Deepwater Horizon Natural Resources Damage Assessment

Water Column Technical Working Group

Examining the Scope of Spill Impacts to Early Stage Fishes in the US Economic Exclusion Zone

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Abstract

Statistical modeling was used to create spatio-temporal estimates/maps of mean larval fish relative abundance in the US Economic Exclusion Zone (EEZ) of the Gulf of Mexico for the period of late April to early August, 2010. These estimates were used to calculate a nondimensional number that represents the proportion, or percentage, of predicted larval fish in the EEZ that were potentially exposed to oil from the Deepwater Horizon incident. The proportion exposed is a function of the 'production schedule' of the population, the location and timing of that productivity, and the spatio-temporal distribution of surface oil.

Introduction

The Deepwater Horizon Incident remains the largest oil spill in a marine environment in United States history. Vast quantities of oil and other contaminants were discharged into the northern Gulf of Mexico from late April to mid-July in 2010. Oil slicks comprising a cumulative total of some 1.1 million square kilometers (i.e., square kilometer-days) were visible on the surface of the Gulf from space over the course of approximately 111 days (Graettinger et al. 2015) from April 23 to August 11, 2010. A subsurface plume developed in the deep Gulf of Mexico and had vertical extents that at times were as thick as the Empire State Building is tall. The unprecedented duration, volume, and spatial extent of the spill indicate that Deepwater Horizon was a significant ecological and economic event for the northern Gulf of Mexico.

The spill triggered a formal Natural Resources Damage Assessment (NRDA) to quantify the extent of injury to living natural resources. Damage assessments often measure injury to fishes in terms of kilograms of organisms directly killed and the kilograms of biomass that would have been produced by those directly killed organisms. Underlying these metrics are assumptions that the absolute abundances of impacted organisms can be comprehensively and directly measured or estimated. For some situations, particularly those in which resources are sessile, turn-over rates are low, and the spill extent small this kind of quantification is difficult, but feasible. However, given the expansive nature of the Deepwater Horizon Incident and the current state of biological and physical monitoring in open ocean systems, this level of quantification becomes exceptionally difficult and alternative views may be needed to illuminate the scope of injury.

Rationale for Ratios

Most relevant biological monitoring in the open Gulf of Mexico and its adjacent estuaries are components of various fisheries management programs. These programs rely on multi-species surveys that are conducted only one to a few times in any given year, take weeks to months to complete, and use nets or some sort of hook and line as primary sampling tools. The information returned by these surveys is in fact the best available science, but - in all cases - the information content of these data is constrained by a variety of practical limitations and is therefore incomplete. These data better represent an index of absolute abundance than a measure of precisely how many organisms exist per unit area or volume. These pragmatic limitations are well known in fisheries management venues and are one of the reasons survey data is incorporated into the fisheries stock assessment process as an index (see for instance, Maunder and Star 2003, Maunder and Punt 2004, Lynch et al. 2012). Given these issues, this technical report attempts to provide additional perspectives on the impact of the Deepwater Horizon incident for a subset of the fish species present in the region of the spill.

This work begins with the *de facto* premise that the foundational data available for the damage assessment arises largely from traditional fisheries sampling approaches that do not necessarily return hard data on absolute abundance. Rather than produce metrics such 'kilograms of species-x directly killed', this work estimates the proportion of those organism expected to be in the ecosystem that were potentially exposed to Deepwater Horizon-related contaminants. These proportions can be used along with information on assessed population sizes, areal extent of quality habitat, locations of more productive areas, etc. to help inform restoration activities. This work also identifies those areas expected to have experienced higher rates of injury – areas which could be targeted for restoration projects.

Working Assumptions

It is important to recognize that a number of important working assumptions are present in these analyses. Core biological data originates from standard fisheries bongo net sampling wherein bongo nets were towed obliquely to provide a vertically integrated index of the number of organisms in the upper 200m of the water column. Species-specific differences in availability, catchability, and retention to bongo net sampling means that the data are likely to represent each species or taxon in somewhat a different manner (Morse 1988, Johnson and Morse 1993). No correction factors were applied to the number per unit area information derived from the bongo sampling to account for processes like gear avoidance or net extrusion. The bongo nets collect small larval fishes and invertebrates that are typically a few days to weeks old, and this work assumes that the indexed bongo abundance adequately reflects those embryos surviving to this life stage – embryos and just post-hatch larvae assumed most sensitive to hydrocarbons (Incardona et al. 2004, Incardona et al. 2014). The vertical distribution of organisms is ignored except that the work assumes that embryos and/or early post-hatch larvae are at some point positively buoyant (Gearon et al. 2015) and are vulnerable to surface oil and those processes mixing surface oil into the water column (i.e., oil and early stage fishes are mixed by the same processes and contact is likely) on a daily time step (Drivdal et al. 2014). Because the work uses a daily time step and incorporates covariates that can account for movement of water masses (e.g., the translation of a turbid water mass from one location to another is captured in satellite data), advective processes are assumed included and otherwise ignored.

Roadmap

The structure of this technical report is to provide a brief description of the methods used to develop daily measures of the relative distribution of early stage larval fishes, the creation of relative 'production schedules', and assessments of the proportion of 'daily production' and overall production potentially impacted by the spill over the course of the 111 days on which oil was present on the surface of the Gulf of Mexico. Details of the statistical modeling and data preparation are limited and readers are referred to the Christman and Keller (2015) technical report.

Methods

The study area was set as the US Economic Exclusion Zone (EEZ) as depicted in Figure 1. This area was selected to provide maximum flexibility and broad system-wide coverage. This approach lends itself to adjusting the extent of the 'bounding box' used to describe the impact area of the Deepwater Horizon Incident later as desired to address particular questions that may arise. The work presented here considers the full study area in all comparisons with the 'footprint' of the surface oil.

The authors recognize that this area is much larger than the spatial extent of the surface oil and that by considering such a large area the work will tend to result in what could be perceived as smaller potential injury estimates. This is not our intent. Consideration of the full EEZ simply provided a well-established spatial domain with which to work.

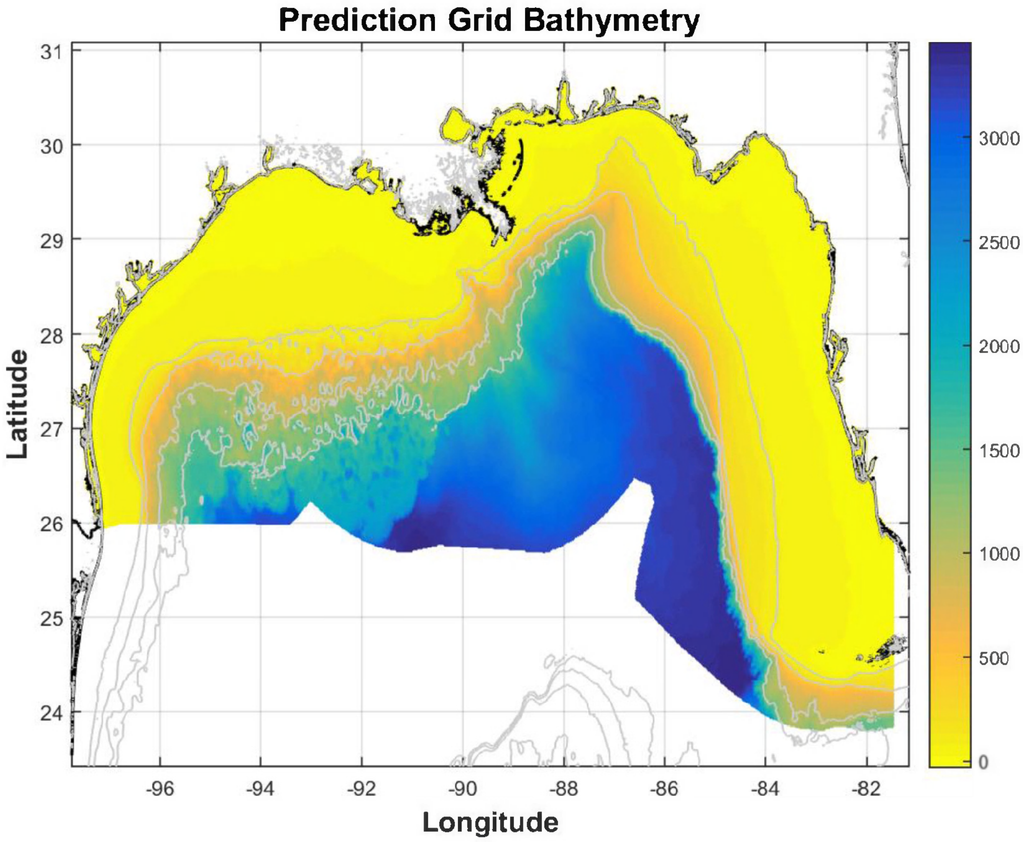

Figure 1 -Study area used in these analyses. Presented is the bathymetry, in meters, as represented in the base prediction grid used in this study. Cool colors (blue) represents deep areas, Warm colors (yellow) represent shallow water. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths. All covariates were mapped onto this grid.

Prediction Grid

A core tool used in these analyses was a standardized prediction grid (Fig. 1 shows the bathymetric data projected onto the prediction grid). The grid resolution was specified to correspond to that of the MODIS satellite data used in this study. The area represented by each of the 408,195 cells is known and averages approximately 1.72 km^2. All covariates were mapped onto this grid and predictions of relative organism abundance were calculated for each cell in the grid. All of the surface oil maps discussed immediately below were also projected onto this grid.

Surface oil extent

Oil was observed on the surface of the Gulf of Mexico via satellite on 88 of 111 days between April 23 and August 11, 2010. The NRDA program constructed a number of satellite products to describe and quantify the extent of surface oiling (Graettinger et al. 2015). The present work used the 5 km^2 TCNNA product, which was mapped onto the prediction grid shown in Figure 1. These TCNNA data provide an estimate of the percentage of each prediction grid cell that was covered by surface oil (see Graettinger et al. 2015). Figure 2 shows the number of days any given prediction grid cell was oiled given the 88 days of satellite observations available for deriving a surface oiling map. The maximum value is 66 days of oil coverage. The colored region itself is the cumulative surface oiling footprint and likely represents a minimum areal extent as 23 of the 111 days had no oil map and some maps had only partial spatial coverage owing to satellite pass coverage and other technical issues. Uncolored areas were devoid of oil in the TCNNA surface oil maps.

