6. Waves are not mentioned. Do you have an idea of its impact and how it compares to the demonstrated differences of a 2D and the 3D approaches?

The impact of waves on microplastics transport is a different subject of study (which we intend to conduct in near future). However, when we discuss the transferability of our results, we have also mentioned that waves enhance vertical mixing (e.g. [Deepwell, and Stastna, 2016](#)) and may also impact the vertical displacement of particles near the surface (page 6, line 9).

Comment 7. Page 6, line 1: How do you justify your statement that a 3D approach can improve the accuracy? You see from your study the different outcomes of the different setups, but not how they compare to reality. Particle physical properties (page 5, line 35) are not taken into account.

All the reviewers made the same comment and we agree with them. We acknowledge that the lack of observations is a shortcoming of this study. Future work is in progress to apply for funding to conduct field work in Jervis Bay in order to validate the 3D model prediction. This study compares the two approaches by considering the 3D approach “as a reference solution” (page 2, line 13), closer to real conditions, and we evaluated the potential consequences of using a 2D approach, the typical approach used in previous studies. We have modified this sentence as suggested by other reviewer: “providing more accurate predictions” was modified by “which impact the predictions” (page 6, line 18).

As discussed in Comment 5, we expected that the 3d approach will be even more important for negative-buoyant particles and this result has motivated a new study has been recently published.

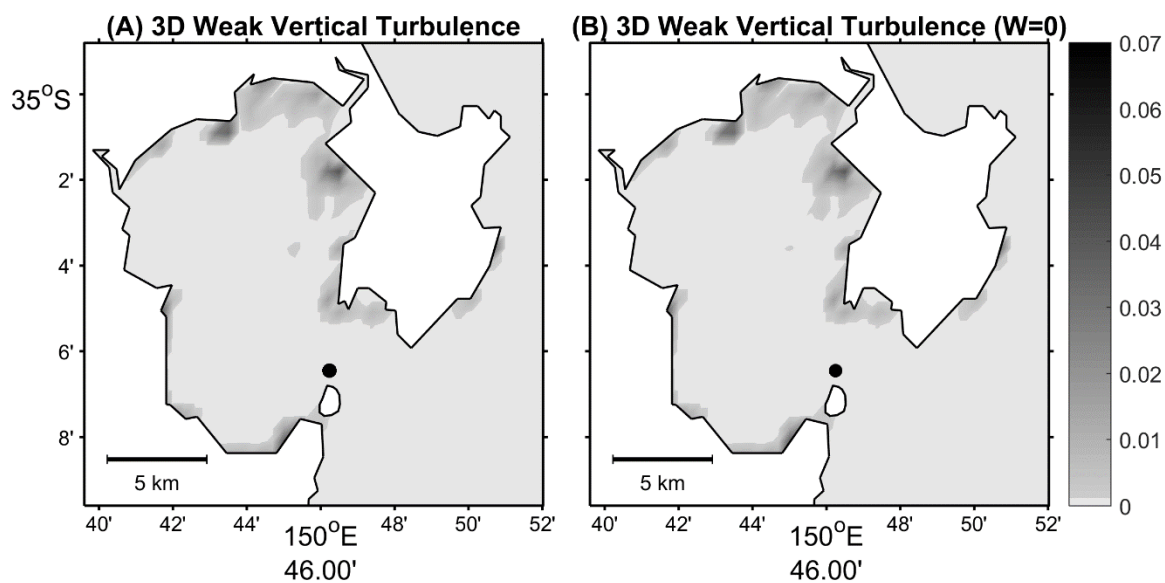
REFeree #2

Comment 1. The conclusion of the manuscript is obvious. Because of vertical transport, MPs may be trapped and driven by the horizontal currents at difference depth, for numerical models at difference sigma layer. And due to the difference of the horizontal current field at different sigma layer, the trajectories and fates of MPs in 3 scenarios are different. I noticed the vertical transport of MPs is driven by random walks, vertical current and vertical diffusivity. The manuscript only evaluated the importance of vertical diffusivity, but what is the contribution of the other two factors?

