AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL076366

Key Points:

- The nonstationary solution of Lagrangian dispersion of floating particles by ocean surface currents is analyzed at global scale
- A convergent pathway over a distance larger than 8,000 km, connecting the subtropical South Indian and South Pacific Ocean is revealed and described
- The variability of the currents is essential to sustain the "superconvergent" pathway

Supporting Information:

- Supporting Information S1
- Movie S1

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Citation:
Maes, C., Grima, N., Blanke, B., Martinez, E., Paviet-Salomon, T., & Huck, T. (2018). A surface "superconvergence" pathway connecting the South Indian Ocean to the subtropical South Pacific gyre. *Geophysical Research Letters*, *45*, 1915–1922. https://doi.org/10.1002/2017GL076366

Received 10 NOV 2017
Accepted 26 JAN 2018
Accepted article online 2 FEB 2018
Published online 20 FEB 2018

A Surface "Superconvergence" Pathway Connecting the South Indian Ocean to the Subtropical South Pacific Gyre

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Abstract We study the dispersion and convergence of marine floating material by surface currents from a model reanalysis that represents explicitly mesoscale eddy variability. Lagrangian experiments about the long-term evolution (29 years) of an initially homogeneous concentration of particles are performed at global scale with horizontal current at one fourth degree resolution and refreshed daily over the 1985–2013 period. Results not only confirm and document the five known sites of surface convergence at the scale of individual oceanic basins but also reveal a convergent pathway connecting the South Indian subtropical region with the convergence zone of the South Pacific through the Great Australian Bight, the Tasman Sea, and the southwest Pacific Ocean. This "superconvergent" pathway at the ocean surface is robust and permanent over a distance longer than 8,000 km. The current variability is crucial to sustain this pathway.

Plain Language Summary Understanding the fate of marine and plastic debris at the ocean surface is an objective to be achieved before informing and discussing with policy and decision environmental makers. The transport pathways of such material need to be precisely determined to estimate the pollution at a global scale. By considering nonstationary ocean dispersion by mesoscale eddy variability, this study reveals a novel convergent zone, over a distance larger than 8,000 km, that connects the subtropical South Indian Ocean with the core of the convergent zone of the South Pacific Ocean. The existence of a "superconvergent" pathway in addition to the five convergent zones is of interest to scientists studying plastic debris and more broadly to modelers and experimentalists studying ocean physics and biogeochemistry.

1. Introduction

Contamination by human-made debris and plastics is increasingly observed in the oceans and ecosystems around the world. A better understanding of this issue, which has implications for human health, is of fundamental importance if we are to control this form of marine pollution. Among the areas for further research that can provide direct support to policy makers are identifying the sources, the transport pathways, the rates of degradation, and the sinks of these materials. These priorities were first recommended for future action in a nongovernmental scientific report on marine research issues (Williamson et al., 2016). The underlying assumption is that strategic research choices and the resulting comprehensive knowledge of the problem should lead to more relevant policy decisions.

Ocean dispersion of plastic materials, and more specifically microplastics, has been studied with numerical simulations aimed at investigating global distributions and pathways. Ongoing efforts with these models incorporate more physical processes such as waves, tides, vertical displacements, and specific behaviors related to the nature of the pollutants including the rates of fragmentation and the frequency of active biofouling (e.g., Hardesty et al., 2017). Using in situ data from several global and regional surveys, Cózar et al. (2014) reported that the worldwide distribution of plastic at the surface of the open ocean was concentrated in the convergence zones in each of the five subtropical gyres. These zones were originally revealed by aggregating the trajectories of surface satellite-tracked drifting buoys (i.e., Beron-Vera et al., 2016; Martinez et al., 2009; Maximenko et al., 2012; Pazan & Niiler, 2004; van Sebille, England, & Froyland, 2012, and other references therein).

