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Ichthyoplankton transport around the Brazilian Fernando de Noronha archipelago and Rocas Atoll: Are there any connectivity patterns?

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To investigate the influence of environmental conditions on ichthyoplankton transport in the FN and AR system, the outputs of a hydrodynamic simulation have been used as inputs to force an Individual-Based Model (IBM) around islands. The results show larval retention over the entire year. This retention is highly correlated with the intensity of the zonal current. Lagrangian analysis reveals connectivity between FN and AR, represented here by larval transport success, which would be important for the conservation of the species in these tropical Brazilian islands.

[Keywords: Individual Based Model (IBM), Ocean Modelling, Transport Success, Retention, Fernando de Noronha, Rocas Atoll]

Introduction

Northeastern Brazilian waters are oligotrophic, i.e., poor in nutrients and are thus almost free of high biogenic activity. The Exclusive Economic Zone (EEZ) of Northeast Brazil ranges from the coast to the offshore region, which includes oceanic islands. These islands, especially the Fernando de Noronha archipelago (FN, 3°50'S-32°25'W) and Rocas Atoll (AR, 3°52'S - 33°49'W), contribute greatly to the productivity of the Northeast Brazil EEZ and host high marine biodiversity with many species of fishes including reef fishes such as Dog Snapper Lutjanus jocu[1] (Lutjanidae)[2,3,4], by using a high-resolution model, have identified a set of physical processes known as the "island mass effect" that would promote nutrient enrichment downstream of these islands. These processes occur around most islands and have been previously described by several authors[5-9]. FN and AR are marine protected areas in the western tropical Atlantic and are registered as a Natural World Heritage site by the UNESCO in 2001[10]. The islands are constantly monitored to protect their conservation status. Marine protected areas play a fundamental role in conservation of biological diversity of marine ecosystems and should have connections with other locations to transfer individuals of species living there[11,12].

Present study consists the transport of ichthyoplankton in FN and transported within the system of FN and AR. Our goal is to investigate the influence of hydrodynamic conditions on the larvae in the marine protected area of FN and AR. Transport of larvae towards AR could be another possibility for larval retention and enabling individuals to develop in this productive area. We also examine if there is larval recruitment in AR and the conditions for this transport success, which allows exploration of the larval connectivity between both islands. For this purpose, we use outputs of a very high-resolution hydrodynamic model4to force an Individual-Based Model (IBM-ICHTHYOP) and simulate the ichthyoplankton transport of Lutjanus jocu. This biophysical model has been already successfully used in the southern Benguela[13], in the Moroccan nearshore regions of the Canary Current System[14], in the Senegalese–Mauritanian coast region[15], in the marine protected areas of the continental shelf of eastern Brazil[16] and in the Gulf of Guinea[17]. To our knowledge, this present work is the first based on Lagrangian modelling focusing on the islands of FN and AR, located in the western tropical Atlantic.

Materials and Methods

Hydrodynamic model

The hydrodynamic model used in this work is an implementation of the Regional Ocean Modelling System (ROMS)[18]. This oceanic model has been configured for the western tropical Atlantic region, focusing on the Brazilian islands FN and AR[4]. ROMS is a three-dimensional, free surface, terrain-following ocean model that solves primitives equations under hydrostatic and Boussinesq approximations. The version developed by the French Institut de Recherche pour le Development (IRD) was configured for this study. The ROMSTOOLS package[19] is used for the design of the configuration. Unresolved vertical subgrid-scale processes are parameterized by an adaptation of the non-local K-profile planetary (KPP) boundary layer scheme, as proposed by[20]. A more detailed description of this model can be found in[18,21].

The study region, located in the EEZ of northeast Brazil, extends from 3ºS to 5.5ºS in latitude and from 31ºW to 35ºW in longitude, in order to take into account the main physical characteristics that interact with the circulation around the islands (Fig. 1). The model has a horizontal resolution of 1/70º (1.5 km). Such a finer resolution permits to take account the influence of the small FN and AR (having and of emerged land, respectively) on the surrounding waters. Detailed and updated cartographic data from the Centro de Hidrografia da Marinha (CHM, http://www.mar.mil.br/dhn/chm/box-cartas-nauticas/ cartas.html) were used and merged with the 0.5' resolution GEBCO database (Global Earth Bathymetric Chart of the Oceans, http://www.gebco.net/) for a better representation of the bathymetry, particularly in the FN and AR areas.

