Sea Scallop Larval and Early Juvenile Transport along the Northeast Continental Shelf: A Modeling Tool to Enhance Scallop Management of Rotationally Closed Areas

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1.0 EXECUTIVE SUMMARY

Project Title: Sea scallop larval and early juvenile transport the along the northeast continental shelf: A modeling tool to enhance scallop management of rotationally closed areas

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RSA Priorities Addressed By This Research: *Other Priority*: *"studies aimed at understanding recruitment processes (reproduction, timing of spawning, larval and early post-settlement stages), and seasonal growth patterns of scallop shell height and meat and gonad weight."*

A scallop IBM model was developed and coupled with the Northeast Coastal Ocean Forecast System (NECOFS). Driven by the NECOFS-assimilated hourly flow and temperature fields, a set of the scallop IBM model experiments were conducted over the period of 1978-2013. The experiments have been focused on three tasks: examining 1) how sensitive the scallop larval settlement is to the parameterization of scallop larval behavior in the early stages, 2) how the interannual variability of the subtidal circulation influence the scallop larval settlement in different years and 3) the connectivity of larval transport between Georges Bank, Great South Channel and Mid-Atlantic Bight region. Physical processes includes the advection by flow field, water temperature, mixing intensity and mixed layer thickness . To qualify the role of physical processes, We first drive the IBM-based pelagic phase scallop population model by spawning based on multiyear averaged abundance and distribution of adult sea scallop for a 37-year period, and then repeat the tracking for the period 1999-2013 based on spawning that is determined by individual year abundance and distribution of adult sea scallop mapped by video and HabCamV4 surveys. Two types of experiments were made for the cases with and without inclusion of diel vertical migration of early-stage scallop larvae in the surface mixed layer. Larval behavior in the mixed layer was parameterized based on the observation described by Gallager et al (1996). The results indicate that the scallop larval settlement is very sensitive to scallop larval behavior in their early stages. Ignoring the thermocline-seeking behavior reduced the resident time of larvae in the water column over Georges Bank, so that a large portion of larvae could be advected southward to Middle Atlantic Bight and not many larvae would stay on Georges Bank. Taking the thermocline-seeking behavior into account increased the resident time of larvae in the water column over Georges Bank. As a result, the larvae, which were from eggs spawn on Georges Bank, mainly circulate with the clockwise residual flow around the bank and eventually settled on the bank, with only a few flowing southwards. This suggests that due to lack of implementing the surface mixed layer dynamics in the scallop-IBM model, the connectivity of scallop larvae between Georges Bank and Middle Atlantic Bight were significantly overestimated in previous works done by Tian et al. (2009). The larval transport to the Middle Atlantic Bight is closely related to the intensity of the cool pool and temperature front. The high abundance was found within the cool pool region over the Southern New England shelf and in the northern region of the Middle Atlantic Bight could be traced back to their origins in the closed area over the Nantucket Shoals close to the Great South Channel.

Industry Partners: This project does not have a field component; therefore, no industry vessels have been involved in research. However, several industry vessels from Lund's Fisheries and F/V "Pamela Ann" are involved in compensation fishing.

2.0 PRELIMINARY RESULTS AND DISCUSSION

Project goals and objectives

- Examine the bio-physical mechanisms for the interannual variability of sea scallop recruitment in the high aggregation regions of GB, GSC and MAB;
- Search for optimal sites for the seeding of sea scallop and predict their post-settlement growth and aggregations.

These project goals will be achieved with objectives of understanding the interannual variability of 1) larval transport and trajectories from various spawning location over time during May-October in the past 37 years over the period 1978-2014; 2)larval concentration in the water column through high aggregation regions; 3) larval settlement locations, timing and intensity; 4) post- settlement growth as it relates to NOAA HabCamV4 surveys; 4) post-settlement swimming behavior, initial and time series of location of juvenile scallops with respect to their swimming behavior and 5) prediction of the connectivity between GB/GSC and MAB. The scallop-IBM experiments will be conducted under the validated NECOFS-produced physical field and NPZD model predicted food concentration.

