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Erik van Sebille
Utrecht University

Gary Froyland
UNSW Sydney

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Origin, dynamics and evolution of ocean garbage patches from observed surface drifters

Erik van Sebille[1,3], Matthew H England[1] and Gary Froyland[2]

[1] Climate Change Research Centre and ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, Australia
[2] School of Mathematics and Statistics, University of New South Wales, Sydney, Australia

E-mail: E.vanSebille@unsw.edu.au

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Abstract
Much of the debris in the near-surface ocean collects in so-called garbage patches where, due to convergence of the surface flow, the debris is trapped for decades to millennia. Until now, studies modelling the pathways of surface marine debris have not included release from coasts or factored in the possibilities that release concentrations vary with region or that pathways may include seasonal cycles. Here, we use observational data from the Global Drifter Program in a particle-trajectory tracer approach that includes the seasonal cycle to study the fate of marine debris in the open ocean from coastal regions around the world on interannual to centennial timescales. We find that six major garbage patches emerge, one in each of the five subtropical basins and one previously unreported patch in the Barents Sea. The evolution of each of the six patches is markedly different. With the exception of the North Pacific, all patches are much more dispersive than expected from linear ocean circulation theory, suggesting that on centennial timescales the different basins are much better connected than previously thought and that inter-ocean exchanges play a large role in the spreading of marine debris. This study suggests that, over multi-millennial timescales, a significant amount of the debris released outside of the North Atlantic will eventually end up in the North Pacific patch, the main attractor of global marine debris.

Keywords: marine debris, ocean surface circulation, surface drifting buoys, Ekman dynamics

S Online supplementary data available from stacks.iop.org/ERL/7/044040/mmedia

1. Introduction

Marine debris collected in so-called garbage patches (Wakata and Sugimori 1990, Kubota 1994, Moore *et al* 2001, Law *et al* 2010, Lebreton *et al* 2012, Maximenko *et al* 2012) poses a severe threat to the near-surface ocean environment (Derraik 2002, Barnes *et al* 2009, Gregory 2009, Teuten *et al* 2009). Over recent decades, a surge in economic growth has led to an enormous input of debris into the ocean, which will linger there for the coming centuries. Plastics in particular pose a risk to marine life, as they degrade very slowly and could enter the (marine) food chain. While in the ocean, plastics and other floating debris are carried by winds and currents. Since the surface currents preferentially converge and subduct in certain locations, the debris in the near-surface layer tends to collect in several relatively confined regions. These regions of accumulation are commonly known as the great ocean garbage patches (Moore 2008).

[3] Address for correspondence: CCRC, Faculty of Science, University of New South Wales, Sydney, NSW 2052, Australia.

The concentration of plastic and other debris in these ocean garbage patches can be many orders of magnitude larger than in other regions of the world ocean (Law *et al* 2010, Maximenko *et al* 2012), warranting a thorough understanding of the dynamics of these patches. To first order, the formation of the patches is governed by the well-established dynamics of Ekman pumping in the subtropical gyres (Maximenko *et al* 2012), where wind-driven convergence of the surface flow leads to accumulation of surface water in the centre of the gyres. As the debris is generally less dense than seawater, it floats and accumulates in the regions of strongest convergence near the surface. Linear open ocean Ekman theory, however, does not predict the timescales of patch formation from debris entering at the coastal margins, nor how eddy mixing or other non-linear processes can counteract the accumulation of debris and provide a flux out of the patch locations. Knowing how fast coastal debris reaches the different garbage patches, as well as how leaky these patches are in time, can help inform monitoring efforts for the coming decades.

A previous study of the formation of the garbage patches (Maximenko *et al* 2012) incorporated an idealized initial state with surface debris uniformly spread over the global ocean, before employing observed surface drifter data to advect the marine debris forward in time. While the main subtropical garbage patches emerge using this approach, in reality the entry of marine debris into the oceans largely occurs at the coastal margins where industrial activity and waste disposal is most highly concentrated. Furthermore, the method of Maximenko *et al* (2012) assumed the advection of tracer to be constant in time and thereby ignored the seasonal cycle of the surface ocean circulation. Here, we study the transport of tracer away from the coastal margin and into the open ocean with a method that incorporates the seasonal cycle and uses a marine debris source function that scales with human population around the coast (Lebreton *et al* 2012). This allows us to study the fate and mixing of marine debris in a more realistic scenario than previously achieved, and to estimate the pathway and ultimate garbage patch location of debris. This method reveals a sixth garbage patch not previously identified. We further examine, for the first time, how each of the garbage patches are connected, how inter-ocean exchange mixes debris from different regions, how 'leaky' the patches are and how they will evolve over century timescales.

