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RESEARCH ARTICLE

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# Dispersal models alert on the risk of non-native species introduction by Ballast water in protected areas from the Western Antarctic Peninsula

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## Abstract

**Aim:** The Western Antarctic Peninsula is challenged by climate change and increasing maritime traffic that together facilitate the introduction of marine non-native species from warmer regions neighbouring the Southern Ocean. Ballast water exchange has been frequently reported as an introduction vector. This study uses a Lagrangian approach to model the passive drift of virtual propagules departing from Ballast water hypothetic exchange zones, at contrasting distances from the coasts.

**Location:** Western Antarctic Peninsula.

**Methods:** Virtual propagules were released over the 2008–2016 period and at three distances from the nearest coasts: 200 (convention for the management of Ballast Water, 2004), 50 or 11 nautical miles (NM).

**Results:** Results show that exchanging Ballast water at 200 NM considerably reduces the arrival of propagules in proposed marine protected areas of the western side of the Antarctic Peninsula. On the eastern side, propagules can reach north-eastern marine protected areas within a few days due to strong currents for all tested scenarios. Seasonal and yearly variations indicate that exceptional climate events could influence the trajectory of particles in the region. Ballast water should be exchanged at least 200 NM offshore on the western side of the Antarctic Peninsula and avoided on the eastern side to limit particle arrival in proposed marine protected areas. Focusing on Deception Island, our results suggested that the Patagonian crab (*Halicarcinus planatus*) observed in 2010 could have been introduced in case of Ballast water exchange at 50 NM or less from the coast.

**Main conclusions:** This study highlights the importance of respecting Ballast water exchange convention to limit the risk of non-native species introduction. Ballast water exchange should be operated at least at 200 NM from the coasts, which further limits particle arrival in shallow water areas. This is especially important in the context of a more visited and warmer Southern Ocean.

Valérie Dulière and Charlène Guillaumot share co first-authorship.

**KEYWORDS**
Antarctic tourism, ballast water, dispersal modelling, invasive species, marine protected areas, maritime traffic, Southern Ocean

## 1 | INTRODUCTION

Antarctic marine life is characterized by high levels of endemism (Griffiths, 2010) as a result of the long climatic, geodynamic and oceanographic histories of the Southern Ocean (Aronson et al., 2007; Clarke & Crame, 2010; Crame, 1999; Pfuhl & McCave, 2005). The Southern Ocean, here, is defined as water masses bounded by the Antarctic continent to the south and the Polar Front to the north (Rintoul, 2009). The Polar Front is the most significant of a series of circumpolar marine fronts associated with the eastward-flowing jets of the Antarctic Circumpolar Current (Orsi et al., 1995). Both the Polar Front and the Antarctic Circumpolar Current form physical barriers preventing Antarctic surface water exchanges between the Southern Ocean and northern ocean areas (Aronson et al., 2007; Griffiths, 2010; Sanches et al., 2016), hence blocking the dispersal of most marine organisms (Convey & Peck, 2019; Peck et al., 2014). As a result of the prevalence of such important marine fronts, combined with strong currents and the remoteness from other landmasses, a unique Southern Ocean marine diversity has been shaped (Barnes & Clarke, 2011; Clarke et al., 2005; Crame, 1999; Lawver et al., 1992).

This unique Southern Ocean marine diversity is however currently challenged by the multiple effects of climate change (Ansorge et al., 2014; Henley et al., 2019). Antarctic coastal marine ecosystems are notoriously sensitive as many shallow-water species have limited resilience abilities and limited southward migration capacities towards more suitable areas (Stenni et al., 2017; Cárdenas et al., 2018; Gutt et al., 2018). Direct and indirect impacts of climate change are expected to alter the structure and functions of these marine ecosystems, leading to species distribution shifts, local extinctions, and favourable conditions for colonization by introduced non-native species (e.g. warmer temperatures, Bender et al., 2016; Hughes & Convey, 2010). Anthropogenic impacts induced by fisheries, tourism and research activities have also been shown to facilitate the transport and introduction of non-native organisms through ship hull fouling and Ballast water exchanges (Hughes & Ashton, 2017; Lee & Chown, 2009c; Lewis et al., 2005).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was created in 1982 to manage marine communities in response to an increasing commercial interest in Antarctic fisheries (such as krill and fish resources) (https://www.ccamlr.org/en/organisation/home-page, accessed October 2020). The Scientific Committee and Commission of CCAMLR yearly review and rule on new marine protected areas projects proposed by national experts. To date, two Antarctic marine protected areas have been initiated and include waters off the South Orkney Islands (in 2009) and within the Ross Sea region (in 2016). Antarctic mineral and core resources are not exploited yet (Westermeyer, 2020) but commercial fishing and tourism are on the rise, in particular along the west coast of the Western Antarctic Peninsula (Bender et al., 2016; Lee & Chown, 2009a; McCarthy et al., 2019). During the last five austral summers (2014–2019), the yearly number of tourists visiting Antarctica has increased from 36,700 to 55,400 (IAATO & International Association of Antarctica Tour Operators, 2019).

As a consequence of increasing human pressure, the Antarctic region has progressively become less isolated and more affected by human footprint (Chu et al., 2019; Joblin, 2020). Among others, the rising maritime traffic has resulted in an increasing risk of introducing non-native species to the Southern Ocean (Bender et al., 2016; Hughes & Convey, 2010), as already reported for terrestrial (*e.g.* the bluegrass *Poa annua*, the brachypterous chironomid *Eretmoptera murphyi* or the enchytraeid worm *Christensenidrilus blocki*, Hughes & Convey, 2010, Chown et al., 2012, Chwedorzewska et al., 2015) and marine environments (*e.g.* the seaweed *Ulva intestinalis*, the crab *Hyas araneus*, the mussel *Mytilus platensis* or the tunicate *Ciona intestinalis*, see Hughes et al., 2020 and McCarthy et al., 2019 for a review). Introduction of non-native species have almost exclusively been reported in the vicinity of research stations and visitor landing sites (Hughes et al., 2015; Lee & Chown, 2009b; Volonterio et al., 2013).

Ship hull fouling and Ballast water release have been reckoned as major vectors of non-native species dispersal and introduction to Antarctic coastal waters (Barnes, 2002; Chan et al., 2015; Hughes et al., 2020; Lavoie et al., 1999; Lewis et al., 2003, 2005). Ballast water tanks are filled at ships' departure ports in South America to safely navigate across the Drake Passage to Antarctica. Fishing vessels progressively discharge most of their Ballast water as it is replaced by their catch. Cruise ships typically discharge Ballast water to travel faster and regularly take up new water to replace the volume left by fuel consumption (Hughes et al., 2020).

Following the Ballast Water Management Convention, by September 2024, all ships will have to conform to the D-2 standard, meaning that all vessels must be fitted with D-2-compliant Ballast water treatment system (https://safety4sea.com/cm-bwm-convention-discharge-standard-d-2-in-full-force/?__cf_chl_jschl_tk__=pmd_bbaba92a72ebf46ebb241c3b6cf01059c8fa75e9-1628238895-0-gqNtZGzNAg2jcnBszQai, accessed August 2021).

Awaiting for this application, the convention itself (Regulation B-4, adopted in 2004) and the echoing text of the Antarctic Treaty Consultative Meeting (ATCM, 2006) both provide intermediate practical guidelines for Ballast water exchange in the Southern Ocean to mitigate the risk of introducing foreign biological particles in coastal areas. Regulation B-4 of the Ballast Water Management Convention mentions that "a ship conducting Ballast Water exchange [...] to meet the standard in regulation D-1 shall: whenever possible conduct such Ballast Water exchange at least 200 nautical miles from the nearest land [...] in case the ship is unable to .... at least 50 nautical miles from the nearest land." Similarly, point 5 of the Antarctic Treaty Consultative Meeting text says "For vessels needing to discharge Ballast water within the Antarctic Treaty area, Ballast water should [...] (be released) at least 200 nautical miles from the nearest land [...] if this is not possible for operational reasons then such exchanges should be undertaken in waters at least 50 nautical miles from the nearest land."

In the present study, a Lagrangian model was developed to simulate the drift of virtual particles as they are transported along the water masses. Such an approach has already been developed in other regions of the world (Edwards et al., 2006; Siegel et al., 2003), but not along the Western Antarctic Peninsula. The model calculates particle trajectories (identified here as potential propagules) according to different point locations where Ballast water is exchanged. This was illustrated by a study on the Patagonian crab, *Halicarcinus planatus* (Fabricius, 1775), reported in Deception Island (nearby Western Antarctic Peninsula coasts) in 2010. The potential impact of Ballast water exchange on the introduction of non-native species in Antarctic coastal waters was analysed through pluri-annual and multi-seasonal time scales. A map of recommended areas for Ballast water exchange is proposed as a tool to support good practices for Ballast water exchange and for conservation purposes.

