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Opleiding Natuur- en Sterrenkunde

Origin of Plastic Found on the Shores of the Galapagos Islands

Bachelor Thesis

Nicoleta Tsakali

Supervisor: Dr.E. van Sebille
IMAU (Institute for Marine & Atmospheric research Utrecht)

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Abstract

Around 8 million tons of plastic end up in the ocean every year. Wind and ocean currents disperse plastic as far as the Arctic and even into deep oceans. Most of the floating plastic is gathered within the gyres, while a significant fraction of it ends up on the ocean surface outside the gyres. The Galapagos Marine Reserve is one of the largest pristine ecosystems in the world and is therefore heavily protected from the excesses of human influence. With around 97% of the islands being off limits to humans, one would expect to find an uncontaminated environment. However, the islands are no strangers to plastic pollution, with even the most isolated ones containing high levels of plastic. In this research we attempt to look into the origin of this plastic. In order to tackle plastic pollution on the shores of Galapagos, we need to find out where all this plastic is coming from and thus enable its removal from the marine environment before it ever reaches the islands. We use Parcels to simulate the trajectories of virtual pieces of plastic originating from North and South America and flowing in the ocean under the effect of geostrofic currents. The results show that most of the plastic debris that ends up within the Galapagos Marine Reserve originates from countries on the west coast of America that are close to the Equator.

The cover image was one of the daily cover images of bing.com

Contents

1 Introduction

The Galapagos island complex is located in the Pacific Ocean 1.000km from the coast of Ecuador. The complex consists of 18 large islands, forming a total of 1667km coastline. The 133.000km^2 nature reserve is home to an amazing variety of species, many of which are uniquely found there. In 1959, the Galapagos Archipelago was designated as national park and in 1979 it was declared an UNESCO World Heritage Site. Today the islands are considered one of the most pristine ecosystems on Earth and are protected from the excesses of human influence [13].

The Galapagos Islands have a permanent population of around 30.000 and are visited by over 200.000 tourists each year. The Galapagos Conservation Trust is in charge of multiple projects of sustainable development varying from sewage treatment plants to reducing plastic pollution. Most of the Galapagos Marine Reserve (97 %) is off limits to tourists and locals alike. Furthermore, all cruises and day trips into the Galapagos National Park (GNP) are supervised by licensed guides who ensure that the GNP rules are followed and no pollution is left behind . However, high levels of plastic can be found even on the most isolated islands, threatening the unique biodiversity of the complex [13]. This paradox brings forth the question "Where is all this plastic coming from?".

Plastic debris can travel over large distances, carried by ocean currents. Dynamics of the upper ocean and its mixed layer, where much of marine debris floats, is quite complex [9]. The global surface current pattern is a result of the surface wind field, the effect of the Coriolis force and the horizontal pressure gradient force.

Winds that blow over the surface of the ocean transfer energy to the upper ocean, thus generating motion in the form of waves and currents. The stronger the wind, the stronger the friction on the sea surface and therefore the stronger the surface current that is generated. However the direction of the current is not parallel to that of the wind, it rather deviates 45^o cum sole. This wind driven current, better know as Ekman current, decreases exponentially with depth and is affected by the Coriolis force [15] [16]. Ocean currents are thus, at least to some extend, driven by the atmospheric circulation. There is though a big difference between the two systems. The ocean is constraint by coastal boundaries. As a result the gyral motion of the atmosphere is heavily enhanced in the ocean. Furthermore, boundaries stop currents flow and force water to gather around them. A surface slope is thus created which gives rise to the horizontal pressure gradient force, that drives the water down the slope. When the Coriolis force acting on moving water is balanced by this horizontal pressure gradient force, the current is said to be in geostrophic equilibrium and is described as a geostrophic current [15] [16].

The complex interplay between winds, the Coriolis force and the pressure gradient force leads to the formation of the oceanic current system (figure1).

Current flow in the subtropics, is mainly attributed to the anticyclonic wind systems that are observed in these latitudes.Because the centers of the gyres that are formed in this area, tend to be closer to the western boundaries, the western currents are fast, intense, deep and narrow while those that flow along the eastern boundaries are characteristically slow, wide, shallow and diffuse. The difference between the western boundary currents and the eastern boundary currents in the South Pacific is not so clear as in the North Pacific, mainly because the South Pacific is open to the Southern Ocean and the South Pacific gyre can be heavily

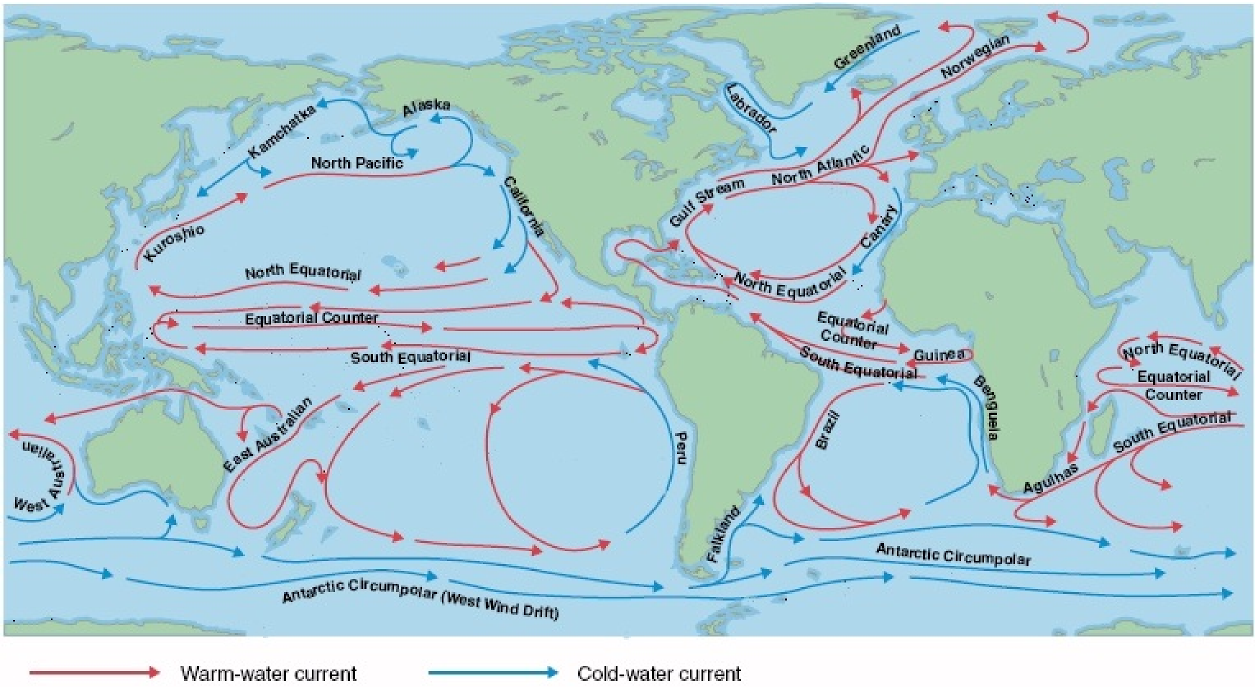

Figure 1: A map of the most important oceanic surface currents

influenced by the Antarctic Circumpolar Current (figure1 [15]

As we look closer to the Equator, the Coriolis force becomes zero (still by latitudes of about 0.5 degrees it is large enough to have a significant effect on flowing water), so we need to rethink how circulation is formed. The Trade Winds tend to drive water to the west. The western coasts, create a sea surface slope up towards the west and form an eastward horizontal pressure gradient force. The winds observed around the ITCZ (Doldrums) are very light, allowing the water to flow 'down' the horizontal pressure gradient, *counter* to the prevailing wind direction thus creating the easterly Equatorial Counter-Current. Even this close to the Equator, the effect of the Coriolis force is evident. The deflection is towards the Equator, which contributes to the convergence observed around 4^oN. The most important currents seen around the Equator are the westward North & South Equatorial Currents and the eastward Equatorial Counter Current. The South Equatorial Current is, on average, the broadest and strongest. These currents flow around the globe and are partly directly driven by the Trade Winds and partly by the geostrophic flow. Just like the Intertropical Convergence Zone (ITCZ) of the trade winds, the Equatorial Currents are shifted to the north of the Equator (figure2) [15].