We think that our conclusion is not so obvious, because practically all the previous numerical studies (see references in the manuscript, page 2, lines 1-2) ignored the potential impact of vertical transport and used a 2D approach to evaluate the horizontal transport of microplastics. Even if the above statements

are known, the scientific community has hypothesized that the vertical transport, induced by turbulence in this case, is not so important as to impact the horizontal trajectories and the fate of microplastics. For that reason, we think it is important to pass this message through this technical note. In addition, we not only show the differences between the 2D and 3D approaches, but we also quantified them for an specific case study.

The vertical diffusivity is given through the random walk, but it is true that there are also vertical currents. However, the selected period is characterized by negligible vertical currents (3-4 order of magnitude lower to horizontal currents), so the differences mainly came from vertical dispersion. We have detailed this information in the final version (page 3, lines 6-7). In addition, we have proved that the differences between the 2D and 3D scenarios are mainly due to vertical dispersion by comparing the probability density map of two scenarios: (a) 3D approach with low turbulent conditions and vertical currents; (b) 3D with low turbulent conditions and no vertical currents (see Figure below). Results show that the accumulation patterns of particles are practically identical for both scenarios, so vertical velocities have a low impact and the difference between the 2D and 3D approaches discussed in this paper, are mainly related to vertical dispersion.



This figure has been included in Supplementary Material 2.

Comment 2. What is the vertical resolution of the hydrodynamic model? How could it be if the vertical resolution changes?

As discussed in the response n°1 to referee 1, the model uses a total of 21 sigma layers, so the depth represented by a given sigma layer changes significantly over the space as a function of bottom depth. For example, the 5m surface layer thickness is represented by the layers 1-5 near the mouth while it is represented by layers 1-12 in the inner bay. In the revised version, we have included the vertical resolution of the first layer in the inner bay and near to the mouth (page 3, line 18)

A decrease of the vertical resolution might decrease the differences between the 2D and the 3D approaches in much as this decrease impacts the accurate representation of currents at the different vertical layers in the system. We have included a sentence to highlight the importance of vertical resolution (page 5, lines 33-34).

Comment 3. page 4 line 22-23: not all the particles stay in the bay in the 3D approach with weak vertical turbulence.

We described that all the particles stayed in the bay for the 3D approach with weak vertical turbulence because only one particle (among thousands) left the bay, so the probability of particles going out is negligible for this scenario. We prefer to keep this statement, but we may include some clarification if required.

Referee comment 4. page 6 line 1-2: Without validation, there is no stand for the author to conclude a “more-accurate” prediction.

See the response nº7 to referee 1.

REFeree #3

Comment 1. Mainly I would be careful in the conclusion drawn by the authors. Since this is purely a numerical modelling study with no ground-truth data and validation of the model, the authors cannot conclude that a 3D approach is “providing more-accurate predictions”. What this study shows is that including a three-dimensional component to a dispersal model alters the connectivity between different marine compartment for marine debris transport in coastal areas.

See the response nº7 to referee 1; the conclusion has been modified as suggested by the reviewer (page 6, line 18).

Comment 2. An interesting result is how the “strong” vertical mixing scenario leaks particles off-shore which could explain natural sorting of plastic debris in coastal environment. The authors should further discuss this as well as the relation between vertical mixing and characteristics of marine litter (type, size, buoyancy etc.).

We already discussed the role of vertical mixing on the “scape” of particles from the bay (page 4, lines 25-28). As discussed at the response nº5 to referee 1, the objective of this paper is to discuss the relevance of a 2D approach for floating low-dense particles, and the impact of the physical properties of microplastics have been discussed in depth in our next paper (reference included in the revised version: page 6, lines 15-16).

Comment 3. I don’t think the manuscript as well as the title should focus only on microplastics. Some findings of this study could apply for larger “young” object.

We prefer to focus the paper on microplastics since the initial motivation is that most of the studies on microplastic modelling consider a 2D approach. However, we have included that the finding can also be applied for other floating objects (page 6, lines 5-6).

Comment 4. Vertical diffusivity of marine debris likely changes with its characteristics, thus the comparison between “weak” and “strong” vertical mixing is an evidence of natural filtering for the transport of marine litter offshore. The authors should emphasize this point.