2. Methods

2.1. The observational global drifter data set

In this study, we use observational drifter data from the Global Drifter Program to assess the evolution of debris in the ocean. Within the observational Global Drifter Program (Niiler 2001, Lumpkin 2003, Lumpkin *et al* 2012), buoys that get advected with the near-surface flow have been released since the early 1980s; these can be used to study where and over what timescales marine debris accumulates in the global ocean. The drifters have a battery life of up to 5 yr and the post-processed data yields geo-locations of the buoys every 6 h. Global coverage is reasonably comprehensive, with more than 85% of the ocean surface having over 100 location fixes per $1^\circ \times 1^\circ$ grid box (van Sebille *et al* 2011, Maximenko *et al* 2012).

All buoys used here are deployed with a drogue at 15 m, but many of them lose their drogue during their lifetime, so that 48% and 52% of the data is from buoys with and without drogues, respectively. Although Maximenko *et al* (2012) showed that non-drogued buoys largely aggregate in the same region as drogued buoys, the dynamics of the two types of buoys is different (Poulain *et al* 2009, Grodsky *et al* 2011). Specifically, non-drogued buoys are more sensitive to direct wind forcing and wind drift, whereas drogued buoy trajectories track the ocean flow at 15 m depth, and so are more representative of the upper ocean geostrophic flow and Ekman transport. Here, we combine both types of buoy trajectories. First of all, this allows us to work with a much larger data set, which greatly improves the accuracy of our method (see below). Secondly, the marine debris in the real ocean is also a combination of plastics in the neuston (the layer where the wind has a very large effect) and near-neutrally buoyant plastics in the mixed layer (Kukulka *et al* 2012, Morét-Ferguson *et al* 2010, Cole *et al* 2011). Finally, biofouling on the smallest plastics increases their density and results in some being submerged (Andrady 2011) or even sink to the ocean floor (Bergmann and Klages 2012). Hence, the combination of drogued and non-drogued buoys most closely resembles the variety of vertical positioning of surface layer marine debris.

2.2. The transit matrix approach

Observed buoy trajectories are too short lived to resolve the connectivity between ocean regions on the timescales we are interested in here. In order to overcome this problem, we use the buoy trajectories as input for a tracer matrix, a statistical method of analysing observational data that has been shown to adequately capture the observed dynamics of the ocean circulation on both regional and global scales (Froyland *et al* 2007, Dellnitz *et al* 2009, van Sebille *et al* 2011, Maximenko *et al* 2012). All available buoy trajectories are gridded onto a $1^\circ \times 1^\circ$ grid and then used to create a set of transit matrices $\mathbf{P}_b$. These transit matrices give, for each grid box, the probability that particles move to any other grid box in 60 days. Using periods shorter than 60 days yields transit matrices with less than 10 crossings in some regions of the oceans where drifter coverage is low, whereas using periods longer than 90 days means that the seasonal cycle is not adequately resolved.

In order to represent the annual variation in the surface currents, which can be particularly large in the equatorial region, each transit matrix uses data from only a two-month period. For instance, $\mathbf{P}_1$ is the transit matrix from all buoy trajectories with 60 day segments starting in January or February, $\mathbf{P}_2$ is the same but then for March and April, and so on through to $\mathbf{P}_6$ for November and December.

