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Basin-scale sources and pathways of microplastic that ends up in the Galápagos Archipelago

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Abstract. The Galápagos Archipelago and Marine Reserve lies 1,000km off the coast of Ecuador and is among the world's most iconic wildlife refuges. However, plastic litter is now found even in this remote and iconic island archipelago. Prior to this study, the sources of this plastic litter on Galápagos coastlines were unidentified. Local sources are widely expected to be small, given the limited population and environmentally-conscious tourism industry. Here, we show that remote coastal sources of plastic pollution are also fairly localized and limited to South and Central American coastlines, in particular Northern Peru and Southern Ecuador. Using virtual floating plastic particles transported in high-resolution ocean surface currents, we analysed the backward-in-time and forward-in-time pathways and connectivity between the Galápagos region and the coastlines around the East Pacific Ocean. We also analysed how incorporation of wave-driven currents (Stokes drift) affects these pathways and connectivity. We found that only virtual particles that enter the ocean from Peru, Ecuador and (when waves are not taken into account) Colombia can reach the Galápagos. It takes these particles a few months to travel from their coastal sources on the American continent to the Galápagos region. The connectivity does not seem to vary substantially between El Niño and La Niña years. Identifying these sources and the timing and patterns of the transport can be useful for identifying integrated management opportunities to reduce plastic pollution from reaching the Galápagos Archipelago.

1 Introduction

Marine plastic litter has in only a few decades time become ubiquitous in our oceans (e.g. Law, 2017). Plastic is now found in even the most remote locations, including the deep seafloor (Woodall et al., 2014), uninhabited islands (Lavers and Bond, 2017), in the Arctic (Cózar et al., 2017) and in the waters around and coastlines of Antarctica (Waller et al., 2017). Yet, there are significant spatial differences in the concentration of plastic. On the surface of the ocean, for example, the estimated

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concentration of small floating plastic is 10 million times higher in the subtropical accumulation regions than in the Southern Ocean (van Sebille et al., 2015). Because of deep upwelling of water in the Southern Ocean and Ekman drift towards the subtropical gyres (Rintoul and Naveira Garabato, 2013), there is a net transport of floating plastic away from the region (Onink et al., 2019). The same is true for regions on the Equator, such as the Galápagos Archipelago, where upwelling and surface divergence mean that the surface flow is predominantly directed away from the Equator (Law et al., 2014).

The Galápagos Archipelago and Marine Reserve are among the world's most valued and most iconic ecosystems. Its special qualities were first noticed when Charles Darwin visited the archipelago in 1835. They were later recognised in the islands being granted the first UNESCO World Heritage status for natural values in 1978, with the marine reserve following the archipelago itself onto the UNESCO World Heritage List two decades later. However, even this remote archipelago is not as pristine as one would hope (Mestanza et al., 2019). So, despite the archipelago being in a region of ocean surface divergence (Fiedler et al., 1991) with relatively low expected plastic concentrations, the blight of plastic pollution has now also arrived in Galápagos. There, it has unquantified but likely significant impacts on the unique ecosystem as well as on the sustainability of the tourism industry which supports the economy of the Galápagos locally, and Ecuador more broadly.

Management and mitigation of the plastic problem in the Galápagos Archipelago requires understanding the scale and sources of the pollution. While some of the plastic found on coastlines and in the marine reserve may originate from the islands themselves, including tourism there, and from fisheries in the Pacific Ocean, there is a widespread view, based on information from coastal clean up efforts (Galápagos National park, unpublished data), that much of the plastic found in the Galápagos comes from mainland America and from continental Asia.

Here, we investigated the pathways of floating microplastic between the Galápagos Islands and coastlines around the Pacific. There is some observational data on pathways into the Galápagos region, from satellite-tracked surface drifters in the real ocean. However, of the more than 30,000 drifters in the Global Drifter Program (GDP) (Elipot et al., 2016), only 40 crossed the Galápagos Archipelago region, defined as between [91.8°W - 89°W, 1.4°S - 0.7°N] (Figure 1). Most of these 40 drifters were released relatively close to the Galápagos, in the Eastern Tropical Pacific Ocean (Figure 1 upper panel). After leaving the Galápagos region, many of the drifters crossed the entire Pacific Ocean. Very clear here is the divergent flow at the Equator, where the drifters move poleward on both Hemispheres (Figure 1, lower panel).