## 2 | METHODS

### 2.1 | Study area

The study area is enclosed by the strong eastward flowing Antarctic Circumpolar Current (Appendix S1) and includes the Scotia Arc region, the Antarctic Peninsula, and the Weddell Sea, as they concentrate most of the maritime traffic between Antarctica and southern South America and therefore the highest risk of non-native species introduction (Lynch et al., 2010; McCarthy et al., 2019).

### 2.2 | Lagrangian model principle and hydrodynamic settings

In this study, we used a Lagrangian particle model, which combines oceanographic information (*e.g*. bathymetry, current direction and speed) forced by atmospheric factors (temperatures, winds, atmospheric pressure) (Huthnance, 1991; Robinson & Golnaraghi, 1994) with biological features (*e.g*. organisms' size, development rate, buoyancy, Van Sebille et al., 2018). The model used in this study is based on the model described in Dulière et al. (2013) and made available as a module of the free and open-source aquatic modelling system COHERENS v2 (Luyten, 2011). This system has already been used to study, among others, oil spill dispersal (Legrand & Dulière, 2014), jellyfish drift (Dulière et al., 2014) and the movement of harbour porpoises (Haelters et al., 2015). Particles are transported under advective and diffusive processes in three dimensions. The classical fourth-order Runge-Kutta method is used to estimate horizontal transport. The diffusive velocities are obtained from random walk theory with constant horizontal and vertical diffusion coefficients of 10 and 0.0001 $m^2 s^{-1}$, respectively. The same diffusion coefficient values are used as in Young et al. (2014) and are equivalent to values observed in the Southern Ocean (empirical values or commonly accepted by modellers; Sheen et al., 2013; Watson et al., 2013). A bouncing condition is used for particles reaching the sea surface or seabed, and particles that leave the model domain through the ocean open boundary are assumed to have left the region. Stranding is not allowed, because it was considered that a larvae should complete the overall development cycle until metamorphosis to survive (Stanwell-Smith et al., 1999). Thus, when a particle reaches a dry cell, its position is set to its previous position at sea. The Lagrangian module is used off-line with a computation time step of 5 min. To ensure the general purpose of this study, the model has been set up with no specific organismal behaviour (*i.e*. swimming or tidal or diurnal vertical migration). Particles are assumed to move along with water masses (*i.e*. no buoyancy effect), with an assumed initial position at 10 m depth in the water column. A sensitivity analysis was performed to compare predicted trajectories with the initial depth being set up at 200 m. No contrasts were observed between model results. The initial 10 m depth assumption was thus kept, considered more logical regarding Ballast water exchange process.

The hydrodynamic conditions used to force the Lagrangian model are based on the 2008–2016 PHY_001_024 datasets produced by the high-resolution global analysis and forecasting system, provided by Mercator Ocean (Law Chune et al., 2019). These products contain daily mean fields of sea surface elevation and horizontal ocean currents. In addition, they also contain sea ice information (*i.e*. concentration, thickness and velocity), seawater potential temperature, seawater salinity and ocean mixed layer thickness. These datasets have been generated with NEMO 3.1 and LIM2 EVP models forced with 3-hourly atmospheric forcing from ECMWF (European Centre for Medium-Range Weather Forecasts, https://www.ecmwf.int/). Daily averaged model products are made available after interpolation from the native model grid to a global standard Arakawa C grid of 1/12° horizontal resolution and 50 fixed vertical levels (from 0 to 5000 m). The quality of the Global high-resolution products has been assessed in Lellouche et al. (2019). 3D vertical ocean currents are estimated from the divergence in the horizontal velocity from the PHY_001_024 forcing fields, assuming null surface and bottom vertical velocity.

The model grid was built from a sub-sample of the global grid of the hydrodynamic forcing field from latitude 45°S down to the South Pole. The horizontal resolution of 1/12° (~8 km) was kept and the 50 vertical levels have been adapted to 50 sigma levels for the COHERENS system. The Lagrangian particle model has been previously validated in Dulière et al. (2013), Legrand and Dulière (2014) and a quality analysis of the hydrodynamic forcing is provided in Lellouche et al. (2019).

Raw results and R codes used to process them are publicly provided at https://zenodo.org/record/5588220#.YXEfqR3godU (folder "Ballast water paper").

## 2.3 | Particle release scenarios

Three scenarios were defined for simulating drift trajectories of organisms potentially released during Ballast water discharge along the Antarctic coasts, according to the Antarctic Treaty Consultative Meeting (ATCM, 2006). The first scenario considers that Ballast water is exchanged 190 to 210 nautical miles (NM) away from the nearest coasts ("200 NM scenario"), which complies with the Antarctic Treaty Consultative Meeting ratified guidelines (Figure 1a). The two other scenarios represent cases of technical issues preventing from carrying out Ballast water release at 200 NM: the second scenario simulates exchange from 40 to 60 NM from the nearest coasts ("50 NM scenario," Figure 1b) and the third scenario hypothesizes a major transgression of the guidelines, with exchange from 2 to 20 NM from the closest coasts ("11 NM scenario," Figure 1c). Six release zones (Figure 1) were defined: Western Antarctic Peninsula (Rz.1), Eastern Antarctic Peninsula (Rz.2), East Weddell Sea (Rz.3), South Orkney Islands (Rz.4), South Georgia Islands (Rz.5) and South Sandwich Islands (Rz.6).

For each release location, particles were released daily over a 9-year period (from 2008 to 2016) to account for seasonal and inter-annual variabilities. For technical reasons, particles have been released every six grid-cell pixel in latitude (every 1/2°) and every four grid-cell pixel in longitude (every 1/3°), in areas where depth reached at least 200 m (to enable the sensitivity analysis previously described). The number of release locations ranges from 8 (for the South Georgia Islands zone Rz.5 in scenario 11 NM) to 224 (for the Western Antarctic Peninsula zone Rz.1 in scenario 11 NM) release points among the release zones and scenarios. Altogether, it is more than 4.5 million particle trajectories that have been studied in the model. A 6-month duration of the drift was chosen. This matches to the longest duration of larval development periods (corresponding to Southern Ocean species). Larvae should complete this drifting period in the water column before starting metamorphosis and settling down on the seabed (Stanwell-Smith & Clarke, 1998; Stanwell-Smith et al., 1999; White, 1998).

## 2.4 | Particles trajectory and age: statistical comparisons

Model simulations have produced large datasets with model estimations of the daily age and positions (latitude, longitude and depth)