The model grid has 40 sigma vertical levels with stretching parameters to keep a sufficient vertical resolution, near the surface of the ocean in the whole integration domain, and near the bottom primarily around the islands[22].

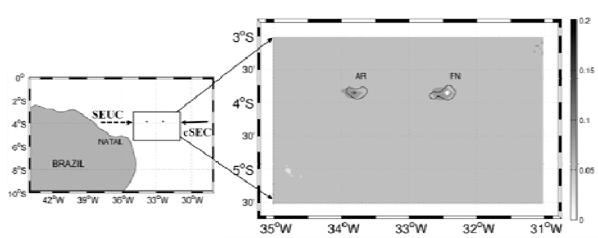

Fig. 1 — Schematic of the western tropical Atlantic region and the study area with the Fernando de Noronha archipelago (FN) and Rocas Atoll (AR). Colours represent the annual mean of the MODIS surface chlorophyll concentration [mg/m^3] over the period 2003-2015. Black contour line indicates the 1000 m isobath. Spawning locations correspond to the coastal zone within the 1000 m isobaths downstream of FN.

At the surface, the model is forced by fresh water fluxes from the ocean surface monthly climatology at 0.5º resolution, provided by the Comprehensive Ocean-Atmosphere Data Set (COADS)[23]. The forced heat flux uses sea surface temperature (SST) at high resolution (~9 km) from the Advancedffig Very High Resolution Radiometer (AVHRR) - Pathfinder climatology field to improve the solution of the model[24]. Monthly wind stress climatology derived from the NASA Quick Scatterometer (QuikSCAT) at 0.25º is used to force momentum fluxes through the surface of the model. This dataset, also known as SCOW (Scatterometter Climatology of Ocean Winds), is available for September 1999 to August 2007[25]. Lateral open boundaries were forced using the monthly climatology of the World Ocean Atlas at 0.25º (**Error! Hyperlink reference not valid.**).

The simulation was integrated for 10 simulated years and averaged outputs were stored for each 2 simulated days. The equilibrium state was achieved after the second simulation year (spin-up period). In this work, we used the output of the circulation of the last simulated year to force the biophysical model.

Individual Based Model and simulations

The Individual-Based Model (IBM) ICHTHYOP (http://www.ichthyop.org/) is a free Java tool used to study the transport of individuals and effects of physical and biological factors on their dynamics; refer to[26,27] for a complete description of the IBM model. This IBM model, forced by the 2 day-averaged velocity of ROMS outputs, is used to simulate the transport of virtual ichthyoplankton in the oceanic region of the FN and AR. In the simulation, the coastal areas of FN and AR are defined by the zone extending from the island coasts to the 1000 m isobath (Fig.1). Biological information for the Dog snapper used in the model is obtained from[2,3]. For each run, 3000 eggs were released downstream of FN, the predefined spawning areas of the species. Based on the pelagic period (17 to 47 days) of this species and considering the slower advection of these protected regions, 14 days is a good lower age limit for considering an individual recruited in the marine protected areas of FN and AR[2,3]. Therefore, the transport success is defined as the individuals transported within a protected area in the time interval of 14 to 47 days.

The oceanic region of FN and AR is characterized by a general westward transport/flow, meaning that no particles are returned to the area. Because all the particles were already transported or recruited after 27 days, the model transport duration has been fixed to 28 days. In this work, individuals are considered recruited if they are within a marine protected area 14 to 28 days after their release. The retention is defined as the number of particles that remain "recruited" in the marine protected area of FN, where they were originally released. The transport success (or recruitment in AR) is defined as the number of individuals transported and recruited in the marine protected area of AR[2]found that larger individuals inhabit shallow water, which could be the spawning zone. With this information, the Lagrangian simulation was performed for 12 release months (January - December) for a temporal study. In addition, two scenarios of simulation, i.e., passive and active transport, have been modelled. In the first scenario (I), we simulated passive particles and tested the depth interval of release (0-30, 30-60, and 60-100 m) on transport. The second scenario (II), which is an active transport, has been configured to examine the effect of the Diel Vertical Migration (DVM) of larvae. The DVM is a behaviour that consists in a vertical swimming near the surface at night, feeding in relatively productive surface waters and to deeper depths during the day, avoiding predators[28,29]. We did not find relevant information about the day when the particles begin to experience vertical displacements in the western tropical Atlantic region. In our study, the target day is considered as the corresponding age of particles at the beginning of their DVM. The target days were set at 7, 10, and 13 days in the simulations of scenario II.

