A LAGRANGIAN ANALYSIS ON COASTAL DISPERSAL OF CORAL LARVAE AND SPAWN AROUND OKINAWA ISLAND, JAPAN

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ABSTRACT: A JCOPE2-ROMS downscaling oceanic circulation model in a triple nested configuration coupled with a 3-D Lagrangian particle tracking model was developed for quantifying coastal connectivity of coral larvae and spawn originated from nearshore areas around Okinawa Island, Japan, located in the East China Sea. Coastal dispersal of neutrally buoyant Lagrangian particles was extensively examined as a proxy of corals. A Lagrangian analysis of ~24.3 millions of particles revealed that the along-island residual currents are responsible for the prevailing clockwise coral transport consisting of the northeastward residual current on the west coast and the opposing currents on the east coast. Semi-enclosed coastline topography locally induces residual stagnating circulations, resulting in notable particle entrainment. In particular, Kin and Nakagusuku bays on the east coast and Cape Hedo at the northernmost tip of the island serve as nodes, where intensive particles accumulation provokes. Therefore, the along-island residual currents and topographic constraint jointly affect the local, short-distance coral connectivity around the island.

INTRODUCTION

Both self-recruitment and remote transport are essential factors to maintain abundant coral ecosystems in tropical and subtropical marine environments. Coastal connectivity has widely been exploited to assess biological linkages of species of interest across certain areas, to deduce geometrical pathways of aquatic fauna, and to determine marine protected areas (MPAs) for preservation of desirable ecosystems. In general, connectivity has been evaluated based on population genetics, in which genetic similarity among individual corals sampled at different locations are carefully diagnosed. In contrast, dispersal of Lagrangian particles transported by 3-D velocity evaluated by circulation models imparts an alternative measure of pelagic coral transport that enables us to statistically quantify connectivity.

The Nansei Archipelago, Japan, has unique marine environment for abundant corals because of the Kuroshio that plays a crucial role in carrying warm water from lower latitude to maintain favorable temperature for corals inhabited in a meridionally stretched chain of the islands fringing the East China Sea (**Fig. 1a**). Uchiyama *et al.* (2018) [1] revealed from a detailed numerical experiment that the northeastward drifting Kuroshio is also responsible for long-distance transport of coral larvae and spawns by \sim 1,000 km during a three-week pelagic stage immediately after they spawn, when they are transported passively by ambient currents. Nevertheless, the short-distance connectivity is found to be much higher than the remote interisland connectivity due to long-distance larval transport. Such high connectivity within an island or a regional archipelago has substantial importance to regional and local biological linkages of corals as well as other marine fauna and flora. Therefore, very high-resolution



Figure 1 – (a) Left: the triple nested JCOPE2-ROMS model domains bounded by black rectangles representing the outermost ROMS-L1 with a lateral grid resolution of 3 km, the intermediate L2 at 1 km, and the innermost L3 at 250 m. (b) Right: the enlarged ROMS-L3 domain squeezed to encompass Okinawa Island, Japan. The background colors indicate bathymetry in m. Colored circles in (b) are the 133 source and sink patches with a 2-km radius defined in the nearshore areas around the island for the Lagrangian particle tracking experiment. A total of 12 areas are further defined by grouping all the 133 patches by topographic features using the same color. Five hundred particles are released once a day from each patch for a period of one year; hence, approximately 24.3 million particles (500 particles \times 133 patches \times 365 times) are analyzed.

circulation modeling is inevitable for investigating effects of complicated nearshore topography such as laterally semi-enclosed embayment, fringing reefs, or steep slopes around reef edges on dynamics and associated dispersal. Nevertheless, such a high-resolution model assessment has never been conducted previously as far as the authors are aware.