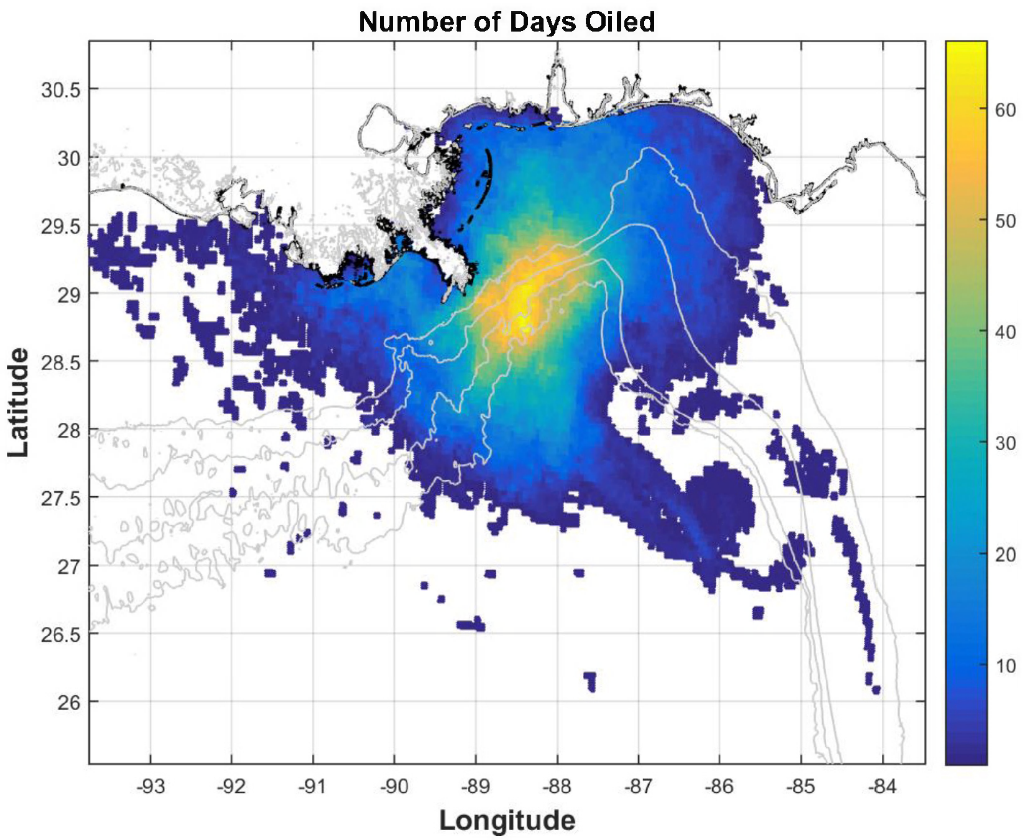

Figure 2 -Cumulative surface oil map. The colored region is the cumulative surface oil distribution in the northern Gulf of Mexico. The coloring depicts the number of days any given location was oiled between April 23 and August 11, 2010. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

Predictor variables

Owing to the size and location of the Deepwater Horizon Incident, the number of species potentially impacted was quite large and there is a paucity of detailed ecological information for many of them. At the onset it simply was not clear which environmental variables may operate to influence the distributions of species in the study area. The need to generate robust distribution information for these species required statistical modeling and a large suite of predictor variables, or covariates. Candidate covariates needed to be widely and consistently available and the selection process needed to be objective. This project also needed the environmental covariates to be available for a period of time before 2010 as well as in 2010. The most reliable source of such variables for the EEZ is from satellite-based remote sensing which supplied regular, synoptically-collected data on ocean color, sea surface temperature and surface height.

The predictor variables, or covariates, used in the analyses were of two types. First, static variables described location or position (e.g., latitude, longitude, depth, sea floor composition, and the local slope of the seafloor). Second, a number of potentially important dynamic variables were identified as candidate predictors. These dynamic variables were chosen to characterize various aspects of water masses (e.g., water clarity, the presence of chlorophyll), time (i.e., day of year, night, day, twilight, moon phase), and some hydrodynamic features (e.g., proximity to a persistent frontal structure). The project assembled a suite of candidate covariates (e.g., ocean color measures such as fluorescent line height, chlorophyll, K490, Rs667, and sea surface temperature and sea surface height) to support the statistical modeling efforts (Christman and Keller 2015). To minimize gaps in the covariates owing to cloud cover, satellite pass timing, etc. a 14 day running mean, centered on the day of interest, was used for each of the dynamic ocean color covariates. Sea surface height related covariates were derived from a daily, science-quality, objectively-analyzed product routinely produced by the NOAA-OAR Atlantic Oceanographic and Atmospheric Laboratory. Ocean color data were secured from the NOAA-NMFS Environmental Research Division of the Southwest Fisheries Science Center (http://coastwatch.pfel.noaa.gov/) and the NOAA-OAR Atlantic Oceanographic and Atmospheric Laboratory (http://cwcaribbean.aoml.noaa.gov/). Figure 3 shows four of the covariates mapped onto the prediction grid for May 10, 2010.

This project was primarily interested in developing a robust capability to predict relative abundances of many different kinds of larval fishes and not necessarily in the ecological processes important to each. This means that while a variable such as Rs667, the reflectance of light at a wavelength of 667 nm which indexes suspended sediment in the water column, may enhance predictive capability, it may not be ecologically important to any particular species of fish. The authors recognize that including ecologically important covariates is desirable, but this was simply not the primary objective of the work nor was it possible to *a priori* identify such covariates given what is known about many of the species considered.

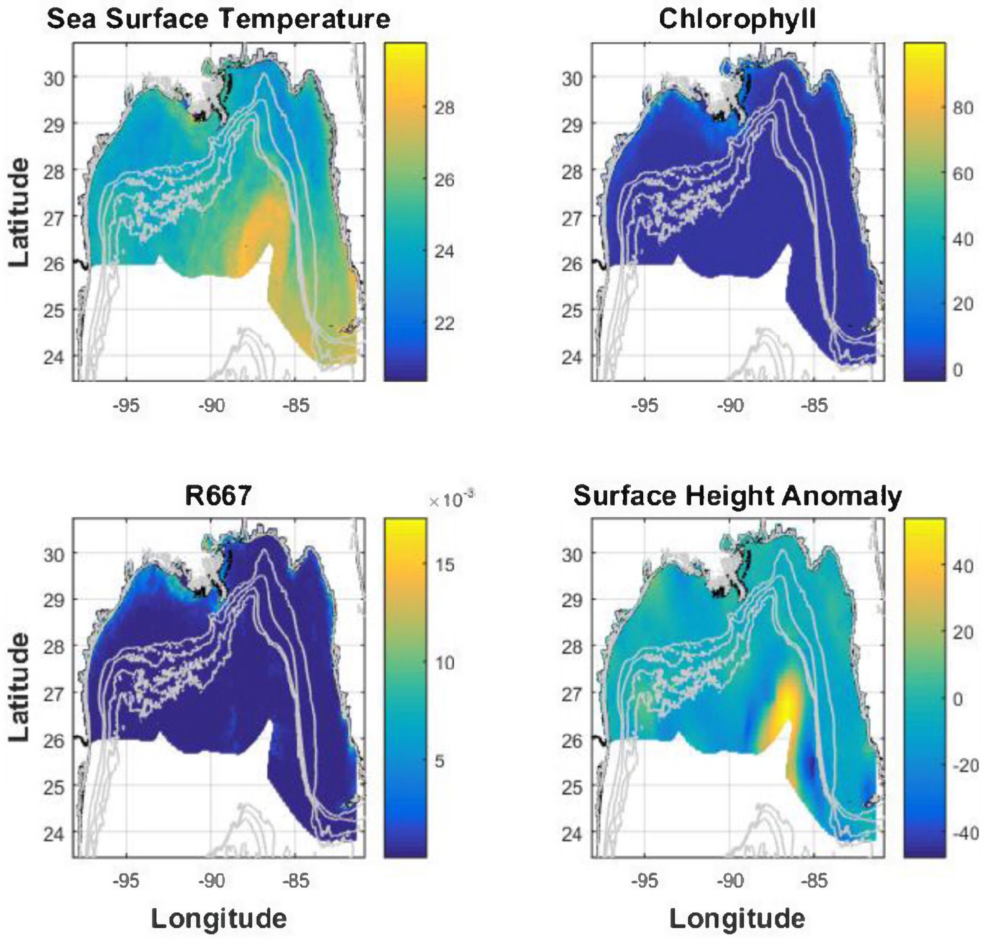

Figure i- Gridded covariates. 14-day average SST, Chl, Rs667, and the daily SHA product are shown for May 10, 2010. Maps like these were developed for 88 days in 2010. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

Base Biological Data

The most comprehensive biological data available in the northern Gulf of Mexico for early stage larval fishes is that of the Southeast Area Monitoring and Assessment Program (SEAMAP: http://www.gsmfc.org/seamap.php) bongo survey. This survey has been conducted for more than three decades and occupies a set of fixed stations twice a year (Figure 4). Station occupation does differ somewhat between surveys in a given year and often varies between years owing to weather or equipment challenges. Samples from these surveys represented the pool of observational data that would provide insights into species-environment associations and distributional patterns. Data collected between 2002 and 2009 was used for model development as this was the proximal period to 2010, best represented expected conditions during the spill, and robust satellite observations were available for the satellite-observed covariates. Additionally, taxon identifications in the SEAMAP database were fairly stable during this time.

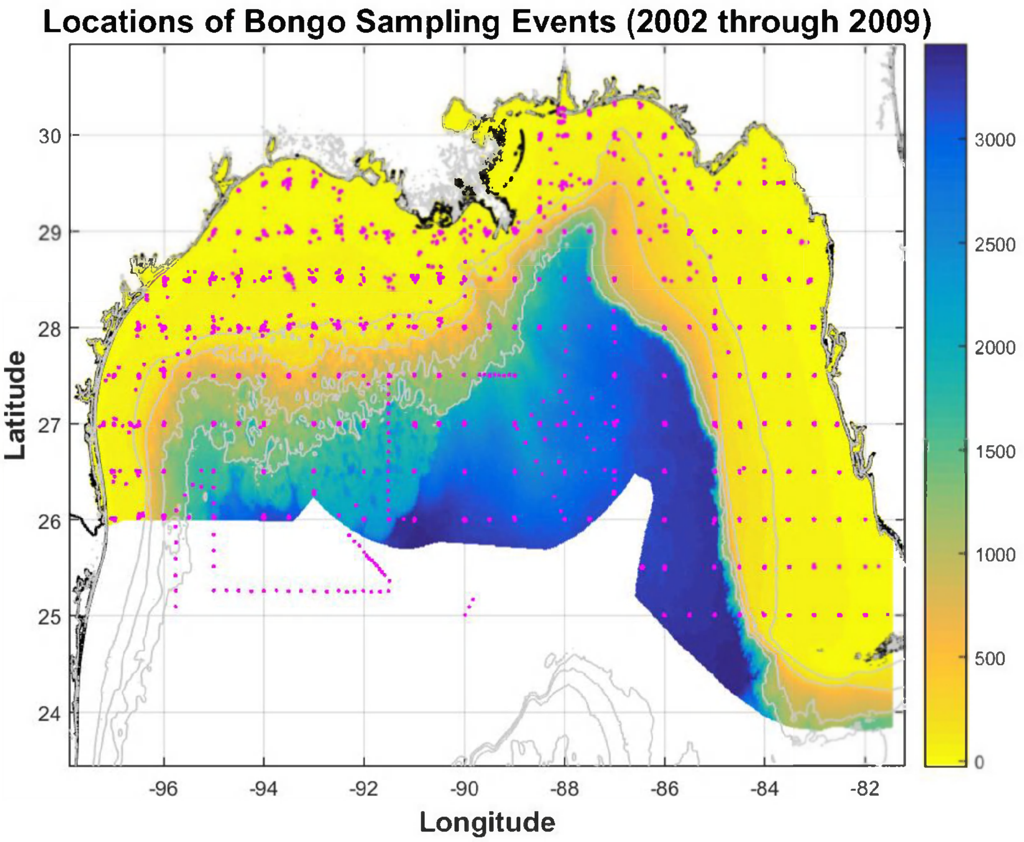

Figure 2 - Locations of SEAMAP bongo sampling events. Shown in magenta are the locations of individual SEAMAP sampling events in the northern Gulf of Mexico between 2002 and 2009, inclusive. Background is the bathymetry of the EEZ as shown in Figure 1.