Iteration of the matrix equation $v_{t+60\text{ days}} = v_t \mathbf{P}_b$, with $b = \text{mod}\ (t/180\text{ days}, 6)$ then yields (Froyland

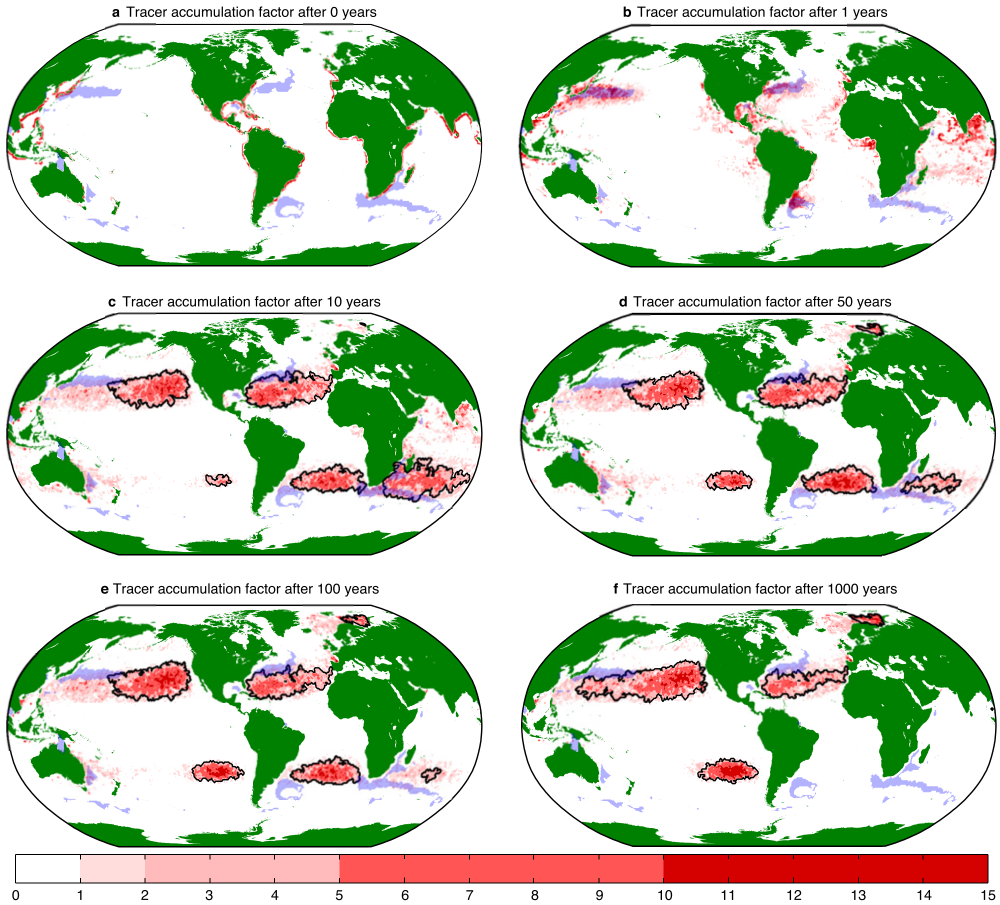

Figure 1. The locations and sources of the six garbage patches. (a) The tracer accumulation factor (TAF) at the moment of release. Coastal population is used as a proxy for the amount of tracer released. The blue patches denote areas where sea surface height variability is larger than 15 cm, an indication of high eddy activity. Note that in these figures, as well as in the video in the supplementary material (available at stacks.iop.org/ERL/7/044040/mmedia), white shading means that the tracer accumulation factor (TAF, see also section 2) is less than 1. (b) The TAF after 1 yr of integrating the tracer. The tracer is advected into the open ocean by the swift-flowing surface currents. (c) The TAF after 10 yr of integrating the tracer. Well-defined patches can be seen in each of the five subtropical gyres. The thick lines denote the spatial extent of the patches. (d) The TAF after 50 yr of integrating the tracer. The Southern Indian patch has become much smaller, while the Southern Pacific one has grown considerably in comparison to the tracer density after 10 yr. A sixth patch is now visible in the Barents Sea. (e) The TAF after 100 yr of integrating the tracer. The patch in the South Indian has almost completely disappeared. (f) The TAF after 1000 yr of integrating the tracer. The patches in the Southern Atlantic and Indian have completely disappeared, and the patches in the South and North Pacific have grown considerably in size.

et al 2007, Dellnitz *et al* 2009) the advection of tracer concentrations v as a function of time t. With relatively little computational burden, this tracer transit matrix can then be integrated forward in time for many centuries, allowing for the investigation of global tracer evolution on millennial timescales.