Plastic debris can be found in all marine environments, from highly populated coastlines to the most isolated islands, from the ocean surface to the deep sea, in sediments and even the polar ice [12]. Plastic litter mainly enters the ocean by land, whereas only a small percentage can be attributed to maritime activities like fishing or shipping [7]. Plastic originating from land has many different ways of entering the ocean. Plastic garbage that is left behind by beachgoers can be pushed into the water by waves and tides. Plastic from uncontrolled rubbish dumps can be drifted to the ocean by storm floods. Finally, although not very common, plastic debris can end up in the ocean after natural disasters like tsunamis or

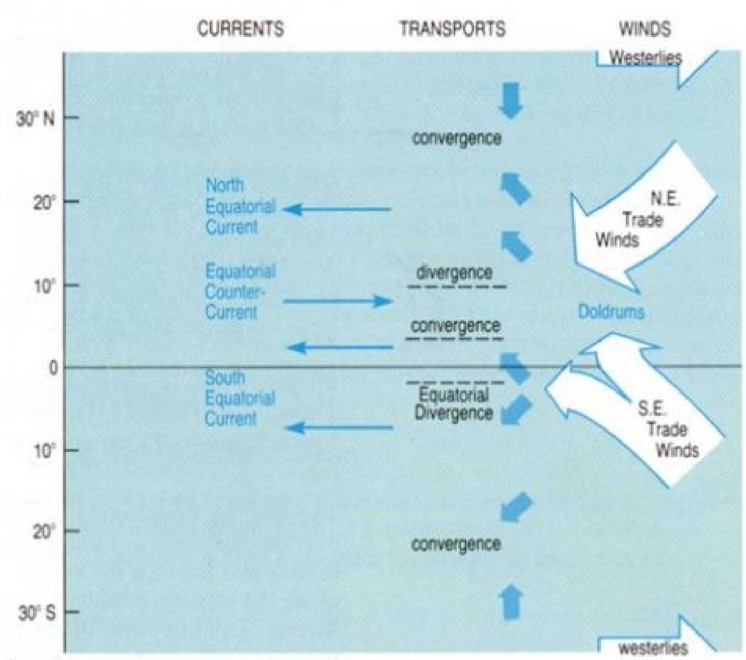

Figure 2: The Trade Winds that enforce the Equatorial Currents

tropical storms [7] [1] [2] .

When plastic enters the marine environment, it is usually large and massive. Due to scraping on the coastline, tearing from the waves and exposure to ultraviolet radiation from the sun, plastic slowly breaks into smaller plastic fragments. [6]Depending on their size, these fragments are categorized as:

- Macroplastics [$diameter > 5cm$]
- Mesoplastics [$diameter > 5mm$]
- Microplastics [$diameter < 5mm$]
- Nanoplastics [$diameter < 5\mu m$] [6].

Microplastics smaller than 1 mm are about the same size as zooplankton and can therefore be ingested by many marine organisms. These tiny plastic pieces attract algae to grow and are can absorb large amounts of toxic material. It is still not yet clear what the ecological impact of microplastics will be. However, this is something that humankind will inevitably be faced with in the future, not only because these particles never completely disappear from the environment but also because their number increases yearly since more and more plastic waste is produced [6] .

Plastic has been documented throughout the ocean from the surface to the sea floor. It can be found in sediments, biota even ice. It can be trapped along the coastline, in estuaries, rivers and lakes. Small pieces of plastic can even be swept in the atmosphere and be carried away by winds [2]. The best-measured reservoir of plastic debris is the amount of floating plastic at the ocean surface [12]. Due to the presence of the large-scale convergence in surface currents, high concentrations of debris are observed in the accumulation zones in the five subtropical gyres (figure3) where plastic is trapped for decades to millennia. In more remote regions, like the Arctic and the Antarctic, far fewer plastic pieces have been documented [2] [5] [12] [11].

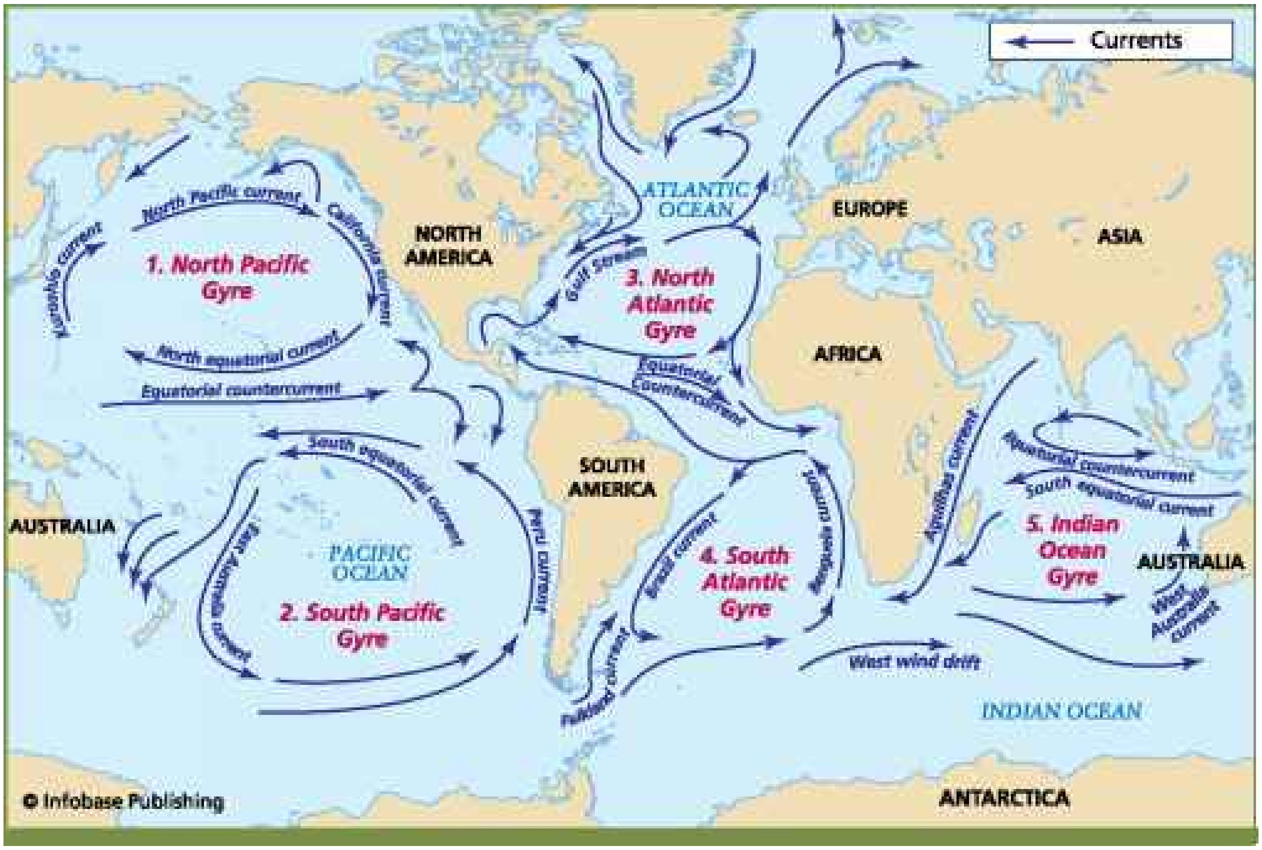

Figure 3: The 5 biggest oceanic gyres

The oceanic accumulation zones known as "*garbage patches*" have attracted media attention and have therefore induced a great amount of research in order to identify and describe them. As a result, there are many data regarding the extend of the garbage patches and the concentration of plastic floating in them. The majority of the sea surface outside these zones remains however unsurveyed and only a few (if any) data can be found on floating plastic outside the patches, introducing potentially large errors in global estimates of the amount of floating plastic [7] [12].

Furthermore, since plastic debris flows with the fairly complicated ocean currents, only limited data exist to describe the spatial extent and temporal variability of floating plastic debris around the Galapagos Islands.

Numerical modeling is one of the most important tools available that can give us some understanding regarding the distribution of plastic debris and can help fill the gaps from observations. The marine debris problem can be viewed as a source, pathway and sink issue. Simulations using numerical models can be applied in all these areas. They are useful in estimating the sources and sinks of plastic in the marine environment and can give us an insight into their pathways [2]. Numerical modeling has been applied to track the pathways of plastics in the ocean backwards in time, until they reach their sourc [2].

Ocean Surface Currents are the coherent horizontal and vertical movement of surface ocean water (over a specific depth regime) with a given velocity and an upper boundary in contact with the atmosphere that persist over a geographical region and time period. The GlobCurent project aims to advance the quantitative estimation of ocean surface currents from satellite sensor synergy. The GlobCurrent hydrodynamic field was coupled to Parcels, a Lagrangian ocean analysis framework that allows us to follow virtual particles on the ocean surface. For a more detailed description of the model please refer to Lange, M., & Van Sebille, E. (2017) [4].

The Galapagos are located in the convergence region of at least three marine currents (figure 4) which are thought to contribute to the problem by transferring plastic from the coasts of North & South America and even from as far as the West Pacific Ocean. Identifying the source of the plastic, will enable its removal from the marine environment before it ever reaches the islands. With this in mind, we used Parcels to simulate the trajectories of virtual pieces of plastic originating from North & South America, to predict how much of that ends up on the coastline of the Galapagos. Furthermore, we followed the trajectories of particles that are supposedly found on the islands backwards in time to determine their possible origins.