Because these surveys are conducted to support fisheries stock assessments, taxonomic resolution is generally better for managed species than it is for unmanaged species. For instance, while excellent detail exists for species such as red snapper, information on other taxa such as *Myctophidae* tend to be coarse. The full SEAMAP database contains at least 506 taxonomic groups of varying taxonomic resolution (Christman and Keller 2015). A subset of 258 taxa were considered and details for 24 are presented here.

Dataset Creation

The primary analyses dataset consisted of a full suite of location, time, and environmental predictor variables for each sampling event occurring between 2002 and 2009 (inclusively) in the SEAMAP bongo database (see Figure 4; 5183 sampling events exist). Each entry in the database essentially represented the standardized density (i.e., number per unit area) of the 258 taxa at each sampled station and values for each of the predictor variables characterizing environmental conditions at the station during the sampling event.

Data from 2010 were not used to develop the models predicting relative mean abundances. This is because 2010 was the year of the DWH oil spill and those data were excluded as they could reflect conditions dependent upon the presence of contaminants in the water column.

Statistical Modeling

The first step was to objectively select from the pool of candidate predictor variables a subset that had good explanatory power to account for variability in observed organism abundances. A variety of methods were used to accomplish this including classification and regression trees. Details of this process are provided in Christman and Keller (2015).

Generalized Additive Models (GAMs) were used as the primary means to determine distribution and relative abundance of early stage fishes in the EEZ. GAMs have been routinely used for this kind of estimation for at least a decade (Wood 2006) and have become a popular and generally accepted tool for such analyses in fisheries science and other areas (see Venables and Dichmont 2004, Elith and Leathwick 2009). Several GAMs were typically constructed for each taxon and rigorously explored for performance and predictive power (see Christman and Keller 2015). The best performing GAM was chosen for each taxon and there are many cases where either a GAM couldn't be constructed, had poor performance characteristics, or the taxon modeled included multiple species with significantly different life history strategies and the GAM was deemed inappropriate.

The GAMs resulted in the creation of daily maps of the relative mean abundance for each taxon at each location in the prediction grid in 2010 when surface oiling maps were available. The location- and taxon-specific standard error of the relative mean abundance was also calculated for each grid cell on each day. Examples plots for both predicted mean relative abundance and standard error on select days are shown below in the case study.

Developing Proportions to Assess Impact

Once the 88 relative abundance maps were created, developing the proportion of the total abundance present in the system that was under the footprint of the oil on any given day spill was straightforward.

For each day that had a relative abundance map, the total relative number of organisms was simply the sum of the estimated organism abundances across all prediction grid cells. Likewise, the total relative number of organisms potentially exposed to oil was the sum of estimated organism abundances across all prediction grid cells covered by oil on that day. If a given grid cell was not completely covered by oil, then the fractional oil coverage in that cell was used to decrease the estimated abundance exposed by the correct amount. The ratio of these two numbers (total under the oil footprint/total in the EEZ) represent the proportion of organisms potentially impacted by the oil on each day - given the assumptions presented in the introduction. These proportions are expressed as percentages in this report.

Functionally, the GAMs worked to estimate the number of organisms likely to be collected in a bongo net at any particular location and under the specified set of environmental conditions at that location. By examining the total estimated abundance present in the system through time (summing over all grid cells on each of the 88 days) a time series of the expected relative abundance system-wide can be generated. This was done to examine the expected 'production schedule' (i.e., the time series) against the temporal and spatial patterns of surface oiling. There were 88 days on which relative abundance maps were generated, but the surface of the Gulf of Mexico was oiled for approximately 111 days. This meant that there were 23 days on which no estimates were available for either the organisms or the surface oiling. The gaps appeared as either a single missing day or as two consecutive days and were filled by linear interpolation between adjacent known values.

Two different measures of the potential impact were generated. The first was a metric that examined the proportion, presented as a percentage, of the estimated 'daily productivity' – the total number of organisms expected to be present on any given day – that was potentially subject to oil and other contaminants. The second was a metric that examined the expected proportion of organisms potentially oiled across the entire 111 day period. This second metric typically returns a smaller value because the production schedule of the organism and the most productive areas do not necessarily coincide with the extent of surface oiling through time.

Case Study

This section provides example analyses for one taxon that was examined. Additional taxa are presented in the Appendix in an abbreviated manner.

To provide some additional context, consider the time series of the percent of the EEZ that was covered by oil in 2010 (Figure 5). This figure was created by simply dividing the areal extent of the surface oil on each day by the total area of the EEZ as represented in Fig. 1. The overall percent of the EEZ oiled ranges from nearly zero to about 5.7% (mean 1.6%) on a daily basis. These values will be useful to consider in the following analyses.

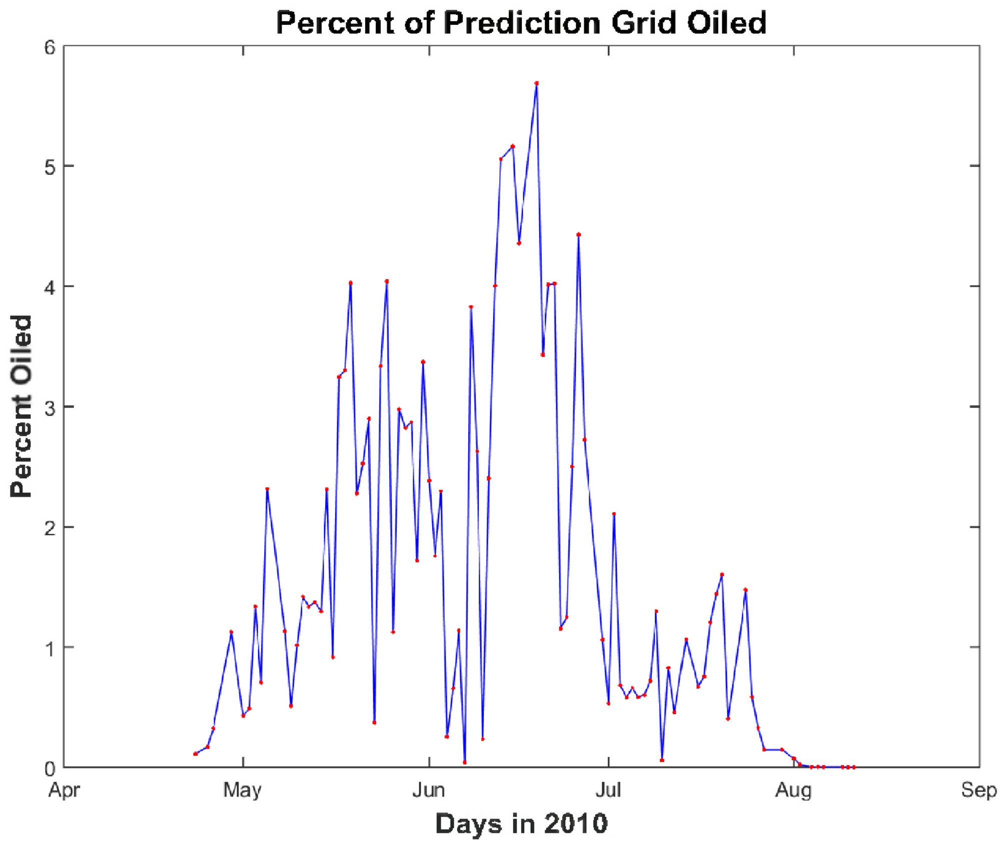

Figure 5 - Percent of the US Economic Exclusion Zone covered by surface oil in 2010 as measured by the TCNNA product. Red markers indicate observed values. Blue line is the time series with missing dates interpolated from adjacent values.

Red Snapper

Lutjanus campechanus is an economically important species that has been managed since 1984 (SEDAR 2013) and exhibits spatio-temporal patterns larval abundance that could result in fairly complex interactions between larvae and DWH contaminants. Early in the spill time frame the predicted relative abundance of red snapper larvae was somewhat low (Figure 6) and increased through the course of the spill (Figures 7 and 8). Of interest is the appearance of higher relative abundances near and inshore of the shelf break.

Aggregating all of the daily relative abundance data within the daily footprints of the surface oil maps identifies those areas where larger numbers of red snapper where potentially exposed to surface oil. These aggregated data, normalized to a maximum value of one, are shown in Figure 9. The pattern exhibited reflects both the frequency of surface oiling in any given cell and the spatio-temporal pattern in the relative abundance maps.

The next analysis was to examine the 'production schedule', or the time series of estimated relative abundance throughout the study area across the time frame of the spill. We also examined the same data constrained to the area covered by oil each day. These data are shown in Figure 10 where the top panel represents the 'production schedule' or total relative number of red snapper expected in the EEZ each day from April 23 to August 11, 2010. The middle panel represents the relative number that we estimate to be under the daily footprint of the oil. The bottom panel represents the estimated percent of total daily production under the oiled footprint on each day. The 'percent exposed overall' is simply the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve) expressed as a percentage.

The expected mean daily exposure for red snapper can range to as much as 10% of the animals in the system on some days. These values are indeed higher than those seen in the area of the EEZ oiled which did not exceed about 5.7% (see Fig. 5). However, the overall percent potentially exposed is on the order of 2.3% of the total that were expected to be in the EEZ during the spill. One reason for this is that the production schedule peaks toward the end of the spill when surface oiling was decreasing (see Fig. 5) and so there was a temporal mismatch.

It is important to recall that these analyses use expected mean relative abundance data as predicted by the GAMs. Estimates of the standard error of the relative mean were also available for each day and cell in the prediction grid. From these one could construct 95% confidence intervals for the mean estimated relative abundance. The primary importance of this concerns the range of possible injury. The estimated mean proportion exposed presented here may best be viewed as lying within a range that extends above and below the means presented here. Figure 11 through 13 show the standard errors calculated for the same three dates for which red snapper relative abundance were shown above.