In the present study, we conducted a triple nested high-resolution synoptic ocean modeling based on the JCOPE2-ROMS downscaling system (e.g., Uchiyama *et al.*, 2017a [2]; 2017b [3]; 2018 [1]; Kamidaira *et al.*, 2017 [4]) coupled with a 3-D Lagrangian particle-tracking model (e.g., Carr *et al.*, 2008 [5]; Romero *et al.*, 2013 [6]) that enables us to quantify coral connectivity near Okinawa Island (**Fig. 1b**) at a lateral spatial resolution of 250 m with accounting for the realistic mesoscale oceanic condition of the East China Sea including the northward drifting Kuroshio. A comprehensive Lagrangian analysis was then performed to quantify the nearshore connectivity to determine the areas to be preserved (MPAs), based on a massive amount of particles mimicking coral larvae and spawn released from a total of 133 source patches mostly located near reef edge regions around the island (**Fig. 1b**). Our primary focus is on effects of the detailed nearshore topography depicted by the very high-resolution model on coastal, local, short-distance connectivity of coral spawn and larvae.

THE TRIPLE NESTED JCOPE2-ROMS MODEL

We developed a downscaling regional circulation model based on the JCOPE2-ROMS system (e.g., Uchiyama *et al.*, 2017a [2]) in a triple nested configuration embedded in the Japan Coastal Ocean Predictability Experiment version 2 (JCOPE2; Miyazawa *et al.*, 2009 [7]) domain. Trilinear spatiotemporal projection of the parent model solution was carried out

to force embedded child ROMS models through the corresponding open boundary conditions as prescribed in Mason *et al.* 2010 [8], with successively decreasing grid spacing from ~10 km (JCOPE2), to 3 km (ROMS-L1), to 1 km (ROMS-L2; Uchiyama *et al.*, 2018 [1]; Kamidaira *et al.*, 2017 [4]), and further down to 250 m (ROMS-L3). The innermost ROMS-L3 model is our test bed here, which was designed to encompass Okinawa Island with 1280 × 1120 horizontal grid cells and 32 vertically stretched terrain-following and surface-following *s*-layers, covering an approximately 320 km × 280 km lateral area (**Fig. 1**).

Surface wind stresses were imposed from the GPV-MSM operational atmospheric product of Japan Meteorological Agency (JMA) at horizontal resolution of $0.05^{\circ} \times 0.0625^{\circ}$. Net heat, fresh water, and radiation fluxes at the ocean surface were obtained from the NOAA COADS monthly climatology with the flux correction described in Uchiyama *et al.* (2017a) [2]. Ten principal tidal constituents from the TPXO7.0 global tidal reanalysis were imposed on the sea surface elevations along the perimeter of ROMS-L2 model to include barotropic tides and resultant intrinsic baroclinic tides excited in the L2 domain. Therefore, internal and barotropic tides were spontaneously propagated in and out through the perimeter of the L3 model with two-hourly update of the open boundary conditions. We conducted an annual reanalysis for the entire one-year period of 2013 excluding a model spin-up time of several months in prior to the main computation. Extensive model-data comparison was performed to ensure the present L3 model has a good reproducibility against the observations (not shown).

LAGRANGIAN PARTICLE TRACKING MODEL

Coastal connectivity around Okinawa Island was estimated from Lagrangian probability functions (PDFs) of an enormous amount of Lagrangian particles originating from the nearshore sites, where spawn and larvae are released (Fig. 1b). We exploited the offline 3-D Lagrangian particle tracking model developed in Carr et al. (2008) [5] and used previously, e.g., in Mitarai et al. (2009) [9] and Romero et al. (2013) [6] with the ROMS model outputs. In the present study, we did not introduce any *ad hoc* behavior models, such as random walk subgrid-scale diffusivity or diel vertical migration, to avoid further complexity and uncertainty. These factors should be examined in future works. Released particles were tracked for up to 30 days, or until they crossed the boundaries of the L3 model domain, or were beached on land cells. Because coral spawn and larvae are fully passive to the ambient currents for 21 days before they settle down, the following analysis was made for the advection time of no more than 21 days to be consistent with the life cycle of corals. Although the coral spawning occurs in late May, we conducted the release of the particles repeatedly every 24 hours for the entire one year period, in order to extend the present model results for connectivity of other marine flora and fauna. Five hundred particles were released from a total of 133 source patches at the depth of 2 m below the mean surface (Fig. 1b). Hence, the total number of Lagrangian particles released is 500 particles \times 133 patches \times 365 times \approx 24.3 millions.