In one study, Maximenko et al. (2012) combined the global set of trajectories of surface Lagrangian drifters with a probabilistic model of dispersion/aggregation using a transition matrix, but they acknowledged that the validity of the assumption of statistical stationarity can be questioned. Moreover, data gaps remain in the present global drifter coverage with few or no direct observations of currents, but the consequences of these shortcomings are not well understood at global scales. In our study, nonstationary Lagrangian diagnoses based on particle trajectories and combined with a time-coherent ocean reanalysis of the surface currents are explored over the period 1985–2013. The methodology is based on the forward evolution of an initially homogeneous array of particles located on each grid point of the model (one fourth degree horizontal resolution) and refreshed at a daily rate. Our results show the expected five main convergence zones of surface aggregation, located in the subtropics and maintained by converging Ekman currents. The present study emphasizes two essential differences with respect to the results reported by Maximenko et al. (2012). We found that the core of the convergence zone in the south Indian Ocean is displaced in the eastern part of the basin, 30° eastward of its previously documented position, while its latitude remains as expected (around 30°S). This result is in agreement with several studies focusing on the dispersion of small floating debris (Eriksen et al., 2014; Lebreton et al., 2012; van Sebille et al., 2015). More importantly, the present analysis reveals a permanent convergence pathway connecting the South Indian and Pacific subtropical zones through the Great Australian Bight, the Tasman Sea, and the Southwest Pacific Ocean. Like the so-called "supergyre" that connects the thermocline waters of the subtropical gyres of the South Pacific, Indian, and South Atlantic Oceans, this surface "superconvergence" pathway connects the subtropical South Indian with the core of the subtropical convergence zone of the South Pacific Ocean.

2. Materials and Methods

2.1. Global Surface Ocean Currents

In the present study, we used the horizontal currents at the level closest to the surface (around 0.5 m) of the global ocean reanalysis C-GLORSv5 presented by Storto and Masina (2016). This reanalysis combines in situ and satellite ocean observations with the general circulation ocean model NEMO (and LIM3 ice model) on the global ORCA025 grid (one fourth degree of resolution and 50 vertical levels) to estimate the time-evolving state of the ocean following a three-dimensional variational assimilation scheme. The reanalysis spans 1979–2013, but we focused on the 1985–2013 period when the assimilation uses the daily satellite sea-surface temperature supplied by National Oceanic and Atmospheric Administration (Reynolds et al., 2007) and along-track altimetric observations provided by AVISO. The ocean model is forced by the European Centre for Medium-Range Weather Forecasts ERA-Interim atmospheric reanalysis using bulk formulas. The present reanalysis shows some improvements as compared to predecessors as discussed and validated in Storto and Masina (2016). Recently, Cipollone et al. (2017) show that data assimilation enhances and corrects mesoscale variability on a wide range of features that cannot be well simulated by the free simulation. Comparisons with observations show that the "eddy-permitting" resolution is sufficient to allow ocean eddies to form and the assimilation recovers most of the missing turbulence as observed by satellite products. In the following we will use the surface horizontal currents available on the ORCA025 native grid at a daily frequency.

2.2. Approach With Lagrangian Diagnoses

To study the marine pathways that connect different parts of the global ocean, we rely on Ariane, a toolkit engineered for the Lagrangian interpretation of the circulation calculated by numerical ocean models (Blanke et al., 1999; Blanke & Raynaud, 1997). Following the framework described by Maximenko et al. (2012), the experiment starts from a homogeneous initial state where a single particle is positioned on each grid point of the ocean model (representing 902,503 particles here). As vertical displacements are not considered, there are no particle sinks. The Lagrangian trajectories will be used to analyze regions of particle concentration induced by horizontal advection at the surface. In this study, particle concentration represents the total number of particles present in each grid cell of the model. Considering the "turn-around" time scales reported by Maximenko et al. (2012), and with the exception of the South Pacific convergence zone (the only turnover larger than 25 years), the integration over a 29 year period used hereafter is sufficient to describe the characteristics of the global convergence areas. Moreover, as only surface currents are taken into account and because there is no possibility for particles to reach land grid cells (a strong property of the Ariane calculations), the circulation is no longer 3-D nondivergent (unlike the full ocean general circulation model solution) and particles may accumulate and remain blocked for a long time in some oceanic grid cells. In comparison with other previous studies, it also means that all the particles remain at their nominal depth and that the global averaged concentration of particles remains constant in time.