Scallop-IBM model

The IBM-based scallop population model consists of four pelagic phases (egg, trochophore, veliger, pediveliger (Figure 1) (Tian et al., 2009a). Individual development in the model is based on age: eggs <2 days, trochophores 2–4 days, veligers 5–40 days, and pediveligers > 40 days (Stewart and Arnold, 1994). Behavioral vertical migration is specified for each life stage. Eggs are spawned on the seabed, are neutrally buoyant, and drift passively without vertical migration. Contrary to the existing models, trochophores have no directionality in their swimming and only randomly spin. Once the first shell is formed (prodisoconch) and the larvae form the 'D' configuration, then their center of gravity is below the velum, which propels them in the vertical direction upwards (Gallager, 1993; Gallager et al., 1996). Veligers are essentially subject to current drift in the surface layers above the thermocline, but actively swim and alternately sink

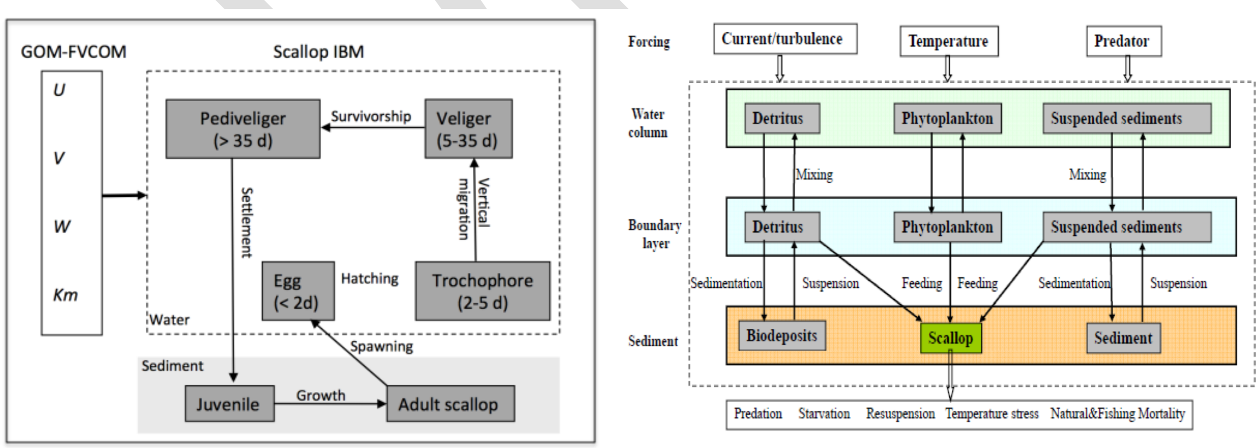

Figure 1: Structures of the scallop-IBM model. Upper: the scallop life stage model including 4 pelagic stages (egg, trochophore, veliger, and pediveliger) and 2 benthic stages (juvenile, and adult) Lower: details of the benthic stage model.

producing a distinct migration pattern. Veligers are sensitive to light transitions, *not* to any prolonged state of light intensity such as day or night (Gallager et al., 1996). Larvae between the ages of 5 and 45 days vertically migrate to the surface and then back to the thermocline both when the sun comes up and when it sets (Gallager et al., 1996). In addition, larvae respond to algal density (food) in a concentration-dependent way by spending more time at depths where algal density is higher (Gallager et al., 1996). Larvae also respond to ephemeral pulses of turbulence greater than 10^{-7} W.Kg^{-1} by withdrawing their velum and sinking rapidly until the turbulent energy has subsided (Pearce et al., 1998). This extensive suite of swimming behaviors has never been captured in a model to date (e.g. Stewart and Arnold, 1994 and Tian et al., 2009a treated larvae as particles with a random walk) and could contribute greatly to the overall transport potential of larvae since they are constantly responding to stimuli and changing their depth. Late-stage pediveligers (>45 days) migrate downwards to the seabed (1.7 mm s^{-1}) to settle, but may remain at the thermocline for more than 100 days and delay metamorphosis if thermal conditions are inappropriate (Pearce et al., 1996). Such a delay in settlement could lead to higher retention if larvae are in a gyre that extends beyond the shelfbreak only to return several days later, particularly in the MAB. Mortality throughout the pelagic phase can be carefully parameterized based on data and conditions provided in the literature (e.g. Gallager et al., 1986a,b, 1988).

