

## CONNECTIVITY OF MARINE PROTECTED AREAS USING BIOPHYSICAL MODELLING

Andressa D'Agostini<sup>1</sup>  
Douglas Francisco Marcolino Gherardi<sup>2</sup>  
Luciano Ponzi Pezzi<sup>2</sup>

<sup>1</sup> LAMCE/COPPE/UFRJ  
Av. Athos da Silveira Ramos, 149, Ilha do Fundão – RJ  
dessa.dagostini@gmail.com

<sup>2</sup> Instituto Nacional de Pesquisas Espaciais - INPE  
Caixa Postal 515 - 12227-010 - São José dos Campos - SP, Brasil  
{douglas, luciano}@dsr.inpe.br

**Abstract.** The connectivity between reef areas in the East Continental Shelf (ECS) of Brazil was investigated with a hydrodynamic model (ROMS) and an Individual Based Model (IBM - Ichthyop), using groupers (genus *Mycteroperca*) as functional group. The hydrodynamic outputs from ROMS used as physical forcings by Ichthyop was compared with satellite data and showed good agreement. IBM experiments were realized releasing eggs from April to September along six years (2002 - 2007) in five groups of Marine Protected Areas (MPAs) along the ECS. An intra-annual variability of recruitment and self-recruitment of grouper larvae was observed, as well as a negative correlation between these population parameters with total Kinetic Energy (KE) in the region. Higher KE is related to higher larval advection to offshore regions and a lower total recruitment and connectivity on coastal MPAs. Our results suggest a high and directional connectivity between MPAs, occurring from north to south with potential influence of Brazil Current which flows in this direction. Some MPAs act predominantly as “sink” areas, and others as “source” areas.

**Palavras-chave:** biophysical modeling, reef fish, larvae dispersal, total kinetic energy, modelagem biofísica, peixe recifal, dispersão de larva, energia cinética total.

### 1. Introduction

Connectivity among marine populations can be detected by genetic analysis [e.g. Craig et al., 2007], tracking natural or artificial markers in larvae (e. g. Thorrold et al., 2002), otolith chemistry [e.g. Di Franco et al., 2012] or by biophysical simulations [e.g. Andrello et al., 2013]. The biophysical modeling approach allows the integration of physical and biological processes to elicit likely recruitment scenarios and dispersion pathways [Cowen et al., 2006; Planes et al., 2009; Andrello et al. 2013]. For this purpose, lagrangian Individual Based Models (IBMs) not only help explore and compare patterns of population ecology [Grimm, 1999] taking into consideration the biological aspects of each individual, but also its relation to physical conditions [Miller, 2007]. The relevance of each physical or biological parameter to larval dispersal can be objectively tested [Paris et al. 2007; Robins et al., 2013], allowing the identification of physical-biological interactions that lead to a higher or lower recruitment and population linkages. The physical environment drives transport/retention of larvae during their pelagic stage and strongly influences their settlement and survival. For example, the influence of turbulent kinetic energy can cause larval advection to offshore areas inhibiting larvae recruitment [Ruiz et al., 2012]. Knowledge of how physical conditions and their persistence act on population connectivity and larval recruitment is becoming a key element in management plans for MPAs. In Brazil, the East Continental Shelf (ECS) is home to the largest coral reef complex in the South Atlantic [Leão et al, 2003]. This has turned the region into the center of coral biodiversity, which is now under the protection of a number of MPAs.

Furthermore, ECS has a circulation pattern with many eddies and meandering currents characterized by a strong seasonal variability [Soutelino et al., 2013]. This complex regional circulation is likely to exert a significant influence on retention and transport of eggs and larvae between MPAs.

## 2. Materials and methods

The ECS of Brazil extends from Todos os Santos Bay ( $12^{\circ}50'S$ ,  $38^{\circ}38'W$ ) in Bahia State to Cabo Frio ( $22^{\circ}52'S$ ,  $42^{\circ}01'W$ ) in Rio de Janeiro State [Villwock, 1994] (Figure 1). The ECS presents a complex topography with the narrowest width of 8 km in Todos os Santos Bay (Salvador - BA) and the maximum shelf width at the Abrolhos Bank 245 km wide [Knoppers et al., 1999].