3. Results

The time evolution of the particle concentration (Figure 1 and see the video in the supporting information) shows, not surprisingly, that the particles are advected away from the equator in less than 1 year in the Pacific and in the Atlantic, as well as from the wind-driven upwelling systems located on the eastern side of these oceans. Only the eastern equatorial Indian Ocean maintains noticeable particle concentrations that move back and forth along the equator in response to the monsoon regime. There are also some convergence patches in the equatorial western Pacific, in association with the zonal displacements of the eastern edge of the warm pool forced by westerly wind bursts (e.g., Maes et al., 2004). However, they are flushed out from the equator after a few years. After 3 years (Figure 1a), and excepting the Bay of Bengal, the Indonesian Seas and the eastern Tropical Pacific fresh pool (near the coast of Central America), the particle concentration has been severely reduced within the 15°N–15°S tropical band (75% of the particles move away from this region). Sensitivity experiments made with two other starting dates (1995 and 2005) show very similar features (not shown). Moreover, in the equatorial and tropical bands, the role of strong mean currents is larger than their variability in energetic regimes that are evidenced from the ratio between eddy and mean kinetic energy (Figure S1 in the supporting information). A comparison of these model-based estimates with those based on the GEKCO velocity product by Sudre et al. (2013) shows strong agreement with regard to basin-scale features as well as with smaller features near coastlines, although there are some stronger contrasts and horizontal gradients in the C-GLORSv5 reanalysis. Finally, it is also obvious that particles begin to converge and aggregate in subtropical regions, only after a few years (Figure 1).

After 10 years, the accumulation zones are centered around 30°S and 30°N within the five well-known convergence zones in the eastern part of the south and north, Pacific and Atlantic Oceans. In the Pacific, the zonal extension is more compact than in the Atlantic, when considered in relation to the scale of each basin. The location of the convergence core in the Indian Ocean is the closest to the coast, that is, almost attached to the western coast of Australia. This result strongly differs from the results reported by Maximenko et al. (2012) using a similar scenario of global dispersion but different ocean currents. For a more quantitative assessment, we followed the centers of mass of particle concentrations in predetermined subdomains centered close to 30° of latitude. At the end of the integration period (i.e., after 29 years), their final positions are (94°E–30°S), (99°W, 28°S), (20°W, 30°S), (143°W, 29°N), and (42°W, 29°N), for the South Indian, South Pacific, South Atlantic, North Pacific, and North Atlantic, respectively (small thin black boxes in Figure 1d). This is consistent with the positions of the main subtropical accumulation areas reported initially by Maximenko et al. (2012) but with the exception of the subdomain in the South Indian Ocean that is found 30° farther to the east. Differences in the Pacific and Atlantic basins are small. Time series of the meridional and zonal variations in the position of the centers of mass indicate that the convergence zones are already quite stable after the first 10 years of the integration (Figure S2). The largest variations are found in the North Pacific zone, up to 3° in latitude and 8° in longitude, and are correlated with the index of the North Pacific Gyre Oscillation (Figure S2) as defined by Di Lorenzo et al. (2008).