To augment the GDP drifter observations, we employ state-of-the-art numerical models. We used a combination of the fine-resolution NEMO global hydrodynamic model for ocean surface currents (Madec, 2008), the WaveWatch III model for waves (Tolman, 2009), and the Parcels v2.0 Lagrangian particle tracking toolbox (Lange and van Sebille, 2017; Delandmeter and van Sebille, 2019). We compared these with the trajectories of floating drifters in the real ocean. There is still a debate in the community to what extent wave-induced currents – so-called Stokes drift (van den Bremer and Breivik, 2018) – has an impact on the transport of plastic (Onink et al., 2019), so we analyzed the particle pathways both with and without this effect of waves. We also describe how the modelling performed here can work alongside other methodologies, to demonstrate the benefits of multidisciplinary approaches to helping resolve the problem of marine plastic pollution.

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2 Methods

We performed four experiments in two sets: one set of experiments where we tracked in backward time where particles that end up near the Galápagos originate from; and one set of experiments where we tracked in forward time where particles that are released from the west coast of the Americas end up. In both sets of experiments, we simulated the transports by ocean surface currents only and by the combination of surface currents and waves. As the NEMO model data is available on 8km resolution, we focused only on the basin-scale transports, and leave transports within and between the different islands of the Galápagos Archipelago for future work.

We used the two-dimensional surface flow fields from the NEMO hydrodynamic model, simulation ORCA0083-N006, which has a global coverage at 1/12° resolution (nominally 8km around the Equator) (Madec, 2008). The NEMO data is available from January 2000 to December 2010, on 5-day temporal resolution.

For the Stokes currents, we used the WaveWatch III data based on CFSR winds (Tolman, 2009), which has a global coverage at 1/2° resolution (nominally 55km around the Equator). The WaveWatch III data is also available from January 2000 to December 2010, on 3-hour temporal resolution.

We advected Lagrangian particles using the Parcels v2.0 toolbox (Lange and van Sebille, 2017; Delandmeter and van Sebille, 2019) in either only the NEMO (currents) fields, or the NEMO+WaveWatchIII (currents+waves) fields. The particles represented microplastic that are sufficiently buoyant to not mix too deep in the mixed layer (Onink et al., 2019). We used a Runge-Kutta 4 integration scheme with a time-step of one hour. We stored the location of each particle on a daily (24 hours) resolution. All scripts that were used to run the simulations are available at https://github.com/OceanParcels/GalapagosBasinPlastic.

On each set of fields, we performed two different simulations. In the first, backward simulation, we released 154 particles every 10 days in a box between [91.8°W - 89°W, 1.4°S - 0.7°N], on a 0.2°x0.2° grid, for a total of 61,908 particles. We integrated these particles back in time for a maximum length of 10 years, or until the first day available in the NEMO dataset.

In the second, forward simulation, we released one particle each 0.5° between 38°S and 31°N every 5 days, for a total of 120,450 particles. For each latitude, we picked the easternmost longitude that is still in the Pacific Ocean, so that our release points traced the coastline of the Americas. We then integrated our particles forward in time for a maximum of 2 years, or until the last day available in the NEMO dataset. We identified those particles that crossed the box at [91.8°W - 89°W, 1.4°S - 0.7°N], the same box as the release for the backward run, and defined these to be passing through the Galápagos Archipelago region.

3 Results

In the backward simulation, most particle trajectories were confined to the Eastern Tropical Pacific Ocean, the South American coastline, and the Antarctic Circumpolar Current (Figure 2). In the currents+waves run, some particles even arrived in the Galapagos region that originated from the Indian Ocean (van der Mheen et al., 2019). However, none of the almost 65,000 particles came from the North or South Pacific accumulation zones (Kubota, 1994; Martinez et al., 2009; Eriksen et al., 2013; van Sebille et al., 2015) or from even close to mainland Asia. While some particles in the currents-only simulation originated from the very southern part of California, most particles originated from much farther south. Interestingly, the inclusion of Stokes drift meant that particles were much more dispersed through the Southern Ocean, in agreement with recent simulations of Kelp in that region (Fraser et al., 2018).

