Ecological connectivity between the Areas Beyond National Jurisdiction and coastal waters: safeguarding interests of coastal communities in developing countries

Ekaterina Popova, National Oceanography Centre, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH, *UK. E.popova@noc.ac.uk*

David Vousden, Rhodes University, Grahamstown, South Africa

Warwick H.H. Sauer, Rhodes University, Grahamstown, South Africa

Essam Y. Mohammed, International Institute for Environment and Development, London, UK

Valerie Allain, Pacific Community, Noumea, New Caledonia

Nicola Downey-Breedt, Rhodes University, Grahamstown, South Africa

Ruth Fletcher, World Conservation Monitoring Centre, Cambridge, UK

Kristina M. Gjerde, IUCN Global Marine and Polar Programme and World Commission on Protected Areas, Cambridge, MA, USA.

Patrick N. Halpin, Marine Geospatial Ecology Lab, Duke University, Durham NC, USA

Stephen Kelly, National Oceanography Centre, Southampton, UK

David Obura, CORDIO East Africa, Mombasa, Kenya.

Gretta Pecl, Centre for Marine Socioecology, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia

Michael Roberts, National Oceanography Centre, Southampton, UK; Nelson Mandela University, Port Elisabeth, South Africa

Dionysios E. Raitsos, Plymouth Marine Laboratory, UK

Alex Rogers, Somerville C. Oxford University, UK

Melita.Samoilys, CORDIO East Africa, Mombasa, Kenya; University of Oxford, Department of Zoology, Oxford UK

Ussif Rashid Sumaila, Institute for the Oceans and Fisheries & the School for Public Policy and Global Affairs, the University of British Columbia, Vancouver, USA

Sean Tracey Institute for Marine and Antarctic Studies, University of Tasmania, Tasmania, Australia

Andrew Yool, National Oceanography Centre, Southampton, UK

Author contributions

EP was the lead author and responsible for overall development and integration of the paper. DV, EP, WS and EM were responsible for writing sections on specific aspects of ecological connectivity and its implications for policy. EP, SK and AY designed numerical experiments on ocean connectivity conducted by SK who provided numerical analysis and produced the figures. WS and NK provided compilation of data for the migratory connectivity map. All authors made important contributions to the contents of the paper during a manuscript conception workshop (either in person or remotely) and subsequent discussions of the final product.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

The initial workshop to generate the ideas took place in Seychelles in April 2018 with financial support from SIDA. Data analysis was jointly supported by SIDA and the UK GCRF project SOLSTICE. The modelling tools and approaches were supported by the UK GCRF project SOLSTICE and the UK National Capability project ACCORD. V. Allain was supported by the Global Environment Facility's Oceanic Fisheries Management Project #2. G. Pecl was supported by an Australian research Council Future Fellowship. D. Raitsos was supported by the King Abdullah University of Science and Technology (KAUST) Office of Sponsored Research (OSR) under the Project No. 3268. This work used the NEMO ocean general circulation model (https://www.nemo-ocean.eu/) and the ARCHER UK National Supercomputing Service (http://www.archer.ac.uk) for high resolution simulations of this model. Lagrangian analysis was carried out using computational tool ARIANE developed by B. Blanke and N. Grima.

Ecological connectivity between the Areas Beyond National Jurisdiction and coastal waters: safeguarding interests of coastal communities in developing countries

Abstract

The UN General Assembly has made a unanimous decision to start negotiations to establish an international, legally-binding instrument for the conservation and sustainable use of marine biological diversity within Areas Beyond National Jurisdiction (ABNJ). However, there has of yet been little discussion on the importance of this move to the ecosystem services provided by coastal zones in their downstream zone of influence. Here, we identify the ecological connectivity between ABNJ and coastal zones as critically important in the negotiation process and apply several approaches to identify some priority areas for protection from the perspective of coastal populations of Least Developed Countries (LDCs). Initially, we review the scientific evidence that demonstrates ecological connectivity between ABNJ and the coastal zones with a focus on the LDCs. We then use ocean modelling to develop a number of metrics and spatial maps that serve to quantify the connectivity of the ABNJ to the coastal zone. We find that the level of exposure to the ABNJ influences varies strongly between countries. Similarly, not all areas of the ABNJ are equal in their impacts on the coastline. Using this method, we identify the areas of the ABNJ that are in the most urgent need of protection on the grounds of the strength of their potential downstream impacts on the coastal populations of LDCs. We argue that indirect negative impacts of the ABNJ fishing, industrialisation and pollution, communicated via oceanographic, cultural and ecological connectivity to the coastal waters of the developing countries should be of concern.

Keywords:

Ecological connectivity; Areas Beyond National Jurisdiction; marine ecosystems; coastal zone; ocean governance

1. Introduction

Communities living along the ocean coastlines, especially those in the developing world, perceive the value of the goods and services provided by the ocean mostly from a national perspective, related to the territorial waters or exclusive economic zone (EEZ). However, the Areas Beyond National Jurisdiction (ABNJ, Figure 1) comprise about 64% of total ocean surface area (Matz-Luck & Fuchs, 2014), and there is a growing appreciation of the importance of the ABNJ for the provision of critical ecosystem services (e.g. Rogers et al., 2014). Despite this, to date there has been little consideration or understanding of the role, influence and importance of the ABNJ to coastal waters (defined here as predominantly territorial waters). Nevertheless, there is a growing body of evidence to suggest that the ABNJ and the coastal waters are tightly connected, and that activities in the ABNJ are impacting the coastal zone, particularly where communities living along the coastlines are reliant on marine resources for their food security or livelihood. The following review and discussion addresses this body of evidence.

Figure 1 here

Under a principle of "Freedom of the Seas" of the United Nations Convention on the Law of the Sea (UNCLOS), states have a freedom of navigation, overflight, the laying of submarine cables and pipelines, the construction of artificial islands or installations, fishing and conduct of scientific research in the High Seas (Anderson, 2006). Thus, ABNJ is particularly vulnerable to human activities as no single state has a legal or political mandate for its protection (e.g. Matz-Luck & Fuchs, 2014). Nevertheless all share a legal duty under UNCLOS for the protection and preservation of the marine environment and to cooperate for this purpose (UNCLOS Articles 192, 194.5 and 197). However, in practice, the diverging interests of environmental protection and the sustainable management of ocean ecosystems on the one hand, and the exploitation of living and non-living marine resources and other economic activities such as maritime transportation on the other, stand in the way of international agreement on protection.

The major types of services that the High Seas are providing for humankind can be divided into four major groups: provisioning, regulating, habitat and cultural services (Rogers et al. 2014), similar to the generic marine ecosystem services frameworks (e.g. Sale et al., 2014). Many of these services have an indirect effect on the coastal zone. For instance, carbon sequestration by the ABNJ has indirect impact on the coastal zone by acting to decrease climate warming and sea level rise. However, other services have a direct, more immediate impact on the coastal zones, especially those with a tight ecological connectivity (see section 3 for definition) to the ABNJ.

For example, one of the ABNJ habitat services, lifecycle maintenance (referring to the maintenance of life cycles of migratory species, TEEB, 2010), is of critical importance to coastal areas. Here, deterioration of a habitat that is used by migratory species for breeding or for the protection / nurturing of juvenile life stages may force these species to travel longer distances to find alternative locations, during which they will be exposed to elevated risk or mortality. Similarly, the exposure of migratory species to fishing and shipping impacts along their migratory corridors can undermine the work of coastal communities to protect vulnerable species within their own waters and shorelines (Harrison et al., 2018).

Dunn et al. (2017) have suggested that the spatial / geographical proximity of a state's maritime borders to open ocean ABNJ – its so-called "adjacency" – is not the only indicator of connectivity when planning conservation measures for contiguous ABNJ. They argue that oceanographic, cultural and ecological connectivity with the ABNJ needs to be considered when assessing a coastal state's interests and possibly priorities for protection.

Various suggestions of management practices, which might restrict fishing in the ABNJ (e.g. Sumaila et al., 2015), have raised strong concerns about global food security. However, a few studies have demonstrated that the ABNJ fisheries play a negligible direct role in global food security (e.g. Sumaila et al. 2007, Schiller et al. 2018). Indeed, most of the species caught in the ABNJ are being supplied to the upscale markets in affluent countries (Schiller et al. 2018). Similarly, analysis of fishing vessel activity data, shows that the High Sea fishing is predominantly a wealthy nations activity with less than 3% of the of effort attributed to vessels flagged to lower-income countries (McCauley et al. 2018).

Although a direct positive impact of the ABNJ fisheries to global food security might be minimal, their indirect impact on the food security of the least developed countries (LDCs) could potentially be significant and requires urgent evaluation. For example, ABNJ fisheries may affect both target and associated and dependent species via bycatch, habitat degradation or genetic impoverishment. We develop estimates of the connectivity between the ABNJs and the coastal waters, and review current knowledge of ecological connectivity in the oceans of relevance to interactions between coastal waters and the ABNJs. Our conclusions highlight strong connectivity between some areas of the ABNJ and the coastal zones and suggest that the socioeconomic consequences of downstream impacts of the ABNJ should be taken into account when proposing conservation or management measures.

It should be noted that the terminology of 'High Seas' and ABNJ or Area(s) Beyond National Jurisdiction is often used freely and interchangeably in the popular and even scientific literature. This can cause confusion, especially when dealing with the geopolitics of these areas. UNCLOS does provide some clarity on this by defining that the areas beyond the limits of national jurisdiction (ABNJ) include:

A. the water column beyond the Exclusive Economic Zone (EEZ), or beyond the Territorial Sea where no EEZ has been declared, called the High Seas (Article 86); and
B. the seabed which lies beyond the limits of the continental shelf, established in conformity with Article 76 of the Convention, designated as "the Area" (Article 1).

This therefore distinguishes the 'Area' (seabed) from the High Seas' (water column above) and the total of both would then be referred to as the Area Beyond National Jurisdiction (ABNJ). Throughout this paper, the authors we will refer to the ABNJ (which addresses both singular and plural usage) to cover both vertical distinctions. The term 'High Seas' will be used, as appropriate, when citing directly from an existing publication that uses that specific terminology or when the discussion is, indeed, referring only to the High Seas water column.

2. Marine ecological connectivity

Ecological connectivity is a complex natural phenomenon linking various components of marine ecosystems in time and space. Ecological connectivity between distant marine ecosystems is effected through two types of connections: passive or circulation connectivity mediated by the ocean currents and active or migratory connectivity achieved by active swimming by marine species (e.g. Cowen et al., 2006).

2.1. Circulation connectivity

Energetic ocean currents are the key medium by which distant ocean regions are connected to each other (e.g. van Gennip et al., 2017), and this includes connectivity of the coastal zones to the ABNJ. The timescales on which this connectivity occurs are of paramount importance since they govern the range and the magnitude of impact of relevant processes.. These timescales regulate the level of impact on the structure of marine ecosystems, the level of exposure to marine pollution and the impact from upstream human activities such as shipping and marine exploitation (e.g. Robinson et al., 2017).

Coastal zones with a short timescale of connectivity to the High Seas are already facing, or may soon be exposed to, a number of significant challenges arising from the pollution, overfishing, mining or geoengineering experiments in the High Seas.

Here we need to first distinguish the direction of connectivity. Upstream connectivity is determined by the source areas from which waters reaching a particular location are coming, and thus which areas are influencing that location (e.g. Robinson et al., 2017). In contrast, downstream connectivity is determined by the 'sink' areas to which the waters leaving a particular location are going, and thus which areas are being influenced by that location (e.g. vanGennip et al., 2017).

Secondly, we distinguish connectivity timescales, for example those comparable to the pelagic larval stages characteristic of many marine organisms, which therefore permit impacts relevant to ecosystem structure (e.g. Cowen et al., 2007; Kinlan & Gaines, 2003) or those, comparable to the timescales of "half-life" of marine pollutants which are of potential threat to marine ecosystems. In the latter case, connectivity to regions of oil exploration or transportation can put locations at risk of oil contamination if connectivity timescales are short enough, but this becomes less important when timescales are longer than those of weathering, biodegradation or dispersal (e.g. Kelly et al., 2018). This approach simplifies the real situation in the ocean, where the sensitivity of habitats receiving pollution varies, where the harm of some pollutants is not straightforward to quantify, and where the two distinctions outlined here are entwined, for instance pollutants damaging pelagic larval stages being dispersed in the same current.

As noted, numerous marine organisms spend all (holo-) or part (mero-) of their lifespans as planktonic forms that disperse passively with ocean currents. Typically, meroplanktonic organisms spend only the early, larval portion of their life history as plankton, and use this period for passive (or nearly passive) dispersal and feeding. As such, dispersal distances for such marine species will partly scale with the time that they spend in planktonic life stages (e.g. Shanks et al., 2003; Shanks et al., 2009; Selkoe and Toonen, 2011), and this time (pelagic larval duration, PLD) varies greatly from species to species, ranging from days (e.g. anemone fish with PLD of a few hours to days) to months (e.g. Spanish mackerel with a PLD of 2-4 weeks, Herwerden et al. 2006; rock lobster with a PLD of ~18 months, Bradford et al., 2015).

Alongside the average timescale of ocean connectivity is its variability. The position, strength and even direction of ocean currents can be highly variable and connectivity between ocean regions is correspondingly affected. Such variability in connection may occur over short time periods in association with changes in atmospheric forcing (i.e. weather) or stochastic eddy variability, or may occur over longer periods related to the wider ocean circulation which is in turn linked to seasonal, interannual and multidecadal climate patterns, such as biannual monsoon seasons, ENSO (El Niño–Southern Oscillation). Further modifications of ocean connectivity due to climate change is already known to be occurring (e.g. Banks et al., 2010), and is anticipated to become more pronounced into the future (van Gennip et al., 2017, Popova et al., 2016).

The strength and persistence of connectivity and the importance of connectivity "stepping stones" can be assessed by a variety of methods including an application of network analysis using a graph theory approach (Treml et al. 2008, 2012) or using Lagrangian approaches based either on numerical models of ocean circulation (vanGennip et al., 2017) or on the remote sensing estimates of ocean currents (Raitsos et al., 2017).

Note that, while most coastal regions have strong connectivity with other regions due to the presence of significant boundary currents (e.g. Gulf Stream, Kuroshio) or features such as coastal upwelling (e.g. California and Humboldt currents), this is not universal. Oceanic islands located in the subtropical gyres of the major basins experience relatively weak currents that translate into limited connectivity on subannual and even subdecadal timescales (Robinson et al., 2017). Such isolation reduces the risk of impacts from pollutants with a short "half-life", but it may also limit potential recruitment and restocking for local marine resources. Regional barriers to larval connectivity may play important roles in speciation and the diversity of distinct marine communities (Treml et al., 2015), as well as in their future management.