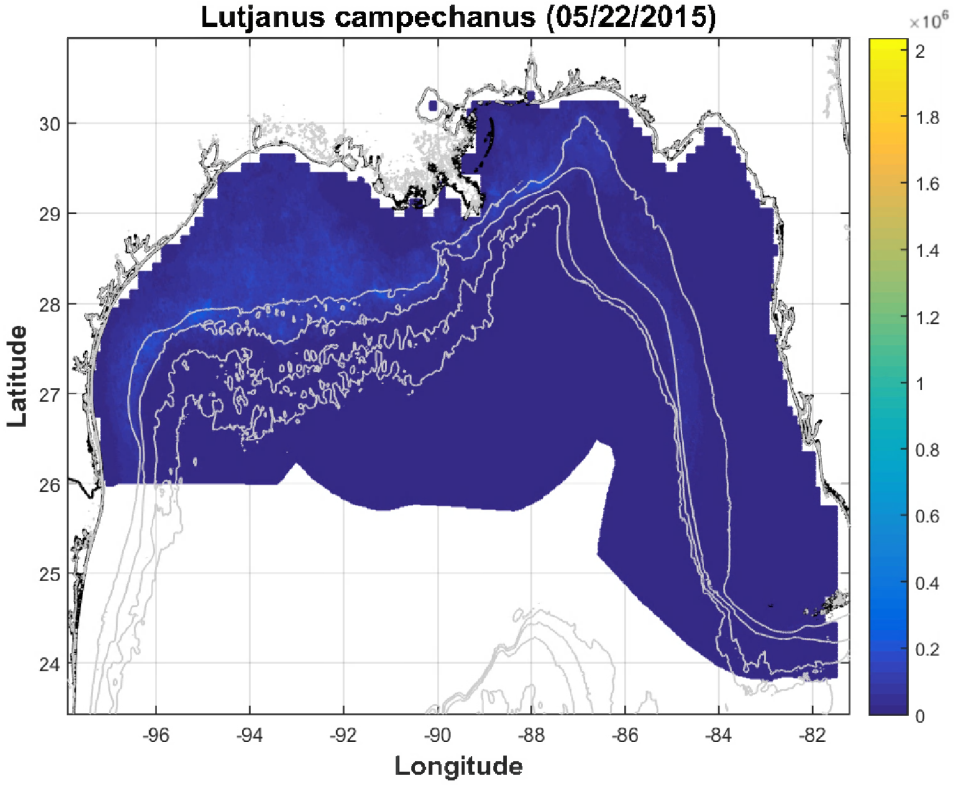

Figure 6 - Estimated relative abundance of Red Snapper on May 22, 2010 in the US Economic Exclusion Zone. Relative abundance on this date is lower than it is in the next two figures.

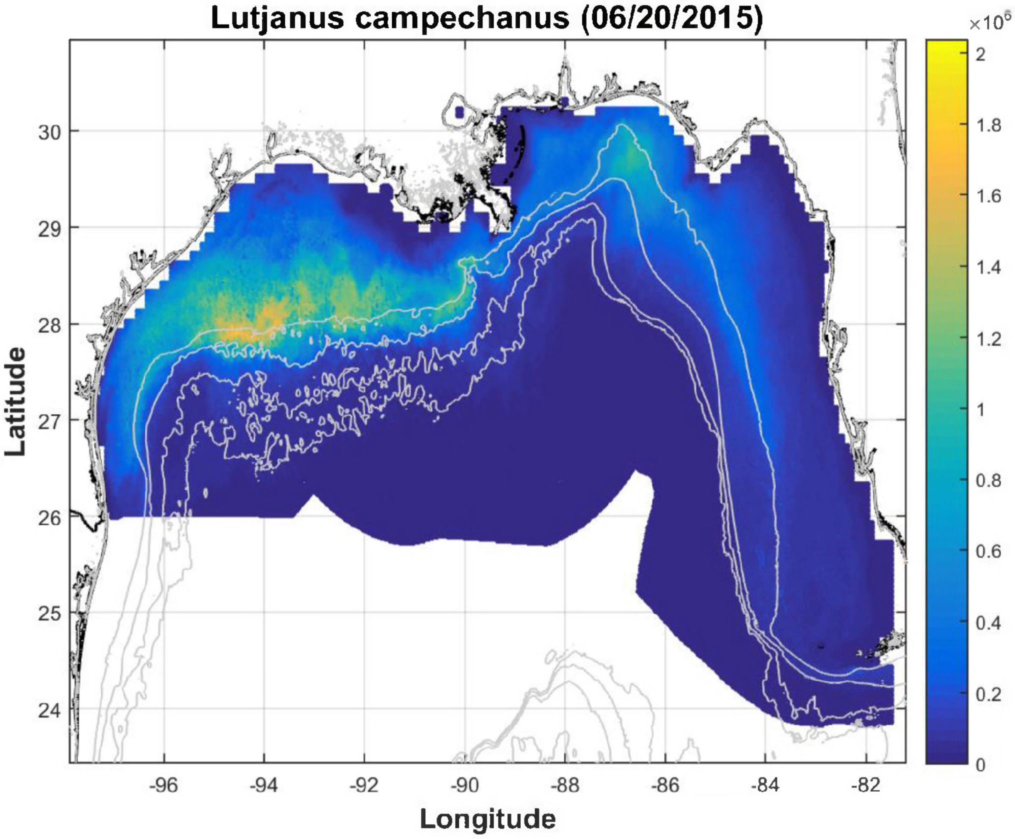

Figure 7- Estimated relative abundance of Red Snapper on June 20, 2010 in the US Economic Exclusion Zone. The relative abundance on this date is intermediate between those presented in Figures 6 and 8.

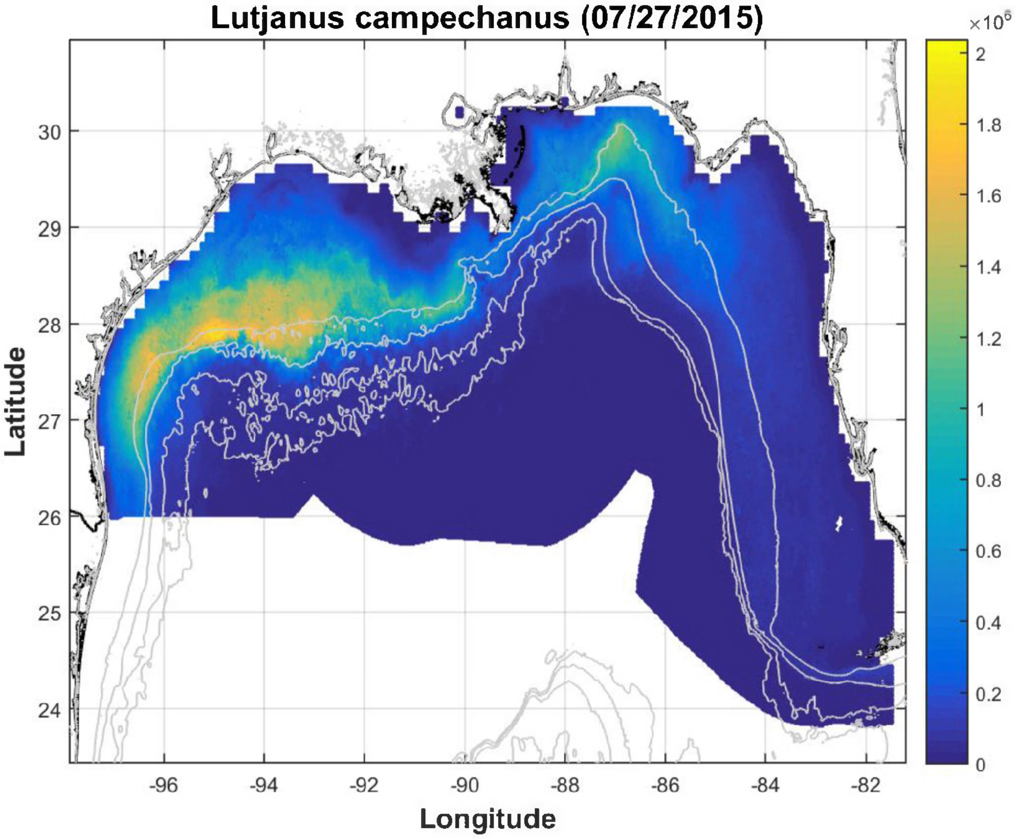

Figure 8 - Estimated relative abundance of Red Snapper on July 27, 2010 in the US Economic Exclusion Zone. Relative abundance on this date is the highest of the dates presented in Figures 6 through 8.

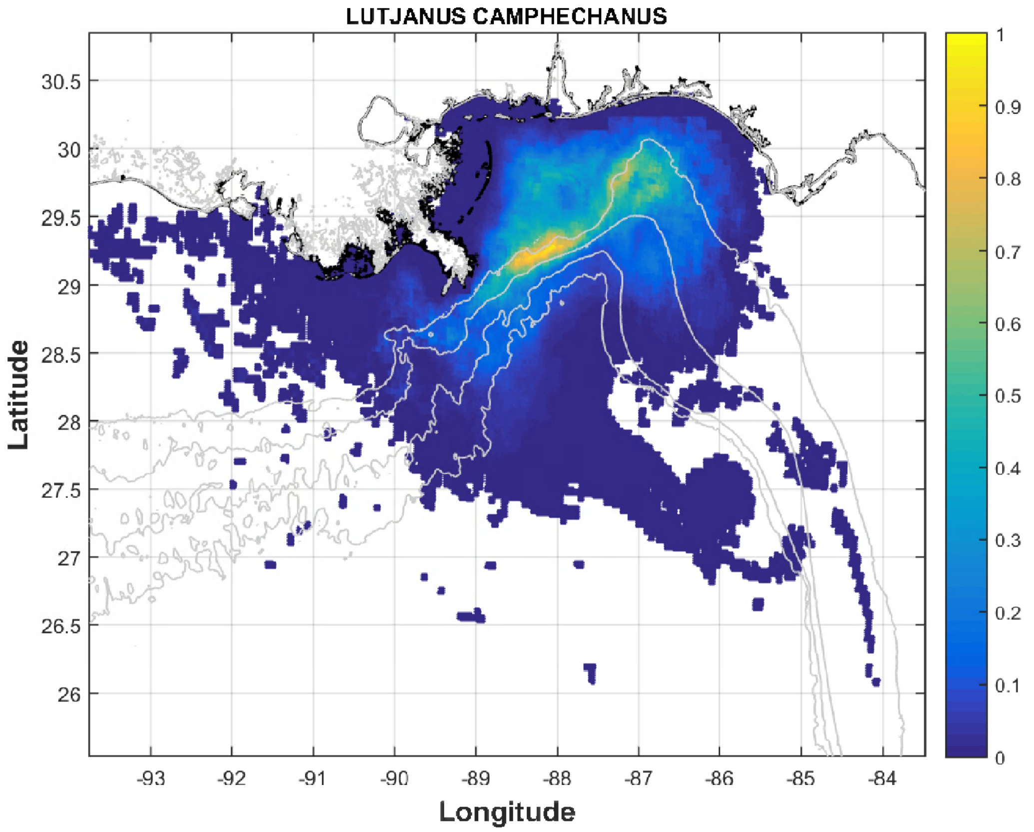

Figure 9 - Aggregated and normalized abundance data under the footprint of the surface slick. A larger number of red snapper where exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