Results and Discussion

Hydrodynamic model evaluation

ROMS outputs were already validated by[4] and reproduce the main oceanic properties of the study region well. The seasonal signal of the SST is well reproduced by the model (Fig.2(b)). The SST increases from September to April and decreases from April to September. Higher SST values are observed in March, April and May and lower SST values in August, September and October are also observed. The seasonal cycle of the model is more similar to WOA and MODIS data than to GHRSST data that generally display a warm bias from April to December when compared with the other SST climatologies. These discrepancies could be explained by the difference in time intervals considered for each dataset. The WOA SST climatology contains data of more than 50 years, while the MODIS SSTs have 10 years and the GHRSST SSTs are for 4 years only. Furthermore, note that these last datasets contain only SSTs during years when global warming was already effective. The difference in spatial mean SST between the model and MODIS remains in the acceptable range in the region (Fig.2(a)), where the bias is less than 1ºC.

The ROMS and DRIFTER observation currents show the same flow pattern (Fig.3). This flow is a global westward zonal current, named the central branch of the South Equatorial Current (cSEC), well represented by the model with a small weakening towards the western limit[30]. This behaviour occurs in the model because the continental slope, which is responsible for the western intensification[31], is not considered in our model. This zonal current shows low seasonal variability[4,32], being stronger in winter

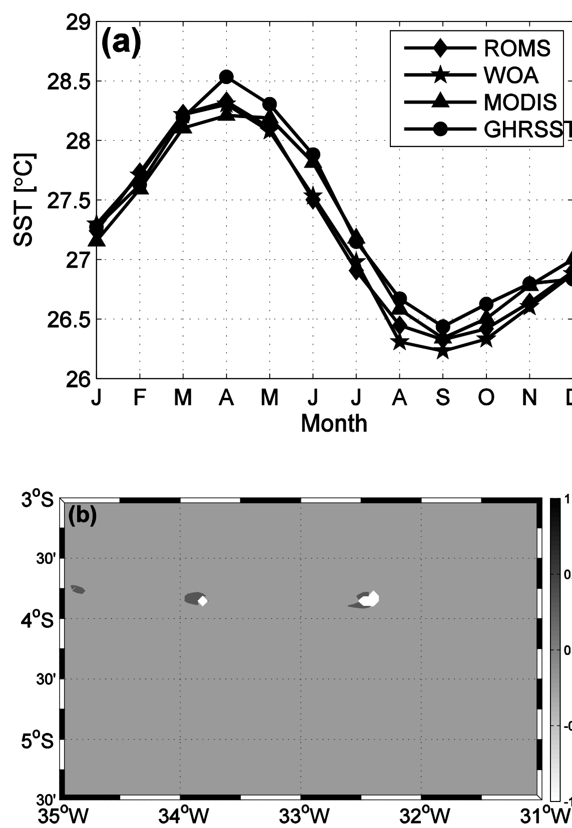

Fig. 2 — (a) SSTs [ºC] seasonal evolution for the model (line with diamonds), WOA (line with stars), MODIS (line with triangles) and GHRSST (line with circles). 2 (b) The difference (ROMS-MODIS) in the SST annual mean.

and weaker in summer, and its seasonal cycle is well reproduced by the model (not shown).

Temporal patterns of retention and transport success

The results show retention of particles in the FN marine protected area throughout the year. On average, this retention is maximal for individuals released from February to July and minimal for those released from August to January (Fig.4(a), top panel). Globally, the maximum particle retention coincides with the period of current strengthening, i.e., when the wake flow of FN is well defined. This wake flow is primarily characterized by the weakening of flow downstream from the island (not shown). The seasonal variability of the larval retention at around FN is linked to the variability of the current in the region. Indeed, the Fig. 5 exhibits a significant correlation (~0.83) between the retention in FN and the intensity of the zonal current flowing in the region. It suggests that the retention in FN increases when the zonal current is strengthened and decreases when it is weakened. Experiments examining the percentage of particles reaching AR highlighted transport success differences between the release months (Fig.4(b), bottom panel). This transport success, also effective for all release months, is more important.in February and March (>15%) and less important in May and October (<3%). In February, the flow is more favourable (well oriented from FN towards AR) to the transport of the particles reaching the marine protected area of AR. Thereby, they could be recruited there and this promotes the increase in transport success (Fig.6(a), top panel). In May the transport is slightly inclined and does not flow directly towards the marine protected area of AR, thus considerably reducing the transport success (Fig.6(b), bottom panel). These findings demonstrate connectivity between both marine protected areas throughout the year, thereby ensuring effective conservation of marine biodiversity[33].