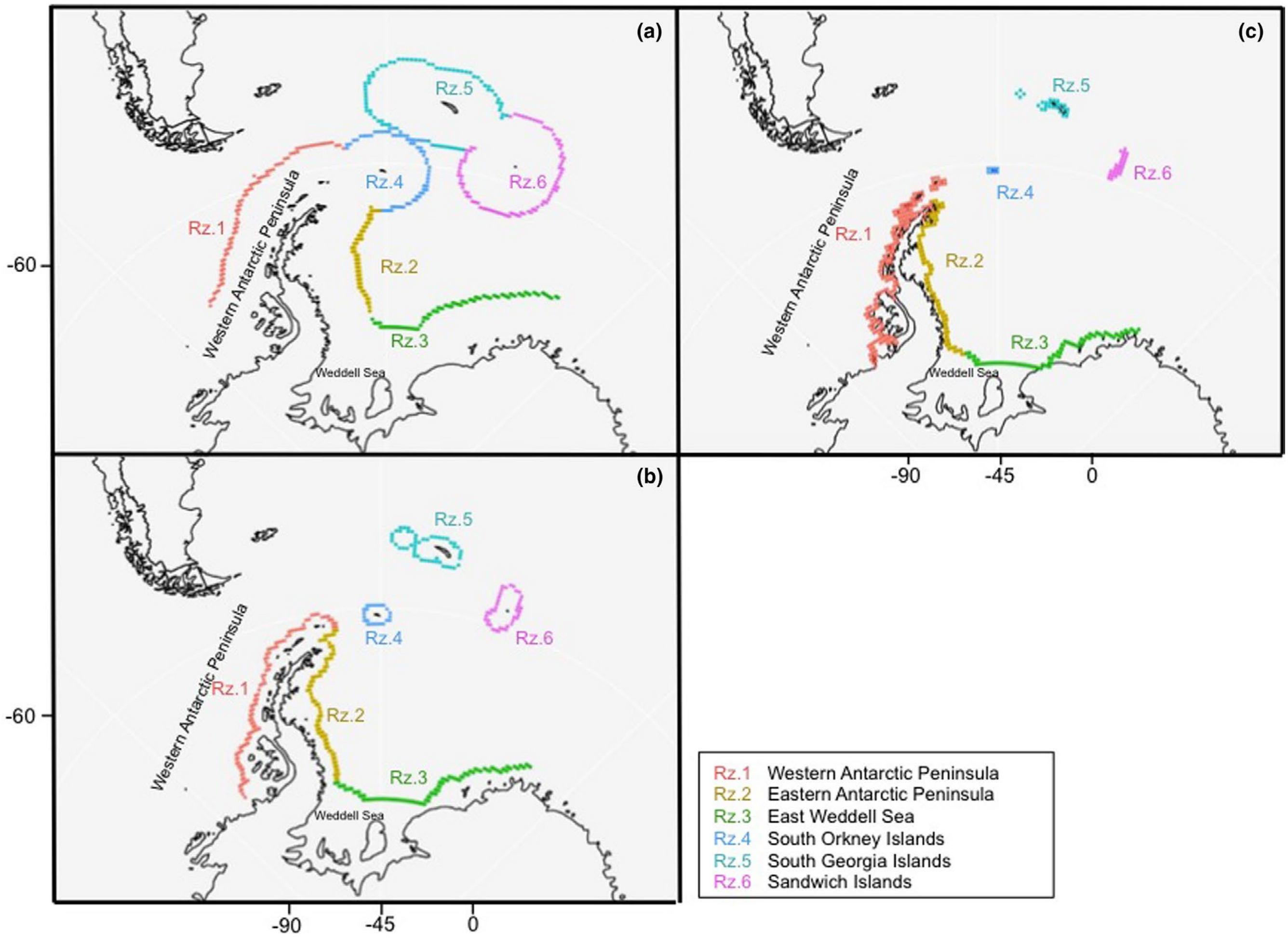


**FIGURE 1** Locations of the six particle release zones for the (a) 200 nautical miles (NM), (b) 50 NM and (c) 11 NM scenarios

of virtual particles. Model results have been post-processed for different years and seasons (January–February–March; April–May–June; July–August–September; October–November–December) and for each Ballast water release scenario, to generate maps of dispersal patterns. Results for averaged years and seasons are first provided to describe the overall dispersal patterns of particles drift. Then, inter-annual and seasonal variabilities are described. Due to the different number of released particles among release areas and scenarios, a scaling correction has been applied for statistical analyses (by dividing the predicted densities by the number of particles present on corresponding release lines—zones where particles were launched, i.e. at 200, 50 or 10 NM; which gives a "weighted number of particles").

## 2.5 | Proposed marine protected areas

The likely consequences of Ballast water exchange on the potential introduction of non-native organisms in marine protected areas of the Western Antarctic Peninsula was assessed by analysing particle entry into proposed marine protected areas. Proposed marine protected areas for this region are the interest of the Chilean and Argentinian delegations at CCAMLR. The SC-CAMLR-38/BG/03 report (CCAMLR report SC-CAMLR-38/BG/03, 2019), proposes seven regulated areas, selected according to multiple arguments, including the spatial distribution of the benthos to top predators, oceanographic processes, climate change and fishing activities (Figure 2). CCAMLR will rule on this proposal at the next international meeting. Among these proposed regulated areas, CCAMLR distinguishes (1) General Protection Zones (GPZ) that aim at protecting habitats, bioregions and species in an attempt to mitigate or eliminate specifically identified ecosystem threats from fishing; and support existing and future scientific research and monitoring and (2) Krill Fishery Zones (KFZ) that include fishing areas in addition to protecting benthic habitats (CCAMLR report SC-CAMLR-38/BG/03, 2019). (3) The established marine protected area of the South Orkney Islands (May 2010) belongs to this conservation proposal and already prohibits any fishing activity, any transshipment activities and any discharge or dumping. All activities occurring in the area should be declared according to the CCAMLR delegation (CCAMLR report 91-03, 2009, Trathan & Grant, 2020).

## 2.6 | Focus on Deception Island

In February 2010, a living and mature female of the brachyuran crab *Halicarcinus planatus* (Fabricius, 1775) was reported in shallow, subtidal waters of Deception Island (Western Antarctic Peninsula) (Aronson et al., 2015) (Figure 3). *Halicarcinus planatus* is usually distributed in shallow water areas of southern South America and along coastal areas of some sub-Antarctic Islands (Falkland, Marion, Crozet, Kerguelen and Macquary islands) (Aronson et al., 2015; Boschi et al., 1969; Richer de Forges, 1977; Varisco et al., 2016). This little crab (shell diameter from 15 to 20 mm, Figure 3) is an opportunistic feeder (Boschi et al., 1969) that is commonly found sheltered below intertidal and subtidal rocks (Richer de Forges, 1977; Vinuesa & Ferrari, 2008).

*Halicarcinus planatus* has a high dispersal potential, with the release of planktonic larvae in the water column that can drift for 45–60 days at temperatures of 11–13°C and 8°C, respectively, before settling on the seabed and triggering metamorphosis (Boschi et al., 1969; Diez & Lovrich, 2010; Richer de Forges, 1977). Recent studies suggest that larvae of *H. planatus* are not capable of drifting across the Southern Ocean due to the strong eastward flow constrained by the Antarctic Circumpolar Current (López et al., unpublished data). If introduced into shallow waters of the Western Antarctic Peninsula (*e.g.* by Ballast water), climate warming is predicted to favour the species' survival (López-Farrán et al., 2021). The hypothesis of a potential introduction of *H. planatus* in Deception Island through Ballast water exchange was tested by sub-setting the model results to a maximum drift period of 2 months, following the known maximal drifting time of *H. planatus* larvae (Boschi et al., 1969; Diez & Lovrich, 2010). The hypothesis has been tested for all three release scenarios.

# 3 | RESULTS

## 3.1 | Dispersal patterns according to the different release scenarios

General dispersal patterns were different among the three release scenarios (Figure 4). The 200 NM scenario leads to the widest dispersal pattern that expands further eastward across the Polar Front to the sub-Antarctic area. The 50 and 11 NM scenarios comparatively lead to narrower and less extended dispersal patterns (Figure 4). Geographical and oceanographic features (such as the Weddell Sea gyre, the Polar Front, the Antarctic Circumpolar Current, the Scotia Ridge) clearly delineate the shape of the dispersal of particles in the corresponding areas.

Release scenarios also show differences in the weighted number of particles (Figure 4), with 15-fold more particles reaching the coastlines for the 11 NM scenario compared to the other scenarios, mainly close-by the coasts of the Western Antarctic Peninsula.

## 3.2 | Recurrent arrivals in marine protected areas during austral summer periods

The number of particles (i.e. gridded weighted number) arriving in each proposed marine protected areas and their origin were summarized in Figure 5. Results show for the austral summer period contrasts between scenarios (Figure 5). The number of particles arriving in all proposed marine protected areas is lower in the 200 NM scenario compared to the 11 NM and 50 NM scenarios, excepted for the South Orkney Island established marine protected area.