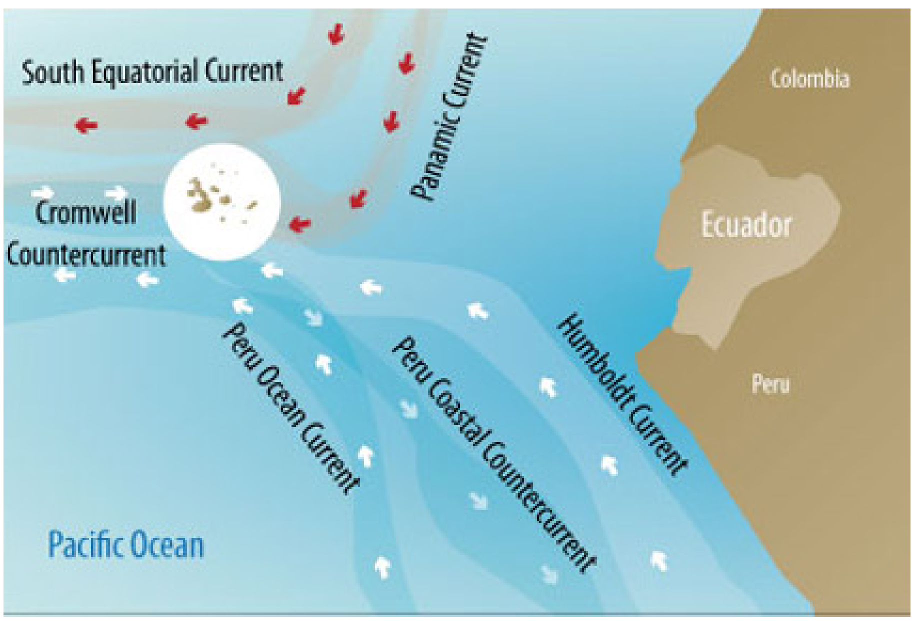

Figure 4: The most important marine currents that converge in the region of the Galapagos islands

2 Methods

To simulate the flow of plastic debris under the influence of surface currents we used Parcels, a Langrangian simulator that enables the creation and tracking of virtual particles. For more details regarding Parcels please refer to Lange, M., & Van Sebille, E. (2017) [4].

In our attempt to study the flow of plastic debris that ends up on the Galapagos we perform two individual simulations.

First we follow virtual particles originating from the countries of the west coast of America to see what percentage of them ends up on the Galapagos area (Forward Run). Our aim on this run is to see what percentage of particles end up on the Galapagos per country, with regard to the total amount of particles released from each country (eg out of 10 particles released from country A, only 1 reaches the Galapagos). On our second run we follow virtual particles from the Galapagos area backwards in time in an attempt to see their possible origins (Backward Run). Our goal is to see what percentage of the particles that are already on the Galapagos originate from each country (eg. out of the 10 particles found on the Galapagos 5 come from country A, 2 from country B and 3 from country C). In both cases we use the GlobCurrent data repository of the geostrophic and Ekman currents. The data are set to a common grid with a spatial resolution of 25 km and a temporal resolution of 1 day. We cover a 13-year period from 2002 to 2014 for the forward run and vice versa for the backward run.

2.1 Forward Run

As described in Lange, M., & Van Sebille, E. (2017) [4], our first step is to insert the hydrodynamic field into Parcels. We then define the variables of each particle that is released in the ocean. We divided the west coast of America into 133 release points of about $100km$ distance (see Appendix figure 12), from which we release a total of 482.790 particles.

We release one particle per day from every station and let it float in the defined field for the first 10 years of the simulation. We then stop releasing particles and let the existing ones flow for 3 more years. Apart from the existing advection kernel that is described in the Lange, M., & Van Sebille, E. (2017) [4] we require the particles to re-enter the field by creating a halo kernel. Since the particles in our code cannot beach, we stop their movement when they reach the Galapagos area (latitude : [-1.375 , 0.625], longitude : [-91.625, -89.125]).

During the run the trajectories of the particles are stored in NetCDF files. We combined the stations depending on their coordinates into the countries of the west coast of America (see figure 14 in the Appendix). We then use Python to do the statistical analysis based on the last position of every particle and see how many particles from each country end up on the Galapagos.

In our analysis we assume that the same amount of plastic is released into the ocean from every location. However this is likely not the case in reality. Each country, depending on its economical and industrial growth generates a different amount of plastic per capita. After taking into account the plastic waste generated by coastal populations (within 50km of a coastline) and the quantity of plastic that is mismanaged, meaning plastic that is not safely disposed or recycled, the authors of Jambeck et al 2015 [3] have quantified the amount of plastic debris that is at high risk to enter the ocean.

Some of the countries we are looking into have coasts both into the Atlantic and Pacific oceans. To correct our data we divided the total amount of mismanaged coastal plastic waste from these countries by 2. In the on the Pacific ocean we divided the total amount by 5. We combined this result with the percentage of particles that ends up on the Galapagos per country from our simulation and got the annual amount of plastic that end up on the Galapagos per country. Finally we weighted our result with regard to the total amount of plastic found on the Galapagos. Our data can be seen in table 1

Country	Mismanaged Plastic west coast (10^3 tns / year)	% Plastic on Galapagos
Canada	3	0
USA (incl. Alaska)	137	0.2
Mexico	50	0.9
Guatemala	45	0.8
El Salvador	118	8.2
Honduras	19	2.7
Nicaragua	42	4.4
Costa Rica	21	4.3
Panama	17	4.2
Colombia	46	3.4
Ecuador	109	30.7
Peru	194	39.7
Chile	21	0.5

Table 1: Mismanaged plastic waste in high risk of entering the Pacific Ocean every year per country and plastic debris that can possibly reach the Galapagos originating from the west coast of America

2.2 Backward Run

We begin by inserting the hydrodynamic field into Parcels, as described in the first simulation. We then define the variables of each particle that is released in the ocean. In this case we release 60 particles per day from the Galapagos Island complex (latitude : [-1.375 , 0.625], longitude : [-91.625, -89.125]) for ten years and follow their trajectories backwards in time. After the first 10 years we stop releasing particles and observe the trajectories of the existing particles for 3 more years.

Apart from the existing advection kernel that is described in the Lange, M., & Van Sebille, E. (2017) [4] we require the particles to re-enter the field by creating a halo kernel. Since the particles in our code cannot beach, we create an extra kernel that stops their movement when they reach the West Coast of America.

During the run the trajectories of the particles are stored in NetCDF files. We then use Python programming language to do the statistical analysis based on the last position of every particle and see what is the origin of particles that are found on the Galapagos.

During the statistical analysis we create a density map of the final positions of the particles on the backward run. In our results we have a few outliers (Panama, Peru, Chile, Galapagos) with very high particle density per grid. In order to have a better outlook of the areas with small numbers of particles we limit the scale of the map to 10 particles per grid.

Finally we look into the trajectories of particles that originate from Antarctica and north-west Pacific and plotted their analytic trajectories.

3 Results

3.1 Forward Run

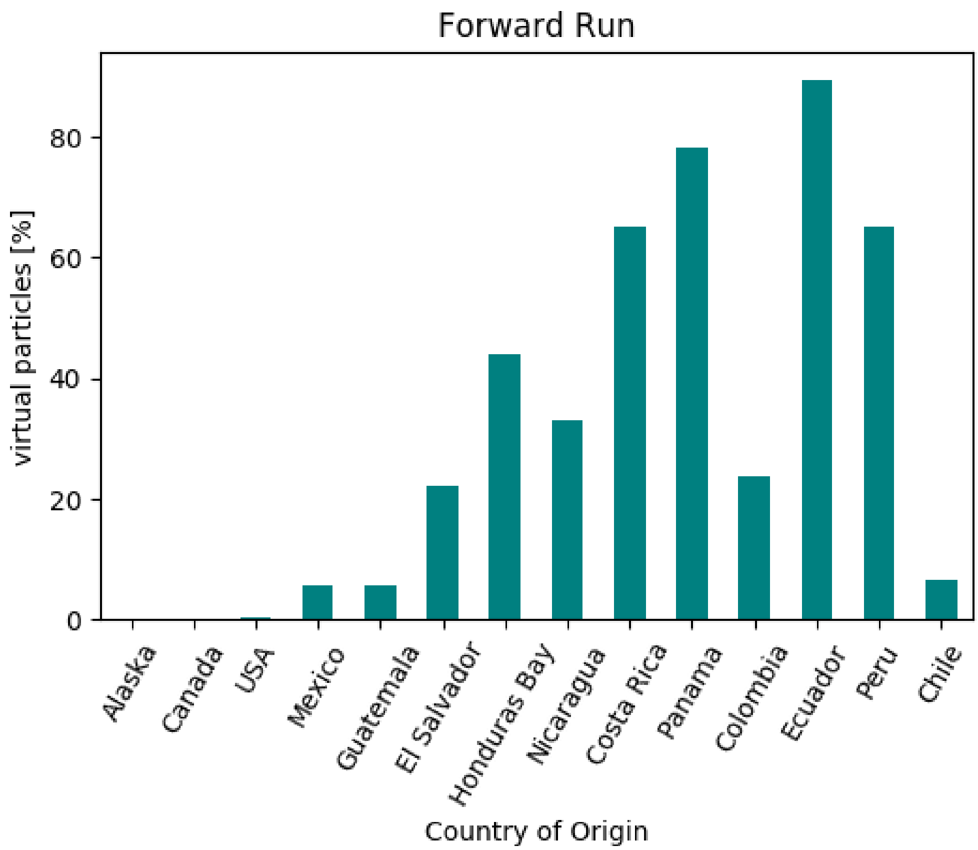

Figure 5: Percentage of particles originating from the countries of the west coast of America that reach the Galapagos, according to the forward run of Parcels.