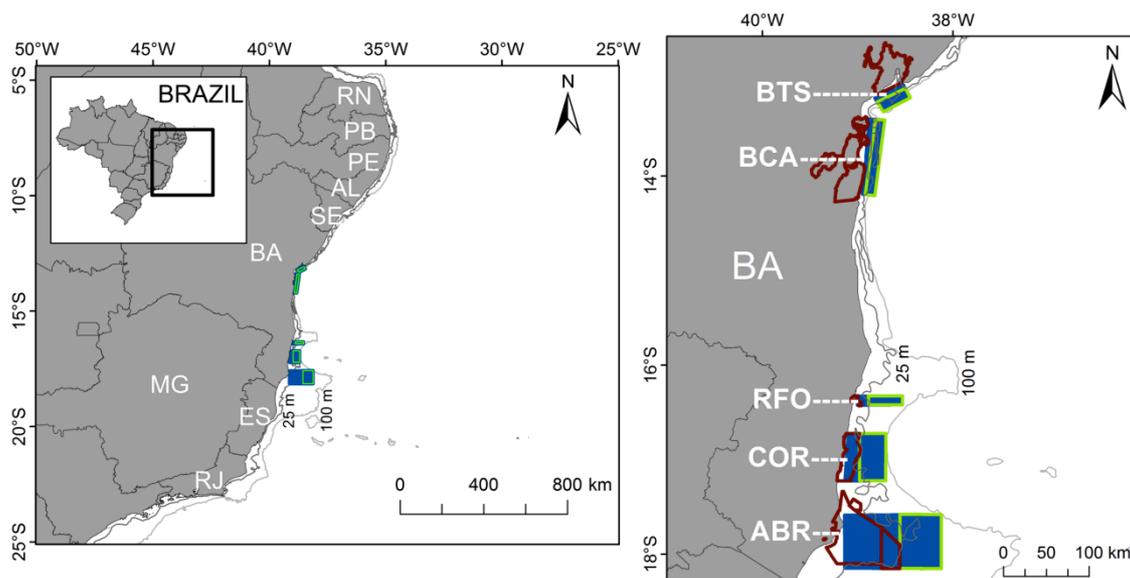


Figure 1. Study area map with the domain of the hydrodynamic model on the left map. The right map shows details of the spawning areas (polygons outlined in light green), recruitment areas (polygons in navy blue), and MPAs shapes (polygons outlined in dark red).

A number of coral reefs are found in the ECS along the State of Bahia (BA) [Leão et al., 2003] and many are protected by MPAs. We have classified these MPAs in five groups according to their location along the coastal region of BA (Figure 1). In the south of BA ( $\sim 18^{\circ}S$ ) is located the Marine National Park (MNP) of Abrolhos and the Area of Environmental Protection (AEP) of Ponta da Baleia, called here the ABR group. Further north ( $\sim 17^{\circ}S$ ) there is the Marine Extractive Reserve (RESEX) of Corumbau, here defined as COR group. Near  $16^{\circ}S$  is located the Municipal Park of Recife de Fora, which we call as RFO group. In the North of BA ( $\sim 14^{\circ}S$ ) are located the AEP of Pratigi, AEP of Tinharé Islands and AEP of Camamu Bay, called the BCA group. Finally at  $13^{\circ}S$  is the EPS of Todos os Santos Bay, called the BTS group. Figure 1 displays the grid area used by the hydrodynamic model ROMS, which includes the ECS and part of southeastern continental shelf. It also shows a map representing the areas of recruitment and spawning defined for the IBM experiments.

### 2.1. Hydrodynamic Model

The Regional Ocean Modeling System (ROMS) model was run for ECS with a grid domain extending from  $5^{\circ}S$  to  $25^{\circ}S$  and from  $25^{\circ}W$  to  $50^{\circ}W$  (Figure 1, left), configured at a horizontal resolution of  $1/24^{\circ}$  (approximately 4.5 km) and vertical discretization of 30 sigma