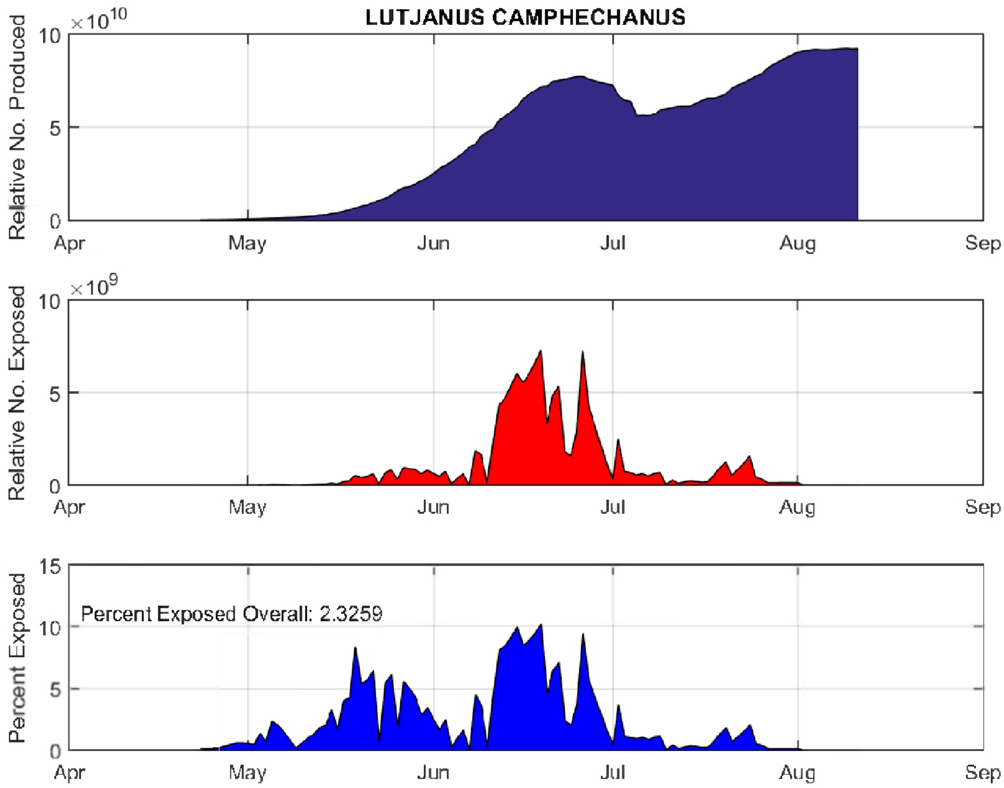

Figure 10 - Time series of red snapper relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of red snapper in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

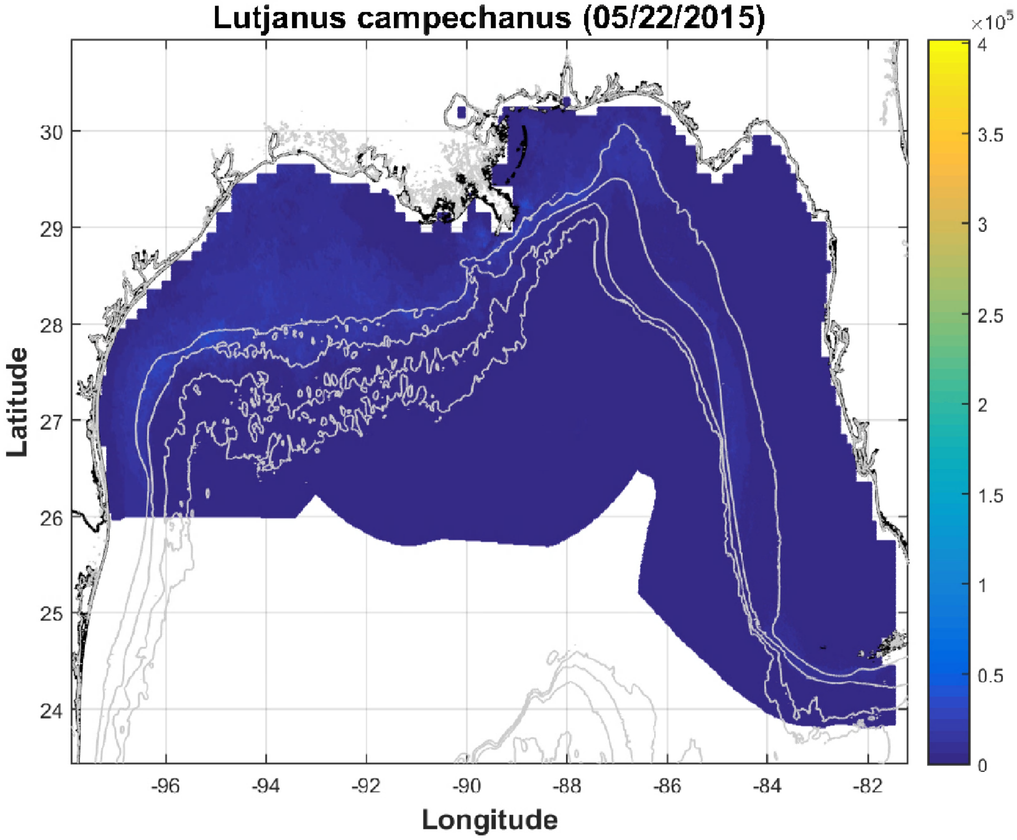

Figure 11 - Standard error of the mean relative abundance for red snapper on May 22, 2010.

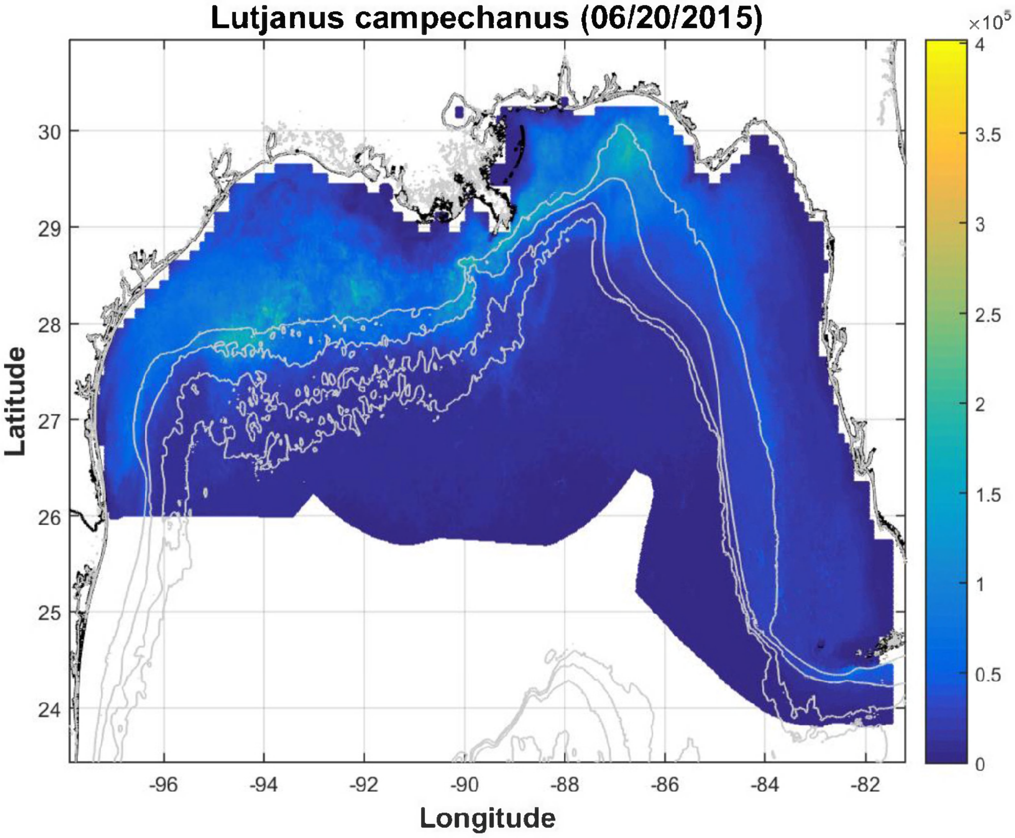

Figure 12 - Standard error of the mean relative abundance for red snapper on June 20, 2010.

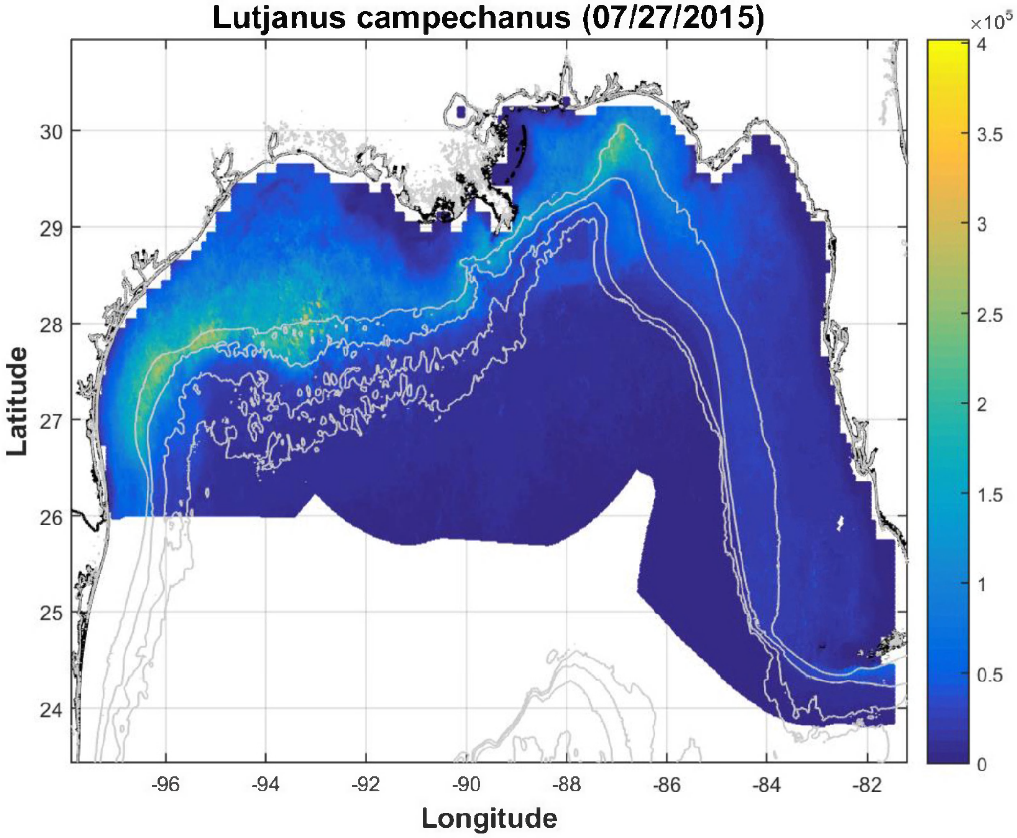

Figure 13 - Standard error of the mean relative abundance for red snapper on July 27, 2015.