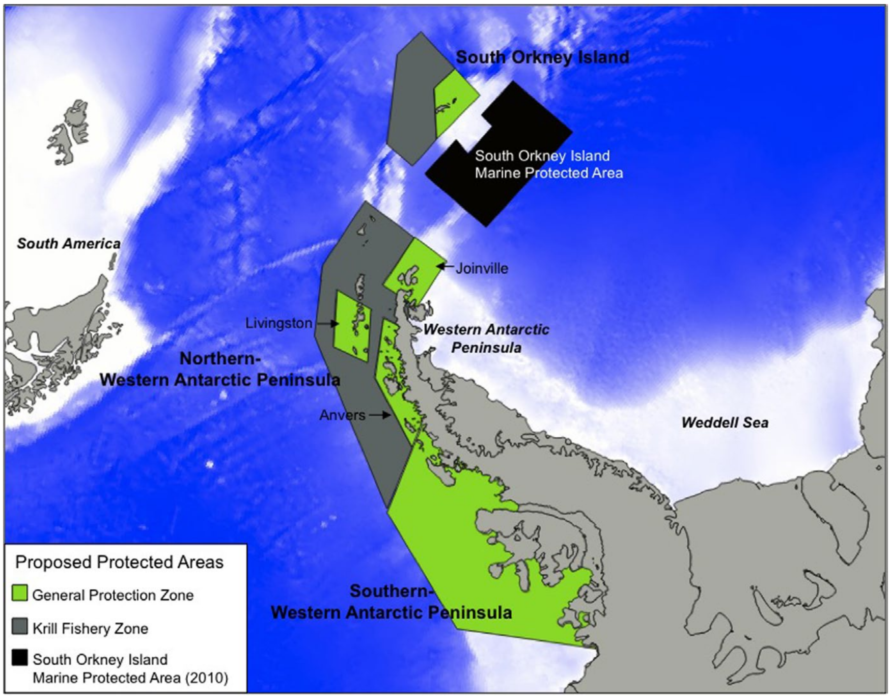


**FIGURE 2** Map of proposed marine protected areas. Modified from SC-CAMLR-38/BG/03 report

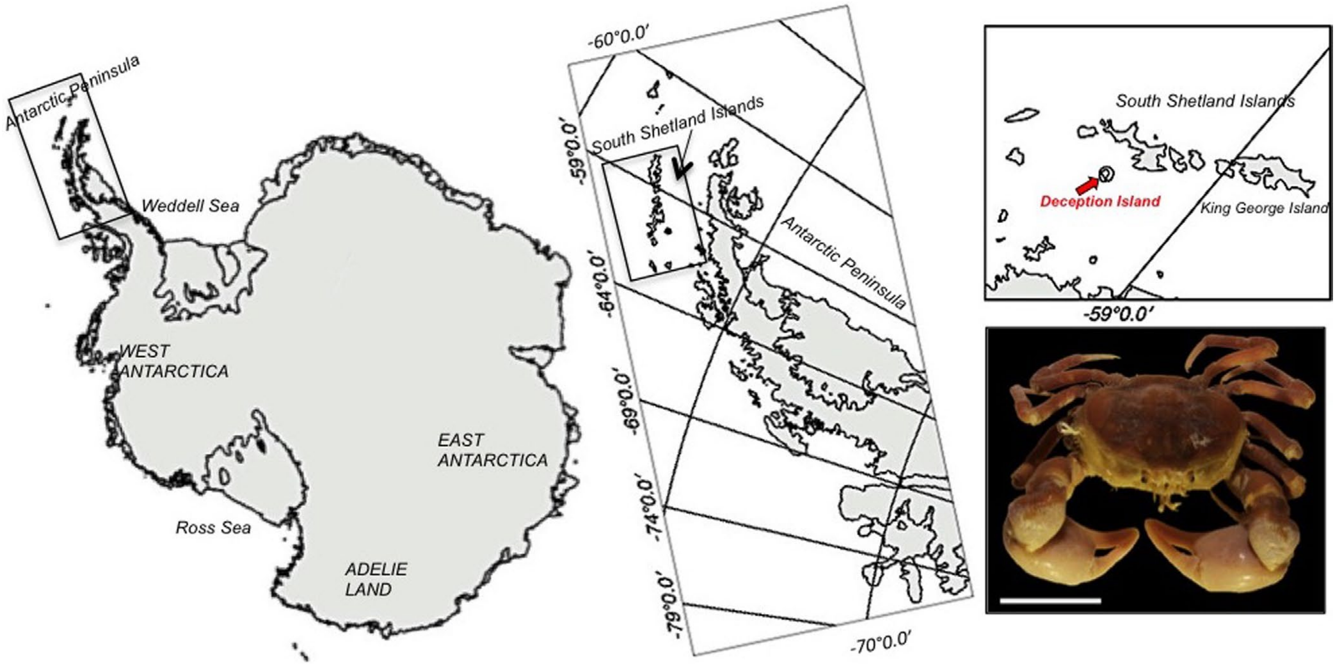


**FIGURE 3** Location of Deception Island in the Western Antarctic Peninsula and representative male individual of the crab *Halicarcinus planatus*, scale = 1 cm © Karin Gérard

These numbers overall decrease by ~99% for the Northern-Western Antarctic Peninsula area, ~30% for the Southern-Western Antarctic Peninsula area, 100% for Anvers, >96% for Livingston and 100% for Joinville, for the 200 NM scenario in comparison to the two other scenarios. Particles that reach marine protected areas in scenario 200 NM mostly originate from the western or eastern coasts of the Western Antarctic Peninsula (Rz.1 and Rz.2).

In the 11 NM and 50 NM scenarios, the marine protected areas of South Orkney Islands (KFZ, GPZ and the already established protected area) are mainly affected by particles released close to South Orkney (Rz.4). Contrastingly, when particles are released 200 NM away from the coasts of South Orkney (Rz.4), the number of particles reaching these three proposed marine protected areas is predicted to strongly decrease (−98.9 and −98.5% for 50 and 11 NM scenarios, respectively). When released from 200 NM offshore, particles coming from the Eastern Antarctic Peninsula zone (Rz.2) drift north-eastward and reach the South Orkney Islands established marine protected area in large numbers. The eastward flow of the Antarctic Circumpolar

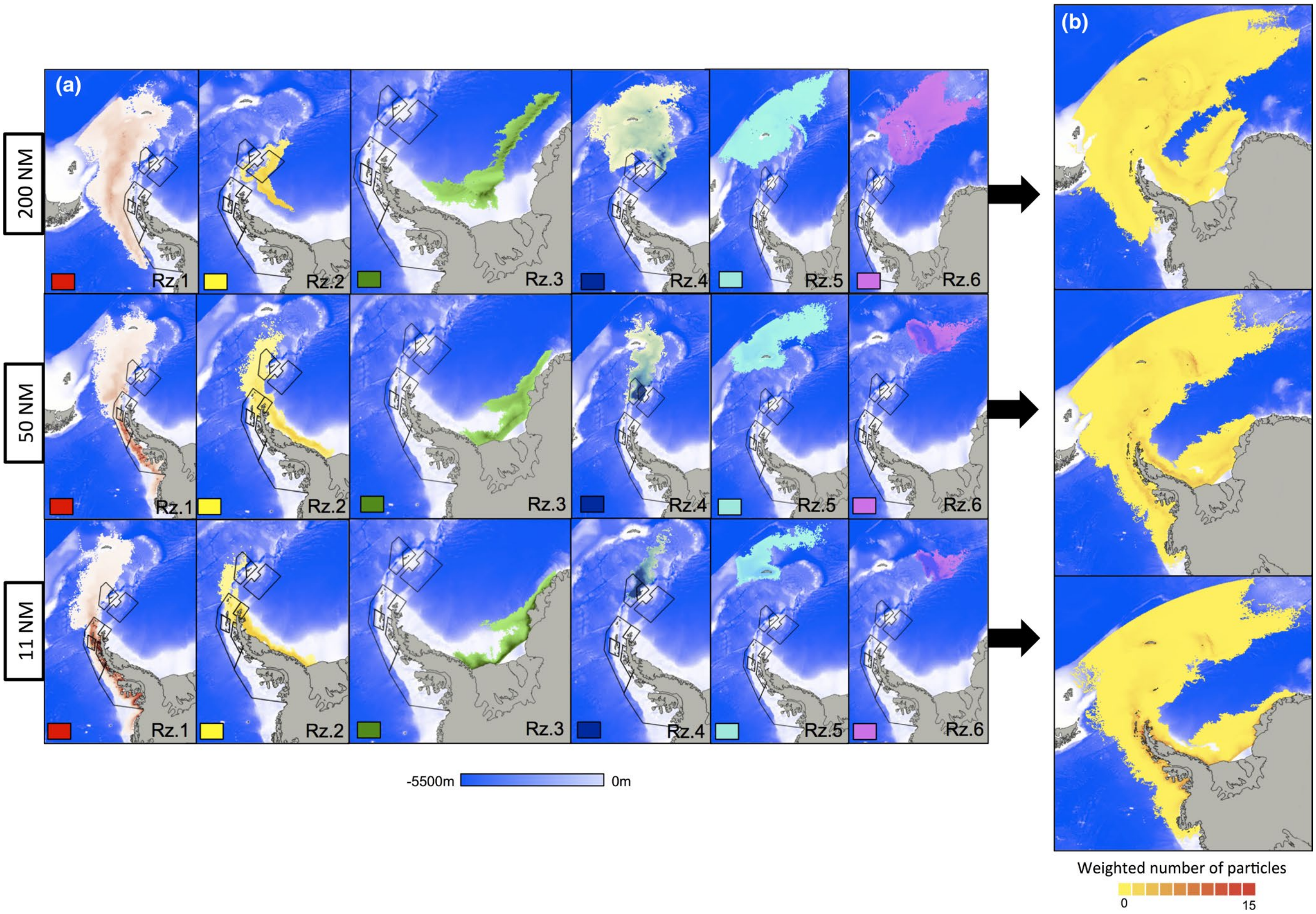


FIGURE 4 Model estimated dispersal patterns for the three release scenarios: 200 nautical miles (NM), 50 NM and 11 NM. Left panels (a): dispersal patterns per release zones (presented in Figure 1); right panels (b) dispersal patterns for all release zones combined. These dispersal patterns are averaged trajectories for the 9-year simulation period, all seasons included. The weighted number of particles is the scaled number of particles, relative to the number of release locations, which differs between scenarios. Blue background: bathymetry chart

Current prevents particles released from South Georgia and Sandwich Islands areas (Rz.5 and Rz.6) to reach the proposed marine protected areas although they might impact other areas located further east. Releasing particles from the Weddell Sea area (Rz.3) also never impacts the proposed marine protected areas.

## 3.3 | Particle age upon arrival in marine protected areas

Figure 6 presents the minimal and average time particles taken to reach studied marine protected areas, after what they may drift to another direction until ending their development cycle. Results provide an indication about the connectivity potential between release zones and marine protected areas. The average age of particles reaching the proposed marine protected areas varies from 93 to 165 days, 74 to 131 days and 59 to 136 days for the 200, 50 and 11 NM scenarios, respectively (Figure 6). For the 11 NM scenario, the first particles generally reach the proposed marine protected areas in less than 10 days (except for the South Orkney Islands established marine protected area) and for the 50 NM scenario, in less than 20 days (except for Anvers and the South Orkney Islands established marine protected area). For the 200 NM scenario, it generally takes longer (over 25 days, except for the Southern-Western Antarctic Peninsula and the South Orkney Islands established marine protected area) for the particles to reach the marine protected areas. Particles reaching the Southern-Western Antarctic Peninsula, the Northern-Western Antarctic Peninsula and the marine protected areas of South Orkney Islands (KFZ, GPZ and the already established protected area) are older when released at a distance of 11 NM from the coast than when released at a distance of 50 NM.