The countries of North America (Canada & USA including Alaska) have almost zero contribution, with less than 1% of their particles reaching the Galapagos (figure 5). The percentages remain low as we go into Central America with around 10% of the particles from Mexico and Guatemala reaching the Galapagos. The percentage of particles reaching the islands increases for lower latitude countries with the exception of Colombia and Chile. We see that the particles coming from mid-latitude countries (El Salvador, Honduras Bay, Nicaragua, Costa Rica, Panama, Ecuador and & Peru) are the ones most likely to reach the Galapagos, with percentages between 30% and 80%. With the exception of Colombia, there seems to be an almost linear connection between proximity to the Equator and percentage of particles that reach the Galapagos. Colombia, despite being very close to the Equator, has a percentage of around 20% only.

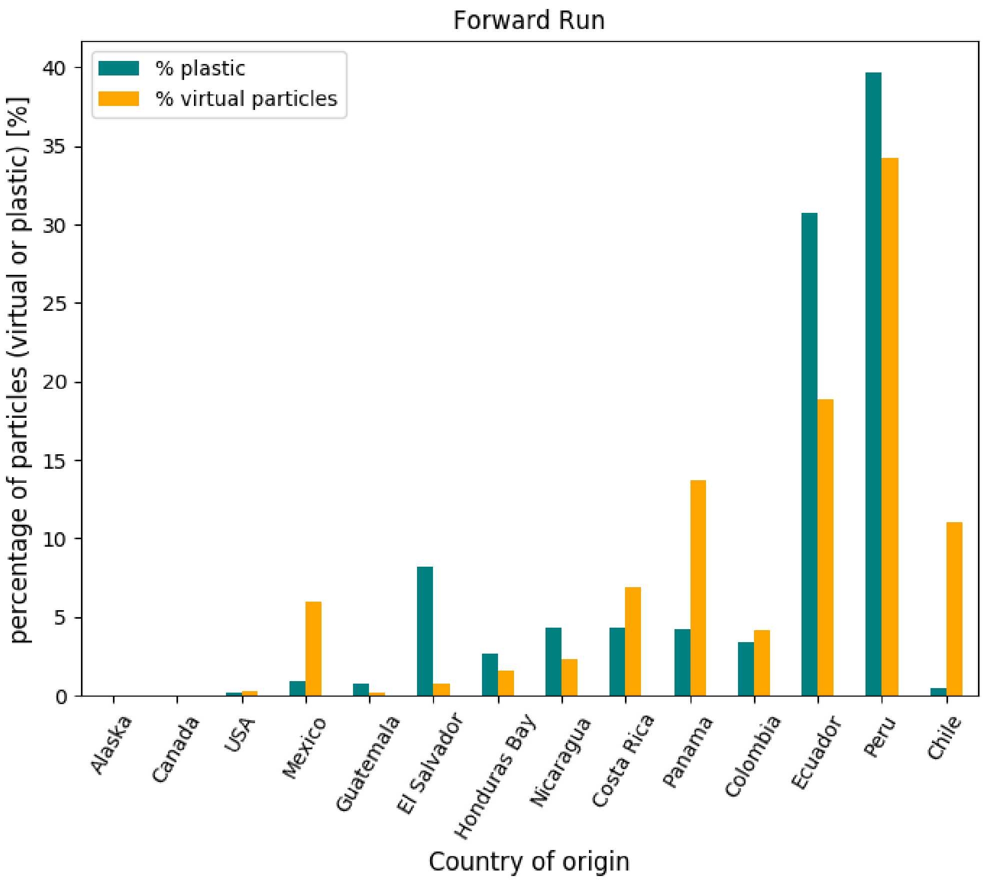

Figure 6: Percentage of plastic (blue bars) and of virtual particles (orange bars), reaching the Galapagos per country with regard to the total amount plastic / virtual particles (respectively) that reach the islands. For the estimation of plastic debris weight, see methods table 1.

When we weight the amount of virtual particles that end up on the Galapagos (orange bars) with the total amount of virtual particles that end up on the islands, the overall image is a bit different (figure 6). Peru appears to be the most important contributor with a share of around 35%. Between 10% and 15% of the virtual particles can be attributed to Ecuador, Panama and Chile. The contribution of the rest of the mid-latitude countries is not so important (around 5%). The percentage of virtual particles coming from Canada and USA is less than 1%.

Looking into the percentage plastic debris that reach the Galapagos islands per country (blue bars) we see a clear pick at Equador and Peru (figure6). By far the most important contributors of plastic on the Galapagos appear to be Ecuador and Peru, with more than 60% of the plastic that is found on the islands originating from these two countries. Around 5% of plastic is in danger of reaching the Galapagos from mid latitude countries (Honduras, Nicaragua, Costa Rica, Panama & Colombia). Finally, Chile, Canada, USA, Mexico and Guatemala contribute almost no plastic to the islands, with percentages less than 1%. There is a noticable peak for El Salvador at around 10%.

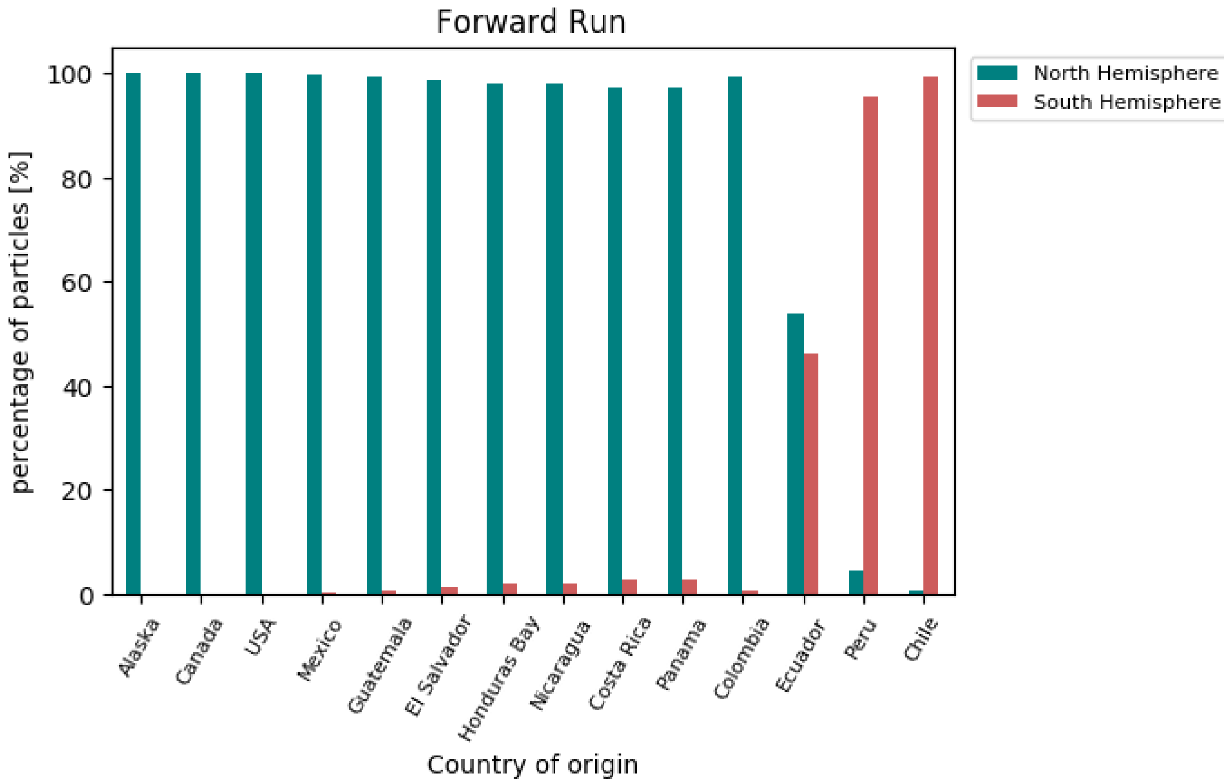

Figure 7: Percentage of particles ending up on the North (South) Hemisphere per country (forward run)

The percentage of particles ending up on the North and South Hemisphere per country (blue and red bars respectively) revealed an interesting behavior as seen in figure 7. Almost 100% of the particles originating from North America (Canada and USA including Alaska) remain in the North Pacific. As we look into lower latitudes the percentage of particles ending up in the South Pacific slowly increases, but still remains under 10% for countries above the Equator (Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama & Colombia). For Ecuador (which is on the Equator) the particles are split between North & South Pacific almost evenly. For countries located under the Equator (Peru & Chile) the percentage of particles that remain in the South Pacific is almost 100%.