levels. ROMS is a three-dimensional, free-surface, terrain-following numeric model which solves the Navier-Stokes equations using Reynolds mean, hydrostatic and Boussinesq approximation [Shchepetkin and McWilliams, 2005; Haidvogel et al, 2008]. The model was forced every six hours with long and shortwave radiation fluxes at surface, rain precipitation, sea level pressure, relative humidity, air surface temperature and wind velocity at 10 m. These atmospheric fields were acquired from Climate Forecast System Reanalysis (CFSR) dataset, which has a temporal resolution of six hours [Saha et al., 2010]. Open ocean boundaries and initial conditions were forced with monthly means of sea surface temperature (SST), salinity, current velocities and sea surface height (SSH) obtained from Simple Ocean Data Assimilation (SODA) [Carton and Geise, 2008]. In this model setup it was not implemented tides. Three experiments were run with ROMS: a spin -up, a long-term and an hourly experiment, each one serving a different objective (Table 1). Model performance was evaluated comparing seasonal averages of monthly SST obtained from ROMS with AVHRR/Pathfinder v.5 satellite data [Kilpatrick et al., 2001] for the entire period of the long-term experiment (1982-2007). Model monthly means of sea surface elevation (zeta) were compared with Sea Surface Height (SSH) derived from AVISO altimetry data (product MADT – Monthly Absolute Dynamic Topography) for the 1993 to 2007 period. Sea surface currents (SSC) derived from ROMS for the period between 1993 and 2007, were compared with the Ocean Surface Current Analysis Real-time (OSCAR) product [Bojean and Lagerloef, 2002].

## 2.2. Individual Based Model

The Individual Based Model (IBM) Ichthyop is a free lagrangian tool designed to study the effects of physical and biological factors, such as ocean currents, water temperature and larval behavior, on ichthyoplankton dynamics [Lett et al., 2008]. This IBM was forced by hourly ROMS outputs of ocean current velocities, temperature and salinity. Eggs were released once every month, from April to September, starting at the first day of full moon along six years (from 2002 to 2007), totaling 36 experiments. These eggs were tracked for 45 days, corresponding to their plankton larval duration (PLD). For each experiment, 30,000 eggs were randomly released within a maximum depth of 30 meters, with larger MPAs releasing proportionally more particles than smaller ones. The number of released particles was chosen based on a sensitivity test using simulations varying from 10,000 to 80,000 particles. Recruitment, self-recruitment and mortality were tested and no significant difference were found ( $p > 0.05$ ) when varying the number of particles for any parameter. We have, therefore, decided to release 30,000 particles in all experiments that showed a good larvae dispersal visualization and relative low computational cost. It should be noted that this particle number is not intended to replicate a realistic scenario, but rather offer a simulated representation of potential larval dispersal pathways to evaluate the connectivity between MPAs. Eggs were tracked for two days until hatching and larvae were tracked for 43 days, totaling 45 days for each experiment. Information on the precise location of *Mycteroperca* aggregations in the study area are not available, therefore, the spawning areas (eggs release areas) were delimited offshore the MPAs, within their latitudinal boundaries with depths ranging between 25 and 100 m. Recruitment areas are onshore extensions to the coast of the spawning areas. Particle behavior in the IBM experiments considered: 1) mortality by lethal temperature; 2) advection and diffusive horizontal movements; 3) vertical movement of eggs due to buoyancy; and 4) vertical movement behavior of larvae. Mortality was considered when larvae was advected to waters with temperature outside the temperature range of larval development, established between 20°C and 30°C [Gracia-López et al, 2004].

Table 1. Experiments performed with ROMS.

Experiment Name	Interval	Output	Utility
Spin-up	1980 – 1981	Montly	Equilibrium of ROMS numerical solutions
Long-term Experiment	1982 – 2007	Montly	Performance analyze of ROMS model outputs
Hourly Experiment	2002 – 2007	Hourly	Physical forcing for IBM Ichthyop experiment

Recruitment is calculated as the sum of larvae transported from elsewhere, divided by sum of surviving larvae (Equation 3). In results these quantities are expressed in the text and graphics as percentages for ease of understanding.

$$Mort\_tempt=d(c-adv) \quad (1)$$

$$SelfRec_{i,i}=c_{ii}(c_i-adv_i-d_i) \quad (2)$$

$$Rec_{i,i}=c_{ij}(c_j-adv_j-d_j) \quad (3)$$

where:

Mort\_tempt: mortality by temperature;

d: individuals advected to areas with lethal temperatures (< 20°C or > 30°C);

c: individuals in the model domain at the end of the experiment;

adv: individuals advected outside the model domain at the end of the experiment;

Rec: recruitment percentage;

Self-Rec: self-recruitment percentage;

$c_{ii}$ : individual originated from MPA “i” recruited to MPA “i”;

$c_{ij}$ : individual originated from MPA “i” recruited to MPA “j”.

