Anais XIII Simpósio Brasileiro de Sensoriamento Remoto, Florianópolis, Brasil, 21-26 abril 2007, INPE, p. 4595-4602.

Modeling spiny lobster larval dispersion in the tropical Atlantic using satellite data.

Camila Aguirre Góes[1]
João Antônio Lorenzzetti[1]
Douglas F. Marcolino Gherardi[1]
Jorge Eduardo Lins Oliveira[2]

[1] Instituto Nacional de Pesquisas Espaciais - INPE
Caixa Postal 515 - 12245-970 - São José dos Campos - SP, Brasil
{camila, loren, douglas}@dsr.inpe.br

[2] Universidade Federal do Rio Grande do Norte - UFRN/DOL
Av. Praia de Mãe Luíza s/n; Via Costeira, Cep: 59.014-100 - Natal - RN, Brasil
jorgelins@ufrnet.br

Abstract. Spiny lobsters (Palinuridae) have a relatively long planktonic larval phase lasting around one year. Therefore, the mean ocean currents are expected to have a potential for transporting lobster larvae over long distances away from the original spawning areas. We have investigated larval dispersion across tropical Atlantic (20ºN-15ºS; 15ºE-45ºW), using an advection-diffusion model in an attempt to determine the connectivity among different adult stocks. The model updates the position of each larva everyday, along 365 days using the surface geostrophic velocity fields derived from altimeter satellite. Results of simulations indicate that the larval stocks from the African coast do not spread far from the spawning areas. Simulations also indicate that the Brazilian adult stocks could be maintained with larvae released from oceanic islands such as São Pedro and São Paulo Archipelago, Atol das Rocas and Fernando de Noronha. Finally, it is possible that middle South-Atlantic islands (i. e. Ascension Island), could act as stepping-stones between the African and the South-American spiny lobster stocks.

Key-words: Larvae dispersion, altimeter satellite, Palinuridae, *phyllosoma*, advection-diffusion model.

1. Introduction

Three species of spiny lobsters (*Panulirus echinatus*, *P. laevicauda* and *P. argus*) are harvested along the Brazilian coast, representing an annual revenue amount of 50 to 60 million US dollars. These three species have a relatively long-lived planktonic larval phase of about 12 months. *Phyllosomas* are transparent leaf-like plankters whose body shapes appear well suited for drifting with the ocean currents and are generally regarded as having little or no active direct horizontal swimming ability. Therefore, the mean ocean currents are expected to represent an important role to transport larvae over long distances away from the original spawning areas. This raises the question on how any of these adult lobsters' populations can be maintained in regions where the mean flow should advect larvae away from the coast. Some previous studies have been made about spiny lobster larvae dispersion especially on Australian coast (Chiswell and Booth, 1999; Griffin *et al.*, 2001; Chiswell, *et al.*, 2003) and Hawaiian Archipelago (Polovina *et al.*, 1999) using hydrodynamic models and satellite altimeter data. For the Atlantic, it has been suggested that African stocks might act as a source of spiny lobster larvae for the Brazilian adult stocks (Freire, 2000; Góes, *et al.* 2005; Góes, 2006). In that way *phyllosomas* must drift across the whole tropical Atlantic before metamorphosing near Brazilian coast.

The main purpose of this work is to investigate the possibility that Brazilian stocks of lobster could be supplied by larvae derived from remote populations, located as far as the African coast or middle Atlantic Islands. In addition, we want to investigate the fate of larvae spawned in the Brazilian coast (continental shelf and oceanic Brazilian islands) and to determine the larvae dispersion pathways.

In the present study we report the results of larval transport model simulations, where a number of virtual individuals were released from different areas for which adult lobster populations are known to occur. Simulations were supported by satellite altimeter, plankton samples and drifting buoy data in an attempt to identify possible transatlantic larval pathways.