In the forward run, most particles released from the American coastline ended up in either the North Pacific or South Pacific accumulation zones within the two years that they were advected for (Figure 3). There was a local minimum in the density of particle trajectories on the Equator, especially west of the Galápagos, which agrees with the GDP drifters (lower panel of Figure 1). Compared to the currents-only runs, the convergence zones were more spread-out and reached farther westward in the currents+waves runs. The accumulation zones were also smaller and had lower maxima in the currents+waves fields, partly because the waves constantly push particles eastward onto the shore, so that they had less chance of reaching the open ocean. Indeed, the narrow strip of very high concentrations seen along the South America coastline in the lower panel of Figure 3 confirms that one effect of the waves was to contain the particles close to their release locations.

The fraction of particles that reached the Galápagos region, starting from the western American coast, is shown in Figure 4. Only very few of the particles released south of 16°S or north of 3°N reached the Galápagos, and even for the regions between 16°S and 3°N the fraction of particles arriving in the Galápago region is never higher than 25%. There was a clear difference between the two flow scenarios: in the currents+waves scenario (blue line in Fig 4) the particles that reached the Galápagos came almost exclusively from Peru, while in the currents-only scenario there was also a significant fraction of virtual particles from Ecuador, Colombia, Costa Rica and farther north.

In both forward runs, less than 1% of the particles from the Chilean coast arrived in the Galápagos region, even though in the backward simulation there was a clear pathway along the Chilean coast. This apparent inconsistency between the two simulations is due to the fact that the interpretation of the forward and backward runs is very different. Most of the particles that enter the ocean from the American coastline do not come close to the Galápagos region. However, in the backward simulation we tracked only those that do so by construction they all had to end there. This shows that forward and backward simulations can yield complementary information.

The travel time from the west coast of Americas to the Galápagos was typically a few months (Figure 5). In the currents+waves scenario, almost all particles that reached the Galápagos did so within 3 months (100 days; blue bars in Figure 5). In the currents-only scenario, there was a much longer tail, reaching travel times up to 2 years (yellow bars). Do note however, that none of the simulations here take sinking of particles into account, which can be expected to be more likely for longer times at sea (Kooi et al., 2017; Koelmans et al., 2017).

An analysis of the particles reaching the Galápagos per year showed that there was little impact of El Niños and La Niñas on the transport of particles from the American coastline to the Galápagos region. Only in the case of particles from Colombia was there some apparent relation with El Niño (green line in left panel of Figure 6), but that is only true in the currents-only run (since no particles that start from Colombia reach the Galápagos in the currents+wave forward run).

4 Conclusions and Discussion

We have analysed the pathways of virtual particles representing floating microplastics in two sets of simulations; with currents only and with both currents and waves. It is clear that the inclusion of waves had a major effect on the transport of this plastic, and that especially connections to the Northern Hemisphere are reduced due to the effect of waves. The backward-in-time simulations (Figure 2) revealed that it is extremely unlikely for plastic from anywhere but a relatively local region in the Eastern Tropical Pacific, the coastline of South America, and the Southern Ocean to arrive into the Galápagos region.

It is important to note that the virtual particles in these simulations represent highly idealised plastic only. We did not consider beaching, degradation, sinking nor ingestion of plastic. We also did not consider what happens within the Galápagos region. Finally, we did not explicitly consider sources of fisheries and other marine activities.

The simulations agreed well with the trajectories of the GDP drifters (Fig 1). While 40 drifters is not sufficient to do robust statistical comparison (e.g. van Sebille et al., 2009), the patterns of the drifters show similar patterns as the distributions of the virtual particles, especially for the forward wind+currents simulation. Since these drifters have mostly lost their drogues by the time they reach the Western Tropical Pacific Ocean (blue lines in Figure 1), it is indeed expected that waves play a role in the dispersion of the satellite-tracked drifters.

The differences between the currents only and currents+wind simulations thus demonstrates the importance of the inclusion of wind effects on the transport of microplastics (Lebreton et al., 2018; Fraser et al., 2018; Onink et al., 2019). These wind-driven Stokes currents, however, are not routinely incorporated into numerical hydrodynamic models, and in fact not even well-observed. This may change, however, if the European Space Agency's SKIM concept mission to directly measure surface currents from space is launched (Ardhuin et al., 2018). The research presented here highlights again how important it is for the simulation of floating debris to observe Stokes drift on a global scale.