Effects of release depth on transport

In this section, we study the effect of release depth range in the passive transport simulation scenario by testing three different depth ranges:0-30, 30-60, and 60-100 m.

We found an impact of the release depth on the larval retention. The highest global retention value

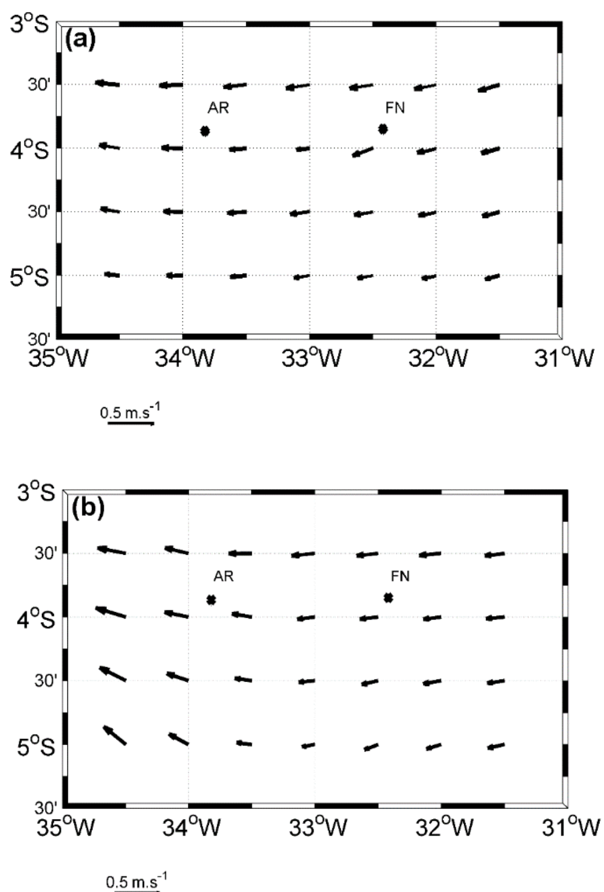

Fig. 3 — Current annual means [m/s] from our ROMS simulation (a) and DRIFTERS (b).

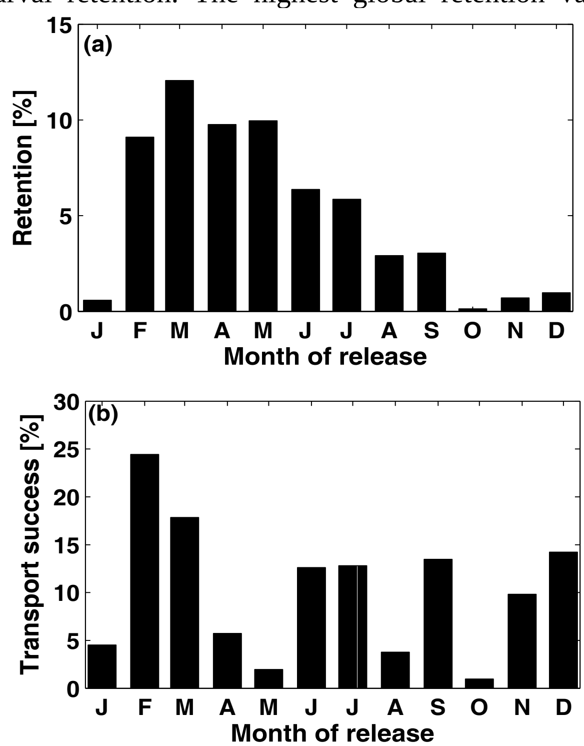

Fig. 4 — Monthly distribution of the (a) retention (in FN, top panel) and (b) recruitment (in AR, bottom panel).