1.1 Tropical Atlantic superficial ocean currents

The study region is the tropical Atlantic from 20ºN to 15ºS, and from 15ºE to 45ºW and the spawning areas chosen were places of registered occurrence of adult populations (**Figure 1**). For a recent review of the tropical Atlantic superficial circulation see Lumpkin and Garzoli (2005). Their surface circulation maps were derived from a recent set of drifting buoy observations. The tropical Atlantic surface circulation consists primarily of an equatorial gyre formed by the North Equatorial Contercurrent (NECC), Guinea Current and the three branches of the South Equatorial Current (SEC), which form or join the North Brazil Current (NBC). The SEC flows westward towards the Brazilian Coast where it bifurcates into the cross-equatorial NBC to the north and the Brazil Current to the south. NBC retroflects eastward into the Equatorial Undercurrent, and the remainder of the NBC continues northwestward until it retroflects at approximately 7ºN; 48ºW (Peterson and Stramma, 1991; Lumpkin and Garzoli, 2005).

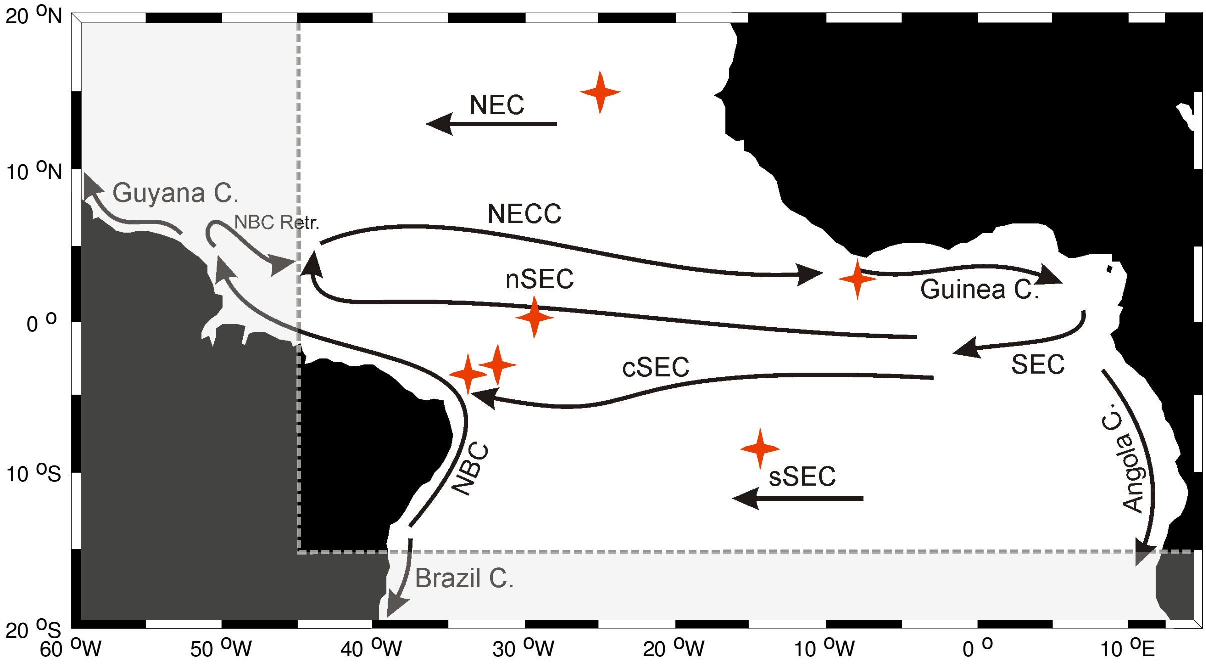

Figure 1. Tropical Atlantic and study area (dashed rectangle). Main superficial ocean currents are indicated by arrows, including the North Equatorial Current NEC, North Equatorial Contercurrent NECC, northern, central and southern branches of the South Equatorial Current SEC, Brazil Current, Angola Current, Guinea Current, Guyana Current, North Brazil Current NBC and its retroflection (NBC Retr.) (adapted from Lumpkin and Garzoli, 2005). Red stars indicate the released areas used to start the simulations: Cape Verde (24-25ºW, 15-16ºN); Ivory Coast (7-8ºW, 3-4ºN); Ascension (14-15ºW, 7-8ºS); São Pedro and São Paulo Archipelago (28-29ºW, 0-1ºN), Atol das Rocas (33-34ºW, 3-4ºS) and Fernando de Noronha (31-32ºW, 3-4ºS).

