Develop an updated Connectivity Modeling Simulation recruitment index for recruitment forecasting

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Use of the Connectivity Modeling System to estimate movements of red snapper (*Lutjanus campechanus*) recruits in the northern Gulf of Mexico

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Introduction

This research makes use of a biophysical modeling framework to understand patterns of recruitment of the red snapper (*Lutjanus campechanus*) in space and time. The purpose of this research is to predict recruitment strength of red snapper due to the effects of oceanographic currents on an annual basis. This annual index of recruitment deviations expected from oceanographic factors can be used to inform recruitment patterns in the stock assessment model. We use the Connectivity Modeling System (Paris et al. 2013), an individual-based model which estimates the movement of particles in a 3-D velocity field, and has the capacity to simulate complex behaviors such as those displayed by fish larvae. The connectivity model is used to simulate the release of red snapper eggs during the spawning season for years 2014 – 2021.

This paper is an update of a working paper that was produced for SEDAR 52 (Karnauskas et al. 2017). Since the previous working paper the biological inputs have been updated with new data, as available, and include: updated oceanographic models, updated definition of settlement habitat, and a reduced suite of sensitivity analyses. All other aspects of model set up were maintained as in Karnauskas et al. (2017). This working paper addresses one of the terms of reference for the SEDAR 74 research track assessment: "Develop an updated Connectivity Modeling Simulation recruitment index for recruitment forecasting."

Methods

The Connectivity Modeling System (CMS) is a biophysical modeling system based on a Lagrangian framework and was developed to study complex larval migrations (Paris et al. 2013). The CMS uses outputs from hydrodynamic models and tracks the three-dimensional movements of advected particles through time, given a specified set of release points and particle behaviors. Optional modules are provided to allow for complex behaviors and movements, simulating observed biological phenomena such as egg buoyancy, ontogenetic vertical migration, and tidal stream transport. The specific model set up used for this study is outlined in detail below.

Ocean velocity fields

The hydrodynamic model we used was the HYCOM + NCODA Gulf of Mexico 1/25° Analysis, a freely available ocean model with daily velocity fields available from 2003 to present (www.hycom.org). HYCOM is a hybrid isopycnal coordinate ocean model (i.e., isopycnal in the stratified open ocean, fixed-depth in the unstratified surface layers, and terrain-following in shallow coastal waters), while allows for optimal simulation of both coastal and open-ocean features simultaneously (Chassignet et al. 2007). Although velocity fields are available since 1993, the model is occasionally updated and these updates are reflected in different "experiments" that have limited temporal overlap. To reduce the potential bias in recruitment estimates from the changes in different experimental setups, we limited the present analysis to the most recent two experiments (expt 32.5 for 2014 - 2018 and expt 90.1m000 for 2019 - 2021).

Initial conditions of the biological model

Inputs regarding spawning timing and location were unchanged from the previous working paper. We simulate particle releases every 3 days throughout the spawning period for all years. To account for the fact that the average spawning fraction varies throughout the spawning season, we scaled the spawning releases by a reported statistical relationship relating the proportion of red snapper females bearing spawning markers with time of year (Porch et al. 2015). We based the location of egg releases on a probabilistic model of red snapper biomass across space (Karnauskas et al. 2017).

In CMS, vertical movements are defined via a probability matrix, which specifies the distribution of virtual larvae in the water column throughout time at different stages of larval metamorphosis (e.g., hatching, preflexion, postflexion). We used the setup as described in Karnauskas et al. (2017), which assumed hatching occurs at day 1 post hatch, flexion at day 12, and postflexion at day 16, with vertical migration behaviors specified separately for each of these stages. The previous working paper included multiple sensitivity analyses regarding vertical migration behavior, and it was determined that the choice in assumptions regarding the fate of eggs during the first 24 hours had little influence on the results. However, results were sensitive to assumptions regarding the vertical migration behavior during the preflexion and postflexion stages. Thus, for the present study, we only carried out sensitivity analyses with respect to different assumptions regarding ontogenetic vertical migration (OVM) of the hatched larvae; as was previously done, we used the observed depth distribution patterns of three congeners: mutton snapper *L. analis* (OVM 1), lane snapper *L. synagris* (OVM 2), and gray snapper *L. griseus* (OVM 3), to parametrize vertical distributions.