This paper focuses on the modelling of one kind of particles: low-dense floating microplastics. We have briefly discussed the implications of these results for another kind of particles, but this is the object of our following paper (Jalon-Rojas et al. 2019, Marine Pollution Bulletin).

Comment 5. Finally, the formulation and the amplitude of particle beaching is not clearly explained in the manuscript and nor is the influence of vertical advection (W velocity). The authors should provide more details on these aspects.

We have detailed the beaching in the revised version (page 2, lines 24-25). Regarding vertical advection, see the response n°1 to referee 2.

References

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Technical note. On the importance of a three-dimensional approach for modelling the transport of neustic microplastics

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Abstract. Understanding and estimating the distribution and transport of microplastics in marine environments has been recognized as a major global research issue. Most of the existing research on transport modelling has focused on low-dense particles floating in surface waters, using a 2D Lagrangian approach and ignoring the vertical displacement of particles. In this work, we evaluate to what extent the vertical movement of particles within surface waters by mixing processes may affect the horizontal transport and fate of microplastics. The aim is to determinate whether a 2D approach is sufficient for the accurate modelling of neustic-microplastics transport or a 3D approach is necessary. For this purpose, we compare visually and statistically the microplastics transport patterns of three simulations in a coastal system: one using a 2D approach; and two using a 3D approach with weak and strong vertical turbulence, respectively. The 2D simulation roughly reproduced the transport and accumulation patterns, but accurate results required a 3D approach. This was particularly important for strong vertical turbulence and regions characterized by strong vertical current shear. Moreover, a 2D approach can lead to errors in the results even with negligible turbulence due to simplifications in the velocity field. A 3D modelling approach is therefore key to an accurate estimation and prediction of microplastics distribution in coastal systems, and consequently for planning mitigation and cleaning programs.

1 Introduction

Marine plastic debris is of increasing concern because of its persistence, toxicological properties, and effects on marine ecosystems, wildlife, and humans (Lithner et al., 2011; Rochman et al., 2013). In particular, microplastics (<5 mm) are the most abundant and potentially hazardous plastic items in marine environments (Andrady, 2011). Microplastics pollution has been documented throughout the world and marine habitats (Eriksen et al., 2014; Galgani et al., 2015), in the surface and subsurface water column, on the sea floor, along coastlines and in the polar regions. Microplastics can also accumulate in marine organisms at different trophic levels (Carbery et al, 2018).

Understanding, estimating and predicting the distribution and transport of microplastics is a key step in addressing this global issue. This is a complex problem that requires in-situ observations and numerical modelling. Numerous studies have used Lagrangian particle-tracking models to assess the sources, pathways and sinks of microplastics in marine environments,

especially at ocean and regional scales (e.g. Wakata and Sugimori, 1990; Isobe et al., 2009; Ebbesmeyer et al., 2012; Lebreton et al., 2012; Critchell and Lambrechts, 2016; Carlson et al., 2017; Liubartseva et al., 2018). These models typically consider particles moving in surface waters, and therefore use a two-dimensional approach based on surface or vertically averaged current velocities. However, microplastics can move through the water column for different reasons (Zhang, 2017) – neutral and negative buoyancy, vertical mixing processes, upwelling/downwelling processes – and a three-dimensional approach could be necessary. In the case of positive buoyant microplastics, observations revealed that they normally remain near the surface but can move within a layer of depth up to 5m due to hydrodynamic mixing processes (Reisser et al., 2015, Kooi et al., 2016). This vertical movement may affect the horizontal trajectories of microplastics in stratified systems, but this impact has not yet been explored.

The aim of this work is to evaluate the accuracy of a two-dimensional approach for modelling the transport of positive-buoyant neustic microplastics under conditions of low and high vertical turbulence in coastal shallow environments. We implement a Lagrangian particle-tracking model to compare the trajectories and fates of microplastics from 2D simulations with those from 3D (used as reference solutions), using Jervis Bay (SE Australia) as a natural laboratory. This comparison is performed both visually and quantitatively using probability-density maps and coastal connectivity analysis. This work also provides a first insight into the pertinence of a 3D approach for modelling the transport of negative-buoyant microplastics subject to sinking and other physical processes involving vertical transport.