## 3.4 | Intra- and inter-annual variabilities

Comparison of dispersal patterns among the nine simulated years show inter-annual variations in the extent of dispersal areas: such variation is mainly noticeable in the sub-Antarctic region and in the East Weddell Sea. Inter-annual variation is more obvious in the 11 NM scenario relative to the total extent of the dispersal pattern (Figure 7; right panel). Interestingly, the dispersal area is broader in

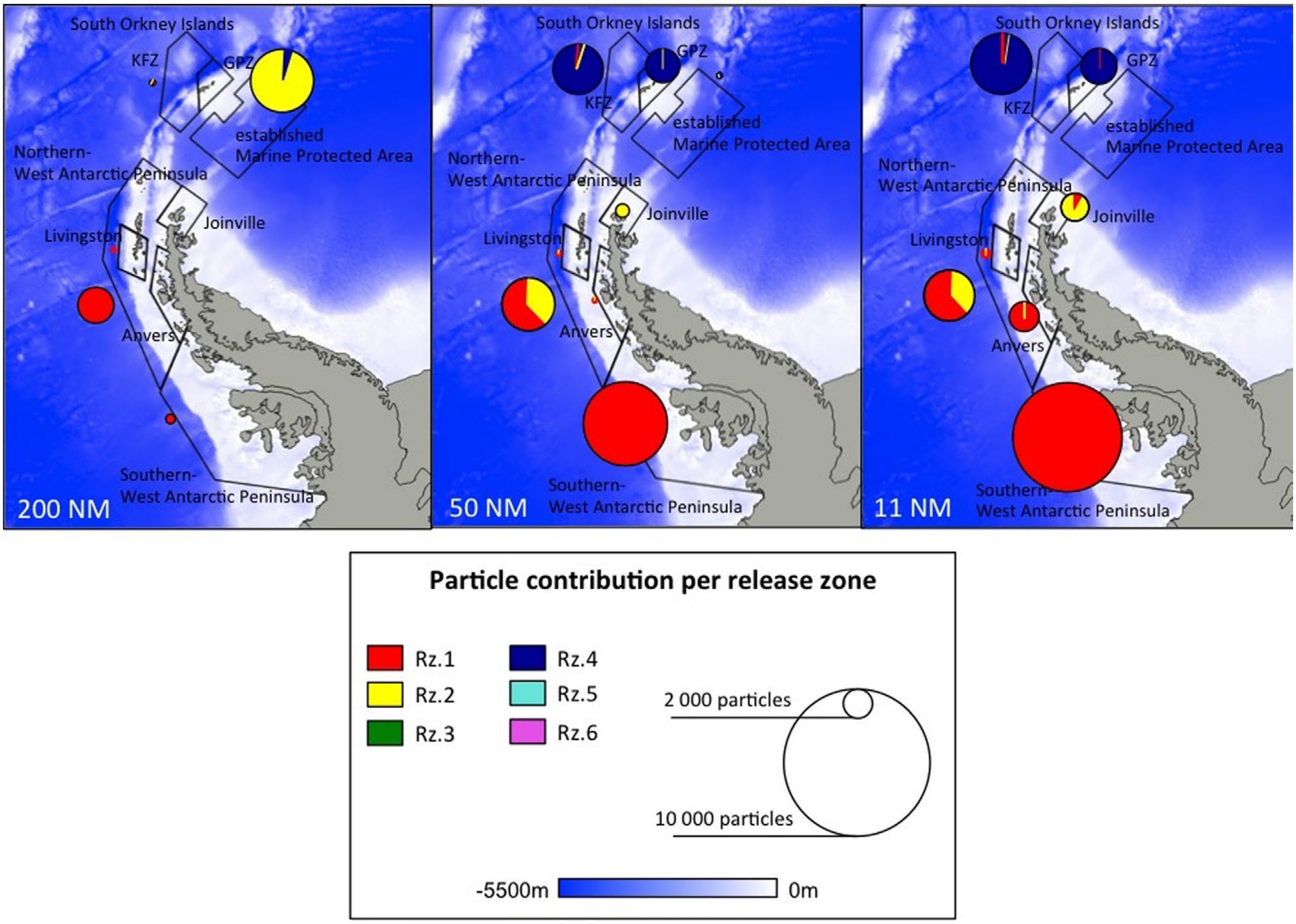


**FIGURE 5** Sums of the weighted numbers of particles reaching the proposed marine protected areas during the January–February–March season (austral summer, being the season with the largest number of ships entering the Southern Ocean) over the 9-year period (2008–2016) and for each release scenario (200 nautical miles (NM), 50 NM and 11 NM). Release zone positions are shown in Figure 1. Details about proposed marine protected areas are given in Figure 2

years 2008 and 2009, more extended to the east in 2014 and 2015 and conversely, more contracted in 2011 and 2012 (results not shown). Inter-seasonal variation is comparatively less marked than inter-annual variation (Appendix S2). Contrasts between years in particle distributions are mainly found in the north-eastern part of the studied area, above the Weddell Sea and in the southern part of the Western Antarctic Peninsula (Figure 7).

Inter-seasonal and inter-annual variations in the origin of particles (release zones) that reach the proposed marine protected areas highlighted a comparable influence of years and seasons on dispersal contrasts (Figure 8). The origin of particles reaching the marine protected areas located along the Western Antarctic Peninsula (Northern-Western Antarctic Peninsula, Southern-Western Antarctic Peninsula, Livingston, Anvers, Joinville), and especially the one located in the south (Southern-Western Antarctic Peninsula) is less variable. In these marine protected areas, particles mainly originate from the Western Antarctic Peninsula and the Eastern Antarctic Peninsula zones (Rz.1, Rz.2).

The variability in the origin of particles reaching the marine protected areas of South Orkney Islands (KFZ, GPZ and the already established protected area), located further north-eastward, is much higher and strongly varies according to the release scenario, season and year (Figure 8). Particles mainly originate from the Western Antarctic Peninsula, the Eastern Antarctic Peninsula or the South Orkney zones (Rz.1, Rz.2 and Rz.4, respectively). Few particles (less than 100 particles, *i.e.* less than 2%) also come from the South Georgia zone (Rz.5). These proportions are logically low given the strong Antarctic Circumpolar Current movement that directs particles eastward (Figure 8).

### 3.5 | Invasion risks

Previous results were summarized in a synthesis map (Figure 9) that indicates the release zones and the simulated risk of particle introduction into proposed marine protected areas. We defined a "high risk," when models simulate the arrival of particles every year and every season in all neighbouring marine protected areas. The "no risk" exchange zones correspond to zones where released particles never reach any proposed marine protected areas. A "moderate risk" category was

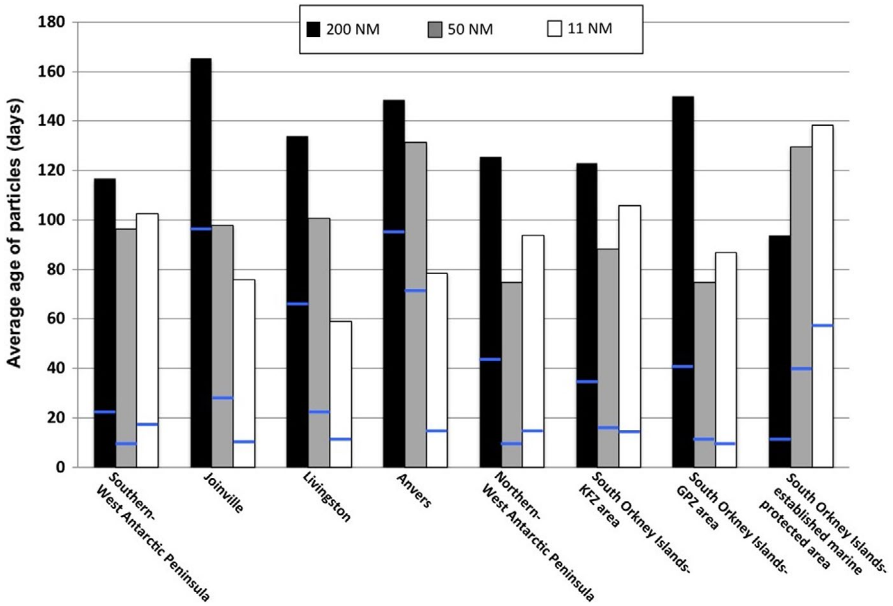


FIGURE 6 Age of particles (in days) reaching the proposed marine protected areas under the 200 nautical miles (NM) scenario (black), 50 NM scenario (grey) and 11 NM scenario (white) for the January–February–March season. Values are averaged over the 9 years (2008–2016), blue solid horizontal lines indicate the average year minimal value recorded within the period (2008–2016). KFZ stands for "Krill Fishery Zone," GPZ for "General Fishery Zone" (see /Proposed marine protected areas in the Material and Method section)