Settlement

The previous settlement habitat definition was derived from the Johnson et al. (2012) review of red snapper juvenile habitat. This information was outdated and thus we conducted a comprehensive review to look for more updated information on red snapper settlement habitat. In our literature review, we identified sixteen studies (Erisman et al. 2020, Dance and Rooker, 2019, Gruss et al., 2018, Powers et al. 2018, Switzer et al., 2015, Rindone et al., 2015, Monk et al., 2015, Johnson et al., 2013, Gallaway et al., 2009, Wells et al., 2008, Geary et al., 2007, Rooker et al. 2004, Szedlmayer and Lee 2004, Patterson et al., 2005, Gallaway et al., 1999, Szedlmayer and Conti, 1999) that focused on elucidating habitat for age-0 juvenile red-snapper. These studies vary in their spatial and temporal coverage. Some studies were localized (eg. Powers et al. 2018, Wells et al., 2008, Geary et al., 2007, Rooker et al. 2004, Szedlmayer and Lee 2004, Szedlmayer and Conti, 1999), while others covered the entire GoM or most of it extension (Erisman et al. 2020, Dance and Rooker, 2019, Gruss et al., 2018, Switzer et al., 2015, Rindone et al., 2015, Monk et al., 2015 Johnson et al., 2013, Gallaway et al., 2009, Patterson et al., 2005, Galaway et al., 1999). Methods were diverse, but data from the NMFS Fall groundfish survey (SEAMAP) was considered in most studies: seven directly analyzed the survey data, while an additional four indirectly considered the results through literature review. Our resulting literature review is thus robust, incorporating all studies and large datasets available for juvenile red-snapper distribution in the GoM region. The results of preferred settlement habitat presented by Gallaway et al., (1999) are largely supported by most recent studies, however, the shallower range of occurrence of age-0 juveniles appear to occur in shallower depths (ca. 10 m) than previously considered (17m), with individuals collected at depths up to 4m deep.

Considering these results, we conducted a sensitivity analysis to verify how much settlement is lost by not considering as viable habitat settlement regions shallower than 17m. Using our current model simulations from 2011-2017, we selected all larvae inside the model domain and alive during their competency period (26 to 30 days). Competent larvae which were found inside of a shallower polygon were counted as settled and removed from the simulation. Our estimations have shown that yearly settlement at shallower settlement sites vary between 5% to 12% of all larvae spawned. Shallow settlement represents 5 to 20% of total settlement. Since settlement in shallower habitat is significant, a second set of simulations was done considering settlement habitat from 10-64m. Successful settlement is defined by those particles which reach the suitable settlement habitat during the competency window, given the suite of previously described parameterized behaviors and attributes.

Results

The results presented here are based on simulations where the total number of particles released was kept constant across months and across years. This allows us to consider changes in recruitment patterns due exclusively to annual variation in ocean current patterns, and not related to changes in spawning stock biomass. The index is calculated by calculating the percentage of successfully settling particles by year, averaging across the different sensitivity runs, and then scaling to a mean of zero. This index can thus be considered as representative of annual recruitment deviations, prior to any density-dependent processes occurring after settlement out of the pelagic environment.

Relative recruitment success across the entire northern GoM varied across years, with the greatest number of successful recruits occurring in 2015 (Fig. 1). Recruitment was near average in 2016, below average in 2017 and 2018, and again below average in 2020. In 2021, the model predictions are somewhat variable depending on the sensitivity analysis; two runs predict recruitment well above average while the third run predicts below average recruitment. The three sensitivity analyses are in good agreement from 2014 to 2016, but starting in 2017 the estimates from different sensitivity runs are more divergent.

While the recruitment index represents dynamics of the entire northern Gulf red snapper population, model output at the coordinate level also allows summarization of results at the scales of the stock assessment areas. These spatial dynamics are easily viewed in the form of a connectivity matrix which shows the spatial patterns in source and sinks for larvae that have successfully settled (Fig. 2). In general, self-recruitment of larvae is the norm (larvae settle at locations close to the location at which they were spawned). This is particularly true for the Western subregion – in most years, 99% of larvae settling in the West are spawned there. The Eastern subregion also has a high number of local spawners settling in most years, although in some years (e.g. 2016, 2018) about one-fifth of the settlers are sourced from other subregions. The Central subregion is most variable from year to year, and in all years is more dependent on settlers sourced from other regions to a greater extent than either the Western or Eastern subregions. In some years (e.g., 2021) contributions from East are much higher than the West, while in other years the pattern reverses (e.g. 2014).