Connectivity to locations of high nutrient content is also of critical importance for marine ecosystems. Among the most notable examples are: the Southern Ocean control of low latitude productivity (Sarmiento et al., 2004), the Arctic Ocean ecosystems sustained by advective connectivity to the nutrient-rich north Pacific and Atlantic oceans (e.g. Popova et al., 2013), vast phytoplankton blooms around Southern Ocean and Madagascar islands sustained by the natural downstream iron fertilisation from shallow sediments (Srokosz et al., 2015; Robinson et al., 2014).

Analysis of circulatory connectivity can provide useful information for ocean management and conservation planning. Analysis of connectivity patterns can be used to describe more ecologically relevant management areas versus jurisdictionally defined boundaries for ocean planning (Treml and Halpin 2012). Regional connectivity patterns can also be used to assess and prioritize regional conservation network design including the analysis of contributing and receiving EEZ jurisdictions (Schill et al. 2015) and prioritization of conservation sites based on their contribution to network connectivity.

2.2. Migratory and cultural connectivity

Migratory connectivity between marine ecosystems is achieved by regular movement of marine species from one place to another, often from breeding to feeding (non-breeding) grounds and back (Webster et al., 2002). This needs to be considered together with the cultural connectivity, as the cultural and ceremonial importance of highly migratory species to the coastal and island nations of the Indian and Pacific Oceans cannot be ignored when discussing governance of the ABNJ. The ocean has long held cultural significance for the traditional communities of these regions, and many species that migrate through the ABNJ are intricately linked to the identity of a number of coastal communities (Johannes, 1981). The vast majority of these coastal communities still partake in small-scale fisheries, often using traditional methods and practices (Johannes 2002, Samoilys et al. 2011). Apart from being significant in terms of identity and a way-of-life, these communities are dependent on marine resources for food, and as a commodity for trade / sale (Johannes 2002; Fache et al. 2016). In some areas, such as Polynesia and parts of Canada (Hoover et al. 2013) and New Zealand fishing for certain species can also hold a ceremonial, cultural or ritual significance. It should also be noted that a number of traditional fisheries still target what are today considered conservation species, e.g. sharks, seals, turtles and sea birds, although management measures to control or make such practices illegal have been introduced in a number of countries. The tourism potential, linked to the availability of charismatic marine fauna, is still in its infancy in many countries but holds significant potential (Cisneros-Montemayor et al. 2010). For many developing counties, marine tourism (e.g. turtle nesting, bird watching, whale watching both land and sea based) is a growing sector, and the protection of migratory species throughout their range is important.

Data from multiple sources were used to map the distribution and / or movement of marine species in the ABNJ of the Indian and Pacific Oceans (Figure 2). It is evident that the tuna resources are distributed throughout much of the west and northern Indian Ocean; and span the low and mid-latitude regions in the Pacific Ocean. Tuna undertake much of their life-cycle in these regions, migrating between spawning and feeding grounds, for example Albacore tuna (Dhurmeea et al., 2016). In the Indian Ocean, the main tuna distribution, as denoted here by the main tuna catch area, spans the territorial waters of many Western Indian Ocean (WIO) countries, and beyond into the ABNJ (Dhurmeea et al.,2016; Dueri et al., 2012a,b; Fonteneau and Hallier, 2015). In the Pacific Ocean, the main tuna distribution

(Fonteneau and Hallier, 2015) spans the territorial waters of the Philippine Islands, the Pacific Island groups of Micronesia, Melanesia and Polynesia, the west coast of the Central and northern South American continents, as well as the ABNJ beyond these EEZs. Considering the large degree of connectivity of these stocks between neighbouring EEZs and ABJN, the establishment and protection of wilderness areas has been noted as a means to preserve tuna stocks (Jones et al, 2018).

Figure 2 here

Tuna are an important resource for many people globally, both as a food source with nutritional and cultural importance, and an important economic income (e.g. Guillotreau et al., 2017, Bell et al., 2015; 2018). This is particularly the case in some developing nations such as countries throughout the Pacific and the Indian ocean, where tuna fishing provides food, employment and income for subsistence and artisanal fishers, as well as commercial and recreational game fishers (Gillett et al. 2001, Bell et al. 2009). For many of these developing countries there is room to expand (although recognising such challenges as infrastructure development, transportation and improved management) these commercial operations within their EEZs and the ABNJ and so enhance domestic fish supply (e.g. Bell et al., 2015). The presence of these large pelagic predators (or gamefish) also presents the potential for growth in terms of recreational fisheries. A number of developing countries around the world have recognised recreational fisheries as a growing industry with the potential to contribute to economic growth, especially with regards to the concomitant growth of local tourism (e.g. Felizola-Freire et al. 2018). Tuna in general are highly migratory species, crossing many exclusive economic zone boundaries and moving into areas beyond national jurisdictions (Miller, 2007). As such, there is the criticism that using traditional marine protected areas (MPAs) to protect such migratory fish stocks is not particularly effective, especially so in the ABNJ where species may occupy large geographical areas (Game et al., 2009). The importance of vertical connectivity has also been expressed in this regard. For instance, an increasing number of MPAs protect the seabed while the water column remains open for extractive use. The seabed and water column are, however, inextricably linked. Emerging research increasingly links upper-ocean communities and processes to seabed ecology and biogeochemistry (O'Leary and Roberts, 2018) suggesting that exploitation of the water column is likely to have a significant and widely distributed footprint in the deep-sea.

Apart from these widely distributed and highly migratory pelagic fish stocks, other species of conservation importance also traverse the ABNJ and the territorial waters of numerous countries. In a recent study analysing the migration of 14 migratory marine species (including sharks, leatherback turtles, sea lions, seals, albatross, shearwaters and blue whales), cumulatively, these species visited 86% of Pacific Ocean countries, with some spending up to three-quarters of the annual cycle in the ABNJ (Harrison et al., 2018). Considerably less is known about movement in oceanic sharks compared with tuna, particularly in the Indian Ocean (Blaison *et al*., 2015). However, emerging telemetry research from the western Indian Ocean, known to be a global biodiversity hotspot for oceanic taxa (Tittensor *et al*., 2010), found tiger sharks (*Galeocerdo cuvier*) exhibiting both coastal and oceanic movements, with one individual moving from coastal waters to the ABNJ and then crossing a total of eight EEZs (Barkley,in press). In 66 days this individual travelled almost 3,000 km and spent just under 10% of its time in the High Seas. This mirrors results from Australia and the Hawaiian Islands (Papastamatiou *et al*., 2013; Holmes *et al*., 2014) and highlights the vulnerability of tiger sharks to multiple fishing operations: coastal, EEZ and those of the High Seas (Barkley et al. in press). Using the quite different technology of isotope analysis, studies such as Bird et al. (2018) use isotopic landscapes (isoscapes) to identify where sharks feed.

Notwithstanding the issue of species migration / transience, utilising MPAs in the ABNJ that target preferred or critical habitats could provide protection for highly migratory species (Hobday and Hartmann 2006; Game et al. 2009). Marine protected areas have been shown to positively influence species abundance and biomass (Halpern, 2003) and with the correct design and implementation, utilising MPAs in the ABNJ could protect highly mobile species and positively influence the economy of developing countries that rely on them.

3. Modelling circulation connectivity between the ABNJ and the coastal zones

3.1 Circulation connectivity indices

Depending on the prevailing ocean circulation, coastal zones differ in their connectivity to the ABNJ and the timescales involved can vary significantly. Due to the strong spatio-temporal variability and directionality of ocean flow (van Gennip et al., 2017), close geographical proximity of coastline areas to adjacent ABNJ is not always a good indicator of strong connectivity between these areas. Here, we aim to quantify this connectivity and provide an objective measure of the associated timescales for each of the coastal and island LDCs.

Using a Lagrangian particle-tracking method in conjunction with a high resolution ocean circulation model (see Supplementary Material), we are able to estimate the passive (oceanographic) connectivity between the coastal waters of developing countries and the ABNJ.

Our approach follows a general methodology proposed by Robinson et al. (2017). In this, we uniformly identify thousands of virtual 'arrival points' in a ribbon-like region running along each country's shoreline and stretching approximately 15 km away from the coast. The width of this ribbon was chosen for two reasons. Firstly, from the point of view of model horizontal resolution (approximately 7 km), this is the minimum distance that is guaranteed to include more than one model grid cells. Secondly, the focus of this study is coastal communities of LDCs, and 15 km is approximately the maximum distance offshore that can be reached by local artisanal fishers. It also approximates with territorial waters which are generally limited to 12 nm (22km) off the coast.

Using these arrival points, together with our high resolution model of ocean circulation, we track "virtual particles" backwards in time (upstream) in time for one year to investigate where each country's coastal waters originate from. The use here of backwards (upstream) particle trajectories identifies where water masses reaching a coastal release point have come from, rather than forwards (downstream) particle trajectories which identify where water masses leaving a coastal release point travel to.

Experimental "arrivals" were recorded four times each year (January, April, July, October) for a decade of the recent past (2005-2014; 40 releases in total). Such an approach allowed us to take into account both interannual and seasonal variability of ocean circulation in our characterisation of coast to ABNJ upstream connectivity.

Readers unfamiliar with Lagrangian modelling terminology may find the following analogy of the backward approach helpful. Imagine that millions of rubber ducks each equipped with GPS (global positioning system) recorders are constantly being released within the ABNJs. Via ocean circulation, some arrive in the coastal waters of a country of interest. Four times a year, for a decade, an observer picks up all of the ducks within 15 km of the coast and uses their GPS records to establish where exactly in the ABNJ they were released a given number of months ago, and what route they took to arrive to the coast.To present an objective measure of the circulation connectivity, we calculated how long it took for each particle to travel from the nearest point in the ABNJ to the coastal location of interest.

We then characterised each country by two metrics:

1. **Connectivity index (in %):** this describes the fractional upstream connectivity of a country's coastline to the ABNJ on a given timescale; with six months chosen here as a standard reference period. **Connectivity index** is designed to give an indication of the fraction of a country's coastline that is impacted by the ABNJ.
2. **Connectivity timescale (in days or months):** this is the representative time period over which a country's coastal zone is connected (upstream) to the ABNJ. It is calculated here as the average time period taken by the fastest quartile of particles to arrive fromthe ABNJ to the coastal zone. C**onnectivity timescale** is thus designed to give an indication of how fast the ABNJ can influence a substantial part (with 25% chosen here as a standard reference fraction) of a country's coastline.

Although both indices can be utilised to inform marine resource governance at a country scale, they are presented here to illustrate the difference between countries and to draw attention to the countries that are most affected by the ABNJ upstream from their coastal waters.

We illustrate the general approach and these metrics in Figure 3a using two contrasting examples: the Federal Republic of Somalia and the Republic of Senegal.

Figure 3 here.

The complex and vigorous surface circulation of the north-west Indian Ocean, with its seasonally-reversing currents driven by the monsoon (Figure 3b), makes the coastline of the Federal Republic of Somalia one of the most ABNJ- connected coastlines in the world (cf. section 3.2 for the full analysis). Of particular importance in shaping this circulation footprint are the East African Coastal Current, the seasonally-reversing Somali Current and the South Equatorial Current (Figure 3b). As the purple colours on Figure 3a show, the Federal Republic of Somalia has an ABNJ connectivity timescale of 36±6 days indicating that it takes on average 36 days to connect 25% of the country's coastal waters to the nearest upstream areas of the ABNJ. The country's corresponding six month connectivity index is 60±3%, indicating that 60% of the country's coastal zone is impacted by waters that originated in the ABNJ on the timescale of six months or less. This example illustrates a country requiring a priority in its conservation efforts as stronger connectivity indicates enhanced coastal vulnerability to the activities in the upstream-connected regions of the ABNJ. In agreement with our results, there is observational evidence that remote ecosystems in this highly dynamic region are connected. For instance, several coral reef dwelling organisms along the Red Sea coast have been shown to exhibit a strong genetic heterogeneity at the southern end where the basin connects to the Indian Ocean, indicative of high gene flow (e.g. Nanninga et al., 2014). Calculating connectivity pathways from remote-sensing datasets, it has also been shown that the southern province of the Red Sea is affected by remote upstream regions in the Gulf of Aden and Indian Ocean (Raitsos et al., 2017). The southern Red Sea is subjected to a considerable biannual water influx from the Indian Ocean via the Gulf of Aden, which facilitates gene flow between the two regions (Saenz-Agudelo et al., 2015; Turak et al., 2007).

By contrast, the Republic of Senegal on the West coast of Africa is one of the least ABNJ-connected coastal zones. Ocean currents in this region are dominated by the relatively weak, southward-flowing Canary Current, which feeds into the westward-flowing North Equatorial Current, and the southward-flowing Guinea Current. As seen from Figure 3, on a timescale of six months, most of the coastal zone remains unconnected to the ABNJ. The six month connectivity index is only 12%, with coastal waters originating mostly from within the country's own EEZ or from neighbouring EEZs. Similarly, the country's ABNJ connectivity timescale is much longer than that of the previous example at 227 days.

3.2. Connectivity indices of select LDC

The connectivity metrics (indices and timescales) described in the previous section were calculated for all 31 coastal and island LDCs as identified by the Development Assistance Committee (DAC) of the Organisation for Economic Co-operation and Development (OECD) list of the Official Development Assistance (ODA) recipients for 2014-2017. They are presented as bar graphs in Figure 4 (a, b) and grouped by oceanographic basins.

As seen from these figures, the most ABNJ-connected LDCs are Kiribati in the Pacific Ocean; Tanzania and Somalia in the Indian Ocean; and Liberia in the Atlantic Ocean.

Figure 4 here

Coastal zones with short timescales of connectivity to the High Seas are already facing, or may soon to be exposed to, a number of significant challenges arising from pollution, overfishing, mining and geoengineering experiments (e.g. Johnson et al., 2018) in the ABNJ. At the same time, not all areas of the ABNJ are equally important for their impact on coastal zones. Figure 5a's map indicates the number of LDCs connected to each area of the ABNJ while Figure 5b's map indicates the length of the LDC coastlines impacted by each area of the ABNJ. These maps identify regions of the ABNJ that potentially require the most stringent regulation of activities because of their potential effects on coastal ecosystem services of the LDCs. Three areas are most prominent in this respect: the central Indian Ocean (the ABNJ part of the Mascarene Plateau); the northern Bay of Bengal; and the "High Seas pockets" of the Pacific Islands.