After testing data normality with a Mann-Whitney test ( $p < 0.5$ ), a nonparametric variance analysis (Kruskal-Wallis ANOVA) was performed (significance level of 5%) to test differences in recruitment and self-recruitment between spawning months, years and release area (MPAs). A Transition Probability Matrix (TPM) was calculated considering larvae originated from MPA “i” which was recruited to MPA “j”, divided by total survival individuals. As proposed by Andrello et al. [2013], we calculated the “connectance”, given by the number of nonzero connections of the TPM divided by the square size of TPM, representing the relative degree of connectivity between MPAs. In order to analyze the influence of the physical environment on larval dispersal, the total Kinetic Energy (KE) per unit mass was correlated with self-recruitment, recruitment and total larval trajectories. The total trajectories are computed from the total distance traveled by larvae by the end of each 45 days experiment. KE is calculated using equation 4 that takes into account the zonal and meridional surface currents, and corresponds to the sum of the turbulent and mean components of the kinetic energy. In this work KE was derived from monthly ROMS surface current outputs corresponding to the period and location of larval dispersion.

$$KE.m^{-1}=1/2*(u^2+v^2) \quad (4)$$

where:

KE: total kinetic energy per unit mass ( $m^2.s^{-2}$ );  
 u: zonal component of current velocity ( $m.s^{-2}$ );  
 v: meridional component of current velocity ( $m.s^{-2}$ ).

### 3. Results and discussion

Larval mortality by temperature presented significant differences between months (April to September,  $p=0.0014$ ), due to lower temperatures (under  $20^{\circ}C$ ) in winter months of August and September. However, between years (2000-2007) mortality by temperature did not differ significantly. Self-recruitment and recruitment did not present significant differences between months ( $p=0.4489$  and  $p=0.4606$ , respectively), nevertheless, recruitment and self-recruitment tend to be higher from April to July when compared to the August-September period (Figure 2). Interannual self-recruitment variability is not significant ( $p=0,546$ ), but recruitment presents significant difference ( $p=0.0072$ ) between years. It is evident that recruitment was lower in 2002, 2004 and 2005 and higher in 2003, 2006 and 2007 (Figure 2). Extreme years illustrate these differences with lower values for 2002 around 1.48% of self-recruitment and 1.9% of recruitment, and higher values in 2007 with 10.69% of self-recruitment and 12% of recruitment. Self-recruitment, recruitment and recruitment contribution from each MPA presented significant differences between MPAs ( $p=1.88e-19$ ,  $p=0.0124$ ,  $p=1.79e-13$ , respectively). A comparison of self-recruitment, recruitment between MPAs, and also the recruitment contribution of each MPA was performed. It was possible to verify which MPAs are more dependent on the input of individuals from other MPAs and which serves as source of individuals. The MPAs with similar self-recruitment and recruitment contribution percentages are BTS, BCA and RFO, indicating that population maintenance in these MPAs have less dependency of individuals from other areas. The BCA and especially RFO present a greater contribution to recruitment than their self-recruitment, acting predominantly as source areas. Self-recruitment in COR is slightly lower than recruitment, showing some dependence of individuals from other areas. In addition, it is the largest source of individuals to other MPAs, thus representing both, an important sink and source of individuals. Overall, the ABR shows the higher differences between recruitment (high), self-recruitment (low), and recruitment contribution (very low), behaving predominantly as a sink area.

Our results indicate that higher percentages of recruitment generally occur between April and July, and are lower in August and September. This pattern can be illustrated using the months of May and September of 2007, which presented the extremes of self-recruitment and recruitment percentages. In Figure 3, it is possible to see that higher KE in September 2007 is coincident with the month of the lowest percentage of self-recruitment (0.6%) and recruitment (1.1%). On the other hand, May is the month with the lowest KE and is coincident with the higher percentage of self-recruitment (47.15%) and recruitment (15.3%) (Figure 3). Looking at the interannual variability, the years with lower KE presents higher values of self-recruitment and recruitment, as shown in Table 3. These results suggest that lower KE contributes for increased retention of larvae on the continental shelf, where they are recruited.