Looking into the last position of the virtual particles (see Appendix figure 13), we see that particles originating from the countries of the west coast of America, tend to stay in the (North or South) Pacific Ocean, with respect to their latitude as explained in the previous paragraph. However that is not the case for Chile. Particles originating from Chile are not constraint in the Pacific Ocean, but travel well into the South Atlantic and Indian oceans (see figure 8).

3.2 Backward Run

During the backward run we follow virtual particles backwards in time, from the Galapagos to their origin. On the horizontal axis of figure 9 we see the different countries of origin that

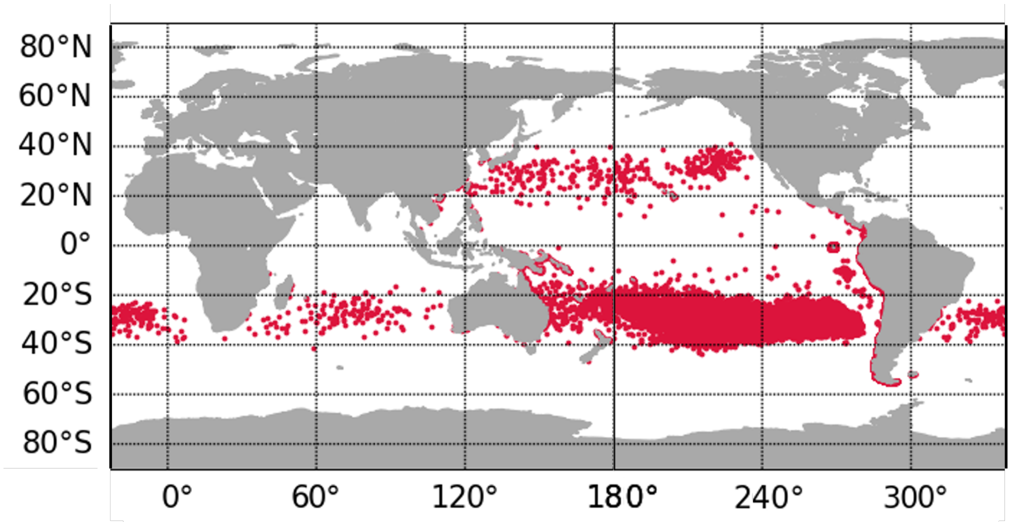

Figure 8: Last position of particles originating in Chile (forward run)

appear during the backward run. The vertical axis shows the percentage of particles that originates from each country. According to the backward run, almost half of the particles found on the Galapagos come from Peru. Chile, Panama and the Galapagos themselves are the source of 10% to 20% of the particles found on the islands. The rest of the countries have almost zero contribution.

Figure 10 shows the density distribution of particles throughout the globe at the end of the backward run. White areas have zero particles and the density increases up to 10 particles per grid in the dark blue areas. The dark blue areas seen only along the coast of America show that most of the particles found on the Galapagos originate from American countries, with the exception of Alaska that has zero particle density. The highest concentrations are seen on the coasts of south America and especially Peru, Chile and on the Galapagos themselves. The origin of many particles is set near Antarctica and some are found in northwest Pacific as well (pink dots).

In figure 11 we see the trajectories of particles originating from Antarctica (figure 11(a)) or northwest Pacific (figure 11(b)), as they where computed during the backward run. Particles originating from Antarctica (11(a)) travel eastward until the reach the southern tip of America. Afterwards they follow the coast towards the north until the Equator and then reach the Galapagos area. Particles that originate from northwest Pacific (11(b)) are advected eastwards across the Pacific until the coast of North America. They follow the coast with small deviations until to the Equator and then flow to the Galapagos area.

4 Discussion

4.1 Forward Run

Looking into the results of the forward run we see that a large percentage (above 40%) of the particles coming from countries around the Equator end up on the Galapagos. Particles from Central America probably drift along the Panamic current that leads them directly to

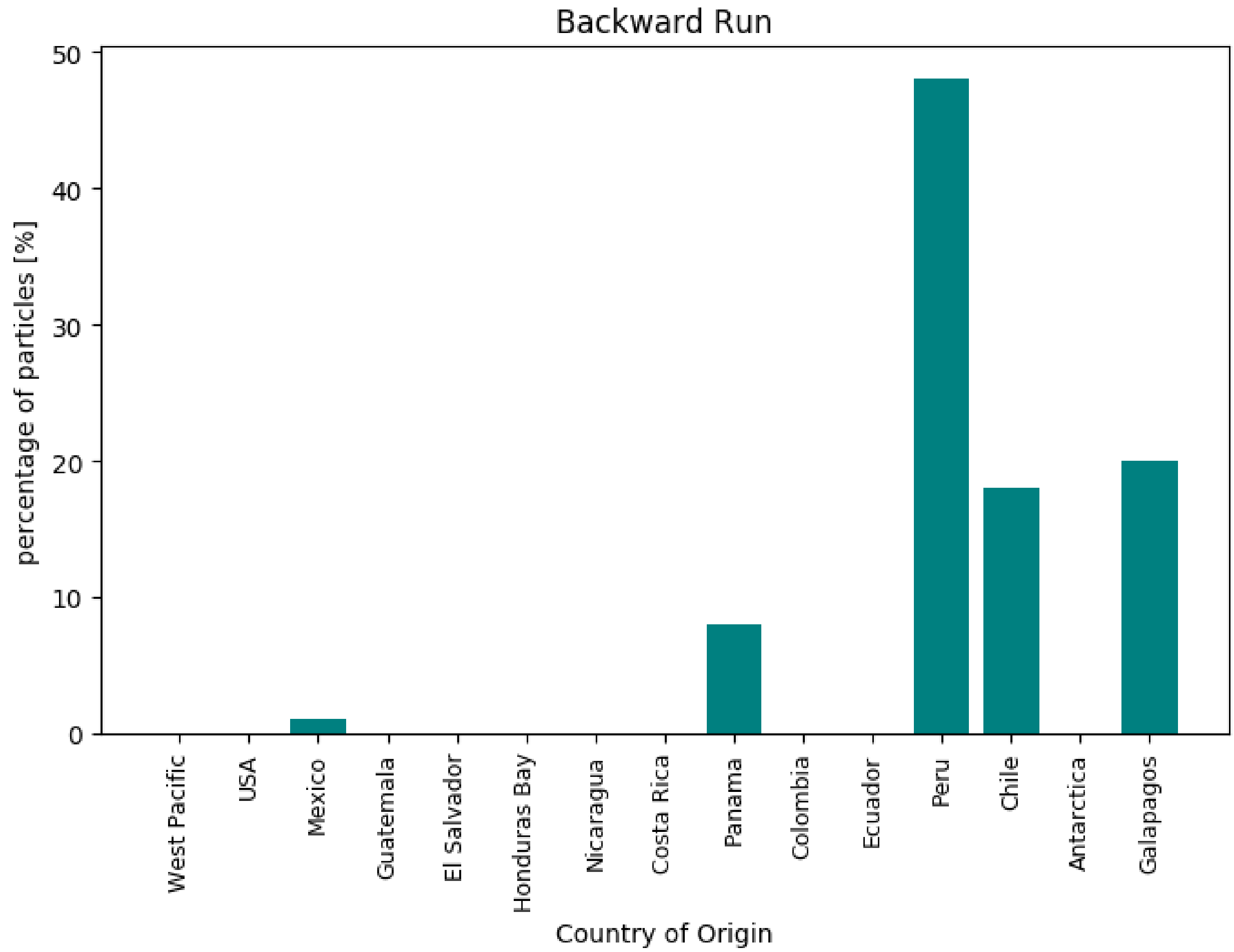

Figure 9: Final position of particles according to backward run. Left axis shows the percentage of particles originating from each country.

the Galapagos marine reserve. Colombia is a striking counterexample of this trend. Despite being next to Panama and Ecuador (more than 80% of the particles from which end up on the Galapagos), only about 25% of Colombia's particles reach the Galapagos. The rest of Colombia's particles end up inside the north and south Pacific patches. Our simulation provides no answer to this paradox. Peru and Chile, the countries that form the coastline of South America also present a very different behavior. Around 70% of the particles coming from Peru end up on the Galapagos, probably being carried by the Humboldt current. In contrast to that, less than 10% of the particles coming from Chile can be found on the Galapagos. (figure 5)