Figure 5 here.

4. Implications of the ecological connectivity for ecosystem services

Marine ecosystem services are defined broadly as the human benefits obtained from marine ecosystems. They fall into four major categories (Alcamo et al., 2003; Sale et al., 2014): 1. provisioning services (seafood, mineral, genetic, medicinal and ornamental resources); 2. regulating services (air purification, climate regulation, waste treatment, biological control); 3. habitat services (lifecycle maintenance, gene pool protection); 4. cultural services (recreation and leisure, aesthetic, cultural, spiritual and historical). Many of the ecosystem services provided by the ABNJ have an indirect effect on the coastal zone. For instance, carbon sequestration indirectly impacts the coastal zone by acting to decrease climate warming and sea level rise. However, via tight ecological connectivity, other ABNJ services have a direct, more immediate impact on the coastal zones. For instance, a large number of commercially and culturally important migratory species straddle both the coastal zone and the ABNJ, with the latter providing a critical lifecycle maintenance service to the former. Deterioration of ABNJ habitat used by such species (Figure 2) may disrupt recruitment by forcing species to travel longer distances to find alternative habitat. Similarly, disturbance of ABNJ areas for spawning or nurturing of juvenile life stages (Figure 2) would directly impact fish stocks in coastal areas connected via the ocean circulation of larvae. Pollution of the High Seas/ABNJ potentially also presents a direct threat to the ecosystem services of the coastal zones via circulation connectivity. Recent examples include the jurisdiction-straddling Sanchi oil spill and its long-distance impacts (Carswell, 2018), and the emerging threat of plastic contamination, driven in part by High Seas contamination by the shipping and fishing industries (GESAMP 2009, 2016).

5. Examples of the importance of connectivity between the ABNJ and the coastal zones

5.1. Costa Rica Thermal Dome

The concept of Outstanding Universal Value (OUV) is central to the World Heritage Convention when defining why a location is considered sufficiently significant as to justify its inclusion in the UNESCO World Heritage List. Currently, there are no World Heritage Sites in the ABNJ, but because of increased awareness of their role in marine ecology, a growing effort is underway to apply the OUV concept in these areas (e.g. Freestone et al., 2016).

Freestone et al. (2016) considered five potential areas of OUV in the ABNJ, including the Costa Rica Thermal Dome. This example is highly relevant here since it is one of the most clearly recognisable and observable ABNJ features, and has strong ecological, circulation and cultural connectivity to the coastal zones of Central American countries (Johnson et al., 2018). The Dome is an upwelling-driven oceanographic system that plays an important role in ecology across the eastern Tropical Pacific Ocean (e.g. Fiedler, 2002; Johnson et al., 2018). The Dome is situated mostly within ABNJ, but, as it is delineated by oceanographic features, it has a variable size and can extend into the EEZs of the adjacent Costa Rica, Nicaragua and El Salvador. Wind-driven upwelling in the area acts to enhance primary production, which attracts fish and their migratory predators. The Dome is recognised as a year-around habitat of endangered Blue Whales, and it serves as a location for their mating and raising of calves. Via migration, the Dome is also closely connected to the population of the Blue Whales along the western coast of North America. Additionally, it overlaps part of the migratory route of Leatherback turtles, and is connected with the Central American turtle nesting beaches. It is also noted for the presence of common dolphins, yellowfin tuna and jumbo flying squid (Johnson et al., 2018).

Commercial fishing and cargo shipping are the most pressing human impacts on the Dome’s ecosystem as it is situated in close proximity to the shipping routes converging on the Panama Canal. In addition, there is a growing concern about the potential use of this high nutrient-low chlorophyll (HNLC) area as a geoengineering site for artificial iron enrichment experiments (Johnson et al., 2018).

Although the Costa Rica Thermal Dome is not adjacent to EEZs of any of the LDCs that are the focus of this article, it presents an interesting, and developing, case study example which arguably should be followed for other similar features. For example, the Mascarene Plateau upwelling system (Payet et al., 2005) is probably the most significant feature in this respect, with strong connectivity to the least developed maritime countries of the East Africa region. Moreover, upwelling and channelling effects on the South Equatorial Current as produced by the Mascarene Plateau, and the subsequent downstream interactions with the east coast of Madagascar and resultant generation of mesoscale eddies within the Mozambique Channel have a major influence on productivity and biomass in the Agulhas Large Marine Ecosystem (Vousden, 2016b).

5.2. Seamounts

Seamounts are mountains rising from the seafloor but not breaking the surface to form islands. Typically formed through volcanic processes, they are abundant (especially in the Pacific Ocean) and usually characterised by enhanced biological activity and diversity, attracting many migratory species. Seamounts are also an important illustration of the importance of the ABNJ for the coastal zones. Growing evidence shows that many geographically-isolated seamounts are not biologically-isolated habitats and instead may have assemblages of benthic species similar to those of the continental slopes and banks of EEZs, at least those regions within the same biogeographic province. At the same time, analysis of fisheries data from around seamounts indicates that they are hotspots of pelagic biodiversity. Higher pelagic species richness was detected in association with seamounts than with coastal or oceanic areas (Morato et al. 2016). Their enhanced productivity supports not only local resident species, but also, what is most important for the topic of this paper, migratory species such as sharks and tuna (e.g. Rogers et al., 2018). The enhanced phytoplankton production adjacent to the seamounts may have an important indirect impact on ecological connectivity. Eddies and currents trap phytoplankton-rich water masses, covering large distances, supporting passive larvae during their vulnerable stage (Raitsos et al., 2017). Indeed, larvae undergoing development in high-nutrient areas have an improved chance of survival following transition into oligotrophic waters (Ward and Harrison 1997), and increased productivity has clearly been shown to support survival in early larval stages (Cowen and Sponaugle 2009). All of the above points underscore the importance of connectivity among the seamounts, and between seamounts and shelf slopes and thus their important role as stepping stones in chains of ecologically connected habitats. Furthermore, against the backdrop of the growing threat of climate change to the marine environment, seamounts are emerging as potential “climate refuges”, deeper and cooler habitats that can serve as a refuge for fauna in a warming and increasingly acidic ocean (Clark et al., 2012).

With a large number of seamounts situated within ABNJ, and some chains spanning EEZs and ABNJ, their exposure to the fishing and anticipated exposure to the impact of marine mining is becoming a pressing issue in light of their significant role in ecological connectivity. However, their recovery from human impacts is slow due to the typically slower growth rates of the large, deep sea megafauna associated with them (Roark et al., 2006). Human impacts are not limited to the immediate area of direct physical disturbance to a sea mount but also include downstream effects. At present these include the impacts of sediment plumes from trawling (especially heavy-weighted bottom trawls) and, in the near future, from deep-sea mining plumes (Miller et al., 2018). Plumes from both have a potential to persist for extended periods of time while advected by ocean currents (Rolinski et al., 2001), and those of deep-sea mining may potentially be toxic (Miller et al., 2018). Fishing on seamounts is focused not only on local deep-sea species, but also targets migratory pelagic species such as sharks and tuna (e.g. Morato et al., 2010), and disturbs the ecological connectivity along seamount corridors. Thus establishing networks of marine reserves on seamounts may help to protect connectivity for economically and culturally important migratory species (Morato et al., 2010).

6. Gaps in evidence for connectivity and impact of climate change

Ecological connectivity across the global ocean is an emerging area of science and some gaps in evidence are inevitable. Establishing the underlying connectivity of ocean circulation relies on the quality of either the ocean model (as done in this study) or the global observational dataset synthesized from ocean float and satellite-derived observations used for obtaining ocean current velocities. Both areas of research have made substantial progress in the last decade, and further progress is expected to be rapid due to advances in computing power, an increasing fleet of advanced ocean floats, coordinated and standardised international efforts for sustained observations (e.g. Global Ocean Observing System, GOOS, http://www.goosocean.org) and more sophisticated remote sensing.

However, relating the spatial distribution of a species to its dispersal ability is one of the fundamental challenges in marine ecology and biogeography (Lester et al., 2007). Although a positive relationship between these two characteristics has been established (i.e. a large range typically correlates with dispersal), other factors responsible for geographic range size can complicate defining the exact limits due to passive connectivity (e.g. availability of food resource, fishing impacts).

Finally, migratory connectivity is an area where evidence and confidence is rapidly increasing due to recent progress in genetic and isotopic techniques (e.g. Bird et al., 2018) and aquatic telemetry (e.g. Hussey et al., 2015). Advances in miniaturization, battery engineering, and software and hardware development, have allowed the monitoring of marine organisms whose habitats stretch across the globe; and is fast accelerating scientists’ ability to observe animal behaviour and distribution, improving our understanding of the structure and function of global aquatic ecosystems (Hussey et al., 2015) and connectivity. The establishment of a global network and centralized database would allow for the collection and dissemination of telemetry data on a global scale (Hussey et al., 2015).

Importantly, patterns of present day ecological connectivity will not remain static in time due to the emerging impact of climate change on both ocean circulation (van Gennip et al., 2017) and the global climate-driven redistribution of species (Pecl et al., 2017). Areas deemed important for conservation may not remain so in the longer term requiring climate-proofing of ABNJ conservation regimes. Consequently, continuous effort will be required to monitor evolving patterns of marine ecological connectivity, as well as the various anthropogenic impacts that can affect it. Thus the impact of climate change may undermine the conservation efforts and will require approaches which go beyond currently proposed adaptive management (Maxwell et al., 2015; Bonebrake et al., 2018).

The rapid development of technologies for monitoring the ocean present new opportunities for progress in this area. The most promising developments in this arena include marine and aerial autonomous systems, satellite-based remote sensing, telemetry and systems that combine Automatic Identification Systems with satellite-tracking technology (e.g. Dunn et al., 2018) in initiatives like globalfishwatch.org. A recent analysis of global long-line fishing fleet behaviour has provided forecasts pelagic fishing effort based on environmental predictors in the high seas (Crespo et al. 2018). These models allow for the monthly prediction of high seas fishing effort (hence species presence) in ABNJ and could be directly useful for assessing the potential exposure of coastal regions to adjacent fishing pressure. In addition, vessel tracking now allows for near real-time monitoring of fishing vessel movements across multiple jurisdictions (Dunn et al. 2018).

Given the levels of uncertainty, complexity, and anticipated future change in the field of ecological connectivity, the precautionary principle should be widely applied. This principle aims to provide a basis for political action to protect the environment from potentially severe or irreversible harm in circumstances where scientific uncertainty prevents a full risk or cost-benefit analysis.

7. Implications for the ABNJ governance

National sovereign rights and jurisdiction over coastal waters and surrounding or adjacent sea areas are defined in UNCLOS[1]. The Convention allows States' Parties to declare a territorial sea up to a limit of 12 nautical miles from its coastal 'baseline', within which that country controls and owns all resources and activities, notwithstanding the right of innocent passage by other nations' vessels. Further to this, a State may establish an EEZ out as far as 200 nm from its coastal baseline which allows that state sovereign rights over the use and conservation of natural resources and controlling catch limits for fisheries in that area. As noted above, in relation to the ABNJ, no single state has jurisdiction over these waters or the seabed beneath them (though they do have obligations and jurisdiction over their citizens as well as vessels flagged under national registries in addition to general duties to cooperate to protect and preserve the marine environment and to conserve high seas and seabed living resources). The real problem lies in the apparent lack of political will or the capacity to implement those obligations. It is important to note that the seabed resources (both mineral and living) below the High Seas may "belong" to the coastal state when they are part of the extended continental shelf, while the 'Area' (as defined by the Law of the Sea) and its (mineral) resources on the seabed beyond national jurisdiction belong to humankind as a whole, and is subject to a special regime under UNCLOS through the International Seabed Authority.

---

[1] http://www.un.org/Depts/los/convention_agreements/texts/unclos/unclos_e.pdf

There are a number of specialized treaties and conventions and associated administrative bodies that cover activities in the High Seas and which should, in principle at least, contribute to their management and the conservation of their resources (Billé et al. 2016). Some examples include the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) adopted by States through the International Maritime Organization, the UN Agreement for the Conservation and Sustainable Use of Straddling Fish Stocks and Highly Migratory Fish Stocks and an array of independently operating regional fisheries management organizations and arrangements that variously address issues related to shipping and maritime pollution as well as fisheries. The International Seabed Authority regulates seabed mining and related activities in the Area and is currently developing regulations to govern deep sea mineral exploitation. However, it is clear that there is still insufficient effort and focus on behalf of the bodies that oversee and administer such treaties and conventions in relation to the effective management and conservation of the ABNJ. Furthermore, there is little, if any interaction, between such efforts and designated responsibilities and they remain mostly sectoral in their approach. Generally, they are focused on politically negotiated areas and boundaries, which restricts their ability to address a more appropriate ecosystem-based approach.

The traditional ‘geopolitical’ definition of rights and jurisdictions as established through UNCLOS provides the framework for national claims and responsibilities. Within these areas a coastal state is expected to uphold certain requirements related to the conservation and sustainability of living marine resources. In this context, the designation of 12-mile territorial waters and a maximum of 200 nm for the EEZ are based on legal delimitations following international political negotiations and agreement. They do not, as such, recognise or take into consideration the extent of marine ecosystems and the connectivity between biological habitats and species and this was not the primary intention of UNCLOS. Much has happened since the 1982 LOS was adopted in the context of understanding of our marine environment, as well as the various threats and impacts to that environment, both chronic and new. The basic principles in place in the law of the sea regime are sound, but it is also clear that they require a great deal of fleshing out, co-ordination and much more systematic and rigorous implementation (Freestone, 2012). The UN Fish Stocks Agreement is one such example of an attempt to balance distant water fishing states’ and coastal states’ interests in shared fisheries resources, with uneven results. Increasingly however, coastal states are realizing the need for more effective and interactive transboundary management, not just between adjacent coastal States or islands but across the EEZ-High Seas geopolitical divide as established by UNCLOS (Vousden 2016b) and this needs to be an ecosystem-based approach rather than being based on geopolitical divides or prior agreements.

Wright et al (2018) reviewed the gaps in the existing framework for the conservation and sustainable use of marine biodiversity in ABNJ. They listed these as:

1) Absence of a comprehensive set of overarching governance principles
2) A fragmented legal and institutional framework
3) Absence of a global framework to establish MPAs in ABNJ
4) Legal uncertainty regarding the status of marine genetic resources in ABNJ
5) Lack of global rules for EIAs and SEAs in ABNJ
6) Limited capacity building and technology transfer
7) Gaps in the framework for management of High Seas fisheries
8) Mixed performance of Regional Fisheries Management Organisations (RFMOs)
9) Flag State responsibility and the “genuine link”

This list represents a challenging amount of ‘gap-filling’ to come even close to effective management of biodiversity beyond national jurisdiction let alone the activities that are affecting that biodiversity which is, inevitably, closely linked to the issues of connectivity raised above.