Discussion

The analyses suggest that the percent of larval fish in the entire Gulf of Mexico EEZ potentially exposed to oil between April 23 and August 11, 2010 ranges from about 0.1 to 7.5 percent, averaging about 2.1 percent, for the taxa presented here. The location of the most intense expected injury varies among taxa and is structured by the spatio-temporal patterns of organism abundance and the oil distribution.

Though summary data are presented as percentages of the entire EEZ, it must be noted that impacts could be much more pronounced and that localized impacts may be particularly important. If, rather than considering the entire EEZ, the analyses considered only high quality habitat or some reduced area the exposed percentages would be higher. Additionally, production in some areas may be critically important for some species. There is a vast literature on connectance in larval fish ecology and the importance of spawning in the correct time and place (Quinlan et al. 1999, Paris and Cowen 2004, Cowen et al. 2007, Cowen and Sponaugle 2009). Injury to areas that serve as source regions for recruitment elsewhere could mean that the net impact was larger and more nuanced than that depicted in these analyses.

The analyses also provide a perhaps novel way to assess injury. By acknowledging that net sampling provides a measure of relative abundance and not necessarily the true abundance, we transformed the problem into one in which the primary metric is the expected proportion of the ‘productivity’ for each taxa that was potentially exposed to oil. While this requires a number of strong assumptions, it also offsets some of the uncertainties associated with adjustments needed to relate abundance as measured by a net to absolute abundance.

These analyses can help provide information to identify and characterize areas of potential injury in terms of size (e.g., the total areal extent of say 90% of the injury overall), intensity (e.g., the upper 10%) and geographic location. This information may be valuable for identifying and implementing restoration projects.

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Appendix - Taxa-Specific Results

This appendix contains the core graphics associated with analyses of additional taxa. These taxa were selected to represent a range of life histories and/or the taxon was economically or ecologically important. Each taxon includes a brief statement describing the group. The first graphic is the normalized, cumulative relative abundance of the organism during the period of April 23 to August 11, 2010. The second is the three panel 'time series' plot showing the productivity schedule, the number potentially oiled, and the daily percent of total production potentially oiled.

ACANTHURIDAE

Acanthuridae is the family of surgeonfishes and allies. The analyses show that potential injury to larval *Acanthuridae* occurred over a broad area and especially south and west of the wellhead. The production schedule during the spill peaked in late May and remained broadly flat otherwise. Daily percent potentially exposed ranged from near zero to about 3%. Overall, approximately 0.7% of the expected number of Acanthuridae larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

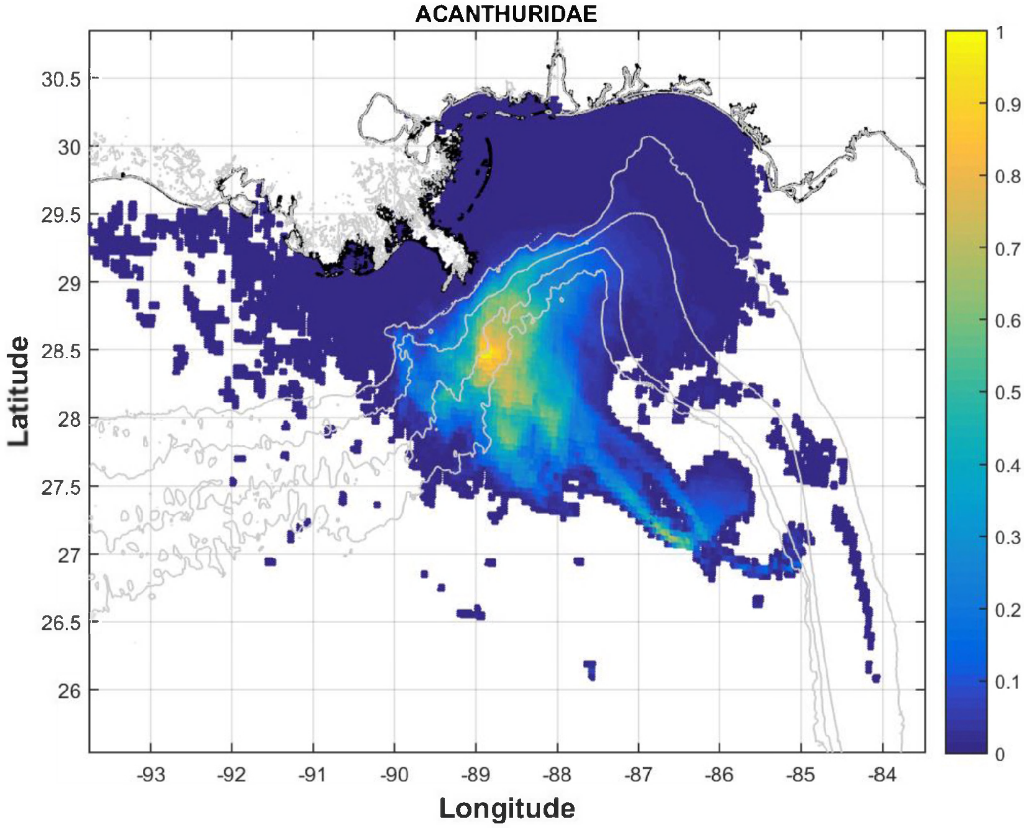

Figure 14 - Aggregated and normalized abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

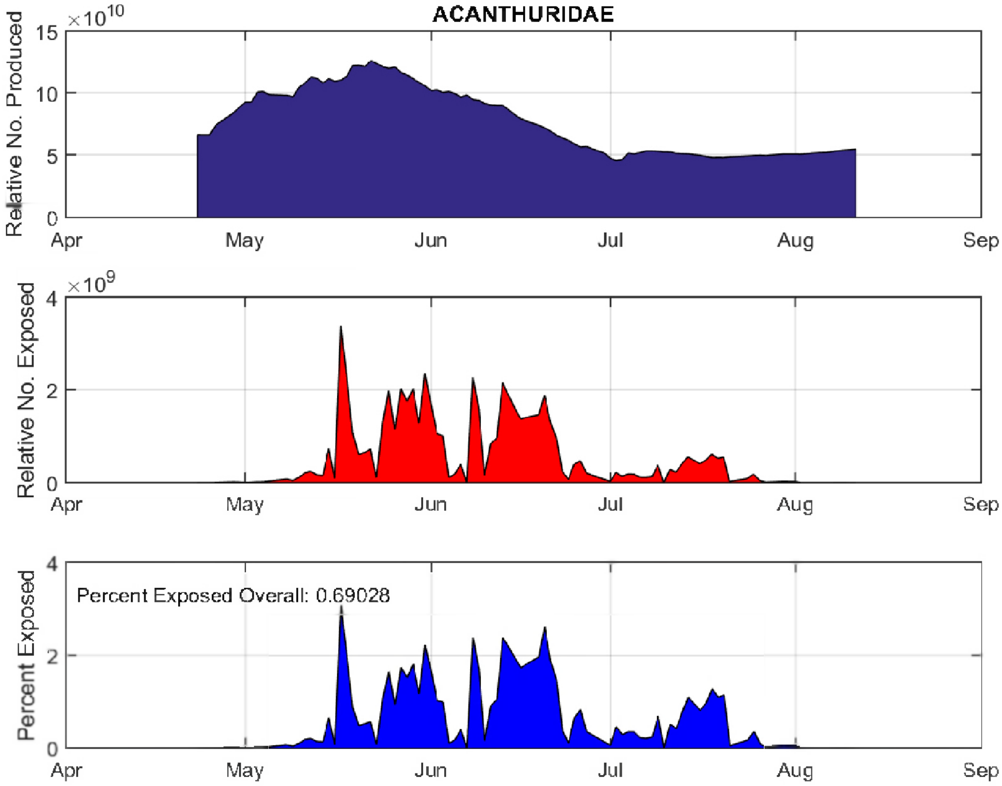

Figure 15 - Time series of Acanthuridae relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of red snapper in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

ANGUILLIFORMES

The Order *Anguilliformes* represents eels such as snake, conger, and moray. The analyses show that potential injury to larval *Anguilliformes* occurred over a broad area and was centered between the 100 and 400m isobaths near the wellhead. The production schedule during the spill peaked in early to mid-July. Daily percent potentially exposed ranged from near zero to about 13%. Overall, approximately 4.2% of the expected number of *Anguilliformes* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

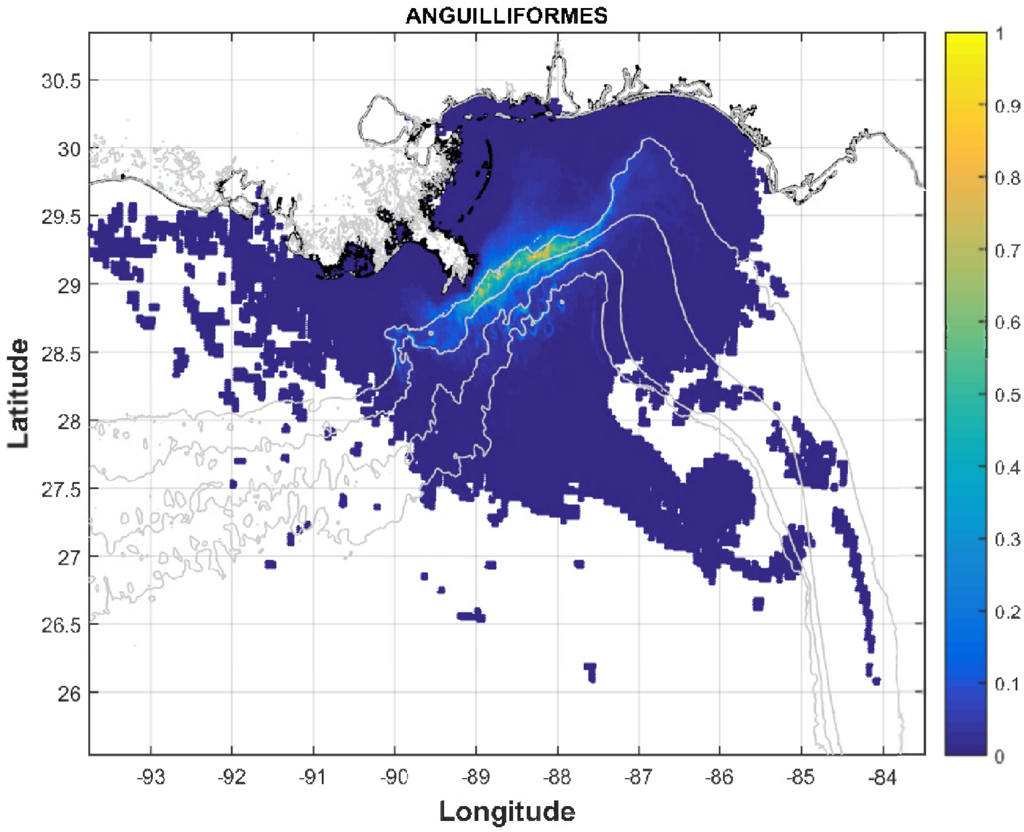

Figure 16 - Aggregated and normalized Anguilliformes abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