Comparing the percentage of particles reaching the Galapagos per country to the percentage of plastic at risk of reaching the Galapagos shores we see that there is no clear correlation between the two (figure 6). Both statistics agree that Ecuador and Peru are the most important contributors but the percentages each one gives are very different. Around 10% of the virtual particles that end up on the islands come from Chile and Mexico but when we look into their contribution of plastic their percentage is less than 1%. Crude as our approx-

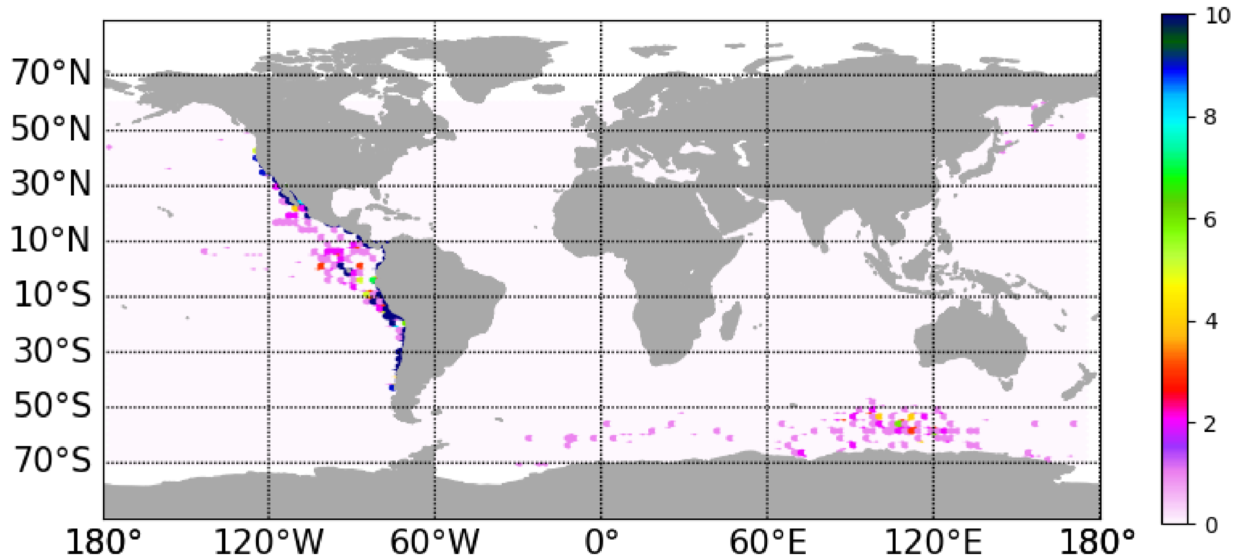

Figure 10: Density plot of the final position of particles according to backward run. The scale has been limited to 10 particles per grid

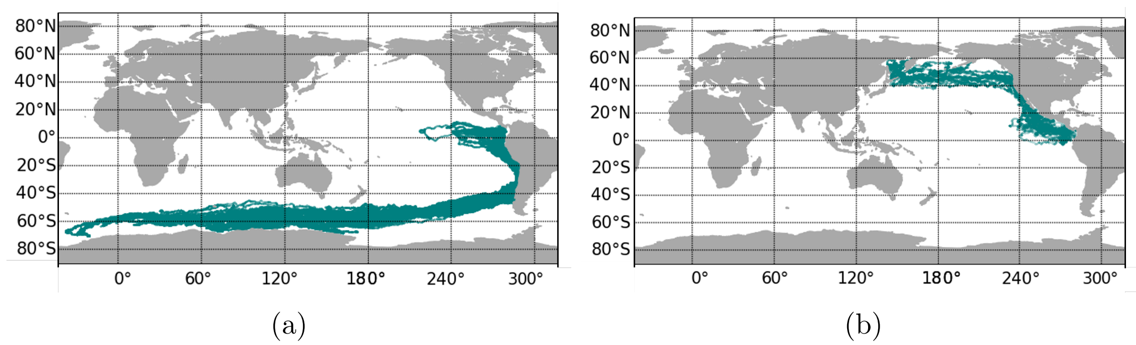

Figure 11: Trajectory according to the backward run of (a) 5 selected particles originating from Antarctica and (b) 3 selected particles originating from northwest Pacific

imations may be regarding the amount of mismanaged plastic of the coastal population of each country that is danger of reaching the islands (since factors such as beaching, sinking, size, disintegration etc of plastic haven't been taken into account), they clearly highlight the importance of solidifying our knowledge on the amount of plastic that is in danger of entering the ocean.

The last positions of the particles revealed an interesting behavior (figures 7 and 13). Particles seem to be blocked next to the shore by the large currents (California & Peru cuurents). They travel along the coast until they enter the nearest gyre and are then trapped there, further attributing to the known garbage patches. This does not seem to happen randomly. The two hemispheres are almost completely seperated. Particles that come from the North Hemisphere will almost certainly remain there and vice versa (figure 7), as expected since the surface currents of North & South Pacific are almost perfectly seperated by the Equatorial (Counter)Currents.

In general, particles from the west coast of America appear to be captured in the Pacific Ocean. That is not the case however for particles originating from Chile, which can be found in both the Atlantic and the Indian Ocean (figure 8). This observation validates the belief that garbage patches (with the exception of North Pacific) are connected and that inter-ocean exchanges are an important factor of the distribution of plastic debris in the ocean [11]. Is is also worth noticing that many particles from the west coast of America end up outside the gyres, on the (shores of) west Pacific (see Appendix figure 13), thus further complicating the determination of the sources of floating plastic in the Pacific Ocean.

Some of the largest ocean currents observed near the Galapagos are the North & South Equatorial currents and the Equatorial Counter current. These currents split the Pacific Ocean in two. They are probably responsible for the clear distinction of particles originating and ending in the North & South Pacific we saw in the forward run. However almost no particles seem to drift on these currents. They act rather as borders between the North & South Pacific gyres, constraining particles in the two garbage patches.

Finally, time plays an important role in the fate of plastic in the ocean. As time passes plastic is degraded into smaller particles [6]. It would be very interesting to repeat the forward run and see how long it takes for particles from different countries to reach the Galapagos complex. We could better predict what sort of plastic (micro-, meso- etc) should be expected in the Galapagos marine reserve. Knowing the time that the plastic debris spends in the ocean, will enable us to predict how fisheries and marine organisms can affect our results. Furthemore, knowing the time of plastic we can expect to find in various areas of the ocean we can better plan the cleanup efforts.

4.2 Backward Run

The most important possible contributors of particles found on the Galapagos islands, as the backward run suggests are Peru, Chile, Panama and the Galapagos themselves. (figure 9) It is interesting to notice here that although in the forward run we saw that a very small portion of the particles that fall in the ocean from the coast of Chile reach the Galapagos (less than 10%) , that small percentage is almost 20% of the total amount of particles that is actually found on the islands. We should also note here, the 20% of particles that come from the Galapagos themselves. Although this seems like a logical assumption, it is not a solid one. During the backward run we drop particles randomly in the Galapagos area. Some of these particles may fall on areas with zero or small velocity (for example on land cells or in small water passages between the islands), get trapped there and thus give us an elevated result. It would be interesting to repeat the simulation, with preset locations in the Galapagos area for example only wet cells or only on the outside border of the complex, to see how these will affect our results.

We where rather surprised to see that the last positions of the particles (figure 10) sets many particles's origin in the Antarctic and North West Pacific. Looking into the trajectories of these particles (figure 11) we see that plastics found on the coast of Antarctica are carried by the Antarctic circumpolar current to Chile. Afterwards, seem to be trapped next to the shore probably by the Peru current, hinting once again that communication between the great ocean currents plays an important role in the distribution of plastic debris in the ocean [11]. They then follow they coast up to the Equator and are then led to the Galapagos area.

On the other hand, particles originating from the Northern west Pacific, are carried across the northern part of the Pacific ocean to the west coast of north America and then follow the coast blocked by the California current up to central America, with small deviations, before they end up on the Galapagos probably driven by the Panamic current. In both cases we have particles that have traveled on the edge of the Pacific gyres.

Looking into figure 11, we see that the particles have traveled long distances along the coast of America. It may be the case that the particles are trapped very close to the shore by the two currents that flow along the shores (California and Peru currents). However, we cannot be sure about that. During the backward run we require particles to stop moving at a certain distance from the coast. This may be affecting our result, obliging particles that in reality would beach to continue their journey. It would be interesting to repeat the simulation using different distances as a limit, to see how and if that would affect our results.

In both runs, we assume that all the particles that fall in the water remain on the surface of the ocean and are only affected by geostrofic & Ekman currents. However, this is not the case. Winds, sinking, beaching, vertical currents and further phenomena of the surface circulation should also be taken into account. It would be interesting to run further simulations incorporating the above mentioned factor to see how they affect our results.

5 Conclusion

In conclusion, both our simulations suggest that the majority of plastic found on the Galapagos islands originates from countries that are located on and around the Equator. Through their results vary, both the forward and the backward run, agree that Peru is probably the most important contributor.