A number of organisations like the International Union for Conservation of Nature (IUCN) have a long-standing commitment to achieving effective protection, restoration and sustainable use of biological diversity and ecosystem processes on the High Seas and the seabed Area (collectively, the ABNJ). At the 2004 IUCN World Conservation Congress, IUCN members called for consideration of additional mechanisms, tools and approaches for the effective governance, protection, restoration and sustainable management of marine biological diversity and productivity in the High Seas. In this context, IUCN has proposed 10 principles for High Seas Governance:

1) Conditional freedom of activity on the High Seas
2) Protection and Preservation of the marine environment
3) International Cooperation
4) Science-based approach to management
5) Public availability of information
6) Transparent and open decision-making processes
7) Precautionary Approach
8) Ecosystem approach
9) Sustainable and equitable use
10) Responsibility of States as stewards of the global marine environment

All of these apply equally to the issues and concerns raised here regarding biodiversity, connectivity and sustainable management through the regulation of associated harmful activities that affect the ABNJ/EEZ interface and contiguous relationship. Further detail on each of these 10 principles can be found on the appropriate IUCN web page[2].

The connectivity, therefore, that is recognised and established through the research undertaken by this publication raises new implications for coastal States and SIDS in the context of their interest and concern in the effects of how activities are managed in areas adjacent/contiguous to their EEZs or even some distance out beyond the EEZ into the ABNJ, particularly where the effects of such activities can be seen to directly impact on coastal community welfare and/or a country's national socioeconomic status.

The movement towards effective ocean governance within interlinked coastal regions is focusing now on the ecosystem-based management approach through the recognition of Large Marine Ecosystems (LMEs) as clearly definable areas within the world's oceans that are not limited by geopolitical boundaries (Vousden, 2016b). Although this is certainly a step forward in terms of logic, it presents new challenges for states and for all stakeholders in marine resources. The transboundary nature of LMEs has created a new and growing demand not only for cross-border collaboration between countries but also for the development of partnerships between government, private sector and other stakeholders that can also address regulatory management of areas beyond national jurisdiction that also fall within the boundaries of the main oceanic currents and other oceanographic parameters that define an LME.

Recently there has been a strong and positive movement toward adopting a more formal agreement for effective management and protection of biodiversity in areas beyond national jurisdiction for the sake of the overall global importance of such biodiversity (Gjerde et al. 2018). The issue of connectivity across the EEZ-ABNJ interface explored here highlights the need for greater discussion of the roles, rights and interests of coastal states to ensure and oversee effective and sustainable 'upstream' management of both passively and actively 'connected' organisms and water quality upon which those states and islands depend.

The issue of management of activities on and in the ABNJ is thus becoming a priority in a number of the world's ocean and coastal regions. The Sargasso Sea, which is primarily High Seas, is one example where countries, that wish to see the sustainable management and conservation of its marine biodiversity, have formed an alliance through the Sargasso Sea Commission in order to develop and

---

[2] https://www.iucn.org/sites/dev/files/import/downloads/10_principles_for_high_seas_governance___final.pdf

propose management measures within a defined Sargasso Sea boundary (Freestone and Bulger, 2016). In the Western and Central Pacific Fisheries Convention Area, countries that have signed up to the WCPF Convention and its Commission agree to abide by its adopted rules and procedures including the Conservation and Management Measures (CMM) as set by the Commission. These CMMs extend across the entire Convention Area including the High Seas so that, essentially, the Commission can then control fishing and associated activities both within and beyond the EEZs (Vousden, 2018). In the western Indian Ocean, the Strategic Action Programme endorsed at the ministerial level by all of the nine countries (mainland coastal States and SIDS) across the region formally recognises the implications of transboundary threats from and into High Seas areas and the need to develop management mechanisms that also address the interests of coastal states in the adjacent ABNJ that fall within the LMEs and border the countries of the WIO region (Vousden, 2015).

Clearly, there is a growing expectation toward a more clearly defined legal, ethical and moral responsibility for all countries and individuals using the High Seas for trade and for profit to take some level of responsibility for their effects, including on those countries that also draw value and benefit as a result of the proven connectivity into coastal waters and communities depending on food security and socioeconomic sustainability. Having demonstrated the presence of such connectivity (both active and passive) between coastal states and ABNJ, the challenge now will be to develop mechanisms to test and adopt relevant measures to enhance the conservation and sustainable use of marine biodiversity in ABNJ including in areas that affect the interests of coastal States, and to develop mechanisms—global and regional, to ensure effective consultation, consideration and action. Such measures would need to be based on knowledge and understanding of the *status quo* baseline for adjacent ABNJ followed by long-term monitoring of changes that can be addressed through adaptive management measures. Defining and allocating responsibility for what amounts to fairly time-consuming and costly studies and on-going research will present a further set of challenges that will also need to be addressed under the new ABNJ/BBNJ agreement.

The first steps have been taken by this current research to understand the importance and time-related nature of the connectivity between the High Seas/ABNJ and EEZs. The next steps will be toward recognising the need and pursuing the development of a global agreement that can ensure the consistent adoption of management practices in all regions and to establish supportive structures at regional scale (Gjerde et al, 2018). A core function will be to define the value of those goods and services for each country/region that are provided through this connectivity so as to justify and drive the identification and adoption of appropriate management measures, in essence an ecosystem and cost-benefit assessment of such connectivity. The clarification and agreement on justifications can accelerate the process of developing appropriate site-specific management practices with all relevant stakeholders.

8. Conclusions and wider implications

- There has been a long-standing disconnect between management of the marine environment in ABNJ and the fisheries productivity and biodiversity within territorial waters. However, a growing body of evidence suggests that these areas are tightly linked via two processes: ecological connectivity and ocean circulation connectivity, both exposing ecosystems of the coastal waters to the downstream influence of activities in ABNJ. For example, it has been shown that overfishing in the ABNJ can affect productivity and fishing opportunities in territorial waters and that, for this reason, some are even advocating a total prohibition of fishing activities in the ABNJ. Thus, effective, precautionary and equitable management of activities in the ABNJ, that includes consideration of the whole life cycle of fishery resources, is critical to protect the rights and interests of coastal states.
- Millions of people living in the coastal areas of developing countries in general, and the Least Developed Countries in particular, rely heavily on marine and coastal resources for their

livelihoods. These resources also deliver substantial revenue which can be used to fund the operation of national governments, service international debt or pay to import food for domestic consumption, thus contributing to national food security and diversification of diets. Consequently, it is fundamental that the wellbeing of vulnerable of coastal communities needs to be considered in connection to the health of the ABNJ.

- Our study shows that ecological and circulation connectivity of coastal waters to ABNJ, and thus their exposure to the direct effects of ABNJ activities, significantly varies between countries and regions. These differences are driven by proximity to ocean boundary currents as well as the dynamical regime of these currents. The specific shapes of adjacent EEZs can also play a role. Similarly, not all areas of the ABNJ are equal in their linkages with the coastline in general, or with the Least Developed Countries in particular.
- Using numerical ocean modelling, our study develops a series of metrics and spatial maps that serve to quantify the connectivity of the ABNJ to the coastal zone. This can identify regions in the ABNJ that are in the most urgent need of management on the grounds of the magnitude of potential downstream impacts on coastal populations.
- Connectivity analysis can be especially useful to the developing countries to prioritize regional ocean management, including in ABNJ, by identifying which countries naturally cluster together through connectivity. This includes more ecologically-defined ocean management units that transcend jurisdictional boundaries.
- The development and dissemination of data and knowledge on connectivity should be explicitly identified under the capacity and technology transfer as well as the Clearing House Mechanism established by the Convention on Biological Diversity to ensure that all governments have access to the information and technologies they need for their work on biodiversity.
- Current debates on criteria to identify marine managed and marine protected areas in the ABNJ often focus on the ecological and biological significance of the habitat/area in question. We suggest that, while these factors are clearly important, the socioeconomic vulnerability of areas downstream of activities in ABNJ should additionally be taken into account. This will help to directly support more effective management and conservation of biodiversity benefits for specific regions –and to ensure that the needs of the most vulnerable and impoverished communities are also addressed.
- We believe that this approach will be crucial in addressing global inequalities, helping achieve Sustainable Development Goals (Goal 1 – No poverty; Goal 2 – Zero hunger; and Goal 14 – Life below water), and enhancing the resilience of coastal communities in poorer countries that are already facing multiple climatic and economic shocks.
- Finally, we urge the international community (scientists and politicians alike) to consider the importance of ABNJ for coastal communities around the world. When identifying and delimiting managed areas or MPAs in ABNJ (including marine reserves), it is critical to account for the socio-economic interests of vulnerable states and communities that are exposed to downstream impacts of ABNJ activities. The new legally-binding instrument to govern biodiversity in ABNJ presents an important opportunity to ensure that sectoral activities in ABNJ are managed equitably, and not only by those with a direct economic interest in the activity. In this way, the needs of vulnerable communities dependent on marine resources are properly taken into account, and all can benefit from the conservation and sustainable use of marine biodiversity in ABNJ.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Figure Captions

Figure 1.

Global map showing the extent of the ABNJ (white) and EEZs (green, VLIZ, 2014). This dataset combines the boundaries of the world countries and the Exclusive Economic Zones of the world. It was created by combining the ESRI world country database and the EEZ V7 dataset. Red countries represent LDCs.

Figure 2.

Map showing the distribution / migration of marine species in the Indian and Pacific Ocean. Depicted are: main tuna distribution (grey, Fonteneau and Hallier, 2015), main yellowfin tuna catch areas (light blue, Fonteneau and Hallier, 2015; POSEIDON, MRAG, NFDS and COFREPECHE, 2014), main bigeye tuna catch areas (brown, Fonteneau and Hallier, 2015; POSEIDON, MRAG, NFDS and COFREPECHE, 2014), main skipjack tuna catch areas (pink, Dueri et al., 2012b; Fonteneau and Hallier, 2015; POSEIDON, MRAG, NFDS and COFREPECHE, 2014), main albacore tuna distribution (yellow, Dhurmeea et al, 2016; POSEIDON, MRAG, NFDS and COFREPECHE, 2014), recorded seabird migration areas (purple, Sequeira et al., 2018), albatross, petrel and shearwater foraging areas (orange, POSEIDON, MRAG, NFDS and COFREPECHE, 2014), areas of high seabird density (red, Le Corre et al., 2012), areas of true and eared seal movement (blue, Sequeira et al., 2018), and salmon tagging beyond EEZ and subsequent migration (green, Dunn et al. 2017). It should be noted that this image has been produced using available data for a small number of migratory species and groups; and empty space therefore does not indicate the absence of highly migratory marine species. Country colours indicate: coastal and island LDCs (yellow), landlocked LDC (dark green), "other low income countries" (light green).

Figure 3.

a) The time, in months, that it takes for ocean surface waters originated in the ABNJ to reach the coastal zone of the Federal Republic of Somalia and the Republic of Senegal (respectively on the eastern and western coasts of the continent; both countries are shown in yellow). The colour of the trajectories indicate the time in months for the surface waters to be advected to the coastal zone, termed on the colour bar as the connectivity time.

b) Schematic diagram of the surface circulation (arrows, after Schott et al., 2009) superimposed with the modelled monthly mean surface current speed. The following main currents are labelled by numbers: Angola Current (0), Canary Current (1), North Equatorial Current (Atlantic, 2), Guinea Current (3), South Equatorial Current (Atlantic, 4), Benguela Current (5), Somali Current (6, north-east monsoon season), Equatorial Countercurrent (7), East African Coastal Current (8), NW Madagascar Current (9), Agulhas (10), South-West Madagascar Current (11), South Equatorial Current (Indian Ocean, 12), North East Monsoon Current (13).

Figure 4.

(a) country connectivity index describing the fractional upstream connectivity of a country's coastline to the ABNJ on a six months' timescale. Countries are grouped by region and ranked from most to least connected within each region. Cambodia (KHM) is connected upstream to the ABNJ on a timescale longer than 6 months, hence the zero index.

(b) Country connectivity timescale showing the representative time period over which a country's coastal zone is connected (upstream) to the ABNJ. Countries are grouped by region and sorted from longest to shortest connectivity timescale within each region - therefore note the x-axis is ordered differently to (a). Countries with a typical connectivity timescale > 1 year are shown with jagged bars and no error bars. Mean for 10 years (2005-2014) is shown, with uncertainty (standard deviation) represented by error bars. Country abbreviations drawn from International Organization for Standardization country codes list (https://laendercode.net/en/3-letter-list.html).

Figure 5.

Map of the ABNJ connectivity to the coastal zones of coastal and island LDCs. Colours over the ocean indicate a) the number of individual LDCs and b) length of the LCD coastline that each region of the ABNJ is connected to within a 6 month timescale. EEZs are shown in grey. Note that (a) is only a measure of how many sovereign states on the DAC list or the length of the coastline each region of the ABNJ is connected to – it does not give information about how strongly or rapidly connected each region is to any given country or portion of coastline. Country colours indicate: coastal and island LDCs (yellow), landlocked LDC (dark green), “other low income countries” (light green).

References

Alcamo J., Ash N.J., Butler C.D., et al. Ecosystem and human well-being. A framework for assessment, 2003Washington, D.C.Island Press Millennium Ecosystem Assessment 245 pp.

Anderson, D. Freedoms of the High Seas in the Modern Law of the Sea. (2006). In 'The Law of the Sea: Progress and Prospects'. Eds. David Freestone, Richard Barnes, and David Ong Chapter 12. DOI:10.1093/acprof:oso/9780199299614.003.0017

Banks, S.C., Ling, S.D., Johnson, C.R., Piggott, M.P., Williamson, J.E., Beheregaray, L.B., 2010. Genetic structure of a recent climate change-driven range extension. Molecular Ecology 19 (10), 2011-2024.

Bell, J.D., Allain, V., Allison, E.H., Andrefouet, S., Andrew, N.L., Batty, M.J., Blanc, M., Dambacher, J.M., Hampton, J., Hanich, Q., Harley, S., Lorrain, A., McCoy, M., McTurk, N., Nicol, S., Pilling, G., Point, D., Sharp, M.K., Vivili, P., Williams, P., 2015. Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. Marine Policy 51, 584-591.