Discussion

This paper represents an update of SEDAR52-WP-20 with updated model inputs and additional years of simulation. Some caution should be taken in interpreting trends during the last three years relative to earlier years of the simulation, due to the lack of overlap in hydrodynamic experiments. Results for the years 2014 - 2018 are based on an older experiment (expt 32.5) which had 27 vertical layers. Years 2019 - 2021 are covered by a newer experiment (90.1m000) which has 36 vertical layers, uses updated topography and a different version of the HYCOM model. Both experiments have the same resolution (1/25° equatorial resolution) and include tidal forcing. Unfortunately, there are no years for comparison of these two particular experiments, which prevents us from determining if there is a potential bias due to the change in setup. However, an inspection of model outputs such as the average depth distributions and average longitudinal and latitudinal position of larvae did not reveal any systematic bias in the most recent experiment.

Regardless of the model experiment, the Loop Current should theoretically be well represented as it is the dominant driver of current regimes. Results indicate that overall patterns in recruitment strength and connectivity between regions are heavily influenced by the position of the Loop Current. For example, years of strong relative recruitment (2015, 2021) are associated with an organized and northward protruding Loop Current, which tends to create current regimes that push recruits onto the shelf and maintain them near suitable settlement habitat (Fig 3). In contrast, years of low recruitment strength (2017, 2018) are associated with a Loop Current that is disorganized and/or located further South during the months of spawning. Loop Current position also influences connectivity among the regions; for example, in 2021 there was an anomalous pattern of Central region receiving much more of its larvae from the Eastern subregion than the Western subregion. This was due to a highly organized Loop Current that was located relatively far into the northwest Gulf in comparison to other years, which sets up a cyclonic circulation pattern in the northeastern Gulf that pulls recruits from the Big Bend region to the Florida Panhandle and Alabama. For that reason, transport from the Central to the West Gulf was also enhanced this year.

Table 1. Index of relative recruitment strength due to oceanographic forces, with the associated coefficient of variation.

year	index	CV
2014	0.004	0.224
2015	0.050	0.181
2016	0.007	0.204
2017	-0.033	0.184
2018	-0.033	0.265
2019	0.0164	0.155
2020	-0.025	0.166
2021	0.014	0.260

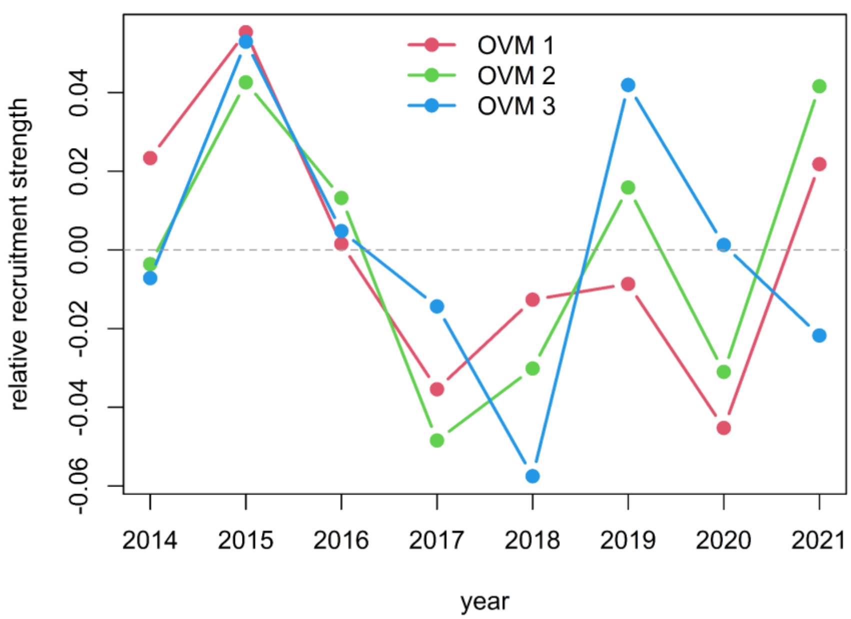

Figure 1. Index of expected recruitment strength for Gulf of Mexico red snapper as estimated by the individual sensitivity runs.