Another important aspect of predicting the sources of plastic is the actual amount of mismanaged plastic that is produced per country. We saw that there is no clear correlation between the percentage of particles reaching the Galapagos and the amount of mismanaged plastic waste. To better estimate the impact of each country on the plastic found on the Galapagos, we need observations regarding the amount of mismanaged plastic in the countries of origin and the amount of plastic that is found on the shores of the islands.

Finally, the behavior of particles originating from Chile highlight the possibility of a connection between the great garbage patches in the ocean. Solidifying this assumption with further simulations and observations can be very useful in predicting the amount of plastic that can be found in the ocean, its origin and future.

6 Laymen summary

The Galapagos island complex is located in the Pacific Ocean 1.000km from the coast of Ecuador and it is considered an UNESCO World Heritage Site. The 133.000km^2 nature reserve is home to an amazing variety of species, many of which are uniquely found there. The islands are one of the most pristine ecosystems on Earth. Despite the efforts to protect the marine reserve from excesses of human influence, the islands are no strangers to plastic pollution, with even the most isolated ones containing high levels of plastic that threatens the unique biodiversity of the complex. This paradox brings forth the question "Where is all this plastic coming from?".

Plastic debris has been documented in all marine environments, from coastlines to the open ocean, from the sea surface to the sea floor, in deep-sea sediments and even in Arctic sea ice. Most of the plastic that enters the ocean comes from the land, with small amounts being derived from maritime activities. As it floats in the ocean, plastic disintegrates into smaller particles that can be as small as zoo-plankton and can be ingested by a wide range of marine organisms, attract algae to grow and absorb toxic materials. Bigger fragments of plastic can entangle marine animals and can carry non indigenous species that can be destructive to ecosystems.

We know today, that plastic can be found throughout the ocean, from the surface all the way down to the deep ocean floor. However calculating the total amount of plastic in the ocean, determining its origin and predicting its fate has proven to be a complicated task, due to the very complicated movement of particles floating in the ocean. There are five great accumulation zones (garbage patches) where plastic is trapped and have been rather well studied. However regions outside the patches (including the Galapagos islands) , where less plastic can be found, are still rather unsurveyed.

One way to study the behavior of particles that flow in the ocean is numerical modeling. In our study we have combined the movement of the surface of ocean with the properties of our particles (where do they enter the water, if they float etc) and with the help of Parcels (a numerical model) we have reproduced the trajectories of particles in the Pacific Ocean. On our first run, we follow virtual particles as they flow from the west coast of America into the Pacific Ocean to see how many of them will end up on the Galapagos. On the second run we begin from the Galapagos. We follow particles that are already on the Galapagos backwards in time to see what their origins may be.

Both our runs indicate that the most important contributor of plastic waste on the Galapagos Islands is Peru. In general it seems that a large amount of particles originating from countries around the Equator end up on the Galapagos. However when we combined this to the actual data of how much plastic falls in the ocean from each country per year, we saw that the countries of central America produce very little plastic waste and therefore the amount of plastic that impact that they have on the Galapagos. Even after this correction, Peru continues to be the most important contributor along with Ecuador.

During our simulations we stumbled across a few interesting results regarding the general behavior of the particles. From the forward run we saw that almost all the particles originating from countries of North America stay in the North Pacific. When looking into particles originating from Central & South America the particles are divided between the North & South Pacific, but in any case seem to be trapped in the Pacific Ocean by ocean currents. A striking exception are the particles that originate from Chile. By the end of the simulation, they could be found not only in the Pacific Ocean, but also in the South Atlantic and Indian oceans. This suggests that particles can move between the garbage patches via ocean currents.

According to the backward run, most of the particles that end up on the Galapagos originated from the West Coast of America and mainly from countries close to the Galapagos. Surprising exceptions are particles whose sources seem to be on Antarctica and Northwest Pacific.

Our simulations suggest that the main contributors of plastic debris on the Galapagos are mid latitude countries on the west coast of America, with the most important one being Peru. However, during our simulations we simplified greatly the movement of particles in the ocean. We didn't take into account that particles can sink and break down. Furthermore, we only took into account the most dominant movement of the surface of the ocean. Smaller scale movement and phenomena, as well as winds, weather and even human activity can affect our results. Apart from that the data we used regarding the plastic that fall in the ocean per country include a lot of approximations. It is therefore needed to improve our simulations and have more detailed data regarding the amount of plastic that falls in the ocean and is found on the coastline before we can make more confident claims.

7 References

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A Appendix

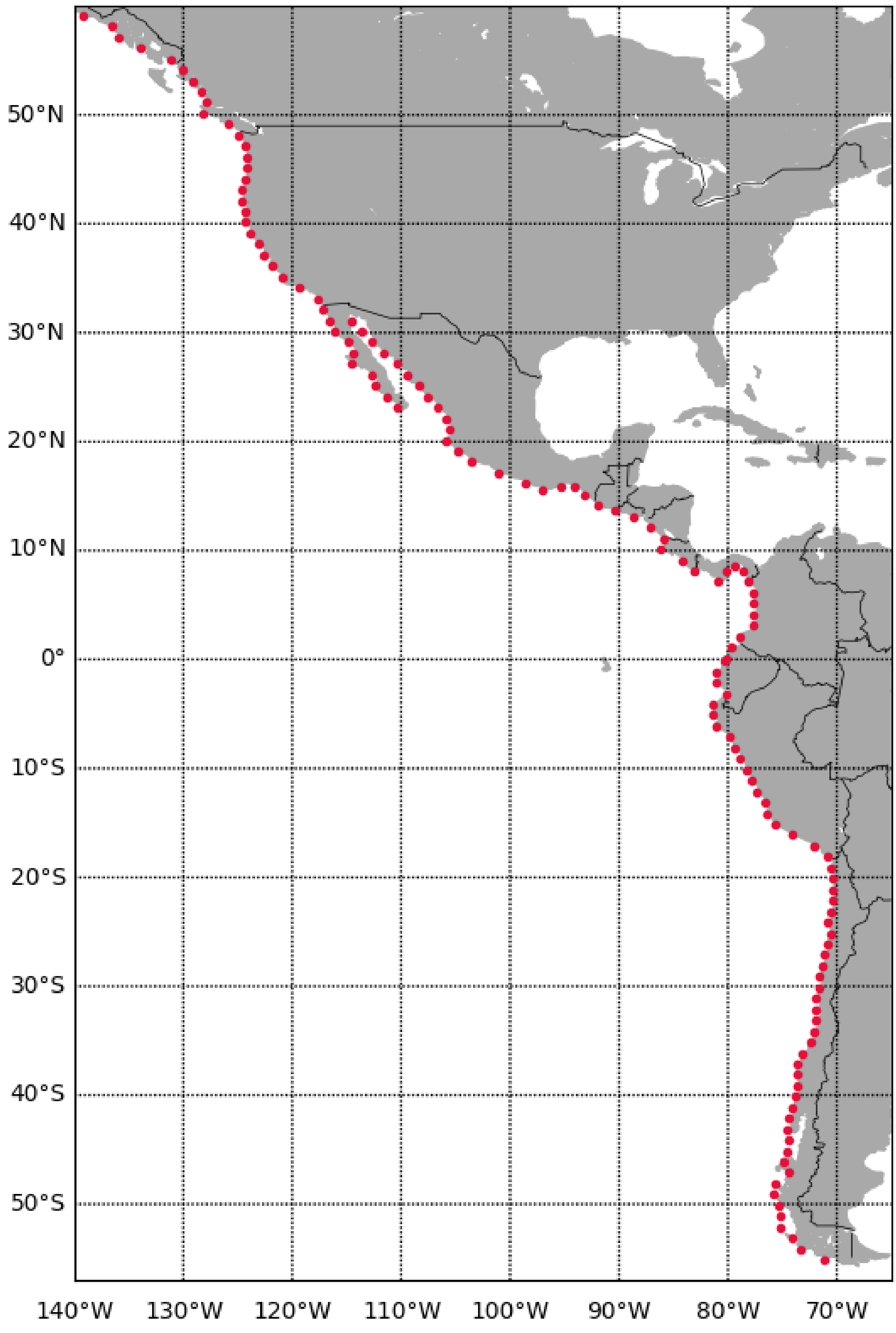
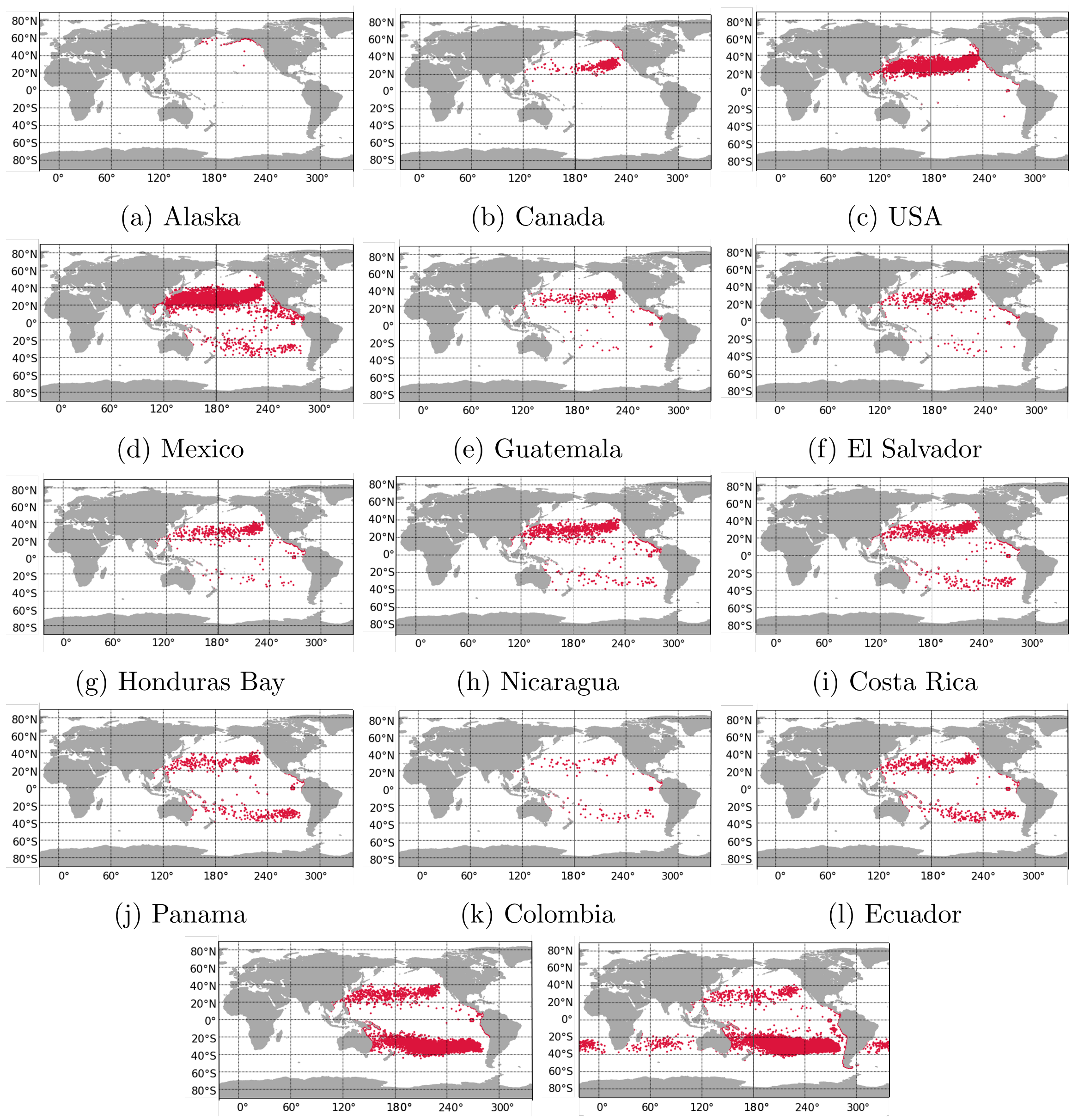