Bell, J.D., Allain, V., Sen Gupta, A., Johnson, J.E., Hampton, J., Hobday, A.J., Lehodey, P., Lenton, A., Moore, B.R., Pratchett, M.S., Senina, I., Smith, N., and Williams, P. 2018. Chapter 14: Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries. *In* Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. *Edited by* M. Barange, T. Bahri, M.C.M. Beveridge, K.. Cochrane, S. Funge-Smith, and F. Poulain. FAO, Rome, Italy. pp. 305–324.

Bell, J.D., Kronen, M., Vunisea, A., Nash, W.J., Keeble, G., Demmke, A., Pontifex, S., Andrefouet, S., 2009. Planning the use of fish for food security in the Pacific. Marine Policy 33 (1), 64-76.

Billé, R., Chabason, L., Drankier, P., Molenaar, E.J., and Rochette, J. (2016). Making Regional Seas Programmes, Regional Fishery Bodies and Large Marine Ecosystem Mechanisms Work Better Together. UNEP Regional Seas Report and Studies No. 196. 229p.

Bird, C.S., Verissimo, A., Magozzi, S., Abrantes, K.G., Aguilar, A., Al-Reasi, H., Barnett, A., Bethea, D.M., Biais, G., Borrell, A., Bouchoucha, M., Boyle, M., Brooks, E.J., Brunnschweiler, J., Bustamante, P., Carlisle, A., Catarino, D., Caut, S., Cherel, Y., Chouvelon, T., Churchill, D., Ciancio, J., Claes, J., Colaco, A., Courtney, D.L., Cresson, P., Daly, R., de Necker, L., Endo, T., Figueiredo, I., Frisch, A.J., Hansen, J.H., Heithaus, M., Hussey, N.E., Iitembu, J., Juanes, F., Kinney, M.J., Kiszka, J.J., Klarian, S.A., Kopp, D., Leaf, R., Li, Y.K., Lorrain, A., Madigan, D.J., Maljkovic, A., Malpica-Cruz, L., Matich, P., Meekan, M.G., Menard, F., Menezes, G.M., Munroe, S.E.M., Newman, M.C., Papastamatiou, Y.P., Pethybridge, H., Plumlee, J.D., Polo-Silva, C., Quaeck-Davies, K., Raoult, V., Reum, J., Torres-Rojas, Y.E., Shiffman, D.S., Shipley, O.N., Speed, C.W., Staudinger, M.D., Teffer, A.K., Tilley, A., Valls, M., Vaudo, J.J., Wai, T.C., Wells, R.J.D., Wyatt, A.S.J., Yool, A., Trueman, C.N., 2018. A global perspective on the trophic geography of sharks. Nature Ecology & Evolution 2 (2), 299-+.

Barkley, AN, Gollock, M. Samoilys, M, Llewellyn, F, Shivji, M, …& Hussey, NE (in press). Complex regional transboundary movements of marine animals. Animal Conservation.

Blaison, A., Jaquemet, S., Guyomard, D., Vangrevelynghe, G., Gazzo, T., Cliff, G., Cotel, P., Soria, M., 2015. Seasonal variability of bull and tiger shark presence on the west coast of Reunion Island, western Indian Ocean. African Journal of Marine Science 37 (2), 199-208.

Bonebrake, T.C., Brown, C.J., Bell, J.D., Blanchard, J.L., Chauvenet, A., Champion, C., Chen, I.C., Clark, T.D., Colwell, R.K., Danielsen, F., Dell, A.I., Donelson, J.M., Evengard, B., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Jarzyna, M.A., Lee, E., Lenoir, J., Linnetved, H., Martin, V.Y., McCormack, P.C., McDonald, J., McDonald-Madden, E., Mitchell, N., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Possingham, H., Pulsifer, P., Reynolds, M., Scheffers, B.R., Sorte, C.J.B., Strugnell, J.M., Tuanmu, M.N., Twiname, S., Verges, A., Villanueva, C., Wapstra, E., Wernberg, T., Pecl, G.T., 2018. Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science. Biological Reviews 93 (1), 284-305.

Bradford, R.W., Griffin, D., Bruce, B.D., 2015. Estimating the duration of the pelagic phyllosoma phase of the southern rock lobster, Jasus edwardsii (Hutton). Marine and Freshwater Research 66 (3), 213-219.

Campling, L., 2012. The Tuna 'Commodity Frontier': Business Strategies and Environment in the Industrial Tuna Fisheries of the Western Indian Ocean. Journal of Agrarian Change 12 (2-3), 252-278.

Carswell C (2018) Unique oil spill in East China Sea frustrates scientists. Nature, 24 January. Available at: https://www.nature.com/articles/d41586-018-00976-9.

Cisneros-Montemayor, A.M., Sumaila, U.R., Kaschner, K., Pauly, D., 2010. The global potential for whale watching. Marine Policy 34 (6), 1273-1278.

Clark, M.R., Schlacher, T.A., Rowden, A.A., Stocks, K.I., Consalvey, M., 2012. Science Priorities for Seamounts: Research Links to Conservation and Management. Plos One 7 (1).

Cowen, R.K., Gawarkiewic, G., Pineda, J., Thorrold, S.R., Werner, F.E., 2007. Population Connectivity in Marine Systems An Overview. Oceanography 20 (3), 14-21.

Cowen, R.K., Paris, C.B., Srinivasan, A., 2006. Scaling of connectivity in marine populations. Science 311 (5760), 522-527.

Crespo, G.O., Dunn, D.C., Reygondeau, G., Boerder, K., Worm, B., Cheung, W., Tittensor, D.P., Halpin, P.N., 2018. The environmental niche of the global high seas pelagic longline fleet. Science Advances 4 (8).

Dhurmeea, Z., Zudaire, I., Chassot, E., Cedras, M., Nikolic, N., Bourjea, J., West, W., Appadoo, C., Bodin, N., 2016. Reproductive Biology of Albacore Tuna (Thunnus alalunga) in the Western Indian Ocean. Plos One 11 (12).

Dueri, S., Faugeras, B., Maury, O., 2012a. Modelling the skipjack tuna dynamics in the Indian Ocean with APECOSM-E - Part 2: Parameter estimation and sensitivity analysis. Ecological Modelling 245, 55-64.

Dueri, S., Faugeras, B., Maury, O., 2012b. Modelling the skipjack tuna dynamics in the Indian Ocean with APECOSM-E: Part 1. Model formulation. Ecological Modelling 245, 41-54.

Dunn, D.C., Jablonicky, C., Crespo, G.O., McCauley, D.J., Kroodsma, D.A., Boerder, K., Gjerde, K.M., Halpin, P.N., 2018. Empowering high seas governance with satellite vessel tracking data. Fish and Fisheries 19 (4), 729-739.

Dunn, D.C., Crespo, G.O., Vierros, M., Freestone, D., Rosenthal, E., Roady, S., Alberini, A., Harrison, A.L., Cisneros, A., Moore, J.W. and Sloat, M.R. 2017. Adjacency: How legal precedent, ecological connectivity, and Traditional Knowledge inform our understanding of proximity. DOI: 10.13140/RG.2.2.21359.12968

FACHE ELODIE, Pauwels S., Veitayaki J. (2016). Pacific Islanders, "custodians of the ocean" facing fisheries challenges : introduction. In : FACHE ELODIE (ED.), Pauwels S. (ed.) *Fisheries in the Pacific : the challenges of governance and sustainability*. Marseille : Pacific-Credo Publications, 7-18. (Cahiers du Credo). Workshop Resources, Boundaries and Governance : What Future for Fisheries in the Pacific ?, Marseille (FRA), 2014/10/13-14. ISBN 978-2-9537485-5-0

Felizola-Freire, K.M., Rashid-Sumaila, U., Pauly, D., Adelino, G., 2018. The offshore recreational fisheries of northeastern Brazil. Latin American Journal of Aquatic Research 46 (4), 765-778.

Fiedler, P.C., 2002. The annual cycle and biological effects of the Costa Rica Dome. Deep-Sea Research Part I-Oceanographic Research Papers 49 (2), 321-338.

Fonteneau, A., Hallier, J.P., 2015. Fifty years of dart tag recoveries for tropical tuna: A global comparison of results for the western Pacific, eastern Pacific, Atlantic, and Indian Oceans. Fisheries Research 163, 7-22.

Freestone, D., Laffoley, D., Douvere, F., Badman, T. World Heritage in the High Seas: an idea whose time has come, UNESCO, Paris, France (2016) Available at http://unesdoc.unesco.org/images/0024/002454/245467e.pdf

Freestone, D. and Bulger, F., The Sargasso Sea Commission: An Innovative Approach to the Conservation of Areas Beyond National Jurisdiction (2016). Ocean Yearbook 30: 80–90 koninklijke brill nv, leiden | doi 10.1163/9789004321595_005

Freestone, D., 2012. International Governance, Responsibility and Management of Areas beyond National Jurisdiction. International Journal of Marine and Coastal Law 27 (2), 191-204.

Game, E.T., Grantham, H.S., Hobday, A.J., Pressey, R.L., Lombard, A.T., Beckley, L.E., Gjerde, K., Bustamante, R., Possingham, H.P., Richardson, A.J., 2009. Pelagic protected areas: the missing dimension in ocean conservation. Trends in Ecology & Evolution 24 (7), 360-369.

GESAMP (2009). “Pollution in the Open Ocean: A review of assessments and related studies”. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 79, 68p.

GESAMP (2016). “Sources, fate and effects of microplastics in the marine environment: part two of a global assessment” (Kershaw, P.J., and Rochman, C.M., eds). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 93, 220 p.

Gillett, R. D. 2016. Fisheries in the Economies of Pacific Island Countries and Territories. Pacific Community, Noumea Cedex, New Caledonia.

Gjerde, K., Boteler, B., Durussel, C., Rochette, J., Unger, S., Wright, G., (2018). ‘Conservation and Sustainable Use of Marine Biodiversity in Areas Beyond National Jurisdiction: Options for

Underpinning a Strong Global BBNJ Agreement through Regional and Sectoral Governance', STRONG High Seas Project.

Guillotreau, P., Squires, D., Sun, J., Compean, G.A., 2017. Local, regional and global markets: what drives the tuna fisheries? Reviews in Fish Biology and Fisheries 27 (4), 909-929.

Halpern, B.S., 2003. The impact of marine reserves: Do reserves work and does reserve size matter? Ecological Applications 13 (1), S117-S137.

Harrison, A.L., Costa, D.P., Winship, A.J., Benson, S.R., Bograd, S.J., Antolos, M., Carlisle, A.B., Dewar, H., Dutton, P.H., Jorgensen, S.J., Kohin, S., Mate, B.R., Robinson, P.W., Schaefer, K.M., Shaffer, S.A., Shillinger, G.L., Simmons, S.E., Weng, K.C., Gjerde, K.M., Block, B.A., 2018. The political biogeography of migratory marine predators. Nature Ecology & Evolution 2 (10), 1571-1578.

Hattam, C., Atkins, J.P., Beaumont, N., Borger, T., Bohnke-Henrichs, A., Burdon, D., de Groot, R., Hoefnagel, E., Nunes, P., Piwowarczyk, J., Sastre, S., Austen, M.C., 2015. Marine ecosystem services: Linking indicators to their classification. Ecological Indicators 49, 61-75.

Hobday, A.J., Hartmann, K., 2006. Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Management and Ecology 13 (6), 365-380.

Holmes, B.J., Pepperell, J.G., Griffiths, S.P., Jaine, F.R.A., Tibbetts, I.R., Bennett, M.B., 2014. Tiger shark (Galeocerdo cuvier) movement patterns and habitat use determined by satellite tagging in eastern Australian waters. Marine Biology 161 (11), 2645-2658.

Hoover, C., Bailey, M., Higdon, J., Ferguson, S.H., Sumaila, R., 2013. Estimating the Economic Value of Narwhal and Beluga Hunts in Hudson Bay, Nunavut. Arctic 66 (1), 1-16.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Flemming, J.E.M., Whoriskey, F.G., 2015. Aquatic animal telemetry: A panoramic window into the underwater world. Science 348 (6240).

Johannes, RE 1981. Words of the lagoon: Fishing and Marine Lore in the Palau District of Micronesia. University of California Press.

Johannes, R.E., 2002. The renaissance of community-based marine resource management in Oceania. Annual Review of Ecology and Systematics 33, 317-340.

Johnson, D.E., Salazar, E.R., Gallagher, A., Rees, A., Rodriguez, C.S., Solano, S.C., Ortega, G.R., Frojan, C.B., 2018. Preventing plastics pervading an oceanic oasis: Building the case for the Costa Rica Thermal Dome to become a World Heritage site in ABNJ. Marine Policy 96, 235-242.

Jones, K.R., Klein, C.J., Halpern, B.S., Venter, O., Grantham, H., Kuempel, C.D., Shumway, N., Friedlander, A.M., Possingham, H.P., Watson, J.E.M., 2018. The Location and Protection Status of Earth's Diminishing Marine Wilderness. Current Biology 28 (15), 2506-+.

Kelly, S., Popova, E., Aksenov, Y., Marsh, R., Yool, A., 2018. Lagrangian Modeling of Arctic Ocean Circulation Pathways: Impact of Advection on Spread of Pollutants. Journal of Geophysical Research-Oceans 123 (4), 2882-2902.

Kinlan, B.P., Gaines, S.D., 2003. Propagule dispersal in marine and terrestrial environments: A community perspective. Ecology 84 (8), 2007-2020.

Le Corre, M., Jaeger, A., Pinet, P., Kappes, M.A., Weimerskirch, H., Catry, T., Ramos, J.A., Russell, J.C., Shah, N. and Jaquemet, S., 2012. Tracking seabirds to identify potential Marine Protected Areas in the tropical western Indian Ocean. *Biological Conservation*, *156*, pp.83-93.

Lester, S.E., Ruttenberg, B.I., Gaines, S.D., Kinlan, B.P., 2007. The relationship between dispersal ability and geographic range size. Ecology Letters 10 (8), 745-758.

Matz-Luck, N., Fuchs, J., 2014. The impact of OSPAR on protected area management beyond national jurisdiction: Effective regional cooperation or a network of paper parks? Marine Policy 49, 155-166.

Maxwell, S.M., Hazen, E.L., Lewison, R.L., Dunn, D.C., Bailey, H., Bograd, S.J., Briscoe, D.K., Fossette, S., Hobday, A.J., Bennett, M., Benson, S., Caldwell, M.R., Costa, D.P., Dewar, H., Eguchi, T., Hazen, L., Kohin, S., Sippel, T., Crowder, L.B., 2015. Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. Marine Policy 58, 42-50.