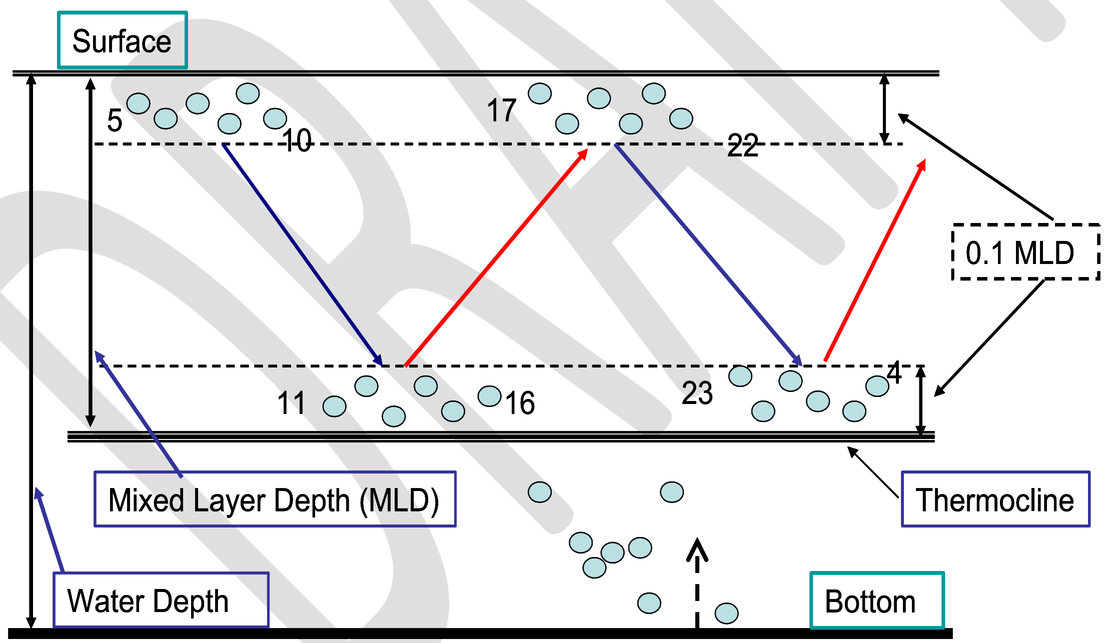

Figure 2: A vertical migration sub-model of larvae in the surface mixed layer between the ages of 5 and 45 days: migrating towards the surface and then back to the thermocline both when the sun comes up and when it sets (Gallager et al., 1996).

A benthic stage with inclusion of feeding, predation, starvation, resuspension and natural/fishing mortality has been implemented into the current version of scallop-IBM. In the previous model, the sea scallop spat, juvenile and young adult are integrated into a single compartment "Scallop", but age, weight, and height attributes are simulated in a continuous manner. Age is incremented at each time step whereas shell height and weight are simulated based on trophodynamics and metabolism. Starvation mortality is linked to metabolism and food assimilation. Insufficient food assimilation to satisfy metabolism energy consumption results in starvation mortality (Ross and Nisbet, 1990). This happens when scallop larvae are dispersed and settled in regions where food items are scarce such as in the deep gulf and certain stratified regions over GB/GSC and MAB. Forcing includes current and turbulence diffusivity, temperature and predators. The NECOFS hourly archived currents and temperature will be used to drive the model and crab and starfish data will be used to specify predation pressure. Food items include phytoplankton, biogenic detritus and suspended terrestrial sediment, with each food compartment having different nutritional value parameterized as a growth efficiency coefficient. Suspended sediments do not possess any nutritional value, but they do interfere with the scallop filtration performance. The inclusion of this compartment is aimed at resolving the interference of suspended terrestrial detritus with the scallop food intake system and filtration clogging at high concentration of suspended matter. The phytoplankton and detritus field will be provided by the Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD model simulation results that were produced by Tian et al. (2014).