The South Indian Ocean is of particular interest because of its link with the South Pacific zone (details follow in the next paragraph) and the eastward displacement convergence of its zone relative to its position in earlier studies. We therefore checked that the position of the convergence zone, and especially its core, was not an artifact of the present model. The results obtained with the C-GLORSv5 data set are indeed confirmed by the recourse to another reanalysis of surface currents based on the Hycom prediction system, at the one half degree horizontal resolution (Chassignet et al., 2009). After a 10 year period of integration (2003–2012) for a similar scenario, but considering only the currents in the South Indian Ocean, the center of mass of the particle concentration is found near 92°E–30°S when derived from Hycom (Figure S3), which is very close to the 94°E–30°S position derived from C-GLORSv5. This latter result is also consistent with the figures as shown by Lebreton et al. (2012) considering the HYCOM model at global scales. Therefore, we can reasonably speculate that the heterogeneous and scarce distribution of surface drifters in the South Indian Ocean used

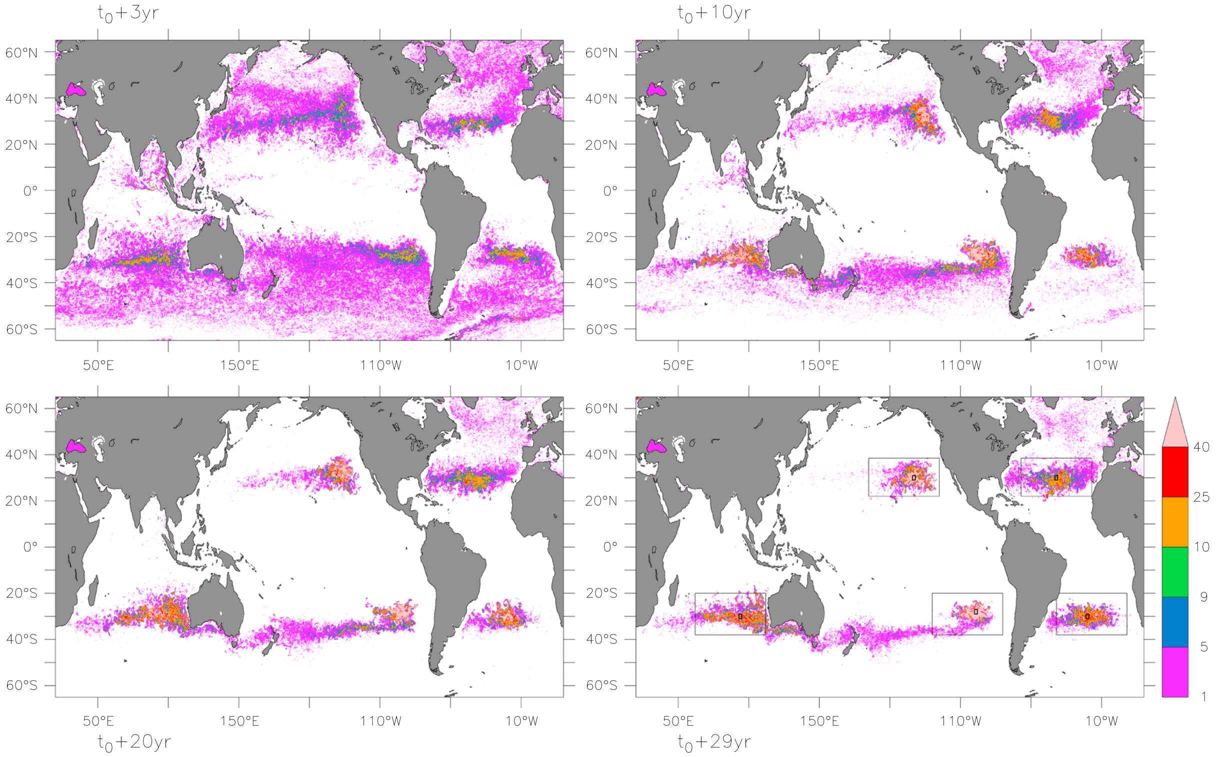

Figure 1. Number of particles per one fourth degree cell resulting from the initially homogeneous experiment after 3, 10, and 20 years and the final step of the 1985–2013 period (29 years). On the lower right panel, the small thick black boxes indicate the position of the center of mass at the end of the experiment, whereas the large black boxes indicate the subtropical convergence areas. Note that the increments in the color bar are not uniforms.

by Maximenko et al. (2012) may induce a bias in their probabilistic model (additional processes such as the wind effect represent some other possibilities). We cannot rule out the possibility that the Ekman component resulting from the wind stress is poorly reproduced by the models and only partially corrected by the assimilation procedure. Further study would be needed to fully resolve this issue.