LAGRANGIAN ANALYSIS

To quantify the dispersal of Lagrangian particles released from source patches, we calculated Lagrangian PDFs following the methodology described in Mitarai *et al.* (2009) [9] from the results of the 3-D particle tracking model. A Lagrangian PDF represents the probability density function of particle displacement for a given elapsed time τ , which is often refereed to as an advection time (T_a). Its discrete representation is:



Figure 2 – Connectivity matrices around Okinawa Island for the advection times T_a of 7, 14, and 21 days. Colors indicate the joint probability C_{ji} defined by Eq. (4). The abscissa shows the grouped source sites (origins) #1–12, while the ordinate is the grouped sink sites (destinations) #1–12 (see Fig. 1b for the grouped patches consisting of each site).

$$f'_{x}(\boldsymbol{\xi};\tau,\boldsymbol{a}) = \frac{1}{N} \sum_{n=1}^{N} \delta(\boldsymbol{X}_{n}(\tau,\boldsymbol{a}) - \boldsymbol{\xi}), \tag{1}$$

where N is the total number of Lagrangian particles, δ is the Dirac delta function, X_n is the position of the *n*th Lagrangian particle, *a* is the initial position of the particle of interest, and ξ is the sample space variable for X. Discrete Lagrangian PDFs are evaluated from the center location of the release sites defined later, averaged over each site. Hence,

$$f'_{x}(\boldsymbol{\xi};\tau,\boldsymbol{a}) \approx \frac{1}{\pi R^{2}} \int_{|\boldsymbol{r}| \leq R} f'_{x}(\boldsymbol{\xi};\tau,\boldsymbol{a}+\boldsymbol{r}) d\boldsymbol{r},$$
(2)

where R is the radius of each release site a. The final form of discrete Lagrangian PDF is obtained after applying an isotropic spatial Gaussian filter G with standard deviation of 3 km:

$$f_{x}(\boldsymbol{\xi};\tau,\boldsymbol{a})\approx\int_{-\infty}^{\infty}G(\boldsymbol{x}-\boldsymbol{\xi})f_{x}'(\boldsymbol{\xi};\tau,\boldsymbol{a})d\boldsymbol{x}.$$
(3)



Figure 3 – An example of temporal evolution of the Lagrangian PDF distributions (colors). This particular example exhibits Lagrangian PDF of the particles released for the one-year period from a total of 11 source patches (black circles) that form site #5 representing the northern half of Nago Bay on the west coast of Okinawa Island, at the labeled advection times T_a (days). The areas with higher (lower) PDFs depicted by warm (cold) colors at the given T_a days after repeating releases correspond to statistically larger (smaller) numbers of the particles positioned there at T_a . Note that although the particle tracking was conducted three-dimensionally, the PDFs are plotted after the vertical summation. This operation implies that vertical displacement of the particles is not explicitly illustrated. In this example, many particles are transported northward along the western shore, then pass the northern tip of the island to further be brought to the eastern shore at $T_a = 7$ days. Later at $T_a = 14$ and 21 days, non-trivial PDFs are observed along the east coast. These sequences demonstrate that nearshore clockwise particle transport is prevailed, whereas the modest southward transport from site #5 manifests that counter-clockwise transport is rather minor.

Coastal connectivity $C_{ji}(\tau)$ is defined as the probability of Lagrangian fluid particles transported from a source site *j* to a sink site *i* over a time interval τ (*viz.*, an advection time).

$$C_{ii}(\tau) = f_x \left(\boldsymbol{\xi} = \boldsymbol{x}_i; \tau, \boldsymbol{a} = \boldsymbol{x}_i \right) (\pi R^2), \tag{4}$$

where x_j and x_i are source and sink patch locations, and the normalization by πR^2 converts the PDFs to probabilities.