This project forms part of a wider multi-disciplinary programme involving scholars and research teams in marine biology, ecotoxicology, environmental psychology and archaeology. Working collaboratively, and in partnership with local communities, this collaborative effort is expected to develop a better understanding of the causes and consequences of marine plastic pollution in Galápagos than existed previously. Given the understanding of oceanographic currents, the degree of management and policy instruments available, and iconic status of Galápagos, the Archipelago is well, even uniquely positioned to provide a demonstration of how a marine reserve can manage and reverse its marine plastic burden. The hope is also that the processes, methodologies, management tools and partnerships established in Galápagos can be extended to other places around the world. Understanding how currents and waves carry plastic from points of deposition ('taps') to places of accumulation ('sinks') is vital. By combining this understanding with the results of other approaches can bring additional insight. For example, an archaeological methodology being trialled in Galápagos uses 'object biographies' or 'life stories' to create narratives around individual items collected from beaches in the Archipelago (Schofield, 2018; Schofield and Wyles, in prep.) to help understand how they got there.

Fieldwork conducted in May and November 2018 involved collecting a representative sample of plastic items from a beach on San Cristobal. These items were then examined in a series of 'Science to Solutions' workshops involving academics and members of the local community, with the aim of building narratives around the coded and visual information each object contains. The coded information typically includes details of place and date of origin, and the original content (of containers), while visual inspection can betray length of exposure, for example through signs of bleaching and colonisation by marine life.

Preliminary results support the results of the analyses reported here, that plastic objects are mostly of South American origin, or from continental Asia. Crucially, however, the items from Asia (evident in the languages of the labelling) are very fresh, and had clearly not been in the sea for long when they 'landed' in Galápagos. The hypothesis here is that these items were coming from fishing boats originating in Asia, and not directly from the countries themselves. Working collaboratively, these very different disciplines and methodologies illustrate the benefits of cross-disciplinary and cross-sector partnership to help understand (if not resolve) a major global challenge.

Code and data availability. All scripts that were used to run the simulations are available at https://github.com/OceanParcels/GalapagosBasinPlastic, and the trajectory files are at http://doi.org/10.24416/UU01-5JUDNV. The Parcels code is available at http://oceanparcels.org. The Elipot et al. (2016) Global Drifter Program drifter data is available at ftp://ftp.aoml.noaa.gov/phod/pub/buoydata/hourly_product/v1.02/. The NEMO hydrodynamic data are available from http://opendap4gws.jasmin.ac.uk/thredds/nemo/root/catalog.html. The WaveWatchIII Stokes drift data are available from ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST/GLOBAL/.

Video supplement. Animations of the four experiments described here are available as Supplementary material to this manuscript.

Author contributions. EvS devised the study, analysed the results of the simulations, and led the writing of the manuscript. PD and EvS ran the Parcels simulations. All authors participated in the writing and editing of the manuscript.

Competing interests. No competing interests are present

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This is part of a multidisciplinary project which involves marine biologists (Ceri Lewis, Adam Porter and JJ, University of Exeter; Juan Pablo Muñoz, University of San Francisco, Quito; Kathy Townsend, University of the Sunshine Coast; Richard Thompson, University of Plymouth, Denise Hardesty, Commonwealth Scientific and Industrial Research Organisation, Australia), a conservation scientist (Brendan

Godley, University of Exeter), an ecotoxicologist (Tamara Galloway, University of Exeter), environmental psychologists (Sabine Pahl, University of Plymouth and Kayleigh Wyles, University of Surrey), an archaeologist (JS), and a physical oceanographer (EvS). It is coordinated by the Galapagos Conservation Trust, through AD and JJ (now also at University of Exeter). In addition to many of those people listed above, the workshop described in this paper involved significant participation from the Charles Darwin Research Station and the Galápagos Science Centre in collaboration The Directorate of the Galápagos National Park.