The geographical distribution of the subtropical convergence zones as reproduced by the C-GLORSv5 currents appear stable after the first 10 years of integration (Figure 1 and the video provided in the SM), and a large fraction of the particles have aggregated in them with the exception of the North Atlantic subpolar gyre and a weak but permanent and robust convergence ribbon connecting the South Indian Ocean to the South Pacific Ocean. Connectivity between gyres has been previously reported by Lebreton et al. (2012) and van Sebille et al. (2015) when studying the dispersion of small floating debris in the oceans and suggesting a potential exchange route between subtropical oceanic basins. In our study, the long-term particle concentration along this ribbon remains low, especially in comparison with the centers of subtropical gyres (Figure 1d), but is relatively well stabilized after 15 years of Lagrangian integration. This feature appears to be as permanent as the convergence subtropical zones it connects. Figure 2 shows the time evolution of the particle concentrations in the five subtropical gyres specified in Figure 1d. Starting from unity, all the concentrations rise at a quite similar rate and begin to stabilize after 10 years, with the exception of the South Pacific region that continues to increase during the full 29 year long integration. Interestingly, only the concentration in the South Indian zone is associated with a decrease after about 15 years. In order to extend the Lagrangian integration, we ran a supplementary experiment by using again the same sequence of currents for another equivalent period (29 additional years). While this approach introduces an obvious time discontinuity, it doubles the time integration up to 58 years. The trends in concentrations revealed in Figure 2 were mostly confirmed, that is, stable values in the Atlantic Ocean, a very slow increase in the North Pacific, and a large increase and a decline in the South Pacific and the Indian Ocean, respectively. If we extrapolate in time the evolution of the concentration of particles in the South Indian Ocean using a constant decrease rate, it would take around 92 years to flush out its convergence region. Because the

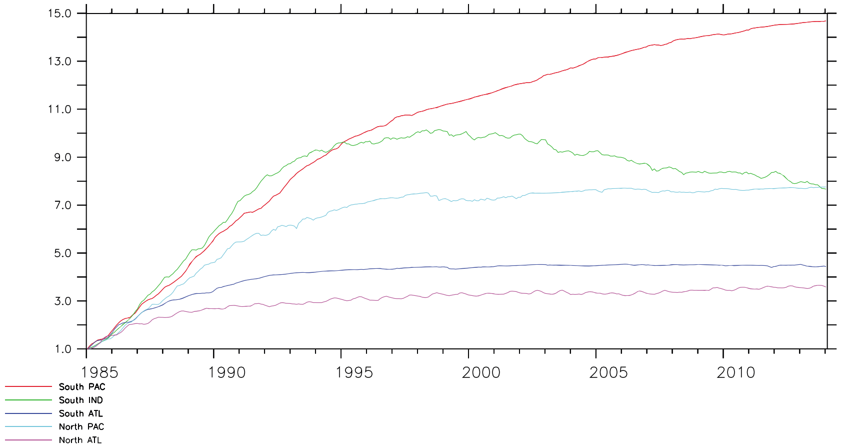

Figure 2. Time series of the number of particles per one fourth degree cell averaged over the five subtropical convergence areas (large black boxes in Figure 1d). At the initial time step concentration is constant and equal to unity.

concentrations in the rest of the oceans remain almost constant, these particles must accumulate in the convergence core in the South Pacific Ocean, which explains the almost continuous rise in this region.