2. Material and Methods

2.1 In situ data

We used plankton samples collected with a bongo net (300 and 500 µm) dragged oblique from 200m depth, at selected oceanographic stations, on board of NOc. Antares within the Brazilian Northeast Exclusive Economic Zone (EEZ). All larvae were identified to the species level and development stage, indicating the time spent in the plankton. Samples showed a predominance of larvae in the advanced stages of development (VIII, IX, XI), corresponding to 8, 9 e 11 months of planktonic life.

2.2 Advection-Difusion Model

Our simulations start with the release of 5000 virtual larvae and each one was tracked for a series of time steps corresponding to one year by iteratively applying successive advective displacements due to water flow with additional random displacements associated to diffusion. Starting at a chosen x_t and y_t initial position, the location of each pseudo larvae after a time interval Δt, $x_{t+\Delta t}$, $y_{t+\Delta t}$,was updated at each time by the equations (Polovina *et al.*, 1999):

$$x_{t+\Delta t} = x_t + \frac{[u_{(xt,yt,t)}\Delta t + \varepsilon\sqrt{kx\Delta t}]}{\cos(y_t)}$$

$$y_{t+\Delta t} = y_t + [v_{(xt,yt,t)}\Delta t + \varepsilon\sqrt{ky\Delta t}]$$

where:

t = time (day);
x e y = position of the larvae (degrees of latitude and longitude)
u e v = zonal and meridional geostrophic velocities components (degree/day)
ε = normal distributed random variable (zero mean, unit standard deviation)
kx = zonal eddy-diffusion coefficient (degree^2/day)
ky = meridional eddy-diffusion coefficient (degree^2/day)

The first and second terms inside the brackets correspond to the advective and the diffusive displacements, respectively. The cosine function in the longitudinal displacement equation corrects for the convergence of meridians with latitude.

At any pseudo larvae position, the corresponding u and v geostrophic velocities used in the model were obtained by linear interpolation of the closest four velocities grid elements. No time interpolation was done during the seven day period of each week.

The time step was set to one day (Δt=1) with 365 iterations for one year of simulation for each virtual larvae. The simulations did not incorporate any biological parameter such as mortality, predation or vertical migration.

2.3 Geostrophic component

The geostrophic surface current velocity data used to force the advection-diffusion model were produced from satellite altimeters data provided by SSALTO/DUACS and distributed by AVISO (http://www.aviso.oceanobs.com/) with CNES support. This database is a result of merged observations of TOPEX/Poseidon, Jason and ERS altimeters to achieve improved spatial and temporal resolutions of 1/3 degree and 7 days in a global coverage.

Poleward of 5ºN and 5ºS the zonal and meridional geostrophic velocity components (u, v) are calculated, respectively, from the meridional and zonal slopes of the dynamic height

($u = -\frac{g}{f}\frac{\partial \zeta}{\partial y}$; $v = \frac{g}{f}\frac{\partial \zeta}{\partial x}$) derived from the Sea Level Anomalies (SLA). In the ±5° equatorial band, where geostrophy is subject to singularity, velocities are calculated using the second derivatives of ζ according to Picaut (1989) and Lagerloef, *et al.* (1999). The Absolute Dynamic Topography used in the calculations of u and v are obtained by adding SLA to the Mean Dynamic Topography (MDT), which is obtained from the Mean Surface Height (MSH) subtracted from the standard geoid.

Since our interest is in the effect of the mean geostrophic currents upon the larvae transport, we calculated the mean weekly geostrophic currents were calculated from the period 2000 to 2003, resulting in 52 data matrices of mean zonal and meridional currents.