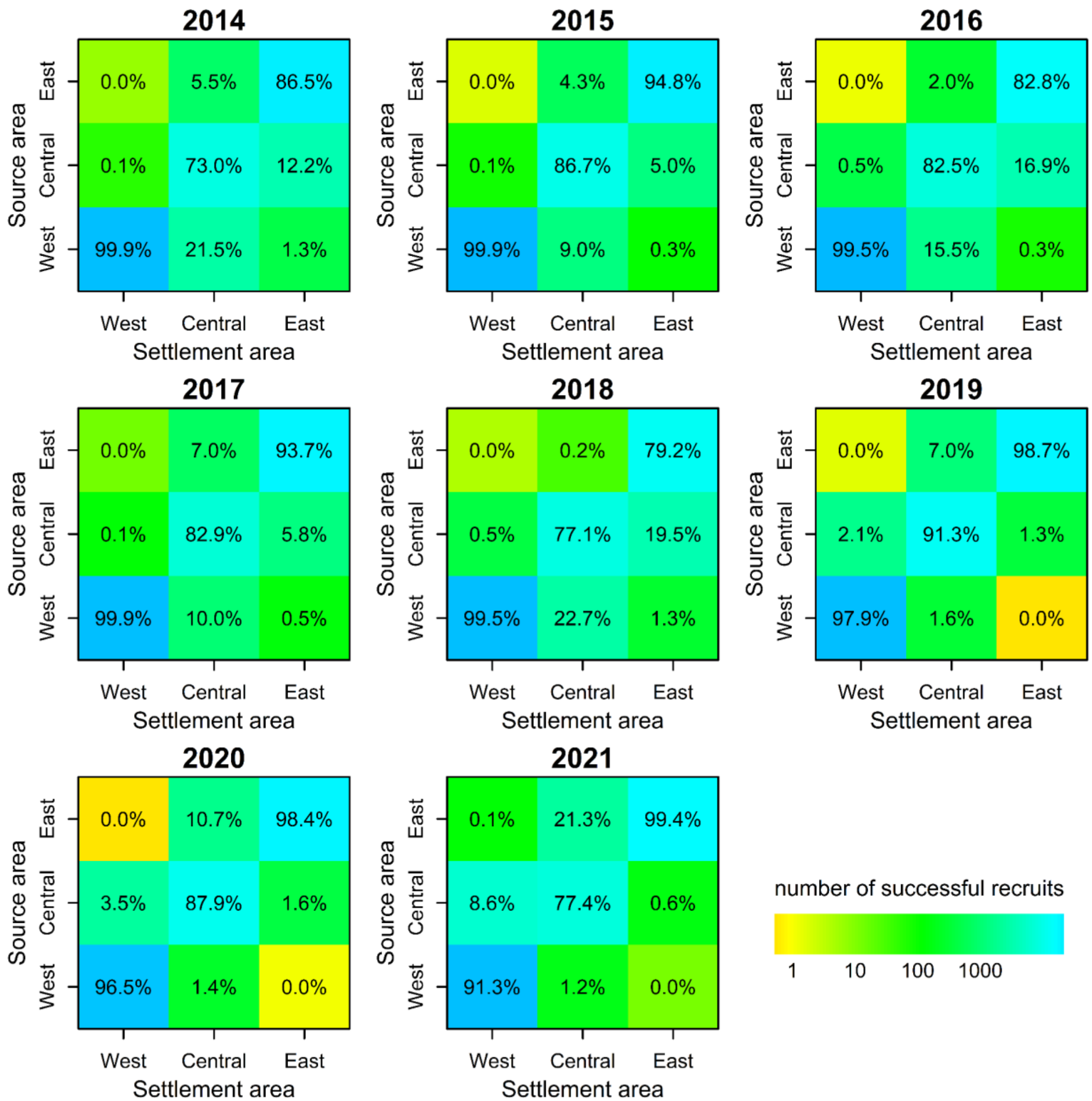

Figure 2. Connectivity matrices showing the transport of larvae across regions by year, averaged over the different sensitivity runs. Percentages refer to the contribution of successful settlers from each source region to the respective sink areas (i.e., columns sum to 100%). Note colorbar is on a log scale.