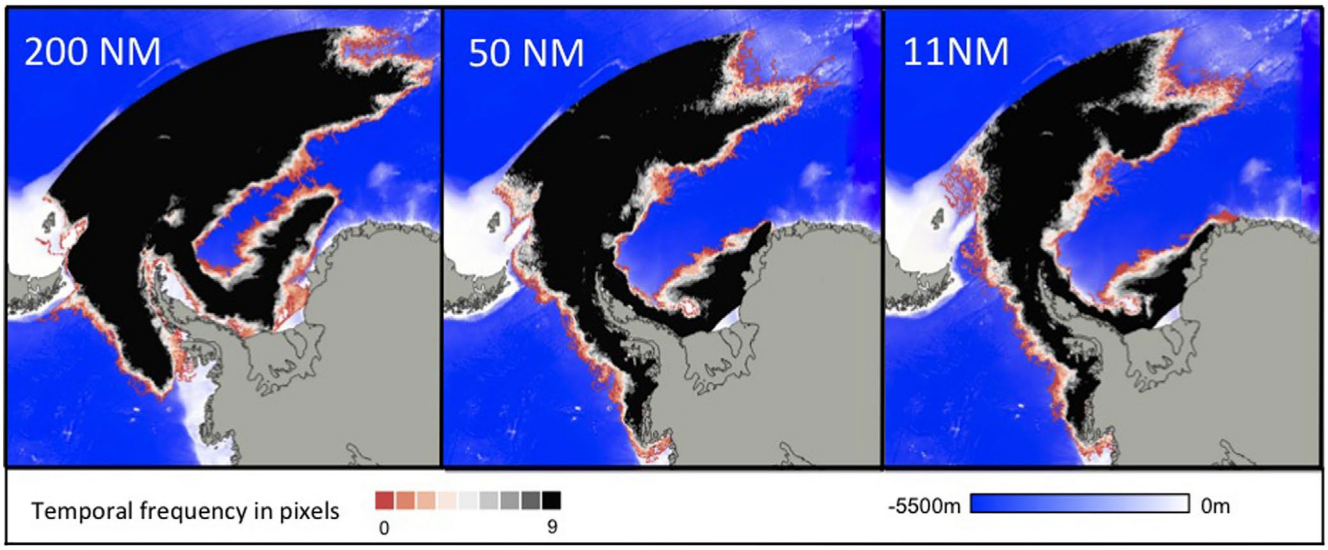


FIGURE 7 Model estimated dispersal patterns assuming the release scenarios: 200, 50 and 11 nautical miles (NM), for particles released from all release zones at the same time. Colours represent the frequency of occurrence among the 9 years (2008–2016) with a maximal score of 9 for pixels that receive particles every year. Blue background: bathymetry chart

added for zones where particles may not reach neighbouring marine protected areas during some years and some seasons (according to climatic events) and/or in significantly lower densities.

Results clearly show that releasing Ballast water on the western and eastern sides of the Western Antarctic Peninsula and nearby Scotia Islands generally leads to a high to moderate risk to introduce particles into proposed marine protected areas, even if released at 200 NM from the nearest coast. In the case of Ballast water exchanged in the East Weddell Sea and around Sandwich Islands (Rz.3 and Rz.6, respectively) particles never reach proposed marine protected areas.

## 3.6 | A focus on Deception Island

When Ballast water is exchanged from distances exceeding 200 NM from the nearest coasts, the Lagrangian model predicts

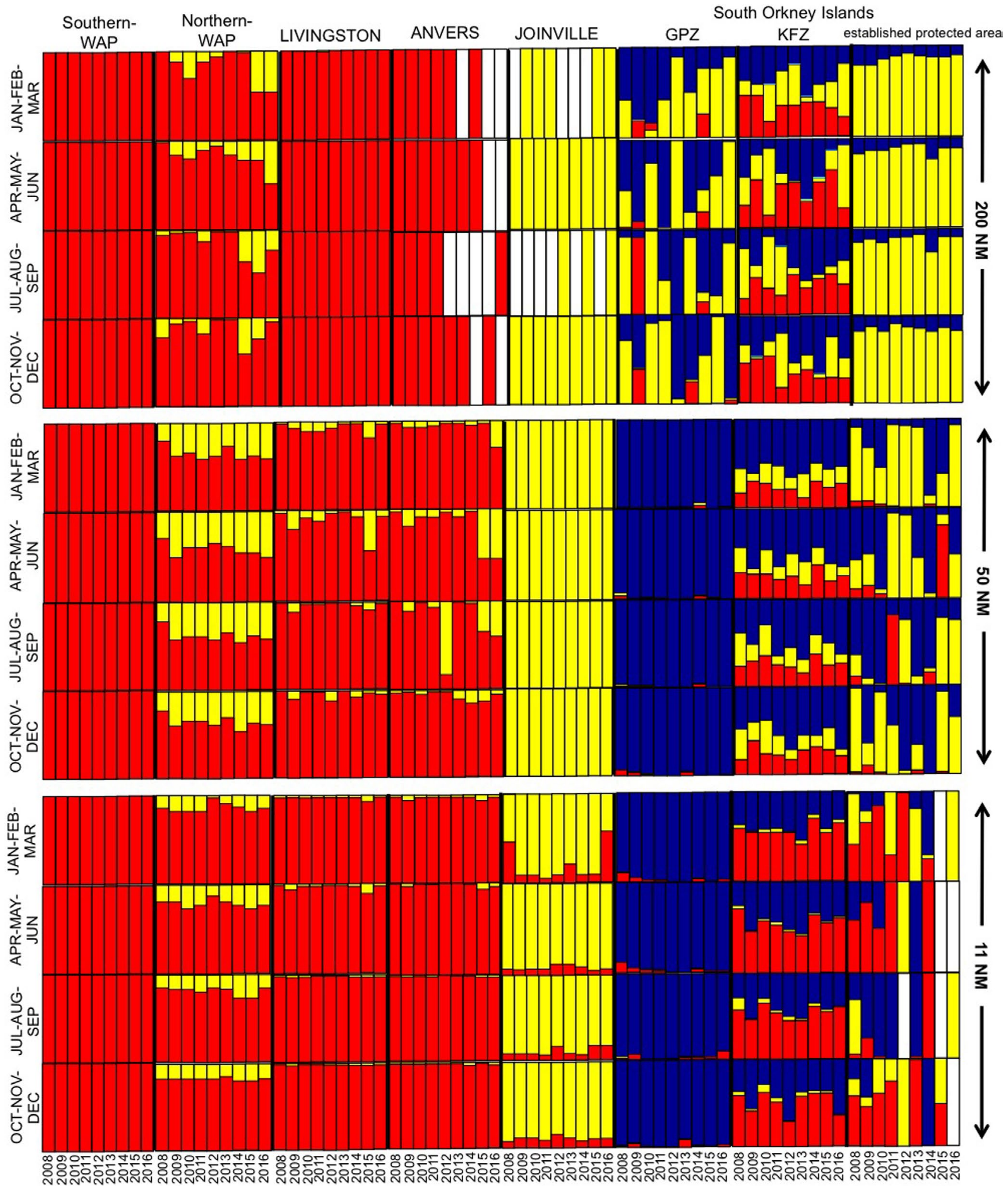


**FIGURE 8** Intra- (vertical sub-panels) and inter-annual (horizontal sub-panels) variations in the origin (release zone) of particles reaching the proposed marine protected areas according to the 200, 50 or 11 nautical miles (NM) scenarios. Red: Western Antarctic Peninsula (Rz.1), yellow: Eastern Antarctic Peninsula (Rz.2), dark blue: South Orkney Islands (Rz.4) and turquoise: South Georgia (Rz.5) (very small proportions for KFZ-SOI for 200 NM scenario). Acronyms for the marine protected areas are presented in Figure 2. WAP stands for Western Antarctic Peninsula. KFZ stands for “Krill Fishery Zone” and GPZ for “General Fishery Zone” (see/Proposed marine protected areas in the Material and Method section)