For this argument to hold, it is important to associate the pathways of these particles with the ribbon shown in Figure 1. We did this by analyzing and tracing backward the particles that reached the South Pacific convergence zone after 29 years (see the original departure box in Figure 1d). Figure 3 shows the position of particles in January 1995 that will converge to the South Pacific gyre and reach the area in December 2013. Ten years into the experiment, some particles could be traced back not only as far as Southern Ocean in the Indian sector (near 40°E–50°S) but also to the subtropical zone of the South Indian Ocean near 30°S. The connection to the core of the South Pacific convergence zone is clearly made through the Great Australian Bight, the Tasman Sea, and the southwestern region of the Pacific Ocean between 35° and 40°S. In the forward experiment, the same pathways could be identified, but with a broader meridional extension. The whole source domain of the particles that eventually converge toward the South Pacific subtropical gyre is successfully obtained after 20 years of the backward experiment (Figure S4). Not surprisingly, almost all the South Pacific Ocean contributes at the beginning of the experiment, a result that is consistent with previous studies (Froyland et al., 2014; Maximenko et al., 2012).

A detailed view of the time evolution of the particle concentrations along this ribbon connecting the Indian and Pacific Ocean is given in Figure 4 in which each domain represents a box region of 20° and 10° in

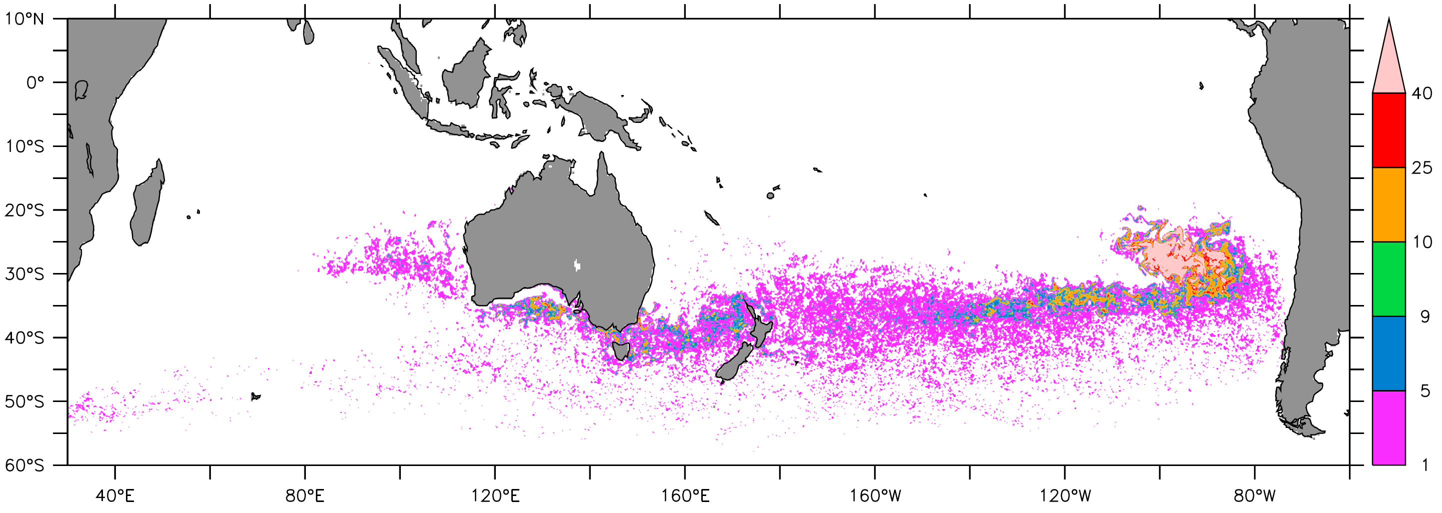

Figure 3. Number of particles per one fourth degree cell in January 1995 that transit toward the core of the convergence gyre in the South Pacific Ocean and reach the area in December 2013. Note that the increments in the color bar are not uniforms.