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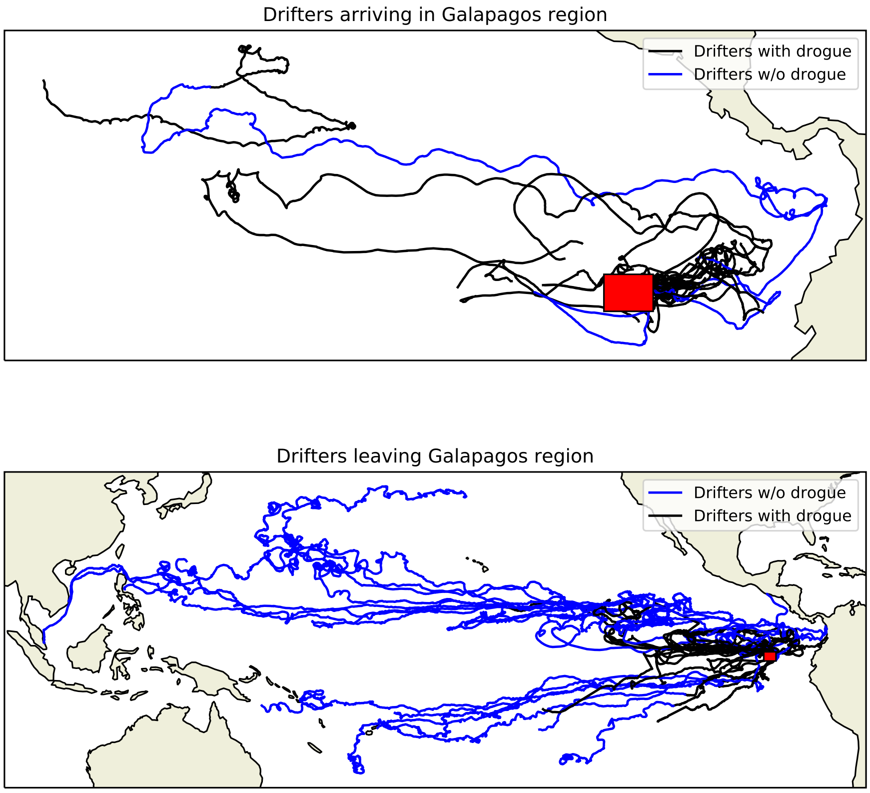

Figure 1. Trajectories of surface drifters in the real ocean, from the GDP program (Elipot et al., 2016). Top panel shows drifter trajectories before they arrive in the Galápagos region. Bottom panel shows drifters after they leave the Galápagos region. Black sections of the drifter trajectories indicate when the drifters still have their drogue attached, in the blue sections these drogues are lost.

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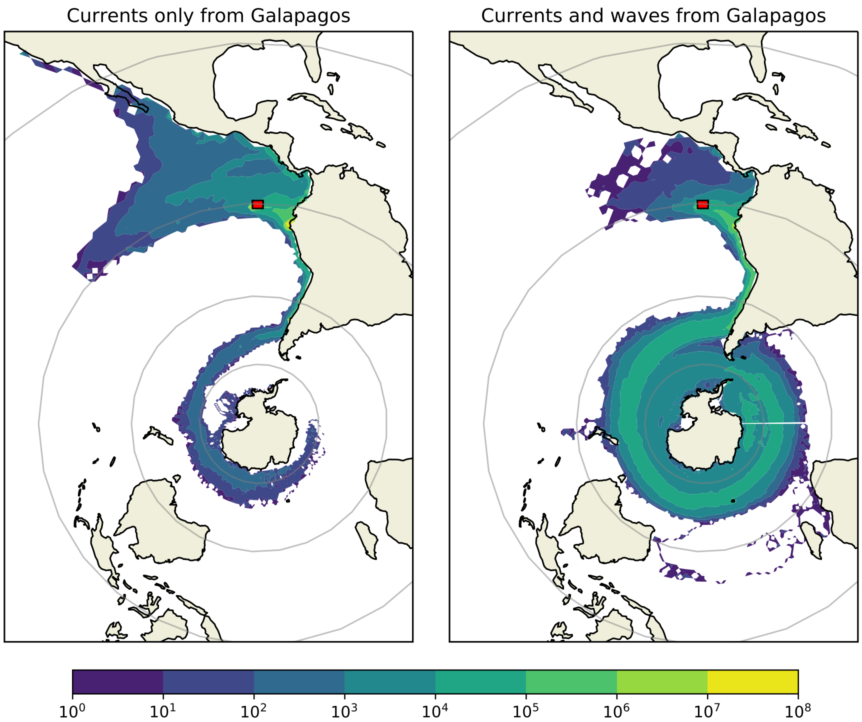

Figure 2. Histogram of backward-time particle trajectories that end up in the Galápagos region (red rectangle) for particles carried by currents only (top panel) and for particles carried by the currents and waves (bottom panel). The scale is the number of particle crossings per 1°x1° grid cell, on a logarithmic scale. Gray circles denote the 60°S, 30°S, Equator and 30°N latitude bands. Beaching is not taken into account in this simulation, and maximum length of the backward trajectories is 10 years. Most backward-time trajectories remain in the eastern tropical Pacific Ocean or originate from the Southern Ocean.