McCauley, D.J., Jablonicky, C., Allison, E.H., Golden, C.D., Joyce, F.H., Mayorga, J., Kroodsma, D., 2018. Wealthy countries dominate industrial fishing. Science Advances 4 (8).

Miller, K.A., 2007. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. Marine Policy 31 (1), 56-70.

Miller KA, Thompson KF, Johnston P and Santillo D (2018) An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps. *Front. Mar. Sci*. 4:418. doi: 10.3389/fmars.2017.00418

Morato, T., Hoyle, S.D., Allain, V., Nicol, S.J., 2010. Tuna Longline Fishing around West and Central Pacific Seamounts. Plos One 5 (12).

Morato, T., Miller, P.I., Dunn, D.C., Nicol, S.J., Bowcott, J., Halpin, P.N., 2016. A perspective on the importance of oceanic fronts in promoting aggregation of visitors to seamounts. Fish and Fisheries 17 (4), 1227-1233.

Nanninga, G.B., Saenz-Agudelo, P., Manica, A., Berumen, M.L., 2014. Environmental gradients predict the genetic population structure of a coral reef fish in the Red Sea. Molecular Ecology 23 (3), 591-602.

O'Leary, B.C., Roberts, C.M., 2018. Ecological connectivity across ocean depths: Implications for protected area design. Global Ecology and Conservation 15.

Papastamatiou, Y.P., Meyer, C.G., Carvalho, F., Dale, J.J., Hutchinson, M.R., Holland, K.N., 2013. Telemetry and random-walk models reveal complex patterns of partial migration in a large marine predator. Ecology 94 (11), 2595-2606.

Payet, R., 2005. Research, assessment and management on the Mascarene Plateau: a large marine ecosystem perspective. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences 363 (1826), 295-307.

Pecl, G.T., Araujo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.C., Clark, T.D., Colwell, R.K., Danielsen, F., Evengard, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Janion-Scheepers, C., Jarzyna, M.A., Jennings, S., Lenoir, J., Linnetved, H.I., Martin, V.Y., McCormack, P.C., McDonald, J., Mitchell, N.J., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Popova, E., Robinson, S.A., Scheffers, B.R., Shaw, J.D., Sorte, C.J.B., Strugnell, J.M., Sunday, J.M., Tuanmu, M.N., Verges, A., Villanueva, C., Wernberg, T., Wapstra, E., Williams, S.E., 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355 (6332), 1389-+.

Popova, E., Yool, A., Byfield, V., Cochrane, K., Coward, A.C., Salim, S.S., Gasalla, M.A., Henson, S.A., Hobday, A.J., Pecl, G.T., Sauer, W.H., Roberts, M.J., 2016. From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. Global Change Biology 22 (6), 2038-2053.

Popova, E.E., Yool, A., Aksenov, Y., Coward, A.C., 2013. Role of advection in Arctic Ocean lower trophic dynamics: A modeling perspective. Journal of Geophysical Research-Oceans 118 (3), 1571-1586.

POSEIDON, MRAG, NFDS and COFREPECHE, 2014. Review of tuna fisheries in the western Indian Ocean (Framework contract MARE/2011/01 – Lot 3, specific contract 7). Brussels, 165 p.

Raitsos, D.E., Brewin, R.J.W., Zhan, P., Dreano, D., Pradhan, Y., Nanninga, G.B., Hoteit, I., 2017. Sensing coral reef connectivity pathways from space. Scientific Reports 7.

Roark, E.B., Guilderson, T.P., Dunbar, R.B., Ingram, B.L., 2006. Radiocarbon-based ages and growth rates of Hawaiian deep-sea corals. Marine Ecology Progress Series 327, 1-14.

Robinson, J., New, A.L., Popova, E.E., Srokosz, M.A., Yool, A., 2017. Far-field connectivity of the UK's four largest marine protected areas: Four of a kind? Earths Future 5 (5), 475-494.

Robinson, J., Popova, E.E., Srokosz, M.A., Yool, A., 2016. A tale of three islands: Downstream natural iron fertilization in the Southern Ocean. Journal of Geophysical Research-Oceans 121 (5), 3350-3371.

Rogers, A.D., 2018. The Biology of Seamounts: 25 Years on. Advances in Marine Biology, Vol 79 79, 137-+.

Rogers A.D., U.R. Sumaila, S.S. Hussain, C. Baulcomb, 2014. The High Seas and Us,
Publishing institution: The Global Ocean Commission, Oxford, UK
URL: http://www.globaloceancommission.org/news/life-in-the-high-seas-storing-500-million-tonnes-of-atmospheric-carbon-every-year/

Rolinski, S., Segschneider, J., Sundermann, J., 2001. Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. Deep-Sea Research Part Ii-Topical Studies in Oceanography 48 (17-18), 3469-3485.

Saenz-Agudelo, P., Dibattista, J.D., Piatek, M.J., Gaither, M.R., Harrison, H.B., Nanninga, G.B., Berumen, M.L., 2015. Seascape genetics along environmental gradients in the Arabian Peninsula: insights from ddRAD sequencing of anemonefishes. Molecular Ecology 24 (24), 6241-6255.

Sale, P.F., Agardy, T., Ainsworth, C.H., Feist, B.E., Bell, J.D., Christie, P., Hoegh-Guldberg, O., Mumby, P.J., Feary, D.A., Saunders, M.I., Daw, T.M., Foale, S.J., Levin, P.S., Lindeman, K.C., Lorenzen, K., Pomeroy, R.S., Allison, E.H., Bradbury, R.H., Corrin, J., Edwards, A.J., Obura, D.O.,

de Mitcheson, Y.J.S., Samoilys, M.A., Sheppard, C.R.C., 2014. Transforming management of tropical coastal seas to cope with challenges of the 21st century. Marine Pollution Bulletin 85 (1), 8-23.
Samoilys MA, GW Maina and Osuka K. (2011) Artisanal Fishing Gears of the Kenyan Coast. Mombasa CORDIO/USAID. 36pp.

Sequeira, A.M., Rodríguez, J.P., Eguíluz, V.M., Harcourt, R., Hindell, M., Sims, D.W., Duarte, C.M., Costa, D.P., Fernández-Gracia, J., Ferreira, L.C. and Hays, G.C., 2018. Convergence of marine megafauna movement patterns in coastal and open oceans. Proceedings of the National Academy of Sciences, p.201716137.

Sarmiento, J.L., Gruber, N., Brzezinski, M.A., Dunne, J.P., 2004. High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427 (6969), 56-60.

Schill, S.R., Raber, G.T., Roberts, J.J., Treml, E.A., Brenner, J., Halpin, P.N., 2015. No Reef Is an Island: Integrating Coral Reef Connectivity Data into the Design of Regional-Scale Marine Protected Area Networks. Plos One 10 (12).

Schiller, L., Bailey, M., Jacquet, J., Sala, E., 2018. High seas fisheries play a negligible role in addressing global food security. Science Advances 4 (8).

Schott, F.A., Xie, S.P., McCreary, J.P., 2009. INDIAN OCEAN CIRCULATION AND CLIMATE VARIABILITY. Reviews of Geophysics 47.

Selkoe, K.A., Toonen, R.J., 2011. Marine connectivity: a new look at pelagic larval duration and genetic metrics of dispersal. Marine Ecology Progress Series 436, 291-305.

Sequeira, A.M.M., Rodriguez, J.P., Eguiluz, V.M., Harcourt, R., Hindell, M., Sims, D.W., Duarte, C.M., Costa, D.P., Fernandez-Gracia, J., Ferreira, L.C., Hays, G.C., Heupel, M.R., Meekan, M.G., Avenn, A., Bailleul, F., Baylis, A.M.M., Berumen, M.L., Braun, C.D., Burns, J., Caley, M.J., Campbell, R., Carmichael, R.H., Clua, E., Einoder, L.D., Friedlaender, A., Goebel, M.E., Goldsworthy, S.D., Guinet, C., Gunn, J., Hamer, D., Hammerschlag, N., Hammill, M., Huckstadt, L.A., Humphries, N.E., Lea, M.A., Lowther, A., Mackay, A., McHuron, E., McKenzie, J., McLeay, L., McMahond, C.R., Mengersenv, K., Muelbert, M.M.C., Pagano, A.M., Page, B., Queiroz, N., Robinson, P.W., Shaffer, S.A., Shivji, M., Skomal, G.B., Thorrold, S.R., Villegas-Amtmann, S., Weise, M., Wells, R., Wetherbee, B., Wiebkin, A., Wienecke, B., Thums, M., 2018. Convergence of marine megafauna movement patterns in coastal and open oceans. Proceedings of the National Academy of Sciences of the United States of America 115 (12), 3072-3077.

Shank, T.M., 2010. Seamounts Deep-Ocean Laboratories of Faunal Connectivity, Evolution, and Endemism. Oceanography 23 (1), 108-122.

Shanks, A.L., 2009. Pelagic Larval Duration and Dispersal Distance Revisited. Biological Bulletin 216 (3), 373-385.

Shanks, A.L., Grantham, B.A., Carr, M.H., 2003. Propagule dispersal distance and the size and spacing of marine reserves. Ecological Applications 13 (1), S159-S169.

Srokosz, M.A., Robinson, J., McGrain, H., Popova, E.E., Yool, A., 2015. Could the Madagascar bloom be fertilized by Madagascan iron? Journal of Geophysical Research-Oceans 120 (8), 5790-5803.

Sumaila, U.R., Lam, V.W.Y., Miller, D.D., Teh, L., Watson, R.A., Zeller, D., Cheung, W.W.L., Cote, I.M., Rogers, A.D., Roberts, C., Sala, E., Pauly, D., 2015. Winners and losers in a world where the high seas is closed to fishing. Scientific Reports 5.

Sumaila, U.R., Zeller, D., Watson, R., Alder, J., Pauly, D., 2007. Potential costs and benefits of marine reserves in the high seas. Marine Ecology Progress Series 345, 305-310.

TEEB. 2010. Biodiversity, ecosystems and ecosystem services. Pages 41-112 in Kumar P, editor. The Economics of Ecosystems and Biodiversity: ecological and economic foundation. UNEP/Earthscan, London and Washington.

Treml, E.A., J. Roberts, P.N. Halpin, H.P. Possingham, C. Riginos. *(2015)* The emergent structure of multi-species dispersal barriers across the Indo-Pacific. *Diversity and Distributions* 21, 465-476. *http://doi.org/10.1111/ddi.12307*

Tittensor, D.P., Mora, C., Jetz, W., Lotze, H.K., Ricard, D., Vanden Berghe, E., Worm, B., 2010. Global patterns and predictors of marine biodiversity across taxa. Nature 466 (7310), 1098-U1107.

Treml, E.A., Halpin, P.N., 2012. Marine population connectivity identifies ecological neighbors for conservation planning in the Coral Triangle. Conservation Letters 5 (6), 441-449.

Treml, E.A., Halpin, P.N., Urban, D.L., Pratson, L.F., 2008. Modeling population connectivity by ocean currents, a graph-theoretic approach for marine conservation. Landscape Ecology 23, 19-36.

Treml, E.A., Roberts, J.J., Chao, Y., Halpin, P.N., Possingham, H.P., Riginos, C., 2012. Reproductive Output and Duration of the Pelagic Larval Stage Determine Seascape-Wide Connectivity of Marine Populations. Integrative and Comparative Biology 52 (4), 525-537.

Turak, E., Brodie, J. & DeVantier, L. Reef-building corals and coral communities of the Yemen Red Sea. Fauna Arab., 23, 1–40 (2007).

Van Gennip, S.J., Popova, E.E., Yool, A., Pecl, G.T., Hobday, A.J., Sorte, A.J.B., 2017. Going with the flow: the role of ocean circulation in global marine ecosystems under a changing climate. Global Change Biology 23 (7), 2602-2617.

van Herwerden, L., McIlwain, J., Al-Oufi, H., Al-Amry, W., Reyes, A., 2006. Development and application of microsatellite markers for Scomberomorus commerson (Perciformes; Teleostei) to a population genetic study of Arabian Peninsula stocks. Fisheries Research 79 (3), 258-266.

VLIZ (2014). Union of the ESRI Country shapefile and the Exclusive Economic Zones (version 2). Available online at http://www.marineregions.org/. Consulted on 2018-06-27.

Vousden, D., 2015. Large marine ecosystems and associated new approaches to regional, transboundary and 'high seas' management. Research Handbook on International Marine Environmental Law, 385-410.

Vousden, D., 2016a. Local to regional polycentric governance approaches within the Agulhas and Somali Current Large Marine Ecosystems. Environmental Development 17, 277-286.

Vousden, D., 2016b. Productivity and biomass assessments for supporting management of the Agulhas Current and Somali Current Large Marine Ecosystems. Environmental Development 17, 118-125.

Vousden, D., (2018) Western and Central Pacific Ocean Transboundary Diagnostic Analysis. Oceanic Fisheries Management Project, Pacific Island. Forum Fisheries Agency. Pp.204. https://www.ffa.int/system/files/FFA%20OFMP%20II%20ransboundary%20Diagnostic%20Analysis%20Report%20FINAL%20WEB%20%282%29.pdf accessed 11th December 2018.

Ward, S. & Harrison, P. L. The effects of elevated nutrient levels on settlement of coral larvae during the ENCORE experiment; Great Barrier Reef, Australia. *Proceedings of the Eighth International Coral Reef Symposium, Panama* **1**, 891–896 (1997).

Webster, M.S., Marra, P.P., Haig, S.M., Bensch, S., Holmes, R.T., 2002. Links between worlds: unraveling migratory connectivity. Trends in Ecology & Evolution 17 (2), 76-83.

Wright, G., Rochette, J., Gjerde, K., Seeger, I. (2018). The long and winding road: negotiating a treaty for the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction. IDDRI, Studies N°08/18, 82 p.

Supplementary material: Lagrangian modelling of connectivity between ABNJs and LDCs

The numerical experiments discussed in this paper were performed using the offline Lagrangian particle-tracking package, ARIANE, driven by ocean circulation output from a simulation of the Nucleus for European Modelling of the Ocean (NEMO) model. Relevant information about both of these and the experiment design are provided here. For more detailed descriptions of ARIANE and NEMO, the reader is referred to (Blanke and Raynaud, 1997) and (Madec, 2014) respectively.

ARIANE

ARIANE is a Lagrangian modelling package that uses circulation output (i.e. simulated velocities) from ocean general circulation models (GCMs) to drive and track the movement of particles (Blanke and Raynaud, 1997). This approach has the advantage that it can be run 'offline' using pre-existing runs of a GCM at considerably lower computational cost than running the full high-resolution model. This low cost facilitates large ensembles of ARIANE simulations to clearly highlight the advective pathways – and their variability – in modelled ocean circulation.