2 Methods

2.1 Lagrangian Particle-Tracking Model

The Particle Tracking and Analysis TOolbox (PaTATO, Fredj et al., 2016) was used for modelling the advection-diffusion of buoyant particles in 2D and 3D. Advective and diffusive displacement determine the trajectories of particles as:

$$d\mathbf{X}(t) = \mathbf{U}dt + \mathbf{R}\sqrt{2\mathbf{K}dt}, \quad (1)$$

The particle displacement $d\mathbf{X}=(dX, dY, dZ)$ is given by the flow velocity $\mathbf{U}=(U,V,W)$, which can be provided by diverse hydrodynamic models (e.g. POM, ROMS), and a stochastic term related to the dispersion coefficients $\mathbf{K}=(K_{h,x}, K_{h,y}, K_{h,z})$. $\mathbf{R}=(R_x, R_y, R_z)$ represents white-noise random walks with an average and standard deviation of 0.0 and 1.0. Particles can beach when their positions are inside the land domain.

2.1 Model settings

The Lagrangian particle-tracking model was implemented in Jervis Bay (SE Australia, Fig. 1.a) in two and three dimensions, in order to compare the results of two approaches. This semi-enclosed bay is 8 km wide, 15 km long and 15 m deep on average. We used hydrodynamic model results from the Princeton Ocean Model (POM) as inputs. In particular, we used the hydrodynamics data from 24 June to 11 July 1998, as the model was validated using observation of currents, temperature,

salinity and water level during this period, obtaining a very good fit (Wang and Symonds, 1999; Sun et al., 2017; Liao and Wang, 2018). The POM model spatial resolution is 500 m around the bay, and the temporal resolution is 12 s. It uses a total of twenty-one sigma levels in the z-direction, with finer layers near the surface and bottom. During this simulation period, Jervis Bay was characterized by its typical circulation pattern: clockwise and anticlockwise circulation in the northern and southern regions, respectively. The flow exchange through the entrance was highly stratified, with near-surface inflow on the southern side and deeper outflow on the northern side (Fig 1.b). Vertical currents were 3-4 order of magnitude lower than horizontal currents (Fig 1.b). However, the aim of this work is not to discuss the typical patterns of microplastics transport ~~and sinking~~ in Jervis Bay; it is a case study to explore the implications of a 2D approach on the simulation accuracy of neustic-microplastics transport in coastal shallow waters. The reader is referred to Sun et al. (2017) for more details on the hydrodynamic model settings.

We implemented three model simulations to evaluate the accuracy of a 2D approach for modelling microplastics floating in surface waters:

- a) 2D approach
- b) 3D approach with weak vertical turbulence
- c) 3D approach with strong vertical turbulence

The only processes involved in the transport of microplastics in the three simulations were advection, diffusion and beaching, as in most of the existing 2D models for the transport of microplastics. The 2D approach used surface currents in the first sigma ~~level~~ layer of the POM domain (layer thickness around 0.08 m at the inner bay and 0.3 m at the mouth). The reference 3D approaches used the whole 3D velocity dataset. Weak and strong vertical turbulence were defined by low ($10^{-5} \text{ m}^2\text{s}^{-1}$) and high ($10^{-4} \text{ m}^2\text{s}^{-1}$) values of the vertical diffusivity coefficients typical of marine systems (Talley et al., 2011). With weak turbulence, particles remained near the surface during the whole simulation (standard deviation of particles depths, σ , equals to 0.7 m), whereas strong turbulent conditions induced high vertical displacements of particles (σ equals to 2.5 m). In order to compare only the impact of vertical turbulence on the horizontal trajectories, the effect of the horizontal diffusivity on the trajectory of each particle at each time step was considered identical in all three scenarios. Therefore, vertical displacements will be the only possible cause of the potential differences between the horizontal transport patterns of the three different approaches. In order to avoid the random behaviour of ~~horizontal~~ turbulent dispersion having an impact on the comparison of simulations, the same turbulent horizontal and vertical displacements ~~were~~ assigned to each particle at each time step for all scenarios.