The matrices $\mathbf{P}_b$ are row normalized, which means that the amount of tracer is conserved. In these experiments, therefore, we do not consider the beaching of marine debris (Lumpkin *et al* 2012) or the abyssal sinking of particles due to heavy biofouling; focusing instead on the evolution of that part of the marine debris inventory that remains in the open ocean for decades to centuries. Furthermore, we focus on the open ocean pathways of marine debris, which means we do not explicitly account for near-shore flows through which the marine debris has to migrate from the land to the open ocean.

2.3. The tracer release experiment

Debris tracer is released according to coastal population density (Lebreton *et al* 2012) using a gridded product (CIESIN-CIAT 2005). Ideally, the tracer would be initialized using actual observed marine debris fluxes into the ocean, but such data are not available on a global scale. Human population is arguably the most relevant and best-constrained proxy for marine debris fluxes (Marxsen 2001, Halpern *et al* 2008). Additional socio-economic data, such as gross national economic and manufacturing indices, do not necessarily relate to coastal ocean debris input, as waste disposal efforts vary widely from region to region.

For each grid box that is adjacent to the ocean, tracer in the grid box of the transit matrix $\mathbf{P}_b$ is scaled to the local population density within 200 km from the coast (figure 1(a)). In some regions, particularly in the Indonesian Archipelago and in the North Sea, the coverage of observational drifters is

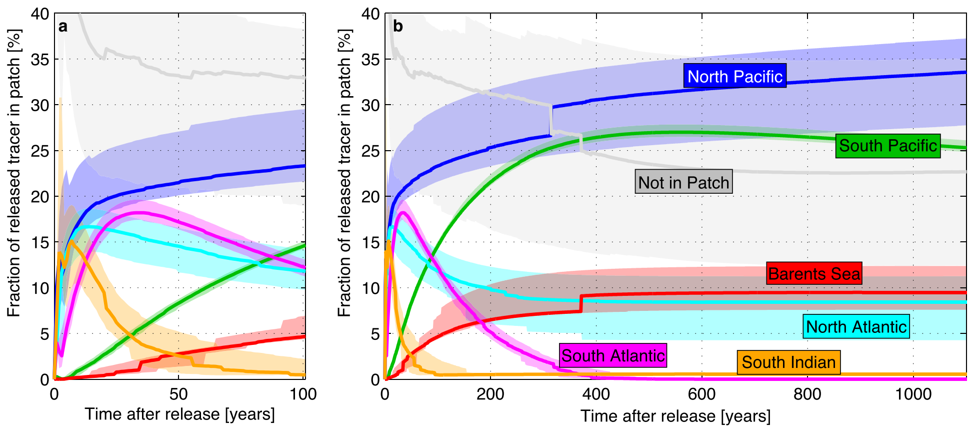

Figure 2. The evolution of the amount of tracer within the six garbage patches. For each of the six garbage patches, the amount of tracer in the area where the TAF > 2.0 (thick lines, see also figure 1) as a function of time for (a) the first 100 yr after release and (b) the first 1100 yr. The shaded areas depict the sensitivity to the choice of TAF value, here shown as the range 1.0 < TAF < 3.0. Near instantaneous jumps in the patch size are due to mergers of patches and depend on the exact value of the TAF criterion used. The North Pacific patch keeps on growing for at least 1100 yr after the release of tracer, while the South Pacific patch slowly decays after reaching a maximum size at 500 yr. The North Atlantic and Barents Sea patches reach an equilibrium size after approximately 300 yr, while the South Atlantic and South Indian patches completely disperse within 400 and 100 yr, respectively. The amount of tracer not within any of the six main patches stabilizes at approximately 22% of total tracer released. Part of this tracer not in patches accumulates in small localized areas such as the Bay of Biscay (figure 1(d)), but most of it (13% of the total tracer released) resides on the fringes of the patches, where the TAF < 2.0. Note that in this model, tracer is released only in the first year, and that by construction tracer is conserved, meaning no export onto the coasts or into the deep ocean.

too poor to locally construct a transit matrix. Ocean grid cells in these areas are therefore not included as tracer release sites. Furthermore, no tracer is released within the Mediterranean Sea since no observational drifters cross the Gibraltar Strait, and hence this flow cannot be resolved by the tracer transport calculations.