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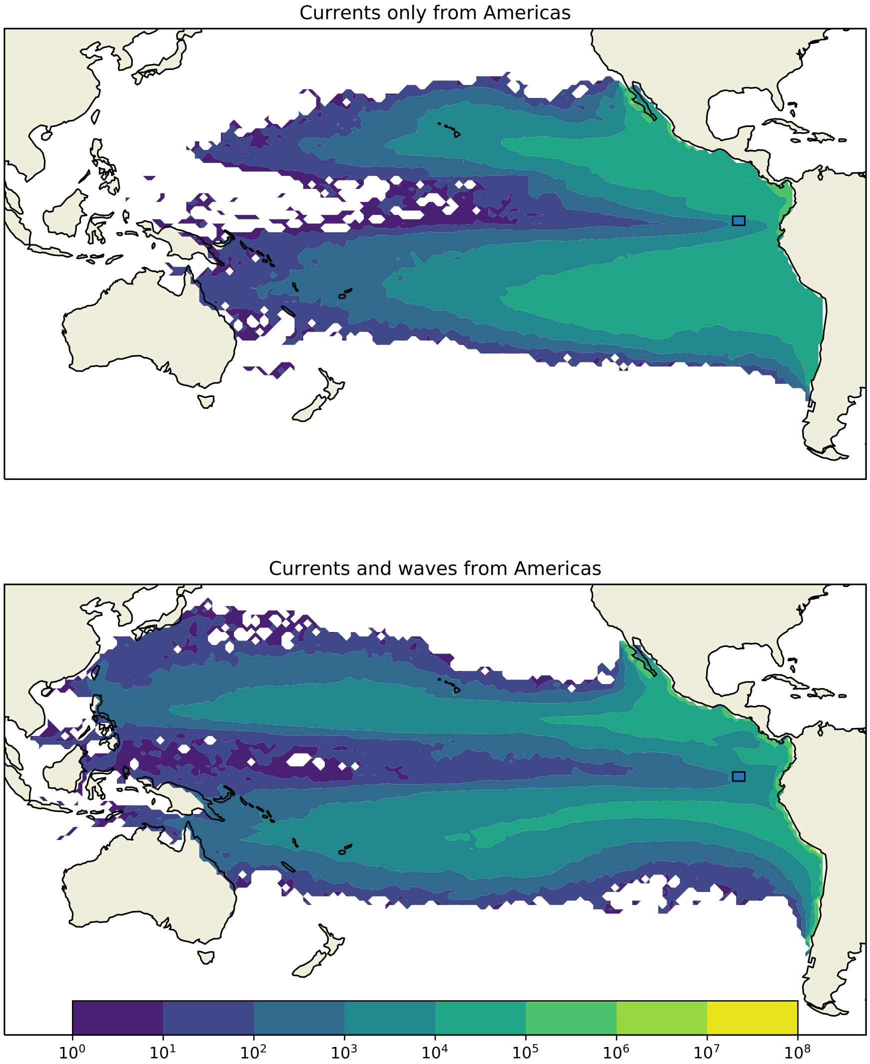

Figure 3. Histogram of forward-time particle trajectories that start on the western coast of the Americas, on a logarithmic color scale, for particles carried by currents only (top panel) and for particles carried by the currents and waves (bottom panel). Maximum length of the forward trajectories is 2 years. Most particles end up in one of the subtropical gyres, and the Galápagos (black square) is at a relative minimum in both simulations.

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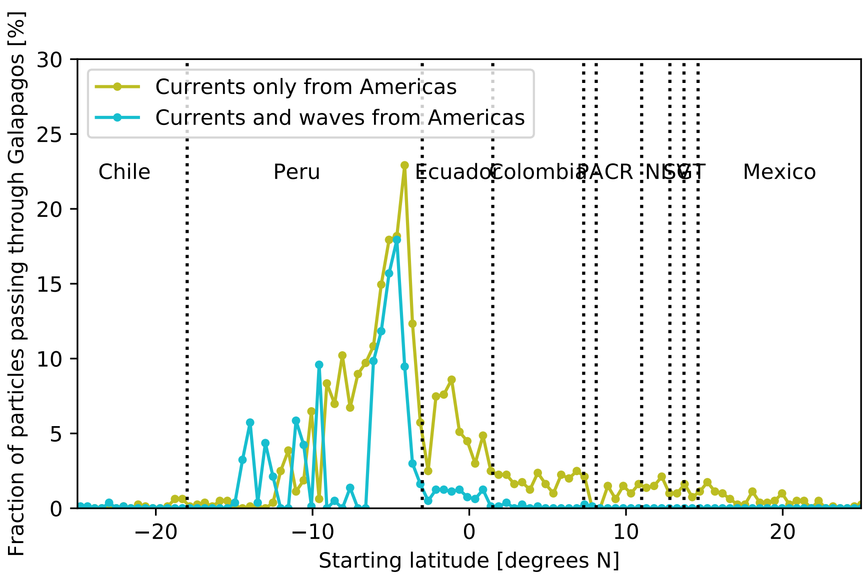