All the simulations were seeded at 18 locations (Fig 1) covering the whole coast of Jervis Bay in order to analyse the bay connectivity. Twenty particles per hour were released at each seeding site in surface waters during three days from 26 June 1998, a total of 25,920 particles per simulation. A sensitivity analysis of model results to the number of particles is provided in the Supplementary Material to demonstrate that results were not affected by this parameter. Simulations were run for five days, as most of particles reached the coast during this period.

2.3 Probability distributions and connectivity analysis

To evaluate the prediction accuracy of a 2D approach in modelling the transport of neustic microplastics, we compared the trajectories and fates of microplastics obtained from 2D and 3D simulations using three methods: (1) visual and descriptive comparison of the resulting trajectories and fate; (2) probability-density maps; and (3) coastal connectivity analysis.

- **Probability-density maps**

This analysis facilitates visualizing and understanding particle trajectories by binning particle positions into histograms. It calculates the probability that a particle moves from one location to another over a time interval τ by counting the number of particles per bin and then normalizing by the total number of particles. Bins were defined by the grid of the hydrodynamic model (500×500m). The result is a probability map of particle density.

- **Coastal connectivity analysis**

Coastal connectivity $C_{ji}(\tau)$ is the probability that a particle leaving a source site j arrives a destination site i over the time interval τ , calculated in the same way as for the probability-density maps, using the site locations shown in Fig. 1 as source and destination locations. Destinations are rectangular areas of 1.5 km² centred on the site locations of Fig. 1. $C_{ji}(\tau)$ was thus calculated for five time intervals $\tau = 1, 2, 3, 4$ and 5 days. This results in five 18×18 connectivity matrices that describe the probability of microplastics particles being transported between different sites along the whole Jervis Bay coast. Readers should refer to van Sebille et al. (2018) and Mitarai et al. (2009) for a detailed description and application of both probability-density maps and connectivity analysis.

3 Results and Discussion

The trajectories and fates of microplastics released at the different source locations (Fig. 1) were plotted for the three scenarios to gain a first insight into the differences between the 2D and 3D approaches. Figure 2.I illustrates these results for microplastic particles released at sources 2 and 9. A first comparison of the three scenarios shows differences in the dispersion patterns of particles between the 2D and 3D simulations. In general, particles released at a given source reached similar coastal regions in all three approaches. However, the particles seemed to have a higher horizontal spread in the 3D approach (Fig 2.I.B-C), especially with strong vertical turbulence (Fig. 2.I.C). In the case of particles released near the entrance (source 1), the vertical turbulent displacement can induce either a surface inflow or a deep outflow, so some particles could leave the bay in outflow deep currents with strong turbulence (Fig. 2.I.C), whereas all the particles stayed in the bay in the 2D approach (Fig. 2.I.A) and the 3D approach with weak vertical turbulence (Fig. 2.I.B). Even in these two last cases, in which particles barely moved vertically, the dispersion patterns showed some differences. Whereas most of particles reached the coastal region in the 2D simulation (Fig. 2.I.A), some particles remained in suspension in the bay after 5 days of simulation in the 3D approach (Fig. 2.I.B). Differences between 2D and 3D weak-turbulence simulations were less evident for particles released in the inner bay, for example at source 9 (Fig. 2.I.A-B). In this case, most of the particles had accumulated in the inner bay by the end of the

simulation; with strong turbulence, some particles ended up in the middle of the bay (Fig. 2.I.C). However, this kind of analysis does not tell us whether most of the particle trajectories followed the same pattern in all three approaches, so that the visible differences did not show significant trends, or whether the visible differences showed the most common trends.