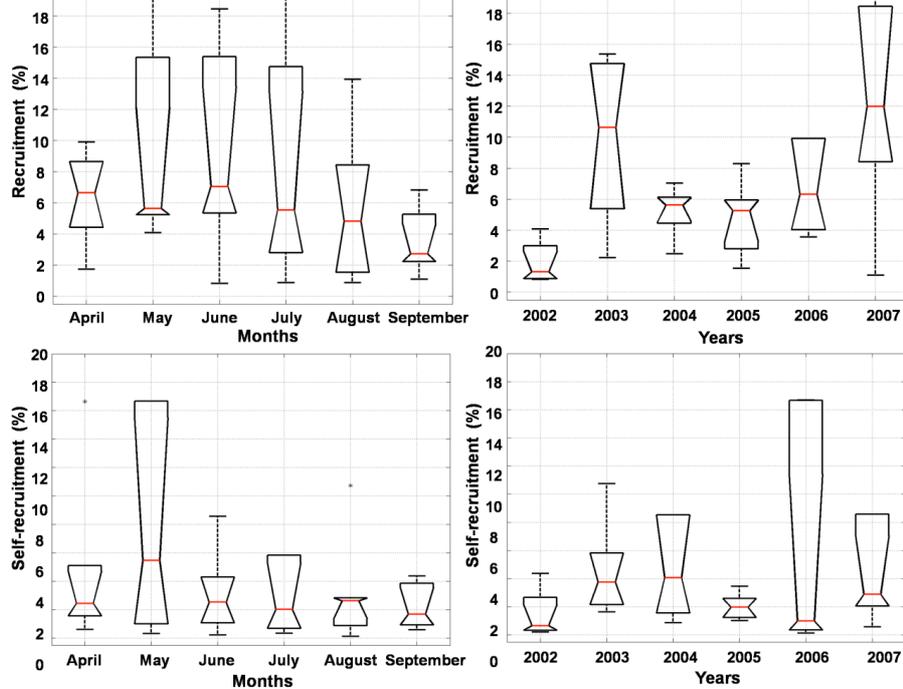


Figure 2. Median and quartiles of intrannual (left) and interannual (right) variability for self-recruitment (above) and recruitment (below) of *Mycteroperca* sp..