CONNECTIVITY AND LAGRANGIAN PDF

Figure 2 represents the L3 model-derived connectivity matrices C_{ji} around Okinawa Island for the advection times T_a of 7, 14, and 21 days. The abscissa and ordinate show the grouped source and sink sites, respectively (see **Fig. 1b** for the definition). For instance, for the particular combination of the abscissa #7 and the ordinate #11, C_{ji} (= $C_{7, 11}$) at $T_a = 14$ days is found to be ~10⁻³, which is interpreted that one coral spawn out of 1000 released from site #7 can be transported to site #11 (*viz.*, the probability of 10⁻³) in 14 days to settle down there. Overall, high connectivity manifests on and around the straight line with a slope of 1:1 (*viz.*, 45°) depicted by reddish colors, exhibiting that these particles mostly remain near the released sites after the given advection time. This is true for the initial stage ($T_a = 7$ days), whereas the particles are diluted and dispersed to other sites surrounding the island in later times ($T_a = 14$ and 21 days).

Influences of coastal currents on particle transport manifest in a complicated manner; particle dispersal occurs neither isotropically nor unidirectionally. If the northeastward drifting Kuroshio were most influential, dispersal would have to appear also in the northeastward direction. However, the computed connectivity manifests that site #12 at the

northernmost tip and #8–9 on the east coast behave as *nodes*, around which particles tend to accumulate notably. As depicted by the example of temporal evolution of Lagrangian PDFs originated from site #5 (**Fig. 3**), the particles released from the west coast are mostly transported in the clockwise direction around the island with passing site #12 and drifting upstream toward the east coast. These particles barely pass the southernmost tip (#6–7) to form counter-clockwise transport around the island. In contrast, the particles released from the east coast (not shown as PDFs, but as connectivity matrices in **Fig. 2**) are largely accumulated in sites #8–9 even at later times, where semi-enclosed coastal geometry and resultant local lateral circulations act to entrain particles in there. While sites #8–9 provoke relatively stagnant environment for particles, the northeastward residual currents on the west coast and southwestward residual current on the east coast influence site #12, which concurrently induce a clockwise circulating local whirl that promotes particle accumulation near #12. These features are apparent in **Figs. 2** and **3** in particular in earlier time, whereas Langangian PDFs decreases with time and eventually majority of the particles exit the L3 model domain.

CONCLUDING REMARKS

Long-distance larval transport due to the northeastward drifting Kuroshio (Uchiyama et al., 2018 [1]) and short-distance, local entrainment associated with coastal topographies (the present study) coincidently contribute to formation of the local and remote biological network across the Nansei Archipelago in the East China Sea. Around Okinawa Island, the latter mechanism is characterized by the transport associated with residual coastal currents along the island that bifurcates at the southernmost tip (sites #6–7, Tokashiki Strait; Fig. 1b) to provoke northeastward transport on the east coast while weak southwestward transport on the west coast of the island, and then form a clockwise residual circulation. The Lagrangian particles mimicking corals were released from the nearshore areas, drifted seaward at about several km from the shore, and subsequently advected by the along-island clockwisecirculating residual current. During the northeastward transport, some portions of the particles are trapped in semi-enclosed topographies due to localized lateral circulations and residual whirls, in particular around sites #8-9 (Kin and Nakagusuku Bays) on the east coast where particles become notably stagnant. A similar particle entrainment occurs at the northernmost tip (site #12, Cape Hedo) due to a highly localized clockwise whirl. These results clearly indicate that very high-resolution circulation modeling is essential to quantitatively account for nearhore behavior of corals under strong topographic constraint in shallow nearshore areas, where the particles mostly remain even for several weeks after the releases.

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