For a statistical quantification and comparison of the transport trends of the different approaches, we turn to probability density-
5 maps; these shows the probability that a particle released at a given source moves to different regions of the bay. Figure 2.II shows the accumulation regions of particles released at sources 2 and 9 after five days of simulation. The accumulation patterns of the different approaches were not as different as suggested in Fig. 2.I, and the transport patterns were roughly similar for the 2D and 3D approaches. In all three scenarios, particles released at sources 2 and 9 accumulated mainly in the northern and eastern regions of the bay (Fig. 2.II). Nevertheless, there were clear differences between the 2D and 3D results. For particles
10 released at source 9 in the inner bay with strong vertical turbulence (Fig. 2.II.C), these differences were significant. Whereas there was a significant accumulation spot of microplastics on the eastern coast of the bay for the 2D and 3D weak-turbulence approaches (dark grey, Fig.2.II.A-B), the particles fate was more spread out with strong vertical turbulence (Fig. 2.II.C). For particles released near the entrance (source 2), differences in the fate patterns appeared between the 2D and 3D approaches, even for weak vertical turbulence (Fig 2.II.A-B). In this case, there was a higher spread of particles in both 3D approaches.

For an overview of how the different modelling approaches influenced the transport patterns of neustic microplastics in the whole bay and as particles were released, Fig. 3 shows the percentage of particles traveling from and to the different coastal regions of the bay (18 sites in Fig. 1; see Section 2) for the three different scenarios, and simulation times from 1 to 5 days. This analysis confirmed most of conclusions reached above. First, both the 2D and 3D approaches provided similar transport patterns, but there were some clear differences. These differences appeared even when vertical turbulent dispersion was weak,
15 although they were more evident with strong vertical turbulence. In particular, particle fates were concentrated over a shorter length of the coast in the 2D approach (fewer destinations for each source and higher probabilities of a specific destination, Fig. 3.A), whereas the particle spread was greater in the 3D approaches, especially for strong vertical turbulence (more destinations, with lower probabilities for each source; Fig. 3.B-C). These differences were more significant: (1) in sources near the entrance due to the higher vertical gradients of horizontal currents (see sources from 1–9, 17 and 18 in Fig. 3); and (2) for
20 longer simulation times, as more particles had time to reach the coast, in particular from simulation times higher than 3 days (Fig. 3.III-IV).

In summary, the vertical transport of particles within surface layers due to mixing processes can affect the horizontal trajectories and fates of microplastics, particularly in systems with sharp horizontal velocity gradients. Although a 2D approach can predict general patterns, a 3D approach is recommended to improve the accuracy of the results, especially in the presence
30 of strong turbulence. 3D simulations may even be necessary with weak vertical turbulence. This is because a 2D approach can cause errors in the results due to the use of velocities at a single sigma layer which represent different depths along the particle trajectory. This can lead to unphysical vertical movements and therefore to wrong horizontal patterns in very stratified systems. Vertically averaged current velocities could also lead to errors in the horizontal trajectories. In the 3D approach, the vertical resolution of the hydrodynamic model should be finer enough to represent the vertical current shear accurately.

All these findings may be transferable to (1) the other hydrodynamic conditions of this bay which are also dominated by baroclinic processes (coastal trapped waves, upwelling, cooling events; e.g. Wang and Symonds, 1999; Sun et al., 2017; Liao and Wang, 2018), (2) other stratified coastal systems such as estuaries characterized by a density circulation, but also to oceanic water characterized by vertical current shear induced by wind and wave-driven Ekman flow or density-driven processes, for instance (Lund et al., 2015; Lanotte et al., 2016). Besides the microplastics, these results can also be applied for other floating “young” objects. A 2D approach may be sufficient when vertical current shear is negligible. In the present case study, the transfer of particle through the water column was mainly due to vertical dispersion, while vertical advection was negligible (see the impact of vertical advection on Supplementary Material 2). However, these results also highlight that the vertical movement of particles induced by other physical processes, such as upwelling, downwelling, wave enhancing vertical mixing, and particle sinking (in the case of non-buoyant particles), upwelling and downwelling, could also affect the horizontal transport of microplastics, even in a higher degree, and a 3D approach could be mandatory. Some modelling studies consider the particle sinking in a 2D approach (Critchell and Lambrechts, 2016; Liubartseva et al., 2018), so the vertical current shear during the vertical transport is not taken into account. Further progress on microplastics modelling requires thus the development of three-dimensional models that consider the particle sinking, which in turn depends on particle physical properties (density, size, shape, Chubarenko et al., 2016). This has been analysed in depth in our work (Jalon-Rojas et al., 2019).