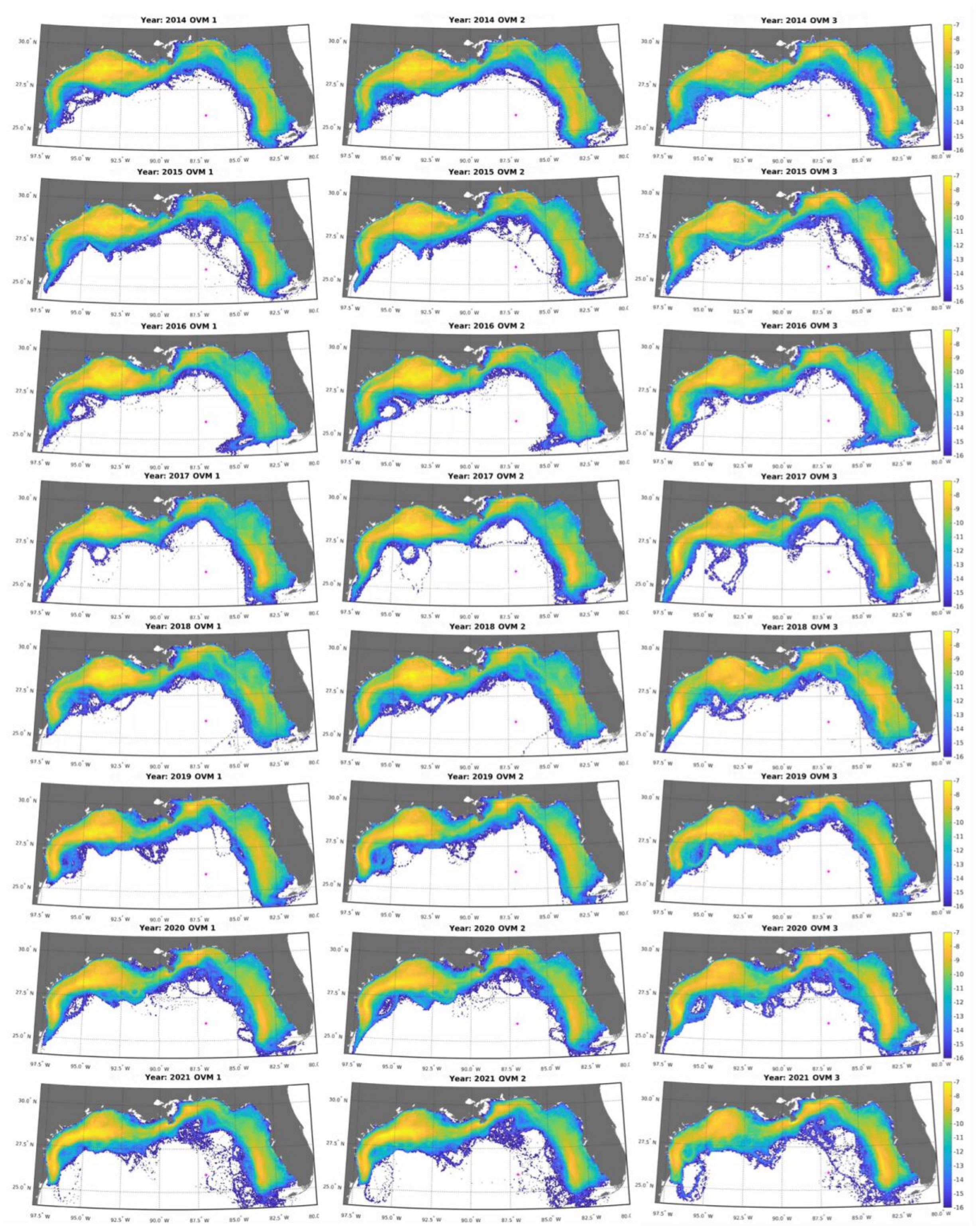

Figure 3. PDF of particle trajectories for each year and sensitivity analysis, for those larvae which successfully settled. Note colorbar is on a log scale. Magenta point marks coordinate 26°N and 87°W to facilitate the visualization of Loop Current variability.

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