Figure 4. The fraction of particles that pass through the Galápagos box as a function of starting latitude for the forward run, for particles carried by currents only (yellow line) and for particles carried by the currents and waves (blue line). Dashed lines denote the approximate boundaries of different countries along the west-American coast. Most particles that pass through Galápagos start from Northern Peru and Southern Ecuador.

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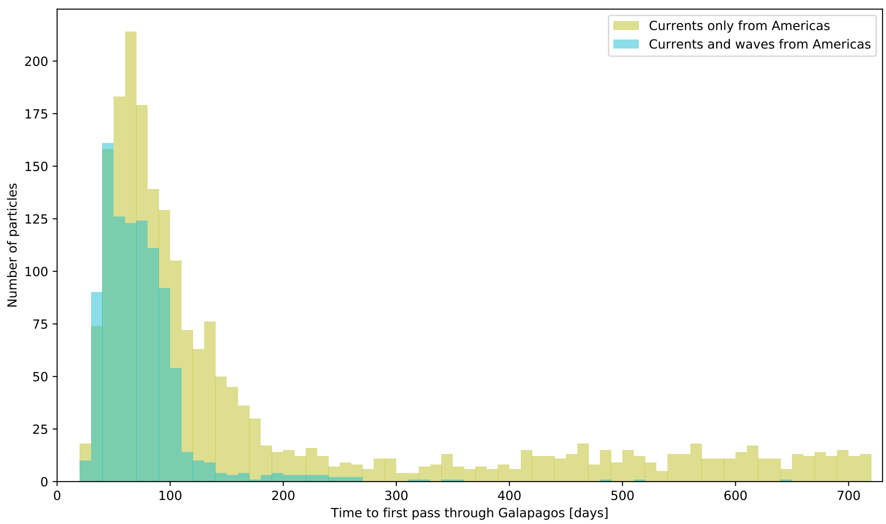

Figure 5. Histogram of the time in days required for particles to travel from the west coast of America to the Galápagos region, for particles carried by currents only (yellow bars) and for particles carried by the currents and waves (blue bars). Most particles arrive within 3-4 months, although there is a significant tail all the way to 2 years for the simulation with currents only.

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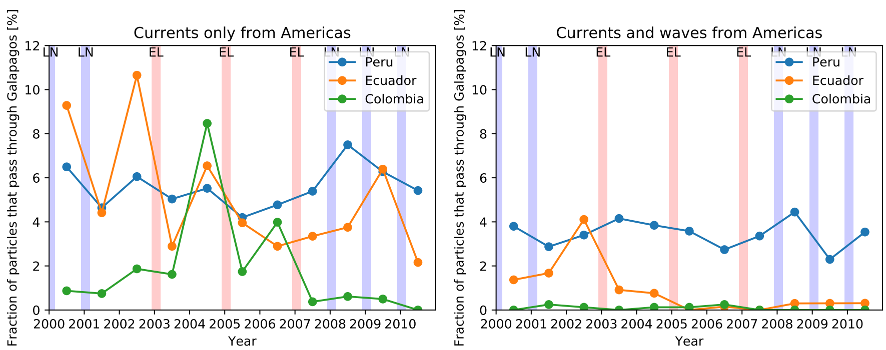

Figure 6. Time series of the fraction of particles starting in Peru, Ecuador and Colombia that pass through the Galápagos region, for particles carried by currents only (left panel) and for particles carried by the currents and waves (right panel). Blue bars indicate La Niña periods, red bars indicate El Niño periods. While there is no apparent relation between ENSO state for Peru and Ecuador, it is clear that the fraction of particles carried by currents only that end up in the Galápagos region from Colombia is much higher during El Niño than during La Niña periods.