The geostrophic currents were compared to *in situ* observations derived from surface drifters, provided by the Global Drifter Program/Surface Velocities – GDP/SVP of NOAA, available for download at the Marine Environmental Data Service (http://www.meds-sdmm.dfo-mpo.gc.ca/). We compared 73 randomly selected values of geostrophic and drifter-buoy velocities for the same space and time interval. Agreement between both data sets, measured by the linear correlation coefficient, is very high ($r = 0.93$) for zonal velocity (u) and reasonable ($r = 0.63$) for meridional velocity (v).

2.4 Eddy-Difusion coefficient

As indicated in the previous section the diffusive part of the model depends on the values of *kx* and *ky*, the zonal and meridional eddy diffusion coefficients. Having a large data set of drifter trajectories available for this region (http://www.meds-sdmm.dfo-mpo.gc.ca/), we estimated these coefficients using the methodology described by Assireu (2003), which is a variant from that proposed previously by Taylor (1921).

We estimated the eddy-diffusion coefficients for 35 sub-areas to assess their spatial variability in the region. In the model, we used the average of this sub-areas, obtaining a zonal eddy-diffusion (*kx*) of $3{,}97 \times 10^7$cm²/s and a meridional eddy-diffusion (*ky*) of $2{,}05 \times 10^7$cm²/s.

3. Results and Discussion

Simulations showed marked differences in larval dispersion patterns depending on the location of the source area, and the mean geostrophic flow. We have observed that cohorts can be retained in the release area by eddies for the whole period larval development. In contrast, other simulations showed that larvae can be dispersed over long distances by the superficial ocean currents.

3.1 Cape Verde

The simulations of larvae spawned at Cape Verde showed that after 365 days the local surface circulation tends to retain larvae near from the spawning area, thus larvae seem to be able to recompose and supply their own adult stocks. The local circulation does not allow the westward transport of larvae across the Atlantic, retaining all virtual larvae at the eastern side of the basin. A similar phenomenon is described by Chiswell and Booth (1999), at the northeast of the Tasman Sea, where they found that *phyllosomas* of *Jasus edwardsii* are retained by permanent eddies during the whole development time until the postlarval stage (*puerulus*). At this late life stage the postlarva is able to swim actively back to the coast and recruit the adult stocks. It is common to assume that larvae behave as passive drifters with respect to horizontal transport, however, Chiswell and Booth (1999) suggest that latter development stages of *Jasus edwardsii* larvae and postlarvae may exhibit directed swimming towards coast.

3.2 Ivory Coast

Larvae released near the Ivory Coast were transported eastward by the Guinea Current and reached the coast before the 365 days. This implies that larvae should anticipate the metamorphosis when they find a suitable condition for the settlement.
According to our simulations it is very unlikely that the African and Brazilian stocks could communicate, once larvae spawned near African coast are retained at the eastern side of Atlantic Ocean. It does not however, exclude the possibility of a sporadic larval fluxes connecting adult populations from both sides of Atlantic. It has to be considered that our experiments were done using a four years mean circulation of the area, which excludes anomalies effects.

3.3 Ascension Island

Larvae released from Ascension Island were transported north and westward finding the Brazilian coast at the end of the developing larval period. It should be noted that *Panulirus echinatus* occurs in Ascension and also is found in oceanic banks and islands along Brazilian coast, habiting in less abundance at the Brazilian continental shelf. Particularly in São Pedro and São Paulo archipelago this species is the most abundant decapod (Edwards, A.; Lubbock , 1983b). Plankton samples taken near São Pedro and São Paulo collected 50 *Panulirus echinatus* larvae of which 47 were identified at stage XI of development, corresponding to larvae 11 months old. These larvae should have been brought from distant areas to São Pedro and São Paulo vicinity. This samples represent an evidence of connectivity between those stocks and the simulations reveal the possibility of larvae from Ascension to recompose the Brazilian stocks and suggests that some oceanic islands in the tropical Atlantic could act as stepping-stones for a great variety of fishes and invertebrates, especially those who have a pelagic planktonic larval phase (Rosewater, 1975; Edwards and Lubbock, 1983a; Leite, 2002) (**Figure 2A**).