(~12%) appears for particles released in the 60-100 m depth range and the lowest (~5%) in the 0-30 m interval (Fig.7(a)). These results indicate that the deeper the individuals are released, the more retention occurs at FN. This pattern of larval retention at FN is associated with slower cSEC transport in the deeper layers. However, our results suggest that this factor has a slight effect on the transport success, with values approximately 10% for the three tests. However, it is found that the transport success increases with decreasing depth of release (Fig.7(b)). These findings are similar to a previous study in the Canary Current System[14] found that the coastal retention (the African coast) was enhanced for the particles released in deeper waters. Furthermore, they showed that the transport success (transport from the African coast to the Canary archipelago) was slightly improved for particles released in upper waters.

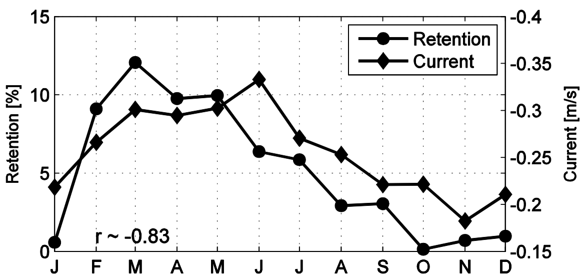

Fig. 5 — Monthly distribution of the retention (at FN; line with circles) and seasonal evolution of zonal current (line with diamonds)

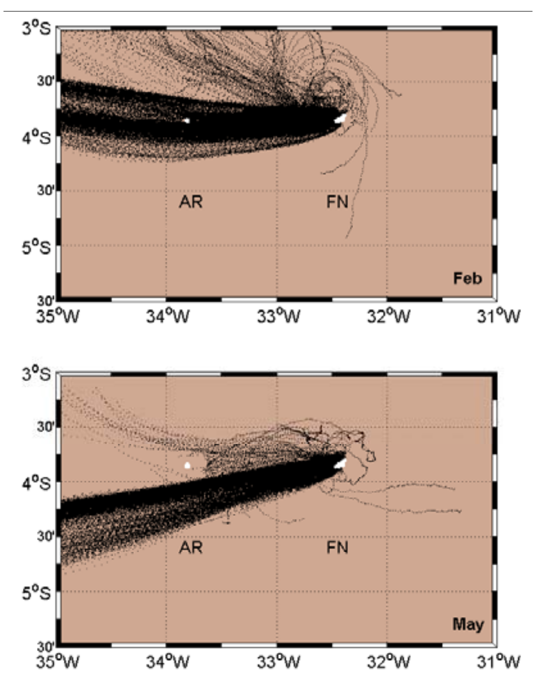

Fig. 6 — Trajectories of virtual ichthyoplankton based on simulations starting in February (top) and May (bottom).

Effects of DVM on transport

In this section, we examine the effect of the beginning of larval vertical swimming on active transport. In these experiences, the DVM occurs between the surface and 60 m depth. Then 7, 10, and 13 target days were employed for this investigation.

The results suggest that the retention rate increases with the target day. Considering the 7, 10, and 13 day DVM simulations, the global retention values are ~1.5%, 2%, and 3%, respectively (Fig.8(a)). These results indicate that, later the particles released start the DVM, the higher the retention rate is observed at FN. Likewise, the target day has the same effect on the transport success as on the retention, i.e., the larval recruitment in AR is more important for individuals who became active particles later. The rate of successful transport is around ~6, 8, and 10% for 7, 10, and 13 target days, respectively (Fig. 8(b)).

During the day, the larvae migrate to deeper water and the slower dynamics at 60 m retain the larvae