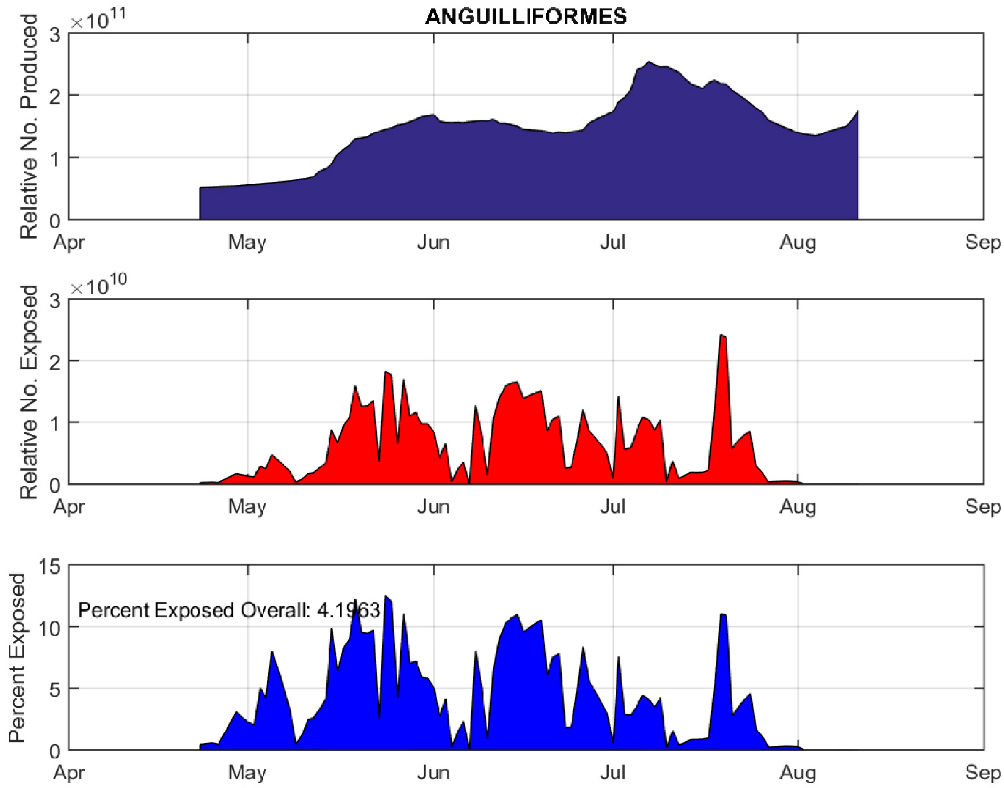

Figure 17 - Time series of Anguilliformes relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Anguilliformes in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

AUXIS

The genus *Auxis* are commonly known as frigate tuna, frigate mackerel, or bullet mackerel. The analyses show that potential injury to larval *Auxis* occurred over a broad area and was centered between the 100 and 1500m isobaths near the wellhead. Potential exposure also occurred throughout the Desoto Canyon area. The production schedule during the spill ramped up from late April to a peak in late June and another in early August. Daily percent potentially exposed ranged from near zero to about 14%. Overall, approximately 7.2% of the expected number of *Auxis* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

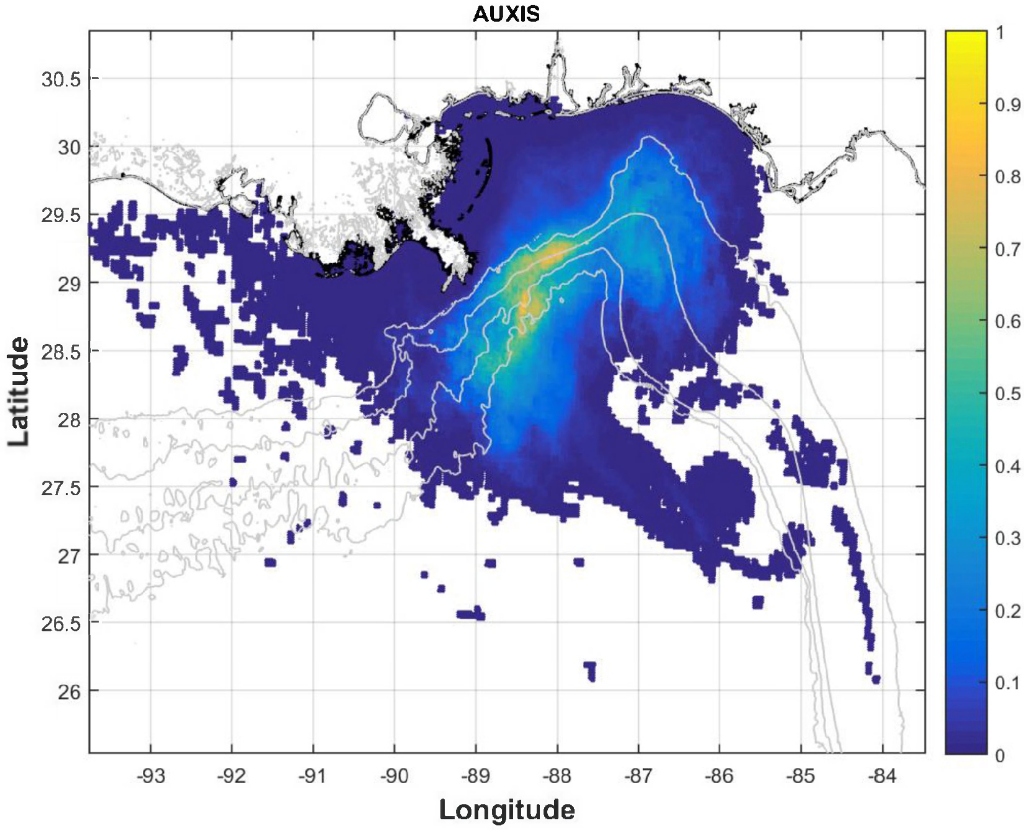

Figure 18 - Aggregated and normalized Auxis abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

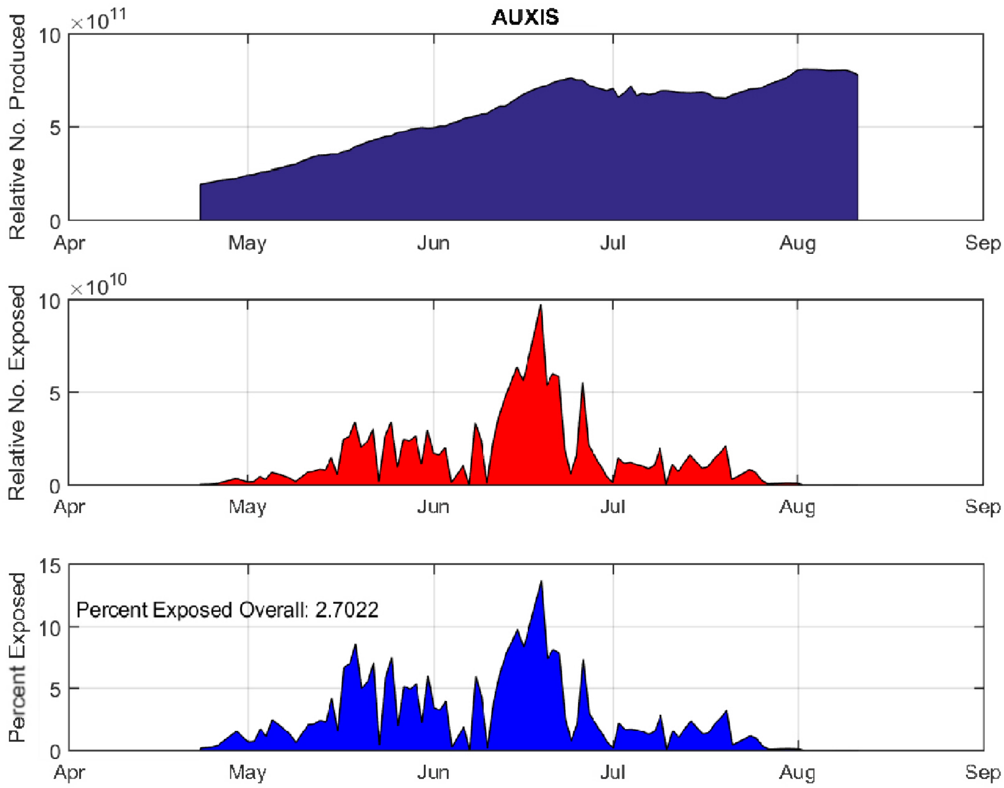

Figure 19 - Time series of Auxis relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Auxis in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

BLENNIIDAE

The family *Blenniidae* is large and diverse. Adults are structure oriented and eggs are generally deposited demersally, but larval stages are pelagic. The analyses show that potential injury to larval *Blenniidae* occurred over a broad area centered more or less along the 100 m isobath. The production schedule during the spill was at its peak at the start of the spill and ramped down through early August. Daily percent potentially exposed was typically near 5%. Overall, approximately 1.8% of the expected number of *Blenniidae* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