3.4 São Pedro and São Paulo Archipelago, Atol das Rocas and Fernando de Noronha - Brazilian Islands.

Virtual larvae released from São Pedro and São Paulo Archipelago (**Figure 2B**), Atol das Rocas (**Figure 2C**) and Fernando de Noronha (**Figure 2D**) are driven to the Northeast Brazilian continental shelf. It is possible that these oceanic islands could be the main source of larvae for the Northeastern Brazilian stocks. The Northeast of Brazil is the most productive region of spiny lobster fishery in Brazilian waters because of its wide Continental Shelf dominated by calcareous red algae offering an ideal habitat for the development of adult populations (Fonteles-Filho, 2005), however, the abundance of larvae near places where adult population occurs does not guarantee a good recruitment (Palmer *et al.*, 1996) and others factors such as habitat availability and predators should be also considered (Polovina *et al.* 1999).

We start the simulations of each area at two different times (April and September), according to the spawning season. These allow us to observe the influence of the seasonality affecting the larval dispersion and showed some influence on the development stage of the larvae. As example we can quote the April spawning from Brazilian Islands, where all the larva found the frontier with 10 months of development, having at least 2 months remained to be transported northward.

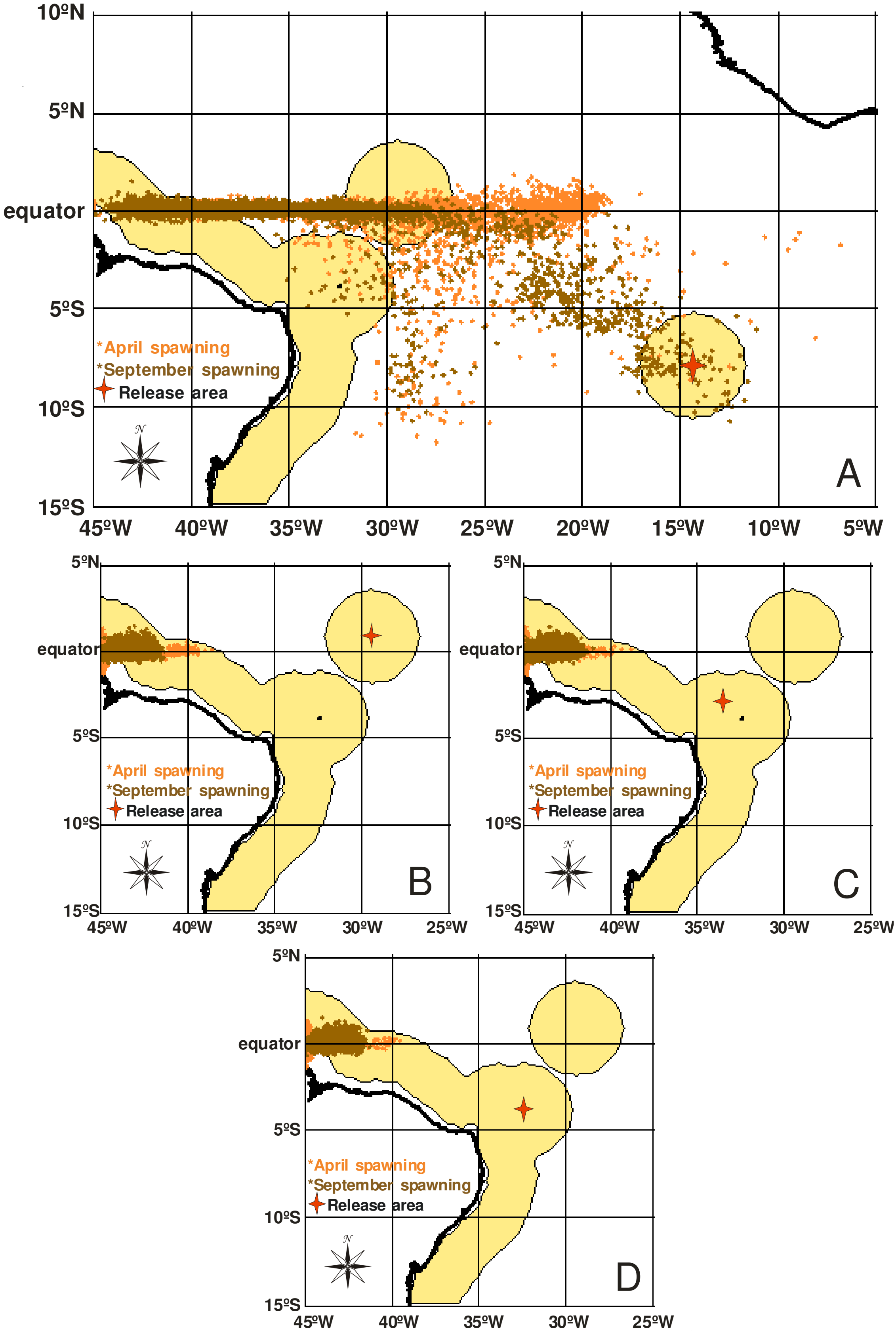

Figure 2: Transport endpoints of 5000 virtual larvae spawned from the release area (✦): A- Ascension Island; B- São Pedro and São Paulo Archipelago; C- Atol das Rocas; D – Fernando de Noronha, using the advection-diffusion model. Yellow part represents the considered feasible area.

4. Conclusions

The simulations presented here clearly indicate that geostrophic circulation of the tropical Atlantic associated to the time necessary for a full larval development do not support a transatlantic larval flux. We contend that Ascension Island may act as a stepping-stone in the connection of lobster populations between Africa and America. This island could maintain the amphi-atlantic connection of larval flow across the basin.