In short, a 3D approach improves the simulation of the vertical position of particles in all turbulence conditions, providing more accurate which impact the predictions of the horizontal trajectories and fates of low-density neustic particles, especially in stratified systems. These results have important implications for the assessment and prediction of pollution hot spots in coastal systems, as well as for planning effective clean-up programs.

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Author contribution

Isabel Jalón-Rojas developed the study concept and performed the analysis under the supervision of Erick Fredj and Xiao Hua Wang. The manuscript was drafted by Isabel Jalón-Rojas and critically reviewed by all other authors. All authors approved the final version of the paper for submission.

Competing interests

The authors declare that they have no conflict of interest.

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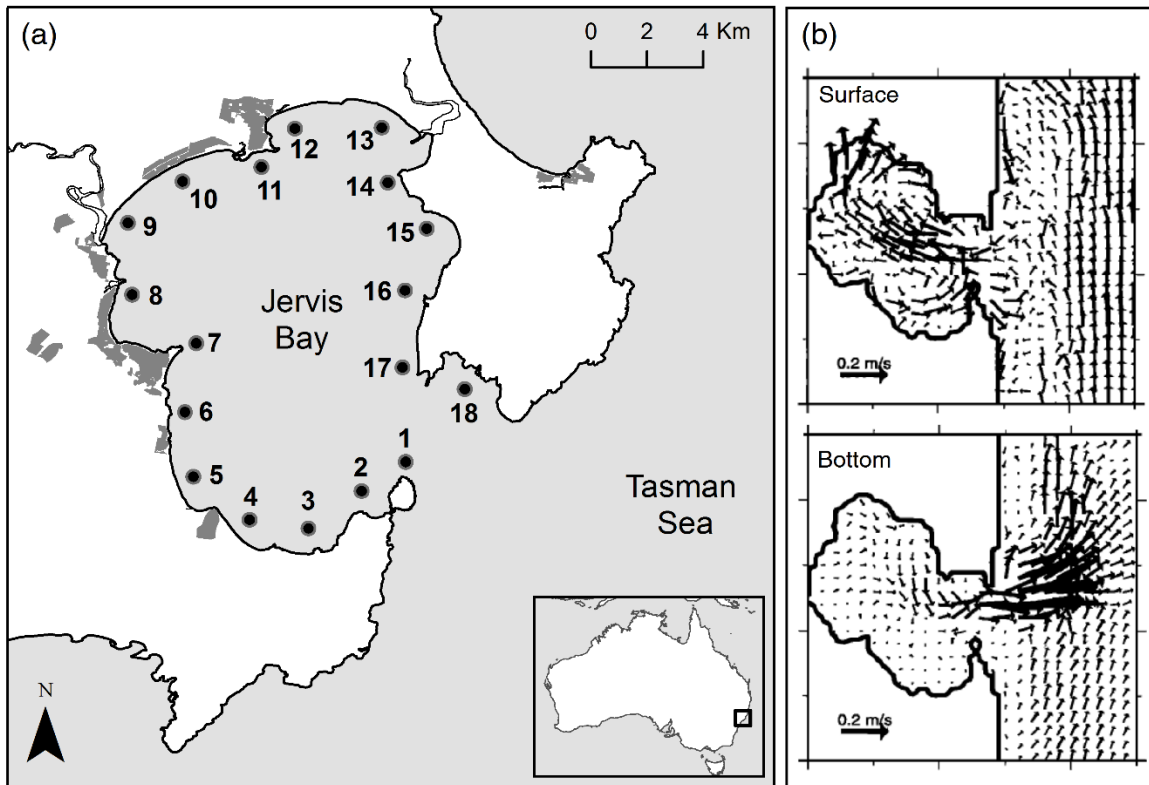


Figure 1: **(a)** Map of Jervis Bay (SE Australia). Black dots show the seeding locations and also the centre of destination regions used in the coastal connectivity analysis. Shaded areas represent urban zones. **(b)** Typical surface and bottom currents of the bay (modified from Wang and Symonds, 1999).