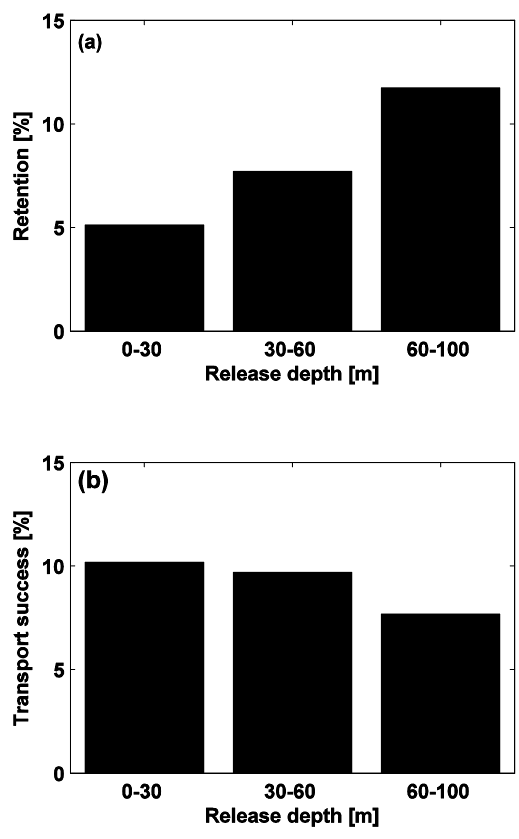

Fig. 7 — -Global (a) retention at FN and (b) recruitment at AR, for different spawning depth ranges.

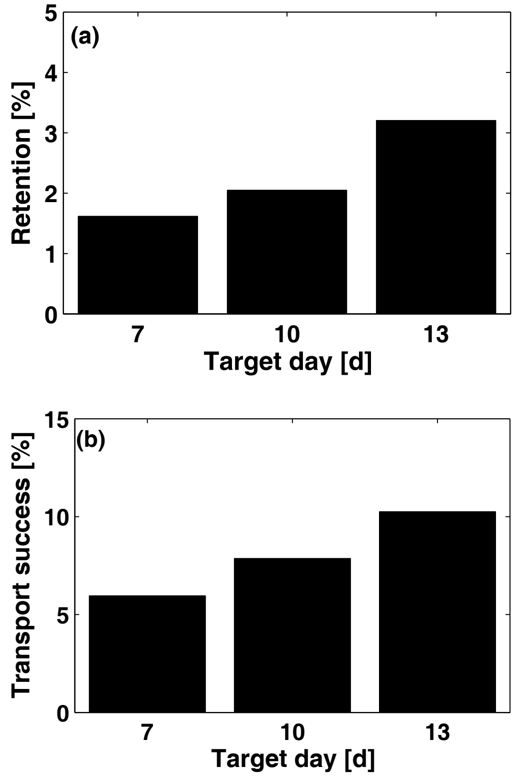

Fig. 8 — Global (a) retention at FN and (b) recruitment at AR, for different target days.

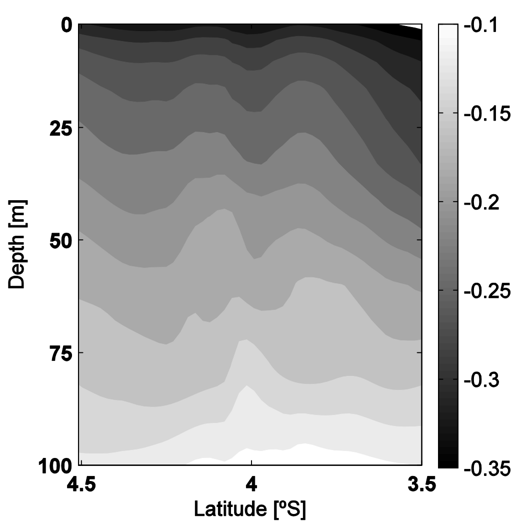

Fig. 9 — Vertical section of the annual mean zonal current [m/s] at 32ºW.

long enough into the system of FN and AR. At night, when the particles arrive to the surface, they are rapidly transported by the stronger current. Indeed, in this study region, the flow is strengthened towards the surface and weakens with increasing depth as shown by the annual mean flow of the zonal current (Fig. 9). Thus, when individuals begin the DVM early, they interact early with the strong surface flow that increases the speed at which particles travel. They are then driven rapidly out of this island system, which could contribute to decreases in the larval recruitment in FN and AR.

Conclusion

The coupling modelling system ROMS-ICHTHYOP has proved to be relevant to investigate the influence of environmental conditions on larval transport in the study region. Our results show that larval retention is highly correlated with the intensity of the zonal current of the study region. During the maximum retention period, the current is strengthened. These findings have also revealed connections between FN and AR, which would be crucial for the conservation of individuals in the system of these islands. Thus, these results imply that AR acts as a stepping-stone and reservoir for marine organism species transported from FN to AR.

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