Scallop data collection

We have collected scallop data from three sources:1) SMAST, 2) NOAA and 3) BIO. The SMAST data covers the period of 2003-2017, NOAA data covers the period of 1979-2017 (HabCam V4 survey) and BIO data covers the period of 2003-2017. The survey locations are shown in Figure 3. The BIO data mainly were collected in the Canadian waters and from the Population Ecology Division (PED), Department of Fisheries & Oceans (DFO), Bedford Institute of Oceanography (BIO).

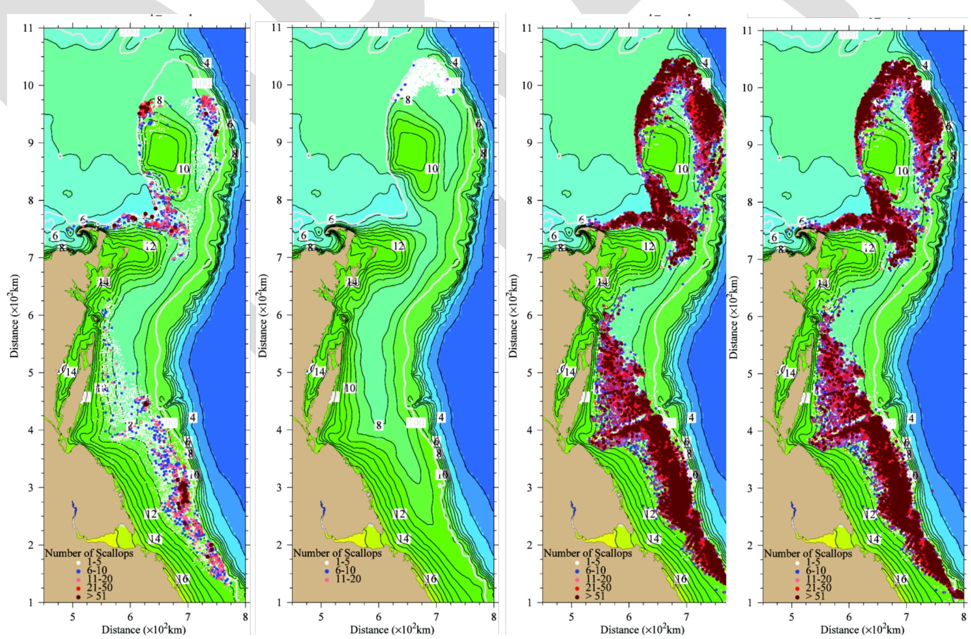

Figure 3: Locations of scallop survey conducted by SMAST (left), FED/DFO/BIO (second from left), NOAA (third from left) and a combination of SMAST. FEDDFO/BIO and NOAA (right).

Design of experiments: Experiment I. The model parameters were the same as those used in Tian et al. (2009b). Active vertical migration was specified for each life stage. At the 2.0-day age, larva started migrating upward towards the surface at a speed of 0.3 mm/s. At the 5.0-day age or later, larva's upward migration speed was decreased to 0.1 mm/s. At 40.0-day age, veligers developed into pediveligers, which actively migrated downwards to the seabed at a speed of 1.7 mm/s and settled on a suitable substrate.