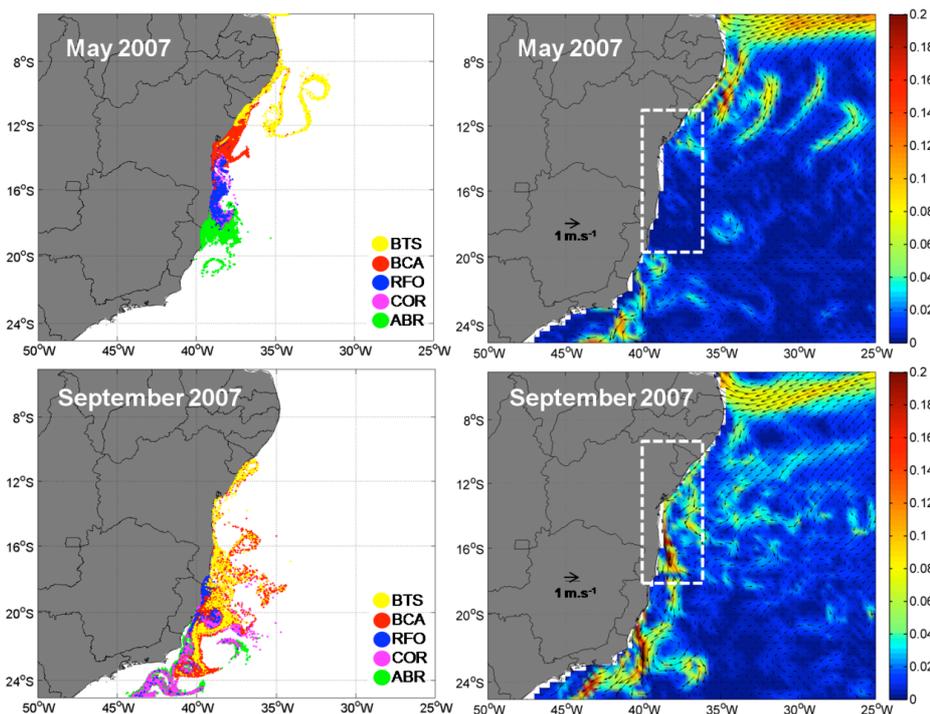
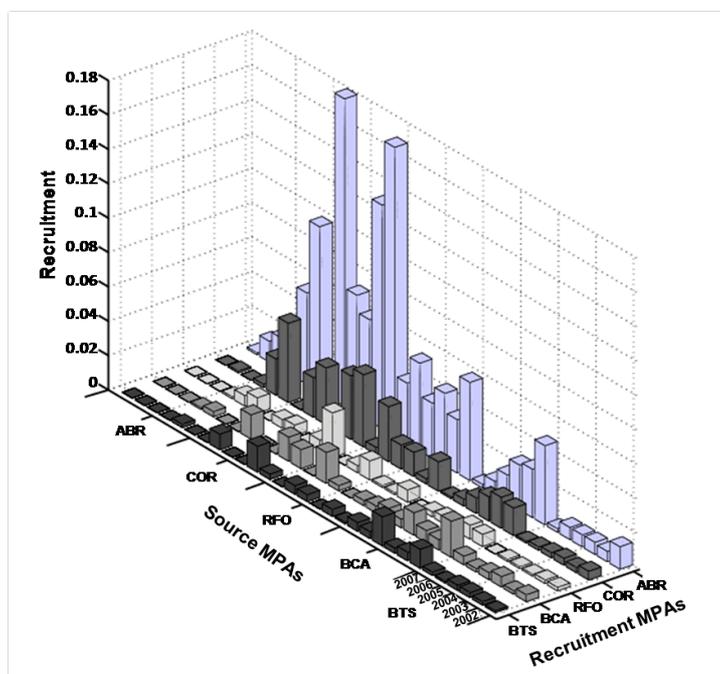


Figure 3. Larval dispersal (left), KE (m<sup>2</sup>.s<sup>-2</sup>, right) and surface current vectors for May (top) and September (bottom) of 2007. The dashed areas highlight the region where the spawning and recruitment areas are located.

The Transition Probability Matrix (TPM) indicates that migration of individuals from one MPA to another (or connectivity), occurs preferentially from north to south, with ABR being the largest sink area of larvae (Figure 4). The TPM standard representation is not suitable for small matrices (5 x 5) and for this reason, we summarized this information in a 3D graph with source nodes and years in x-axis (“Source MPAs”), the sink nodes in y-axis (“Recruitment

MPAs”), and the probability of recruitment in z-axis. ABR receives individuals from all other MPAs especially from the southern RFO and COR, but its contribution to other MPAs is low. COR is the second largest sink area, and a major source area that provides individuals to other MPAs. Connectivity of the other three MPAs (BTS, BCA and RFO) fluctuates yearly with lower transition probabilities. Thus, population maintenance of southern MPAs, mainly ABR, may exhibit high dependency from individuals originated in other MPAs.



#### 4. Conclusions

The present work aimed to understanding the connectivity among MPAs at the ECS of Brazil and its relation with KE through biophysical modeling. This is a pioneer work which enables a better understanding the role of coral reef MPAs and the physical conditions of the environment in the larval dispersal of the genus *Mycteroperca*. The connectivity is high and occurs preferably from north to south, due to circulation patterns and their variability. When KE is higher, larvae are advected out of continental shelf, thus decreasing recruitment and consequently the connectivity among MPAs.