In addition, we verified that the Brazilian Islands (São Pedro and São Paulo Archipelago, Atol das Rocas and Fernando de Noronha) are a likely larval source to recruit the stocks along North and Northeast Brazilian coast. Future works should consider local and mesoscale mechanisms assisting the recruitment for that region.

This is the first attempt to identify the possible pathways of spiny lobster larval dispersion across the Atlantic, integrating lobster biology and ocean dynamics. These results can be used as an aid for the development of adequate policies for a sustainable lobster fishery.

References

Assireu, A. T. **Estudo das características cinemáticas e dinâmicas das águas de superfície do Atlântico Sul Ocidental a partir de derivadores rastreados por satélite**. 2003. 174 p. Tese (Doutorado em Ciências – Oceanografia Física) - Instituto Oceanográfico da Universidade de São Paulo, São Paulo. 2003. Disponível em http://www.ltid.inpe.br/dsr/grupos/hidrosfera/arquivos/arcilan.pdf. Acesso em: 10 abr. 2006.

Chiswell, S. M.; Booth, J. D. Rock lobster *Jasus edwardsii* larval retention by the Wairarapa Eddy off New Zealand. **Marine Ecology Progress Series**, v. 183, p. 227–240, 1999.

Chiswell, S. M.; Wilkin, J.; Booth, J. D.; Stanton, B. Trans-Tasman Sea larval transport: Is Australia a source for New Zealand rock lobster? **Marine Ecology Progress Series**, v. 247, p. 173-182, 2003.

Edwards, A.; Lubbock, R. Marine zoogeography of Saint Paul's Rocks. **Journal of Biogeography**, v. 10, p. 65-72, 1983 (a).

Edwards, A.; Lubbock, R. The ecology of Saint Paul´s Rocks (Equatorial Atlantic). **Journal of Zoology**, v. 200, p. 51-69, 1983 (b).

Fonteles-Filho, A. A. **Síntese sobre distribuição, abundância, potencial pesqueiro e biologia lagosta-vermelha *Panulirus argus* (Latreille) e a lagosta-verde *Panulirus laevicauda* (Latreille) do Nordeste do Brasil**. Relatório de Avaliação do Potencial Sustentável de Recursos Vivos na Zona Econômica Exclusiva MMA – REVIZEE Análise/Refinamento dos Dados Pretéritos Sobre Prospecção Pesqueira. 2005. Disponível em: <http://www.mma.gov.br/port/sqa/projeto/revizee/textos.html>. Acesso em: 10 abril 2006.