Experiment II. In addition to parameters considered in Experiment I, we considered the diel vertical migration of scallop larvae during early stages within the surface mixed layer as observed by Gallager et al (1996). The larvae in the surface mixed layer tended to vertically migrate towards the surface at sunset, and then come back to the thermocline at sunrise. During the spawning period in September, the water is generally well mixed over the top of George Bank at depth less than 40 m and stratified between tidal mixing and shelfbreak fronts in deeper waters in the southern flank of Georges Bank. During that period, the wind-induced surface mixed layer could deepen to ~30-40 m in the stratified region. We included this diel vertical larval migration pattern in the model to examine how this type of larval behavior may affect larval settlement after 40 days.

Locations of spawning for experiments I and II:

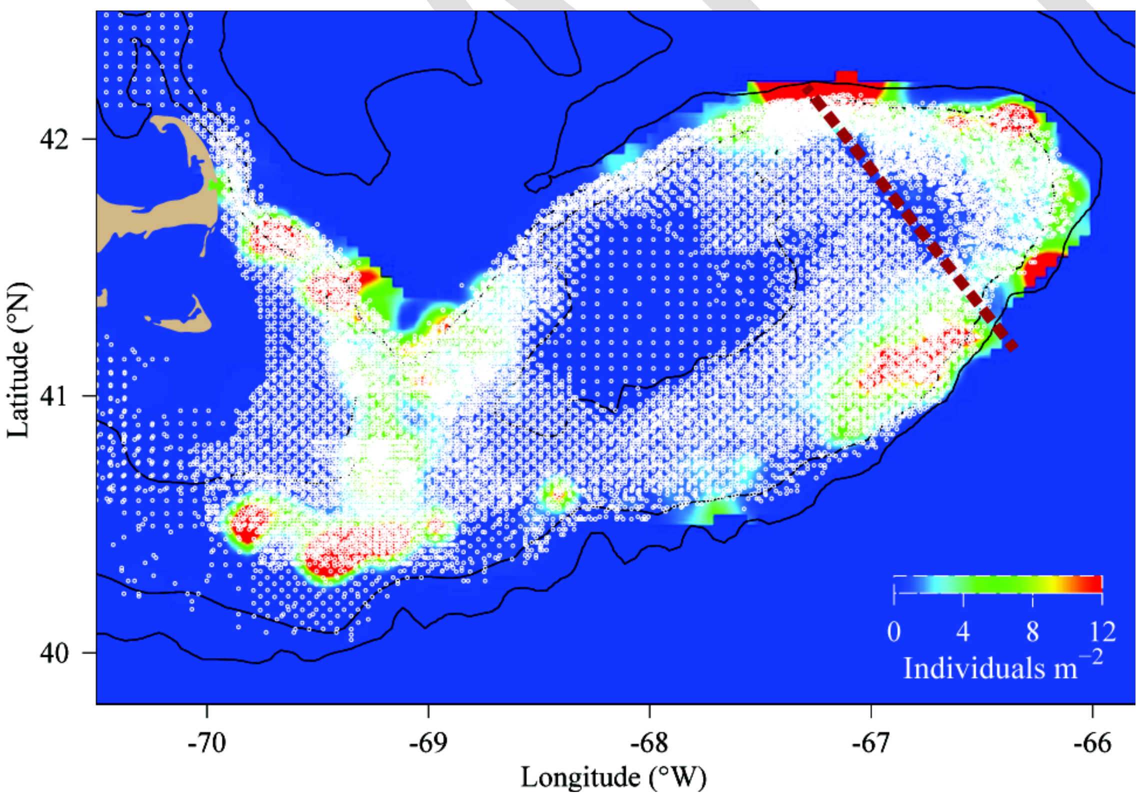

Figure 4: Spawning sites used for experiments I and II. The individuals in each cell were determined using the combined scallop data from SMAST, NOAA and BIO.