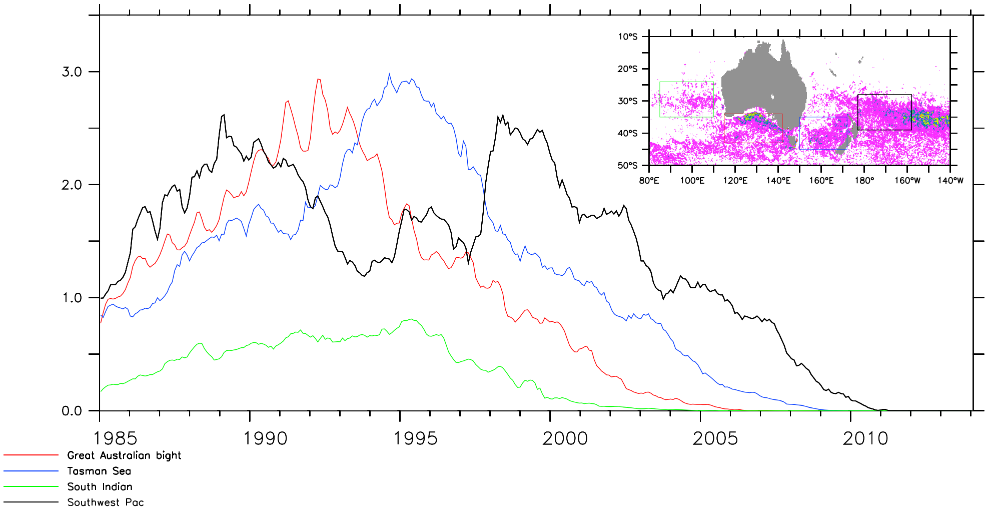

Figure 4. Time series of the number of particles per one fourth degree cell that converge toward the core of the convergence area in the South Pacific Ocean along different parts of the "superconvergence" pathway (see the inset for the definition of boxes).

longitude and latitude, respectively (the positions of the boxes are indicated in the inset in Figure 4). The latitude of the box in the South Indian Ocean is centered on 30°S, and latitudes for the other regions are a little further south, generally following the geometry of the connection pathway. As mentioned previously the particle concentrations are weak and the smallest contribution is provided by the part from the South Indian Ocean region. In the three areas westward of the southwest Pacific, the time evolution peaks before in the first 10 years of integration, and then decreases because the particles converge toward the subtropical south Pacific gyre. This result indicates that the local dynamics also allow for local convergence processes before activating the transfer to a remote region, that is, the core of the convergence zone of the South Pacific gyre. For the southwest Pacific box, a second peak before the 2000s results from accumulation of particles from the other regions. Altogether these analyses confirm the connection established between the subtropical gyre of the South Indian Ocean and the core of the South Pacific convergence zone.