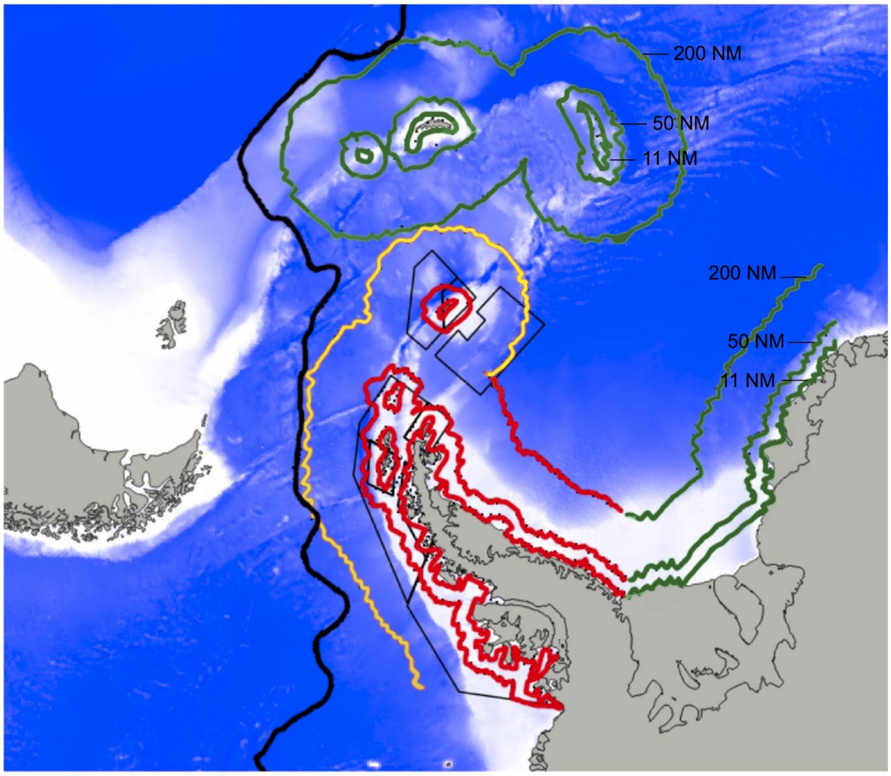


**FIGURE 9** Ballast water exchange zones and their associated simulated risk (dark green: "no risk"; yellow: "moderate risk"; red: "high risk") for particles to reach proposed marine protected areas. The black solid line represents the Polar Front yearly mean position. The risk was estimated for proposed marine protected areas of the considered region only. Other areas that might also be at risk were not included in this study. Distances to the coasts of the different release scenarios (200, 50 or 11 NM) are precised on the figure

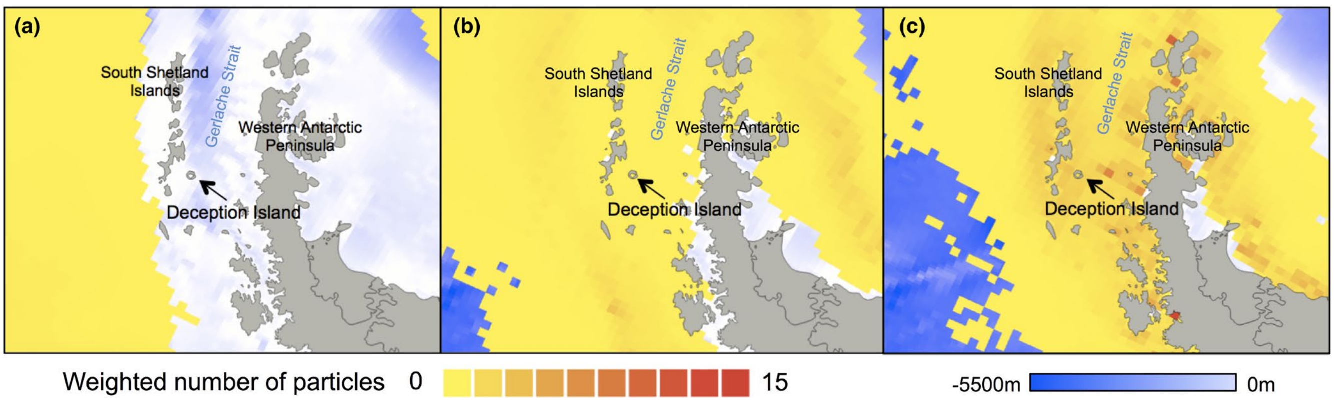


**FIGURE 10** Model estimated dispersal patterns, averaged for the 9-year period (2008–2016), for the January–February–March season (southern summer). Particle drift was simulated during 2 months. The weighted number of particles was obtained by scaling the number of particles by the number of release locations (which differ among scenarios). Results are presented for the three different release scenarios: (A) 200 nautical miles (NM), (B) 50 NM and (C) 11 NM. Particles are released in all areas at the same time. Blue background: bathymetry chart

that no particle reaches the coasts of the Western Antarctic Peninsula, nor the Gerlache Strait where Deception Island is located (Figure 10a). In contrast, particles reach Deception Island and the Gerlache Strait within 2 months drift under the 50 NM and 11 NM scenarios (Figure 10b,c). The weighted number of particles reaching the South Shetland Islands, entering fjords and drifting along the coasts is up to 15 times larger in the 11 NM scenario than in the 50 NM one; a very constant result across years (Appendix S3) and seasons (results not shown). Results are less uniform in the 50 NM scenario, where inter-annual variations cause particles to reach the Gerlache Strait and Deception Island either completely (2009, 2010, 2011, 2012) or partly (2008, 2013, 2014, 2015, 2016).

## 4 | DISCUSSION

### 4.1 | Particle dispersal

Lagrangian models have been widely used over the last decades for defining and delineating marine protected areas in many different regions and oceans (Berglund et al., 2012; Burgess et al., 2014;

Gaines et al., 2003; Thomas et al., 2014) and to study the spread dynamics of invasive species (Brandt et al., 2008; Brickman, 2014). In the Southern Ocean, Lagrangian models have already been used to simulate dispersal abilities and the distribution of fish species or top predators, to understand the main key drivers of population connectivity and assess the position of the main foraging areas, in the aim of determining an effective management of natural resources (Della Penna et al., 2017; Young et al., 2012, 2014, 2015).

In the present work, daily variations of the environment were simulated over a 9-year period and model outputs were analysed to test the significance of dispersal patterns with regard to inter-seasonal and inter-annual variations. In simulating a large number of particles, Lagrangian models integrate natural variability of hydrodynamic systems (Van Sebille et al., 2018). However, the model should rely on assumptions (parameterization of the general environment, of the properties of the simulated particle), which may not be trivial considering the broad spatial scale of the analysis, the overall system complexity and the unknown propagule pressure state (*i.e.* occurrence and density of non-native species in ship Ballast water). Furthermore, some propagule traits such as buoyancy, physiology, survival rate and tidal behaviour were hypothesized; the actual traits of invasive species could potentially have a substantial impact on model outputs (Barbut et al., 2019; Miller & Morgan, 2013; North et al., 2008; Stanwell-Smith et al., 1999; Young et al., 2012), as well as the influence of climate change through its impacts on the physiology and dispersal potential of marine larvae (Quinn, 2017). Some sensitivity analysis could also be realized to improve our results, for instance to evaluate the assumption of the larval drift duration.

Model simulations show that in 6 months, particles can drift along the coasts of the Western Antarctic Peninsula up to South Georgia, driven by the power of the Antarctic Circumpolar Current and highlighting the importance of connectivity between Antarctic coasts and the Scotia Sea region (Appendix S1, Rintoul, 2009; Caccavo et al., 2018; Moffat & Meredith, 2018). Other oceanographic features such as the Weddell Sea gyre and major marine fronts off the Scotia Sea (Polar Front) (Della Penna et al., 2017), along with geomorphological features such as the South Orkney Ridge or the South Georgia shelf also clearly influence dispersal patterns (Figure 4; Vernet et al., 2019; Young et al., 2012, 2015). These features also play a crucial role in the connectivity among sub-Antarctic islands (Young et al., 2012).

Comparisons of the three different scenarios indicate that the distance at which Ballast water is exchanged from the nearest coasts has significant impacts on particle trajectories, on the frequency and weighted number of particles reaching the Antarctic coasts (Figures 4–7). Overall, particles are less likely to reach Antarctic coastal areas when Ballast water is exchanged at least 200 NM away from the nearest coasts (Figures 4 and 5).

Inter-seasonal and inter-annual variability were also shown to have significant effects on modelled dispersal patterns (Appendix S2, Figures 7 and 8). This was expected here, given that Southern Ocean hydrodynamics are highly controlled by the variability of atmospheric and climate regimes at both high and low frequencies (Henley et al., 2019). Indeed, some of our results indicate that in years 2009, 2014 and 2015 particles were spread furthest while dispersal was the lowest in 2011 and 2012. These results are linked to specific climate events and in particular, to regimes of westerly winds in link with El Niño Southern Oscillation events (Carvalho et al., 2005; Ciasto & Thompson, 2008; L'Heureux & Thompson, 2006; Limpasuvan & Hartmann, 1999). Years 2009, 2014 and 2015 were characterized by strong El Niño episodes (warmer temperatures and stronger westerly winds which make the particles drift further east); in contrast, years 2010–2011 were characterized by strong positive Southern Ocean Indexes and with La Niña episodes (weaker westerly winds, dryer and colder atmosphere and a narrower extension of particle drifting area) (Nicolas et al., 2017).