Preliminary results:

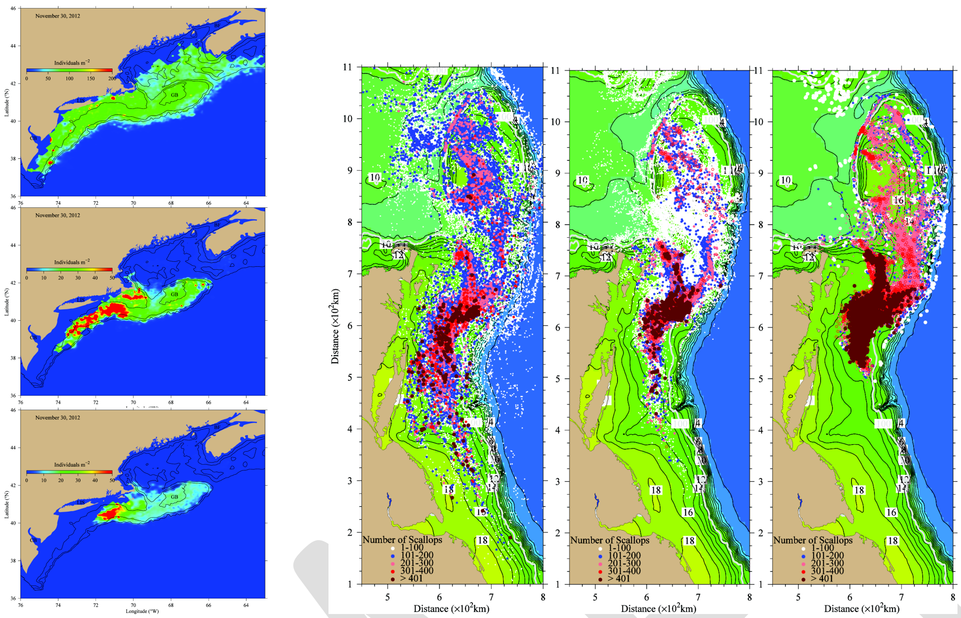

Figure 5: Larvae settlement density distribution (left panel) and the locations of settled super particles (right panel) of 2012 for the cases of 1) the larvae without swimming in the mixed layer (left-upper panel right-first panel), 2) the larvae with swimming in the mixed layer (thickness: 10 meters), (left-middle panel and right-second panel), 3) the larvae with swimming in the mixed layer (thickness: 30 meters), (left-bottom panel and right- third panel).

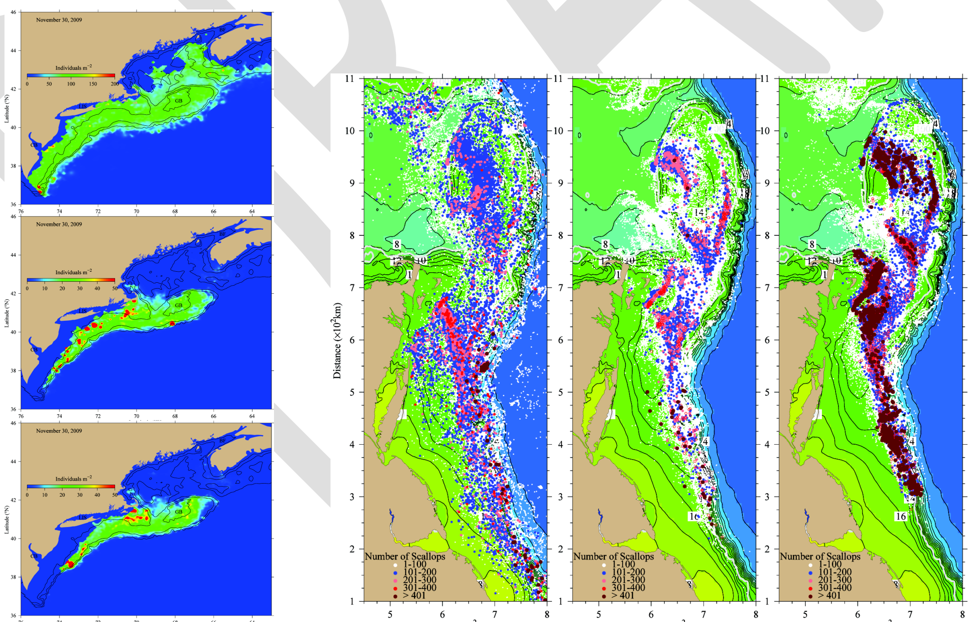

Figure 6: Larvae settlement density distribution (left panel) and the locations of settled super particles (right panel) of 2009 for three cases described in Figure 5.