Initial positions for virtual 'particles' are specified, and ARIANE works by reading in the 3-D velocity fields saved in the GCM output, interpolating to solve for particle translation through model grid cells, and saving particle positions at a requested frequency (daily was used here). ARIANE can be run either forwards or backwards in time – i.e. it can be used to either calculate where particles from a given location will go, or where they would have come from. The latter mode is used here.

This particle tracking approach has been extensively used to investigate problems where advection plays an important role, e.g. (Kelly et al., 2018; Popova et al., 2013; Robinson et al., 2016; van Gennip et al., 2017).

NEMO

For our ARIANE experiments, a 1/12° configuration of NEMO (Madec, 2014) provided the ocean circulation field. This resolution corresponds to a horizontal grid of approximately 7 km, sufficient to be eddy-resolving or at least eddy-permitting throughout the World Ocean. The model has 75 depth levels, 31 of which are in the upper 200m of the ocean with a finest vertical resolution of 1m in the uppermost level.

NEMO was forced at the surface using atmospheric reanalysis data from the Drakkar Forcing Set (DFS) between 1958 and 2015. DFS consists of wind, temperature and humidity from ERA40 reanalysis at 6 hourly temporal resolution, radiative fluxes (longwave and shortwave) at daily resolution, and monthly means for precipitation and river runoff from CORE2 reanalysis (Brodeau et al., 2010). This run of NEMO was coupled to the Louvian-la-Neuve Ice Model (LIM2) sea-ice model (Fichefet and Maqueda, 1997; Goosse and Fichefet, 1999). Output from this run of the NEMO model is saved at 5-day frequency, and it is this (pre-existing) output that was used to drive the Lagrangian experiments discussed above.

Experiment Design

For each country in the 'least developed' category of the 2014-2017 DAC list of ODA recipients, virtual particles were initialised along their coastal regions. Here, 'coastal regions' are defined as the region within approximately 15 km of the shore. Particles were distributed uniformly, with 9 particles per model grid cell (approx. 1 particle per 10 km^2) for each experimental release. All particles were released at the ocean surface, and releases were performed every 3 months between 2005 and 2014 to capture the seasonal and inter-annual variability of ocean currents (for a total of 40 releases). During an experiment, particles were tracked backwards in time by ARIANE, and their positions were recorded daily for one year. The use of backwards (upstream) trajectories here identifies where water masses reaching a coastal release point have come from, rather than in forwards (downstream) trajectories which identify where water masses leaving a coastal release point travel to.

To analyse the connectivity between ABNJs and each respective country's coastline, each particle was logged as being either in or out of areas beyond national jurisdiction at each time step. As noted, all particles began the experiment within 15 km of their country's coast. Upon the first time step that a particle was tracked back to an ABNJ, this was logged as the connectivity timescale for that particular particle. Connectivity timescales and indexes for each country were defined by considering the mean connectivity timescale for all particles (from all 40 releases) tracked from a given country's coastline, and a connectivity index describing the strength of connectivity between ABNJs and each country was defined as the fraction of particles tracked back to ABNJs within 6 months of initialisation.

Supplementary material references:

BLANKE, B. & RAYNAUD, S. 1997. Kinematics of the Pacific Equatorial Undercurrent: An Eulerian and Lagrangian Approach from GCM Results. *Journal of Physical Oceanography,* 27**,** 1038-1053.

BRODEAU, L., BARNIER, B., TREGUIER, A.-M., PENDUFF, T. & GULEV, S. 2010. An ERA40-based atmospheric forcing for global ocean circulation models. *Ocean Modelling,* 31**,** 88-104.

FICHEFET, T. & MAQUEDA, M. A. M. 1997. Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. *Journal of Geophysical Research: Oceans,* 102**,** 12609-12646.

GOOSSE, H. & FICHEFET, T. 1999. Importance of ice-ocean interactions for the global ocean circulation: A model study. *Journal of Geophysical Research: Oceans,* 104**,** 23337-23355.

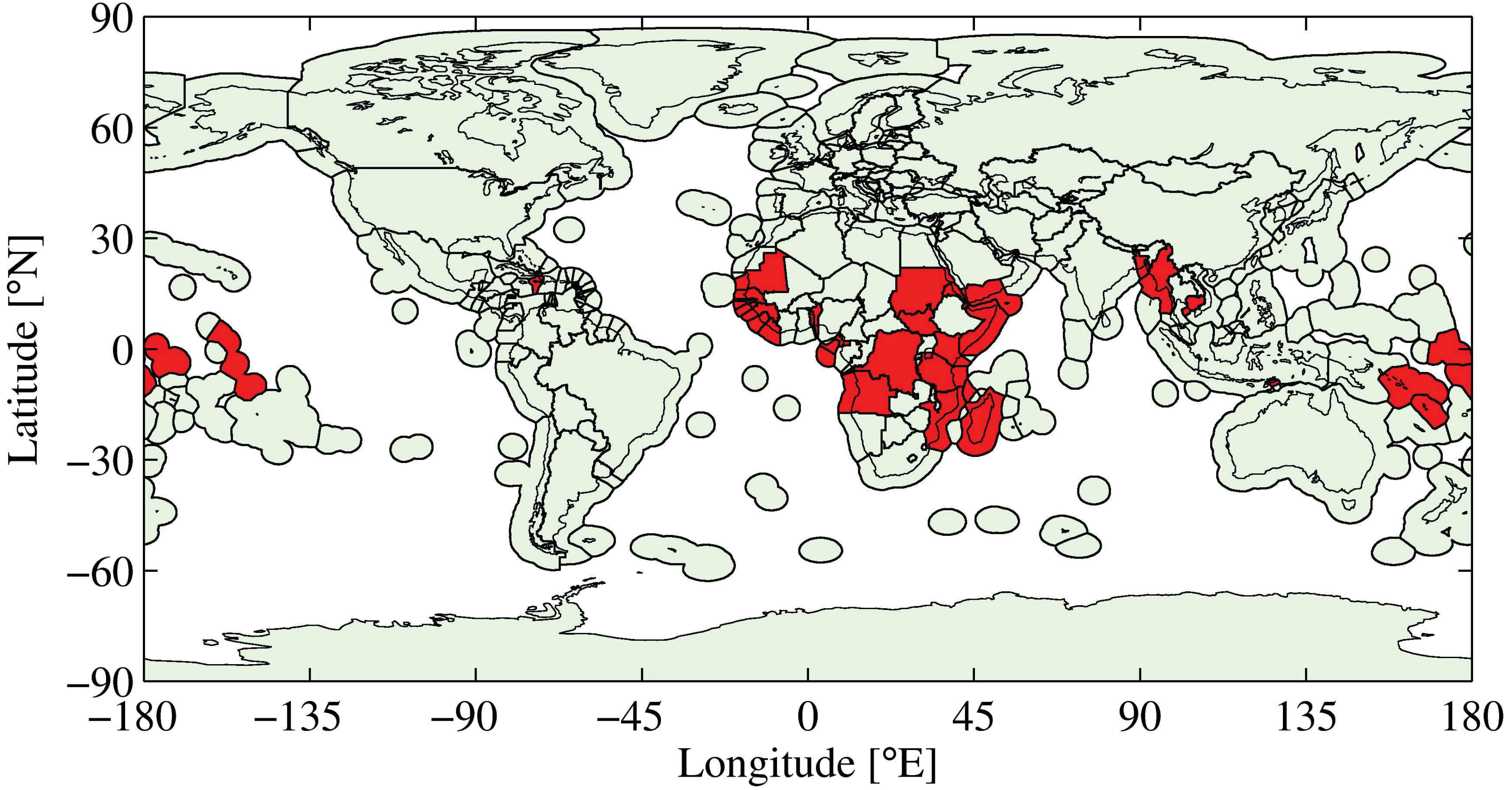
KELLY, S., POPOVA, E., AKSENOV, Y., MARSH, R. & YOOL, A. 2018. Lagrangian Modeling of Arctic Ocean Circulation Pathways: Impact of Advection on Spread of Pollutants. *Journal of Geophysical Research: Oceans,* 123**,** 2882-2902.

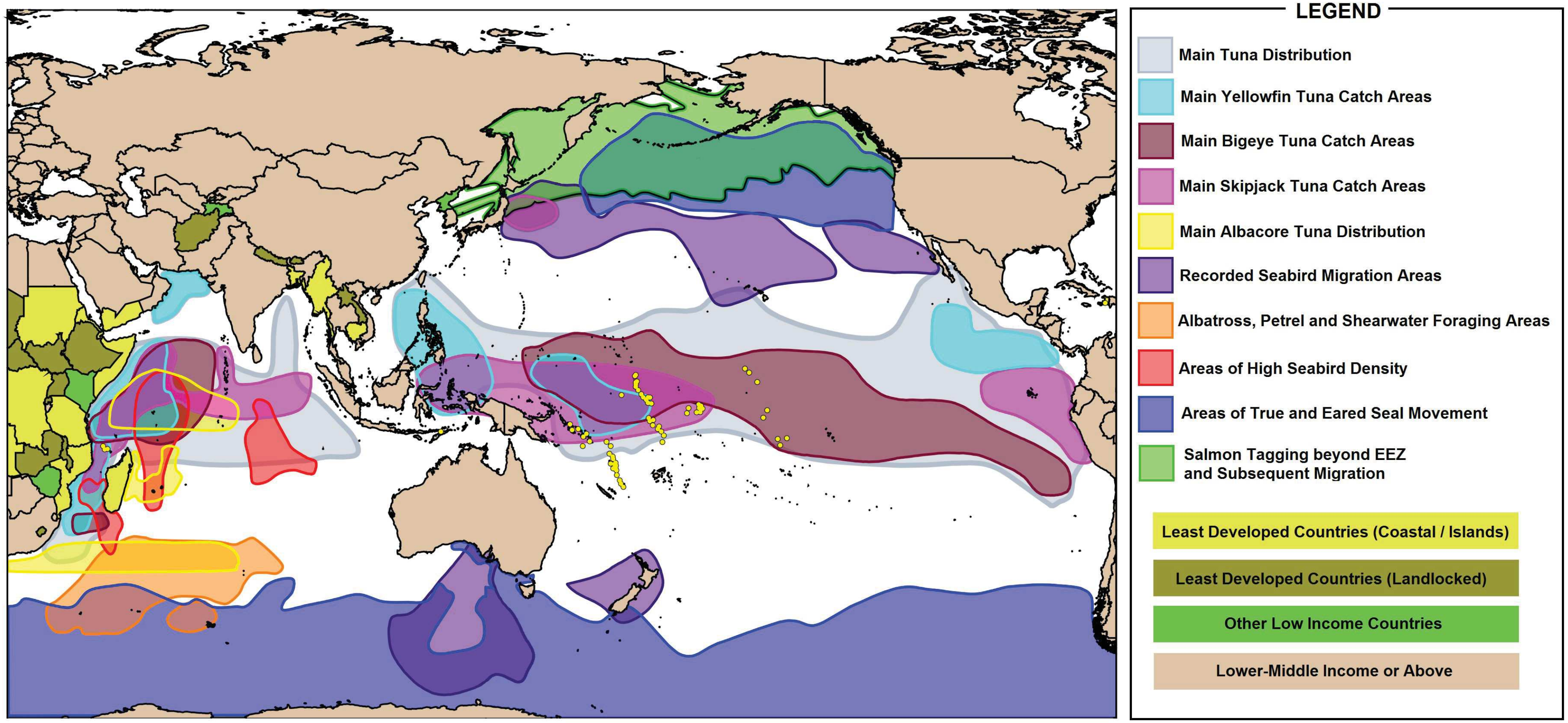
MADEC, G. 2014. "NEMO Ocean Engine" (Draft Edition r5171) "NEMO ocean engine" (Draft edition r5171). Note du Pôle de modélisation, Institut Pierre-Simon Laplace (IPSL), France, No 27 ISSN No 1288-1619.

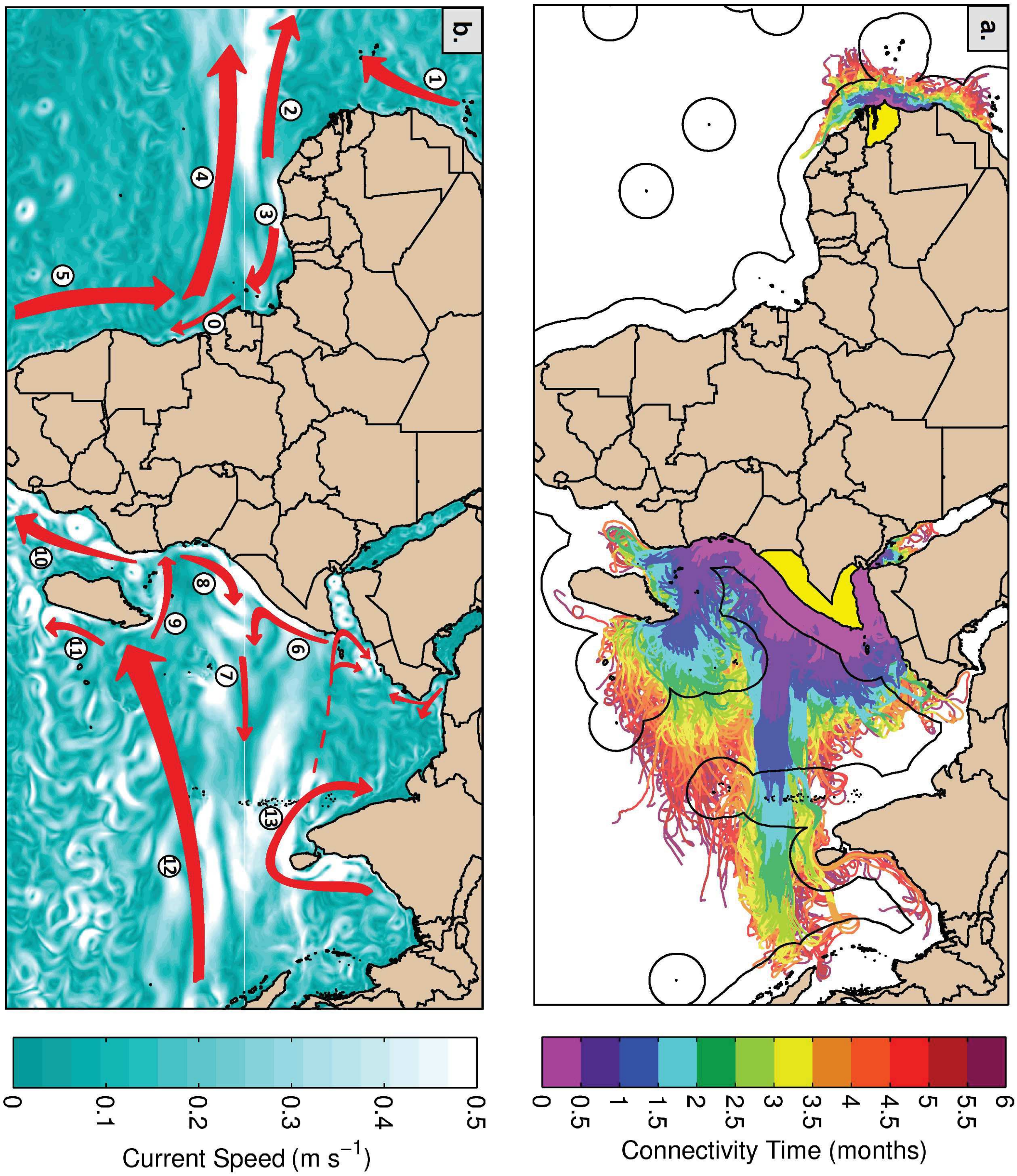
POPOVA, E. E., YOOL, A., AKSENOV, Y. & COWARD, A. C. 2013. Role of advection in Arctic Ocean lower trophic dynamics: A modeling perspective. *Journal of Geophysical Research: Oceans,* 118**,** 1571-1586.