#### 5. Literature cited

- Andrello, M. et al. Low Connectivity between Mediterranean Marine Protected Areas: A Biophysical Modeling Approach for the Dusky Grouper *Epinephelus marginatus*. **PLoS ONE**. 8 (7), 1-15, 2013.
- Bonjean, F., and G. S. E. Lagerloef. Diagnostic model and analysis of the surface currents in the tropical Pacific ocean. **Journal Physical Oceanography**. 32, 1-27, 2002.
- Carton, J.A., and B.S. Giese. A Reanalysis of Ocean Climate Using Simple Ocean Data Assimilation (SODA). **Monthly Weather Review**. 136, 2999-3017, 2008.
- Cowen, R. K., C. B. Paris, and A. Srinivasan. Scaling of Connectivity in Marine Populations. **Science**, Vol. 311, p. 522-527, 2006.
- Craig, M. T., J. A. Eble, B. W. Bowen, and D. R. Robertson. High genetic connectivity across the Indian and Pacific Oceans in the reef fish *Myripristis murdani* (Holocentridae). **Marine Ecology Progress Series** 334, 245-254, 2007.
- Di Franco, A. et al. Dispersal Patterns of Coastal Fish: Implications for Designing Networks of Marine Protected Areas. **PLoS ONE**. 7(2), 1-9, 2012.

- Gracia-López, V., M. Kiewek-Martinez, and M. Maldonado-Garcia. Effects of temperature and salinity on artificially reproduced eggs and larvae of the leopard grouper *Mycteroperca rosacea*. **Aquaculture**. 237, 485–498, 2004.
- Grimm, V. Ten years of individual-based modelling in ecology: what have we learned and what could we learn in the future? **Ecological Modelling** 115, 129–148, 1999.
- Haidvogel, D.B. et al. Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. **Journal of Computational Physics** 227, 3595–3624, 2008.
- Kilpatrick, K. A., G. P. Podesta, and R. Evans. Overview of the NOAA / NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database, **Journal of Geophysical Research**. 106, 9179–9197, 2001.
- Knoppers, B., W. Ekau, and A. G. Figueiredo. The coast and shelf of east and northeast Brazil and material transport. **Geo-Marine Letters** 19(3), 171 – 178, 1999.
- Leão, Z. M. A. N.; Kikuchil, R. K. P.; Testa, V. **Corals and coral reefs of Brazil**, in Latin American Coral Reefs. 1. ed., edited by Cortés, J., p. 9–52, Elsevier, Nova York, 2003.
- Lett, C. et al. A Lagrangian tool for modelling ichthyoplankton dynamics. **Environmental Modelling & Software**. 23, 1210–1214, 2008.
- Miller, T. J. Contribution of individual-based coupled physical–biological models to understanding recruitment in marine fish populations. **Marine Ecology Progress Series**. 347, 127–138, 2007.
- Paris, C. B., L. N. Chérubin, and R. K. Cowen. Surfing, spinning, or diving from reef to reef: effects on population connectivity. **Marine Ecology Progress Series**. 347, 285–300, 2007.
- Planes, S., G. P. Jones, and S. R. Thorrold. Larval dispersal connects fish populations in a network of marine protected areas. **Proceedings of the National Academy of Sciences of the United States of America**. 106(14), 5693–5697, 2009.
- Robins, P. E., S. P. Neill, L. Gimenez, S. R. Jenkins, and S. K. Malham. Physical and biological controls on larval dispersal and connectivity in a highly energetic shelf sea. **Limnology and Oceanography**. 58(2), 505–524, 2013.
- Ruiz, J. et al. Recruitment at the Edge: Kinetic Energy Inhibits Anchovy Populations in the Western Mediterranean. **PLoS ONE**. 8(2), 1–9, 2012.
- Saha, S. et al. (), The NCEP climate forecast system reanalysis. **Bulletin of the American Meteorological Society**. 9, 1015–1057, 2010.
- Shchepetkin, A. F., and J. C. McWilliams. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. **Ocean Modelling**. 9, 347–404, 2005.
- Soutelino, R. G., A. Gangopadhyay, and I. C. A. Silveira. The roles of vertical shear and topography on the eddy formation near the site of origin of the Brazil Current. **Continental Shelf Research**. 70, 46–70, 2013.
- Thorrold, S. R. et al. Quantifying larval retention and connectivity in marine populations with artificial and natural markers. **Bulletin of Marine Science**. 70(1), 291–308, 2002.
- Villwock, J. A. A costa brasileira: **Geologia e evolução**. Notas Técnicas. Porto Alegre, 7, 38–49, 1994.