4. Discussion and Conclusions

The Lagrangian analysis of the multidecadal variability of the subtropical convergence zones reveals a potential interbasin connection through a specific "convergence" pathway, over a distance in excess of 8,000 km, between the subtropical regions of the South Indian Ocean and the South Pacific gyre. Our study, employing the release and tracking of numerical particles in the surface velocity field of an ocean model reanalysis, reproduced the five well-known convergence zones in the subtropical oceans, which act as permanent collection sites of floating marine debris. But above all, our results show that these convergence areas should not be regarded as closed and isolated from one another. In a certain sense, this relates to the ideas put forward by Maes et al. (2016) on the existence of exit routes which allow for the dispersion of particles originating in the core of the southeastern Pacific convergence zone. Our present knowledge of the space and time scales involved in the variability associated with these regions needs further improvement, as does our understanding of the physical mechanisms at work. For instance, Maes et al. (2016) also pointed out that the eddy variability could play an important role in introducing an asymmetry between the sources of particles converging toward the core of subtropical Pacific gyres. In the present study, we show that the particles follow a pathway from the South Indian toward the South Pacific Ocean against the prevailing westward displacement of eddies (Chelton et al., 2011). This is especially the case for the portion of the pathway identified near Australia, around Tasmania, and leaving the Tasman Sea, where long-lived anticyclonic eddies play a role in the so-called Tasman leakage involved in the interocean exchange of thermocline waters (Pilo et al., 2015; Ridgway & Dunn, 2007; Speich et al., 2002; van Sebille, England, Zika, et al., 2012). It is worth noticing by Maes and Blanke (2015) that Lagrangian particles can be transported over long distances and against the prevailing mean surface currents to connect different remote regions. What is also very important here is the difference in the physical mechanism at work in such convergence pathways, that is, eddy-induced variability instead of the wind-generated Ekman currents in the convergence subtropical gyres (e.g., Kubota, 1994). To separate these contributions, we ran two additional experiments, considering in one case the averaged currents over the 1985–2013 period and, in the other case, the mean seasonal cycle computed over the same period. In the first case, the particles converge toward the subtropical gyres, and after 10 years, the concentrations in each convergence core is almost stabilized, or only slightly increasing as in the South Pacific Ocean and in the South Indian Ocean (Figure S5). This reflects the absence of a "superconvergence pathway" between these two regions when time variability is not considered explicitly. In the second case, the transfer of particles from the South Indian toward the South Pacific occurs after a period of 20 years in the experiment, but the transfer rate is weaker (dashed lines in the Figure S5). Finally, it is clear that the superconvergence pathway occurs in a region where eddy kinetic energy is the dominant driver of the local energetics (Figure S1). Therefore, the intrinsic geometry of eddies, as well as their nonlinear interactions with the mean flow and its seasonal cycle, will need to be taken into consideration. All these results speak in favor of a careful and explicit representation of eddy mesoscale variability in models when considering the dispersion of floating material at the ocean surface in future studies.

Located on the western side of the South Pacific convergence zone, the tiny Henderson Island (24°20′S, 128°19′W) in the Pitcairn Archipelago has been recently characterized by the most important density of debris as reported elsewhere in the world (Lavers & Bond, 2017). This result is clearly consistent with the accumulation of the numerical particles and the "superconvergence pathway" that our study has disclosed, but a direct application of our results to the global plastic issue remains challenging. The first reason is the uncertainty about the amount of plastic at sea as well as its source and sink locations (e.g., the part that ends up on island beaches) as widely mentioned in the literature. Another limitation is the difficulty of a direct comparison with the trajectories of actual drifters. For instance, the "superconvergence pathway" does not show up in the real drifter trajectories deduced from the 57 net tows ("net stations") analyzed by Reisser et al. (2013) around Australia, possibly because the drifter tracks highly depend on their release locations and on ocean dynamics. The limited number of real drifters (with respect to the heterogeneity of possible behaviors), not excluding poor information about possible drogue loss, remains one obvious limitation. Future progress in tackling the ubiquitous and growing plastic and litter problem in the global ocean should consider the usefulness of ocean models, as already been stated by several studies and international reports (i.e., Hardesty et al., 2017; Williamson et al., 2016) and, in particular, should take into account the mesoscale and submesoscale variabilities in the simulation of ocean dynamics.

Acknowledgments
Our study benefited from different data sets of ocean models. This includes the HYCOM + NCODA Ocean Reanalysis that was funded by the U.S. Navy and the Modeling and Simulation Coordination Office (output is publicly available at http://hycom.org.glbu0.08/expt_19.1) and the CGLORSv5 outputs from the CMCC center (http://www.cmcc.it). The help of Andrea Cipollone for the latter data set has been especially appreciated. The Ariane toolkit is available at http://www.univ-brest.fr/lpo/ariane. We give special thanks to Dave Berhinger and Erik van Sebille for their reading of the original manuscript and also to Laurent Lebreton and one anonymous reviewer for their constructive comments. This work has been supported by the AXe 1 "ocean engine at very high resolution" of the LABEX MER (http://www.labexmer.eu) and by IRD.

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