A tracer amplification factor (TAF) is used to identify patches. If the total amount of tracer released is C and there are N ocean grid points, the TAF of a grid box (x, y) with local tracer concentration $c(x, y)$ is defined as $\mathrm{TAF}(x, y) = c(x, y)N/C$. If, for example, in some grid box $\mathrm{TAF}(x, y) = 20$, then twenty times more tracer is found within that grid box than if all tracer is uniformly distributed over the global ocean. Using the instantaneous TAF field, patches are defined as connected areas within the different ocean basins wherever TAF > 2.0.

Tracer is released as six pulses over the course of 1 yr, rather than as repeated pulses each time step. The rationale for releasing only over 1 yr is that this provides a clearer picture of how the tracer patches accumulate in time and then disperse. Since tracer does not interact with itself in a non-linear manner, the tracer concentrations resulting from multi-year releases can be constructed using a linear superposition of concentrations resulting from all earlier pulses.

3. Results

After initialization around the coastal ocean (figure 1(a)), the tracer is advected for 1100 yr (see the supplementary material available at stacks.iop.org/ERL/7/044040/mmedia for a video of how the tracer circulates in the ocean for the first 25 yr). After 1 yr (figure 1(b)), the fast-flowing western boundary currents and equatorial jets of the oceans have advected much of the tracer into the open ocean. After 10 yr (figure 1(c)), well-defined regions where TAF >2.0 (i.e. where tracer concentration is more than twice that expected when all tracer is uniformly distributed over the ocean) can be seen in the five subtropical gyres, although the patch in the South Pacific remains relatively small at this stage, largely due to its remoteness from the most densely populated coastlines.

After 50 yr of tracer advection, some of the patches have changed considerably in size (figure 1(d)) compared to the situation 40 yr prior. The South Indian patch has decreased in size, while the South Atlantic patch has grown slightly. The South Pacific patch is still relatively small in spatial extent but has increased in maximum TAF values. Finally, there is a newly formed patch in the Barents Sea. This Barents Sea patch can still be observed after 100 yr (figure 1(e)), while the South Indian patch is considerably smaller than 50 yr earlier. After 1000 yr (figure 1(f)) there are no longer any elevated levels of tracer in the South Atlantic and South Indian patches, while the North Pacific patch is continuing to expand.

Each of the five basin-scale subtropical gyres harbours a discernible garbage patch over time. These regions of convergence, set up by wind-driven Ekman pumping, agree with past observational and modelling studies (Moore *et al* 2001, Maximenko *et al* 2012). As there is no Ekman-driven convergence in the Barents Sea, accumulation of tracer there might be partly related to slow surface convergence due to deep-water formation, and possibly also to surface buoys becoming grounded in the (seasonal) sea-ice. Observations of this area of high debris accumulation in the Arctic region are not yet available, although our results suggest that it may take a few more decades before significant amounts can be detected there.

The accumulation of tracer in the six main patches varies considerably over time (figure 2) and each of the patches has a unique evolution. Nevertheless, all patches except for the North Pacific patch reach a maximum size within the first 500 yr, after which they decay over a range of timescales. Almost all of the patches thus appear to be 'leaky', although some disperse much faster than others. Tracer moves between gyres on timescales similar to those seen in figure 2. For example, the amount of tracer that crosses the Equator in the North Pacific is closely related to the evolution of the North Pacific patch on timescales longer than 30 yr.

The time evolution of the garbage patches is governed by the balance between accumulation due to Ekman convergence and dispersion due to other processes. One of the most important agents that can mix scalar properties over the global ocean is mesoscale eddies (Chelton *et al* 2011). Evidence for the role of eddy mixing in dispersion of tracer in the ocean can be found in figure 1, where the regions of highest observed sea surface height variability coincide with the edges of the patches where relatively low spatial gradients in TAF appear. The amount of eddy activity can also help explain how tightly defined the garbage patches are. For example, the South Pacific patch is farthest away from regions of high eddy activity (figure 1(f)) and also the best-defined patch of all, as is evident from figure 2 (where the area that $1.0 < \text{TAF} < 3.0$ is small).