Freire, F. A. M. **Dinâmica da interdependência dos estoques de lagostas do Oceano Atlântico Sul**. 2000. 54 p. Monografia (Bacharelado em Ciências Biológicas) - Universidade Federal do Rio Grande do Norte, Natal. 2000.

Góes, C. A.; Lorenzzetti, J. A.; Gherardi, D. F. M.; Lins Oliveira, J. E. Correntes superficiais no Atlântico tropical, obtidas por dados orbitais, e sua influência na dispersão de larvas de lagostas. In: Seminário sobre ondas, marés, engenharia oceânica e oceanografia por satélite (OMAR-SAT), 6., 2005, Arraial do Cabo, Rio de Janeiro. **Anais**... Arraial do Cabo: IEAPM, 2005.

Góes, C. A. **Análise da dispersão de larvas de lagostas no Atlântico Tropical a partir de correntes geostróficas superficiais derivadas por satélites**. 2006. 94p. Dissertação (Mestrado em Sensoriamento Remoto) – Instituto Nacional de Pesquisas Espaciais, São José dos Campos. 2006.

Griffin, D. A.; Wilkin, J. L.; Chubb, C. F.; Pearce, A. F.; Caputi, N. Ocean currents and the larval phase of Australian western rock lobster, *Panulirus Cygnus*. **Marine and Freshwater Research**. v. 52, p. 1187-1199, 2001.

Lagerloef, G. S. E.; Mitchum, G. T.; Lukas, R. B.; Niller, P. P. Tropical Pacific near surface currents estimated from altimeter, wind and drifter data. **Journal of Geophysical Research**, v. 104. n. C10. p. 23,313-23,326, 1999.

Leite, T. S. **Caracterização da fauna de polvos (Cephalopoda: Ordem Octopodidae) de águas rasas do litoral do Rio Grande do Norte e ilhas oceânicas do NE**. 2002. 72 p. Dissertação (Mestrado em Oceanografia Biológica) - Fundação Universidade Federal do Rio Grande, Rio Grande do Sul. 2002. Disponível em: http://www.noronha.pe.gov.br/downloads/tese-tatiana1.pdf>. Acesso em: 10 abril 2006.

Lipcius, R. N.; Stockhausen, W. T.; Eggleston, D. B.; Marshall, Jr. L. S.; Hickey, B. Hydrodynamic decoupling of recruitment, habitat quality and adult abundance in the Caribbean spiny lobster: source-sink dynamics? **Marine Freshwater Research**, v. 48, p. 807-815, 1997.

Lumpkin, R; Garzoli, S. L. Near-surface circulation in the tropical Atlantic Ocean. **Deep-Sea Research I**, v. 52, p. 495–518, 2005.

Palmer, M. A.; David, A.; Butman, C. A. Dispersal as region process affecting the local dynamics of marine and stream benthic invertebrates. **TREE**, v.11, n. 8, p. 322-326, 1996.

Peterson, R.G., Stramma, L. Upper-level circulation in the South Atlantic Ocean. **Progress in Oceanography**, v. 26, p. 1–73, 1991.

Picaut, J. Use of the Geostrophic approximation to estimate time-varying zonal currents at the Equator. **Journal of Geophysical Research**, v. 94, n. C3, p. 3228-3236, 1989.

Polovina, J.; Kleiber, P.; Kobayashi, D. R. Application of TOPEX/POSEIDON satellite altimetry to simulate transport dynamics of larvae of spiny lobster, *Panulirus marginatus*, in the Northwestern Hawaiian Islands, 1993–1996. **Fishery Bulletin**, v. 97, p. 132–143, 1999. Disponível em: <http://fishbull.noaa.gov/13polovi.pdf>. Acesso em: 10 abril 2006.

Rosewater, J. An annotated list of marine mollusks of Ascension Island, South Atlantic Ocean. **Smithosonian Contrib. Zool**., n. 189, p. 41, 1975.

Taylor, G. I., 1921. Diffusion by continuous movements, **Proc. London Math. Soc. Ser**. A, 20, 196-211.