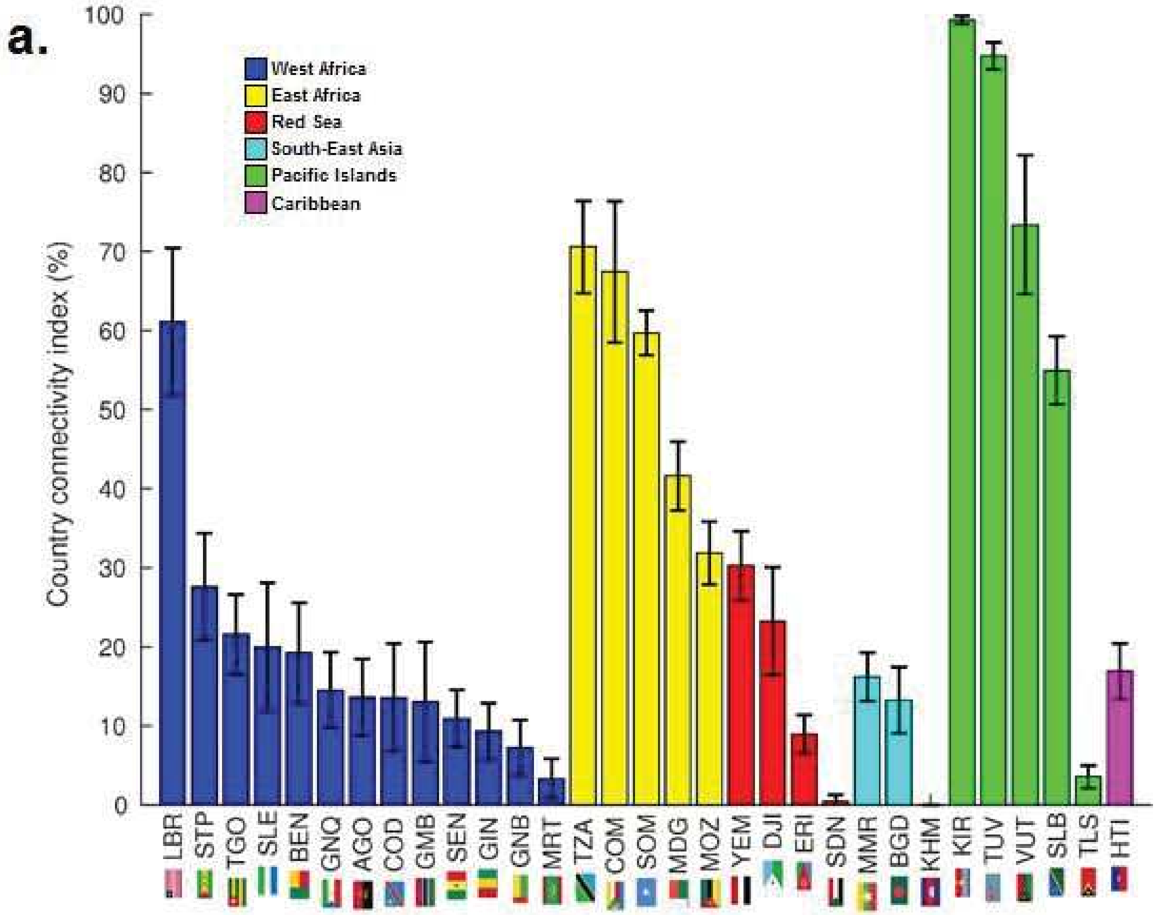
ROBINSON, J., POPOVA, E. E., SROKOSZ, M. A. & YOOL, A. 2016. A tale of three islands: Downstream natural iron fertilization in the Southern Ocean. *Journal of Geophysical Research: Oceans,* 121**,** 3350-3371.

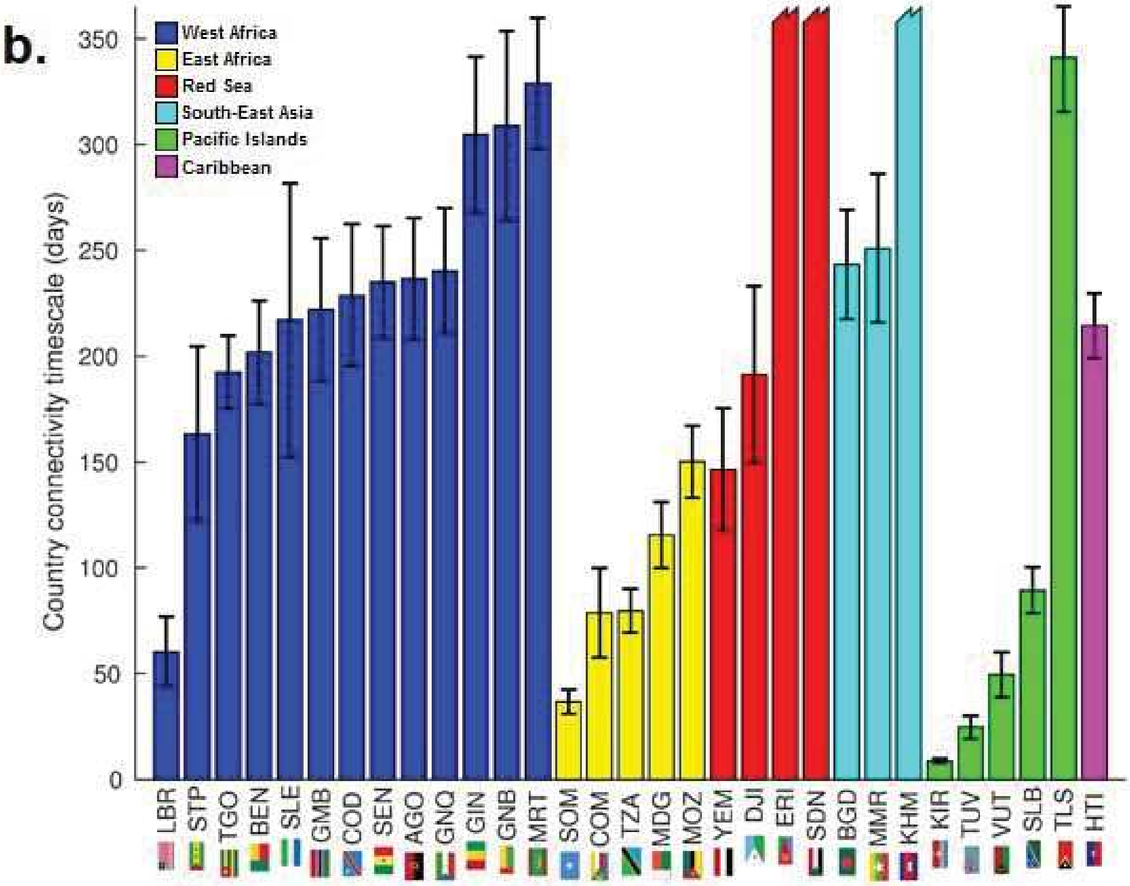
VAN GENNIP, S. J., POPOVA, E. E., YOOL, A., PECL, G. T., HOBDAY, A. J. & SORTE, C. J. B. 2017. Going with the flow: the role of ocean circulation in global marine ecosystems under a changing climate. *Global Change Biology,* 23**,** 2602-2617.

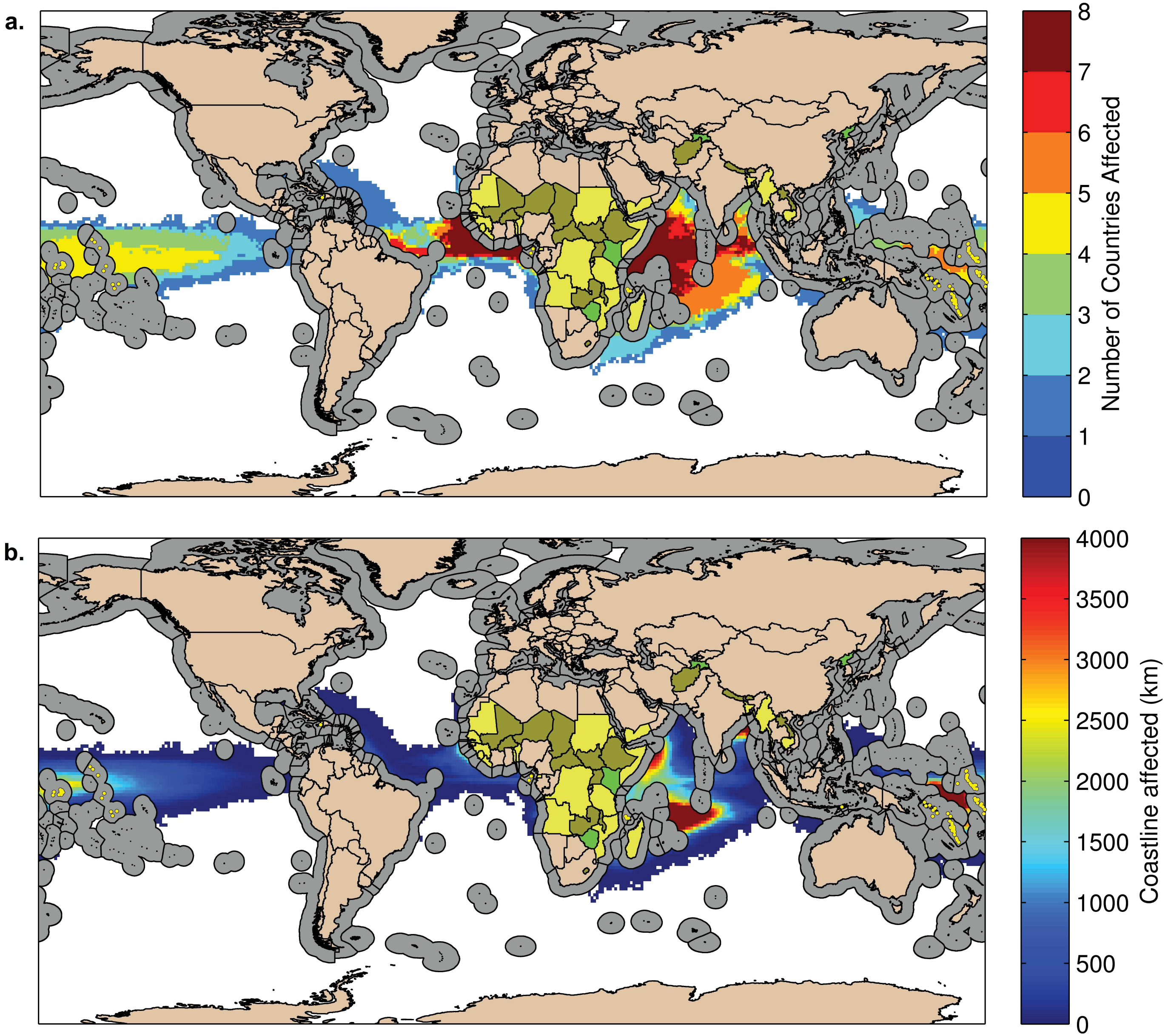

90
60
30
0
−30
−60
−90
Latitude [°N]
−180
−135
−90
−45
0
45
90
135
180
Longitude [°E]


LEGEND
Main Tuna Distribution
Main Yellowfin Tuna Catch Areas
Main Bigeye Tuna Catch Areas
Main Skipjack Tuna Catch Areas
Main Albacore Tuna Distribution
Recorded Seabird Migration Areas
Albatross, Petrel and Shearwater Foraging Areas
Areas of High Seabird Density
Areas of True and Eared Seal Movement
Salmon Tagging beyond EEZ and Subsequent Migration
Least Developed Countries (Coastal / Islands)
Least Developed Countries (Landlocked)
Other Low Income Countries
Lower-Middle Income or Above


a.
b.
Connectivity Time (months)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Current Speed (m s^{-1})
0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
6
7
8
9
10
11
12
13


a.
West Africa
East Africa
Red Sea
South-East Asia
Pacific Islands
Caribbean
Country connectivity index (%)
100
90
80
70
60
50
40
30
20
10
0
LBR
STP
TGO
SLE
BEN
GNQ
AGO
COD
GMB
SEN
GIN
GNB
MRT
TZA
COM
SOM
MDG
MOZ
YEM
DJI
ERI
SDN
MMR
BGD
KHM
KIR
TUV
VUT
SLB
TLS
HTI


b.
West Africa
East Africa
Red Sea
South-East Asia
Pacific Islands
Caribbean
Country connectivity timescale (days)
350
300
250
200
150
100
50
0
LBR
STP
TGO
BEN
SLE
GMB
COD
SEN
AGO
GNQ
GIN
GNB
MRT
SOM
COM
TZA
MDG
MOZ
YEM
DJI
ERI
SDN
BGD
MMR
KHM
KIR
TUV
VUT
SLB
TLS
HTI


a.
8
7
6
5
4
3
2
1
0
Number of Countries Affected
b.
4000
3500
3000
2500
2000
1500
1000
500
0
Coastline affected (km)