The leakiness of the six main patches can be further studied by releasing tracer within each of the six patches separately and then advecting this tracer 2 yr forward in time (figure 3); an experiment that is particularly useful to investigate where and how tracer leaves the patches. For the two Pacific patches, tracer that leaks away remains in the respective basins. For the other four patches, in contrast, there is clearly a preferred direction of leaking. For example, tracer from the North Atlantic patch gets advected northeastward towards the Barents Sea, while tracer from the Barents Sea patch gets advected southwestward towards the North Atlantic patch. An interaction between patches can be seen even more clearly in the South Atlantic and South Indian regions: the two subtropical gyres in these basins span the so-called 'super-gyre' (Speich *et al* 2007), and our results provide direct observational evidence that this super-gyre also manifests in ocean surface flow (figure 3(b)).

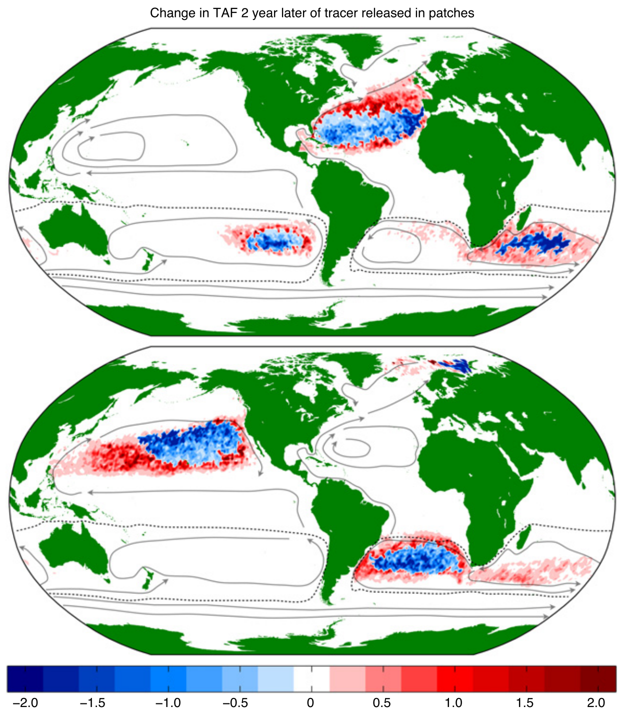

Figure 3. The spatial pattern of leakiness for the six garbage patches. For each of the six garbage patches tracer is released only within the patch at its simulated concentration after 50 yr (the black contours in figure 1(d)). That tracer is then integrated for another 2 yr, and this figure shows the increase (red) or decrease (blue) in TAF after this 2 yr period. There are two separate maps shown in order to disentangle the different patches, in particular the South Atlantic and South Indian ones. Whereas the tracer that leaves the two Pacific patches does so rather isotropically, the leakage of the other four patches clearly has a preferred direction. The grey flow arrows depict the major ocean currents and pathways, with the dashed line encompassing the Southern Hemisphere super-gyre (Speich *et al* 2007).

4. Discussion

This study reveals that on centennial timescales the ocean garbage patches are much more dynamic features than previously appreciated. The findings presented here highlight that despite the convergence zones in the ocean accumulating tracer, these zones are also rather leaky, with tracer being expelled from the patches within a matter of years, although for most of the patches this leakage is then rapidly re-accumulated. The North Pacific patch is ultimately the largest 'attractor' of surface tracer of all, and our study suggests that a significant fraction of the marine debris reaching the open ocean outside of the North Atlantic will eventually end up in that patch. Debris from the South Atlantic and South Indian patches ultimately migrates to the South Pacific patch, from where it slowly crosses the Equator to the North Pacific. The fact that two of the three Southern Hemisphere patches disperse so rapidly could be related to the proximity of the Southern Ocean, which facilitates rapid inter-ocean exchange via the Antarctic Circumpolar Current, vigorous eddy activity and mixing (Sallée *et al* 2008), as well as the super-gyre spanning the three basins.

Overall, the results of the tracer experiment presented here agree well with the findings of Maximenko *et al* (2012), who also used observational drifters to study the fate of the marine garbage patches. Incorporation of a seasonal cycle and a more representative source function do not seem to strongly affect the main features of the garbage patches, except for an additional sixth patch in the Barents Sea. That patch is most likely due to the enhanced release of tracer in highly populated areas around the North Atlantic Ocean.

This study also reveals that on centennial timescales the marine debris problem becomes a global problem, as the leakiness of the patches leads to most ocean-rim nations contributing at least some proportion of debris to most of the patches. Efforts to prevent, clean up or reduce the marine debris patches thus require global coordination and international activity.

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