Figure 12: The red dots are the 133 different stations on the west coast of America from which virtual particles are released in the ocean



(a) Alaska (b) Canada (c) USA

(d) Mexico (e) Guatemala (f) El Salvador

(g) Honduras Bay (h) Nicaragua (i) Costa Rica

(j) Panama (k) Colombia (l) Ecuador

(m) Peru (n) Chile

Figure 13: Last position of particles per country (forward run)

#	lon	lat	Country	#	lon	lat	Country	#	lon	lat	Country
1	-139.125	59.125	USA - Alaska	46	-106.625	23.125	Mexico	91	-76.625	-13.125	Peru
2	-136.625	58.125	USA - Alaska	47	-105.875	22.125	Mexico	92	-76.375	-14.125	Peru
3	-135.875	57.125	USA - Alaska	48	-105.625	21.125	Mexico	93	-75.625	-15.125	Peru
4	-133.875	56.125	USA - Alaska	49	-105.875	20.125	Mexico	94	-74.125	-16.125	Peru
5	-131.125	55.125	USA - Alaska	50	-104.875	19.125	Mexico	95	-72.125	-17.125	Peru
6	-130.125	54.125	Canada	51	-103.625	18.125	Mexico	96	-70.875	-18.125	Peru
7	-129.125	53.125	Canada	52	-101.125	17.125	Mexico	97	-70.625	-19.125	Chile
8	-128.375	52.125	Canada	53	-98.625	16.125	Mexico	98	-70.375	-20.125	Chile
9	-127.875	51.125	Canada	54	-94.125	15.875	Mexico	99	-70.375	-21.125	Chile
10	-128.125	50.125	Canada	55	-95.375	15.875	Mexico	100	-70.375	-22.125	Chile
11	-125.875	49.125	Canada	56	-97.125	15.625	Mexico	101	-70.625	-23.125	Chile
12	-124.875	48.125	USA	57	-93.125	15.125	Mexico	102	-70.875	-24.125	Chile
13	-124.375	47.125	USA	58	-91.875	14.125	Guatemala	103	-70.625	-25.125	Chile
14	-124.125	46.125	USA	59	-90.375	13.625	El Salvador	104	-70.875	-26.125	Chile
15	-124.125	45.125	USA	60	-88.625	13.125	Honduras Bay	105	-71.125	-27.125	Chile
16	-124.375	44.125	USA	61	-87.125	12.125	Nicaragua	106	-71.375	-28.125	Chile
17	-124.625	43.125	USA	62	-85.875	11.125	Nicaragua	107	-71.625	-29.125	Chile
18	-124.625	42.125	USA	63	-86.125	10.125	Costa Rica	108	-71.625	-30.125	Chile
19	-124.375	41.125	USA	64	-84.125	9.125	Costa Rica	109	-71.875	-31.125	Chile
20	-124.375	40.125	USA	65	-79.375	8.625	Panama	110	-71.875	-32.125	Chile
21	-123.875	39.125	USA	66	-83.125	8.125	Costa Rica	111	-71.875	-33.125	Chile
22	-123.125	38.125	USA	67	-78.625	8.125	Panama	112	-72.125	-34.125	Chile
23	-122.625	37.125	USA	68	-80.125	8.125	Panama	113	-72.375	-35.125	Chile
24	-121.875	36.125	USA	69	-80.875	7.125	Panama	114	-73.125	-36.125	Chile
25	-120.875	35.125	USA	70	-78.125	7.125	Panama	115	-73.625	-37.125	Chile
26	-119.375	34.125	USA	71	-77.625	6.125	Colombia	116	-73.625	-38.125	Chile
27	-117.625	33.125	USA	72	-77.625	5.125	Colombia	117	-73.625	-39.125	Chile
28	-117.125	32.125	Mexico	73	-77.625	4.125	Colombia	118	-73.875	-40.125	Chile
29	-116.625	31.125	Mexico	74	-77.625	3.125	Colombia	119	-74.125	-41.125	Chile
30	-114.625	31.125	Mexico	75	-78.875	2.125	Colombia	120	-74.375	-42.125	Chile
31	-116.125	30.125	Mexico	76	-79.625	1.125	Equador	121	-74.625	-43.125	Chile
32	-113.625	30.125	Mexico	77	-80.125	0.125	Equador	122	-74.375	-44.125	Chile
33	-114.875	29.125	Mexico	78	-80.375	-0.125	Equador	123	-74.625	-45.125	Chile
34	-112.625	29.125	Mexico	79	-81.125	-1.125	Equador	124	-74.875	-46.125	Chile
35	-114.375	28.125	Mexico	80	-81.125	-2.125	Equador	125	-74.375	-47.125	Chile
36	-111.625	28.125	Mexico	81	-80.125	-3.125	Equador	126	-75.625	-48.125	Chile
37	-114.625	27.125	Mexico	82	-81.375	-4.125	Peru	127	-75.875	-49.125	Chile
38	-110.375	27.125	Mexico	83	-81.375	-5.125	Peru	128	-75.375	-50.125	Chile
39	-112.625	26.125	Mexico	84	-81.125	-6.125	Peru	129	-75.125	-51.125	Chile
40	-109.375	26.125	Mexico	85	-79.875	-7.125	Peru	130	-75.125	-52.125	Chile
41	-112.375	25.125	Mexico	86	-79.375	-8.125	Peru	131	-74.125	-53.125	Chile
42	-108.375	25.125	Mexico	87	-78.875	-9.125	Peru	132	-73.375	-54.125	Chile
43	-111.375	24.125	Mexico	88	-78.375	-10.125	Peru	133	-71.125	-55.125	Chile
44	-107.625	24.125	Mexico	89	-77.875	-11.125	Peru				
45	-110.375	23.125	Mexico	90	-77.375	-12.125	Peru				

Figure 14: 133 stations on the west coast of America grouped into countries according to their coordinates