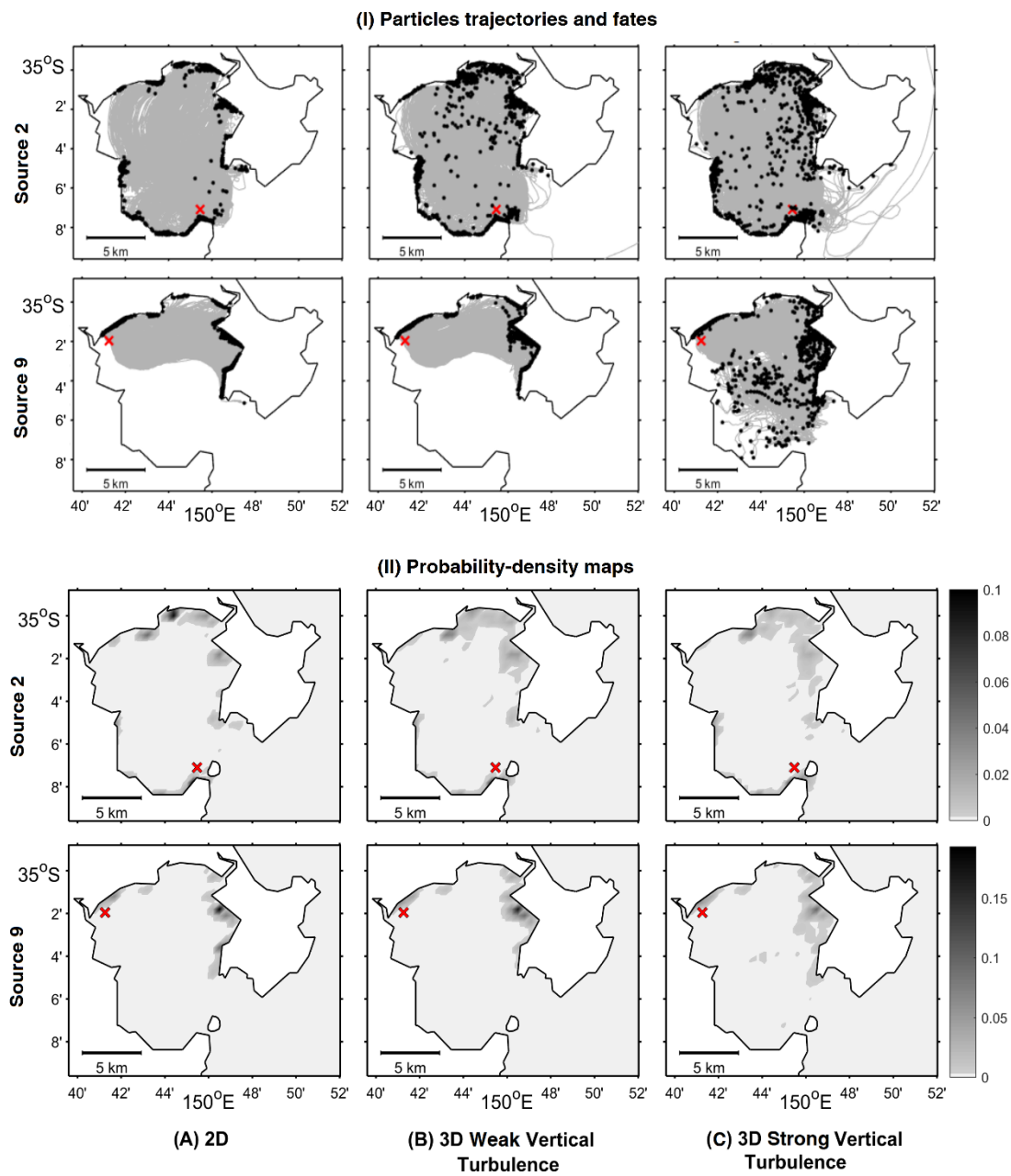


Figure 2: (I) Trajectories (grey lines), fate (black dots) and (II) probability-density distribution (greyscale bar) of microplastics released at sources 2 and 9 (red crosses) after 5 days of simulation for the three different scenarios: (A) 2D approach; (B) 3D approach with weak vertical turbulence; (C) 3D approach with strong vertical turbulence.