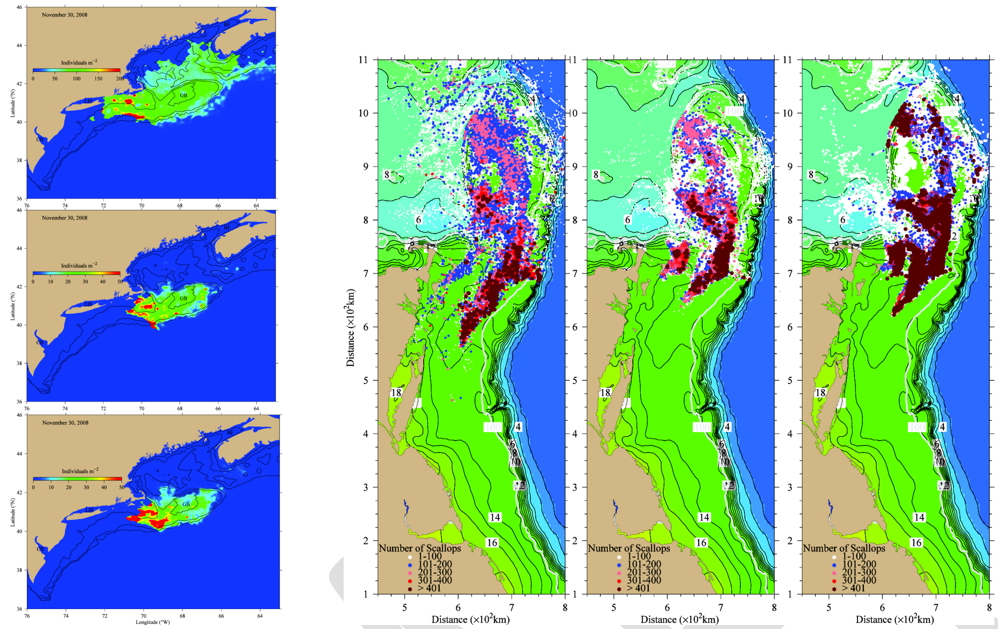

Figure 7: Larvae settlement density distribution (left panel) and the locations of settled super particles (right panel) of 2008 for three cases described in Figure 5.

3.0 SPECIAL COMMENTS

The results indicate that the scallop larval settlement is very sensitive to scallop larval behavior in their early stages. Ignoring the thermocline-seeking behavior reduced the resident time of larvae in the water column over Georges Bank, so that a large portion of larvae could be advected southward to Middle Atlantic Bight and not many larvae would stay on Georges Bank. Taking the thermocline-seeking behavior into account increased the resident time of larvae in the water column over Georges Bank. As a result, the larvae, which were from eggs spawn on Georges Bank, mainly circulate with the clockwise residual flow around the bank and eventually settled on the bank, with only a few flowing southwards. The high abundance was found within the cool pool region over the Southern New England shelf and in the northern region of the Middle Atlantic Bight could be traced back to their origins in the closed area over the Nantucket Shoals close to the Great South Channel.

In the case with the consideration of thermocline-seeking behavior, the scallop larval settlement and dispersion are very sensitive to the thickness of the surface mixed layer. In order to predict the larval transport and dispersion, one requires a physical model that is capable of resolving a realistic surface mixed layer and its variability in time and space. A new method has been developed to estimate the thickness of the surface mixed layer from NECOFS hourly hindcast product and results are being used to re-run Experiment II for the period of 1978-2014.

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