### 4.2 | Results' overview in the general context

The Western Antarctic Peninsula is among the regions on Earth that experience climate warming at the fastest pace, where rising temperatures also directly or indirectly drive other environmental shifts (*i.e.* glacier melting, phytoplankton community shifts, changes in sea ice duration and extent) (Bers et al., 2013; Convey et al., 2009; Convey & Peck, 2019; Schofield et al., 2017; Schram et al., 2015). This makes the Western Antarctic Peninsula one of the most sensitive regions to potential invasions by introduced species in Antarctica (Hellmann et al., 2008; Hughes et al., 2020; McGeoch et al., 2015; Meredith & King, 2005). Increased temperatures and related environmental shifts indeed may favour the acclimation of non-native species introduced from warmer climates over cold-adapted native taxa (Galera et al., 2018; Hellmann et al., 2008).

For a few decades, maritime traffic has also steadily increased in the Southern Ocean and in the Western Antarctic Peninsula in particular, due to its relative proximity to harbours of southern South America (McCarthy et al., 2019). This increasing traffic has been cited as the main cause for non-native species introduction in coastal waters of the Western Antarctic Peninsula (Avila et al., 2020; Cárdenas et al., 2020; Diez & Lovrich, 2010; Fraser et al., 2018; Lee & Chown, 2007; McCarthy et al., 2019; Tavares & De Melo, 2004; Thatje & Fuentes, 2003).

Our study is strongly embedded within this context, by evaluating the impact of ship circulation on marine environments, and in marine protected areas in particular. Results highlight the importance of the distance of Ballast water exchange from coasts to control the frequency and density of particles reaching Antarctic coasts. Focusing more specifically on Deception Island, our simulations indicate that no particle reaches the Gerlache Strait when Ballast water are exchanged at 200 NM from the coasts, suggesting that the non-native crab *H. planatus* could not have been introduced to Deception Island due to Ballast water exchange if the Ballast Water Management Convention and Antarctic Treaty guidelines had been respected. If the introduction to Deception Island indeed occurred through Ballast water of cruise ships sailing southwards from ports of southern South America, which we consider to be a likely scenario, the crab must have been released at a distance equal or less than 50 NM from the Antarctic coasts (Figure 10, Appendix S3). Another hypothesis could be its introduction by ship hull biofouling (Chan et al., 2015; Hughes & Ashton, 2017; Lee & Chown, 2009c), which has not been tested here. These results could be generalized to other species, with the ensuing consequences of species introductions (Britton et al., 2018; David et al., 2017; Walsh et al., 2016).

Our results also highlight that the variability in climate regimes has a strong effect on dispersal patterns: in certain years, particles may drift further and reach areas that are on average not considered to be potentially impacted by non-native species introduction via Ballast water exchange, as already discussed by Fraser et al. (2018) and Waters et al. (2018) for kelp rafting. Other authors stressed the significance of transient events in long-distance dispersal (Leese et al., 2010; Saucède et al., 2014). Such events may become more frequent in future decades, owing to ongoing climate change, since climate projections for the Southern Hemisphere for the 21st century predict a further southward shift and intensification of storm tracks (Perlwitz, 2011) and therefore hypothesize an increasing threat for potential species introductions (Hughes et al., 2020).

### 4.3 | Future management of marine protected areas

The Antarctic Treaty (ATCM, 2006) guidelines recommend that Ballast water should be discharged north of the Polar Front before entering Antarctic waters and "preferably north of either the Antarctic Polar Frontal Zone or 60°S, whichever is the furthest north." In practice, the position of the Polar Front is usually noticed after passing it and exchanging Ballast water in these regions is not realistic considering the weather and sea conditions (Wallis B., person. comm.). Consequently, the 200 NM guidelines, provided both by the Ballast Water Management Convention and the Antarctic Treaty texts, should be as widely as possibly applied by ships that sail across the Polar Front. Our results however suggest that releasing Ballast water at 200 NM around the Western Antarctic Peninsula (Rz.1) may still lead to particles reaching the Antarctic coasts including, the eastern and northernmost proposed marine protected areas of the region (notably Northern and Southern-Western Antarctic Peninsula and Livingston; Figures 5 and 8). The particle numbers reaching the Antarctic coasts are considerably reduced when released at 200 NM from the nearest coasts than when released at 50 NM or 11 NM. Although the origin of particles arriving in marine protected areas varies among years and seasons, the model indicates that Ballast water exchange should best be conducted further away than 200 NM or wherever possibly, avoided altogether on the western side of the Antarctic Peninsula (Figure 9).

When Ballast water is exchanged on the eastern side of the Western Antarctic Peninsula (Eastern Antarctic Peninsula Rz.2 and South Orkney Islands Rz.4), particles are predicted to drift northeastward in the sub-Antarctic region, reaching the protected areas of the South Orkney Islands region within a few days at the earliest, and within 3 months on average (Figures 5–8). Regardless of the release scenario, our simulations indicate that it is not possible to prevent particles from reaching the aforementioned marine protected areas when Ballast water is discharged on the eastern side of the Western Antarctic Peninsula (Eastern Antarctic Peninsula Rz.2; Figures 5 and 8). Avoiding this region for Ballast water exchange is therefore recommended (Figure 9). Exchanging Ballast water in the East Weddell Sea and around South Georgia and Sandwich Islands (Rz.3, Rz.5 and Rz.6, respectively) results in the absence of particles reaching the marine protected areas. East Weddell Sea (Rz.3) is however not suitable for Ballast water exchange due to practical reasons, because this region is ice-covered all year long (Vernet et al., 2019). Results also show that particles released in the South Georgia and Sandwich Islands region will not reach the proposed marine protected areas of the Western Antarctic Peninsula, but the impact on islands located further east was not investigated in the present work.

Given the dense and increasing maritime traffic along the Antarctic Peninsula and Scotia Sea regions, the present model could be improved with more detailed data on ship routes, Ballast water discharge events (Hughes et al., 2020; McCarthy et al., 2019) and propagule pressure within stored water (Lee & Chown, 2009a). Our results strongly highlight the importance of the upcoming 2024 regulation to further protect Antarctic marine life from non-native species introduction, in complement to conservation measures applied for visitors and ships approaching Antarctic coasts (Hughes et al., 2020; Lennox et al., 2015; McGeoch et al., 2015).

## 5 | CONCLUSIONS

This study provides insights on how Ballast water exchange can contribute to the arrival of non-native species in current and proposed marine protected areas of the Western Antarctic Peninsula, being one of the most vulnerable Antarctic regions to biological invasions.

Awaiting for the compulsory settlement of ballast water treatment systems on vessels (in 2024), the existing Ballast water guidelines so far ruled by the Ballast Water Management Convention and Antarctic Treaty (Antarctic Treaty, 1959; ATCM, 2006) are not sufficient to prevent the introduction of species in these marine protected areas, although respecting Ballast water discharges at 200 NM away from the nearest coasts lowers the risk of introduction. This is especially true for Ballast water being exchanged in the areas of the western and eastern Western Antarctic Peninsula. Because of the expected future increase in maritime traffic and the correlated risk of non-native species introduction and invasions potentially increasing due to global warming, we here advocate for delineating Ballast water discharge zones, so that propagules released within Ballast waters would not reach the most fragile Antarctic ecosystems. These discharge zones could be further fine-tuned with more data about maritime traffic and accounting for climatic variability.

We also recommend increasing the ratified distance of Ballast water exchange over 200 NM in the Western Antarctic Peninsula and avoiding discharges in the Eastern Antarctic Peninsula, two recommendations that could be included in future marine protected area proposals. This study shows that Ballast water exchange at 50 NM or closer to the coasts pose a dangerous threat, as these results in drifting propagules reaching Antarctic coasts. This is in particular exemplified by the case study of the introduction of the Patagonian crab *H. planatus* in Deception Island. Our results indicate that, if the crab was indeed brought after Ballast water discharge, the Ballast water would have likely been discharged at 50 NM or closer to the Antarctic coast.

Finally, Ballast water regulation is not the only alternative to mitigate non-native species introduction, as they can also be introduced by the biofouling of ships; another serious threat to be considered for next conservation steps.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/ddi.13464.

## DATA AVAILABILITY STATEMENT

Codes to run the Lagrangian model are difficult to provide, they rely on a complex network of scripts generally described in https://odnature.naturalsciences.be/coherens/getting-started/run-coherens. You can email Valérie Dulière if you want a compilation of the scripts and some help to run the codes (vduliere@naturalsciences.be). Otherwise, raw results and R codes used to process them are publicly provided at https://zenodo.org/record/5588220#.YXEfqR3godU (folder "Ballast water paper").

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## BIOSKETCH

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Author contributions: Valérie Dulière, Charlène Guillaumot and Katrijn Baetens co-conceived the idea, designed the scenarios, analysed and interpreted the results and wrote the manuscript. Zambra López contributed to the development of the idea, Valérie Dulière developed the model, carried out the model simulations and contributed to the post-processing of the model results and figure production. Charlène Guillaumot post-processed the model results and produced the figures. All authors provided critical feedback and contributed to the final version manuscript.

## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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