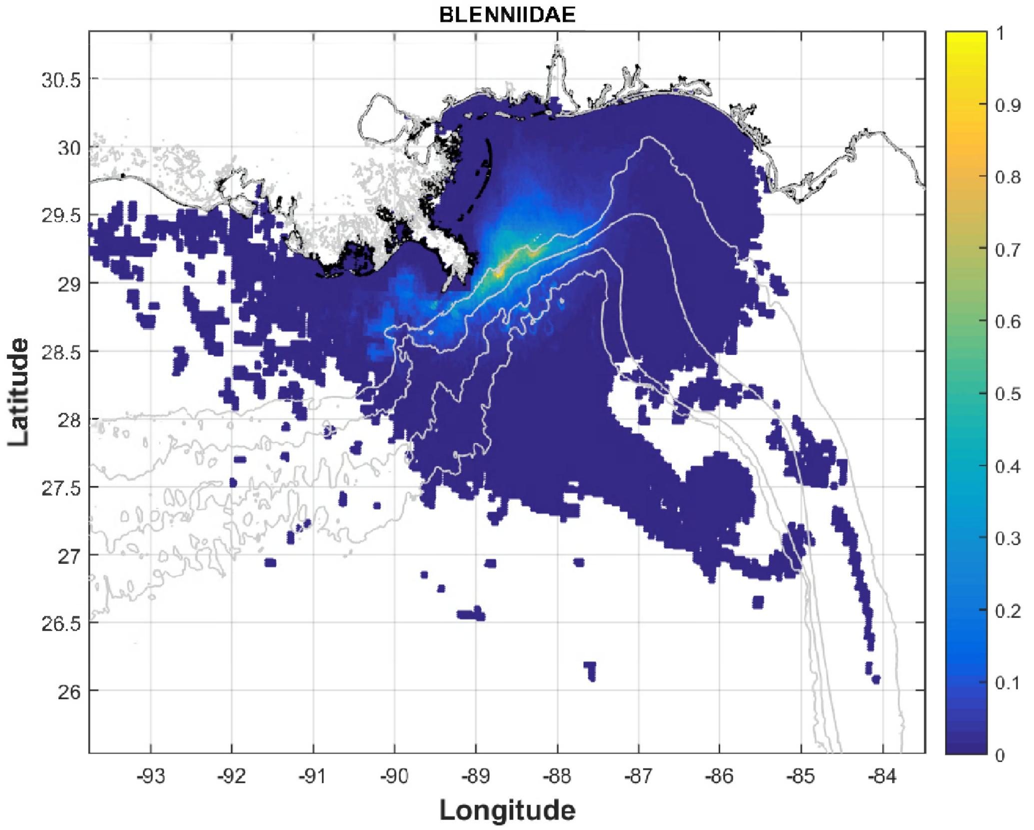

Figure 20 - Aggregated and normalized Blenniidae abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

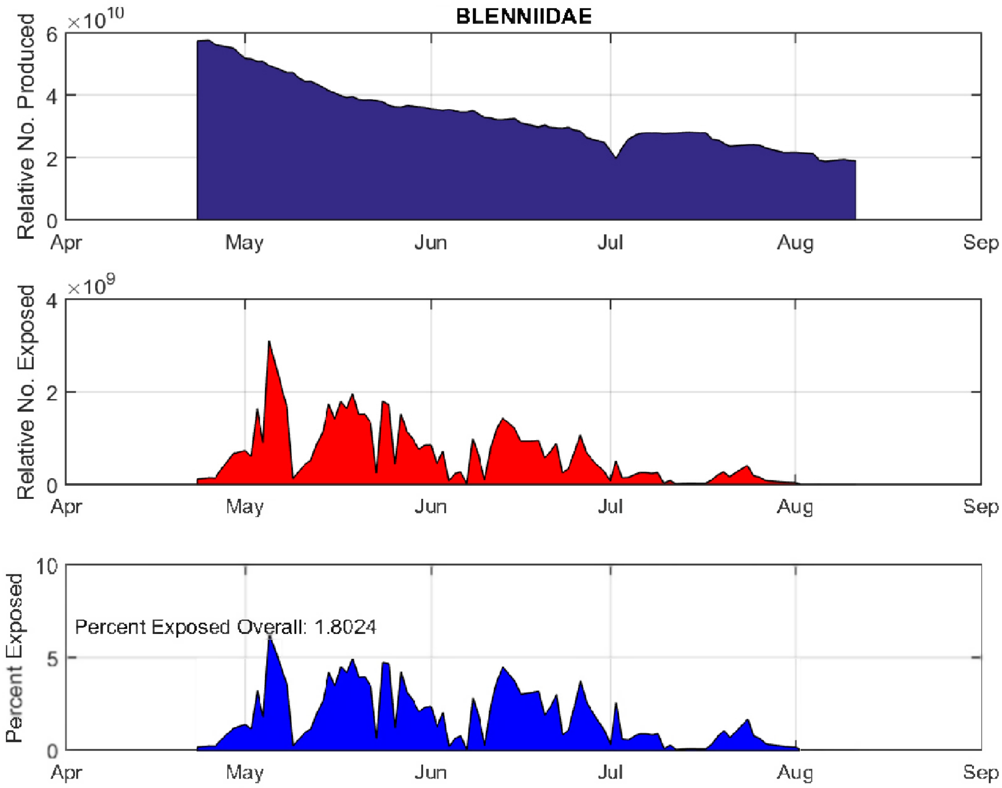

Figure 21 - Time series of Blenniidae relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Blenniidae in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

CHLOROSCOMBRUS CHRYSURUS

The species *Chloroscombrus chrysurus* is commonly known as Atlantic bumper and is important as a prey species for larger predators. The analyses show that potential injury to larval Atlantic bumper occurred over a broad area inshore of the 100 m isobath. The production schedule during the spill was increasing to a larger peak in early August. Daily percent potentially exposed ranged from near zero to about 5%. Overall, approximately 1.1% of the expected number of Atlantic bumper larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

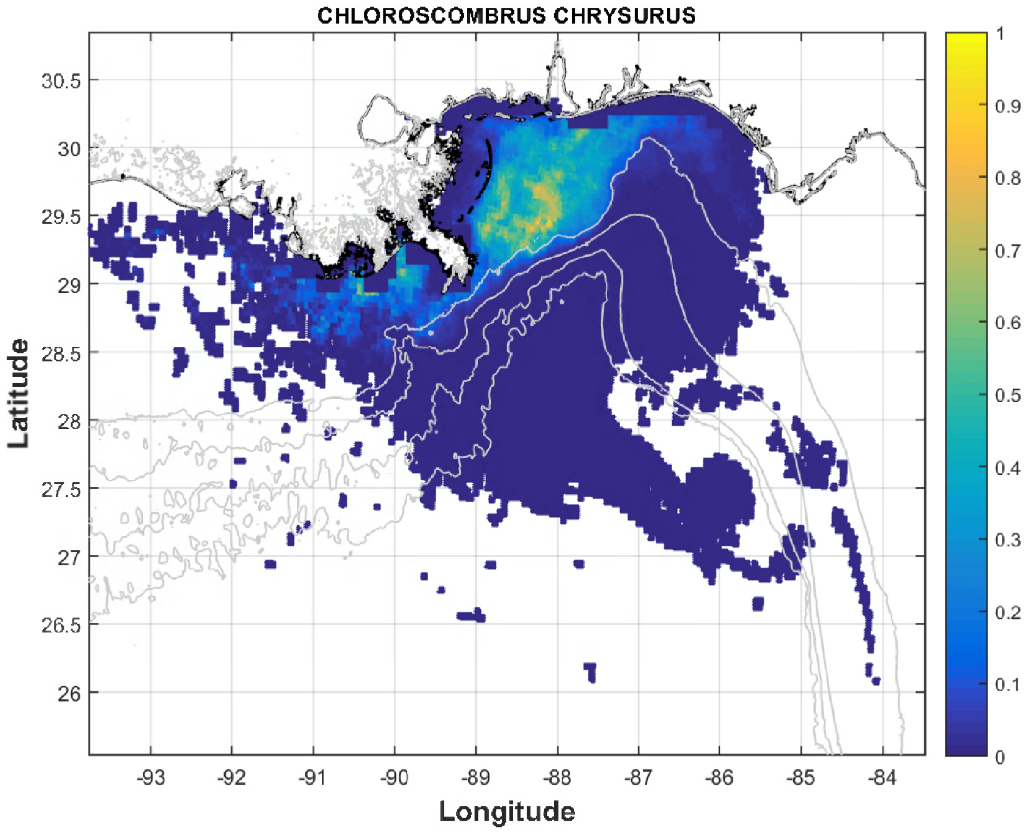

Figure 22 - Aggregated and normalized Atlantic bumper abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

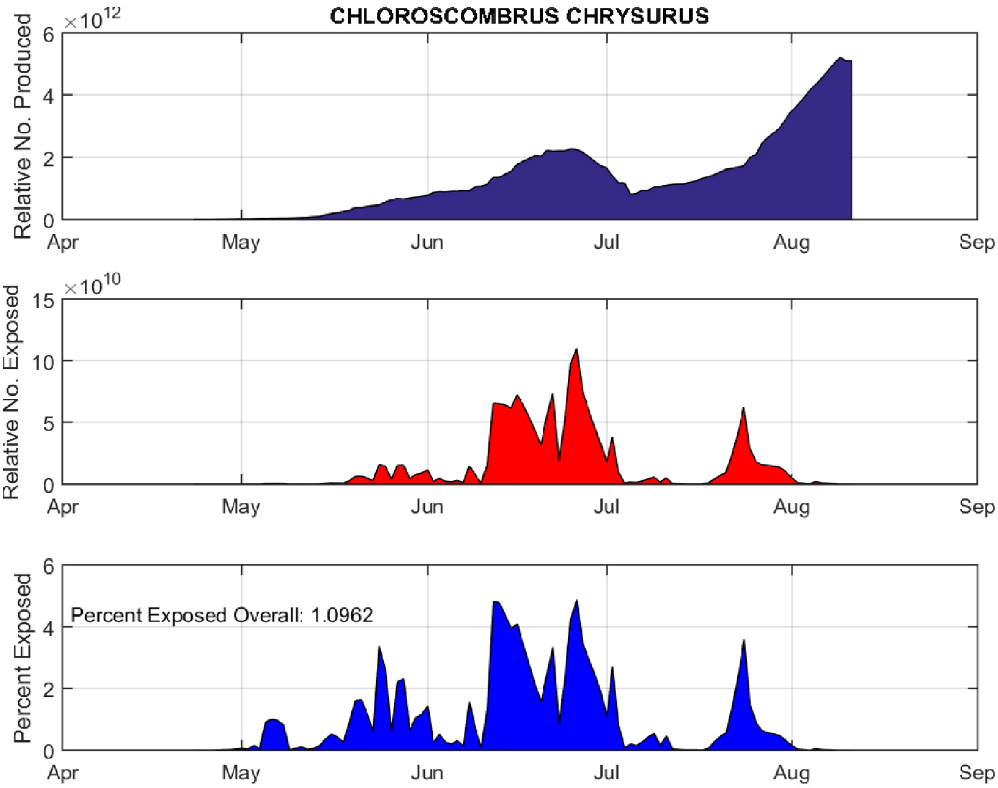

Figure 23 - Time series of Atlantic bumper relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Atlantic bumper in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

CLUPIEDAE

The family *Clupiedae* includes herrings, sardines, shads, and menhadens. The analyses show that potential injury to larval *Clupiedae* occurred over a broad diffuse area mostly inshore of the 1500 m isobath. The production schedule during the spill was broadly flat with a peak in June. Daily percent potentially exposed ranged from near zero to about 10-12%. Overall, approximately 4.1% of the expected number of *Clupiedae* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

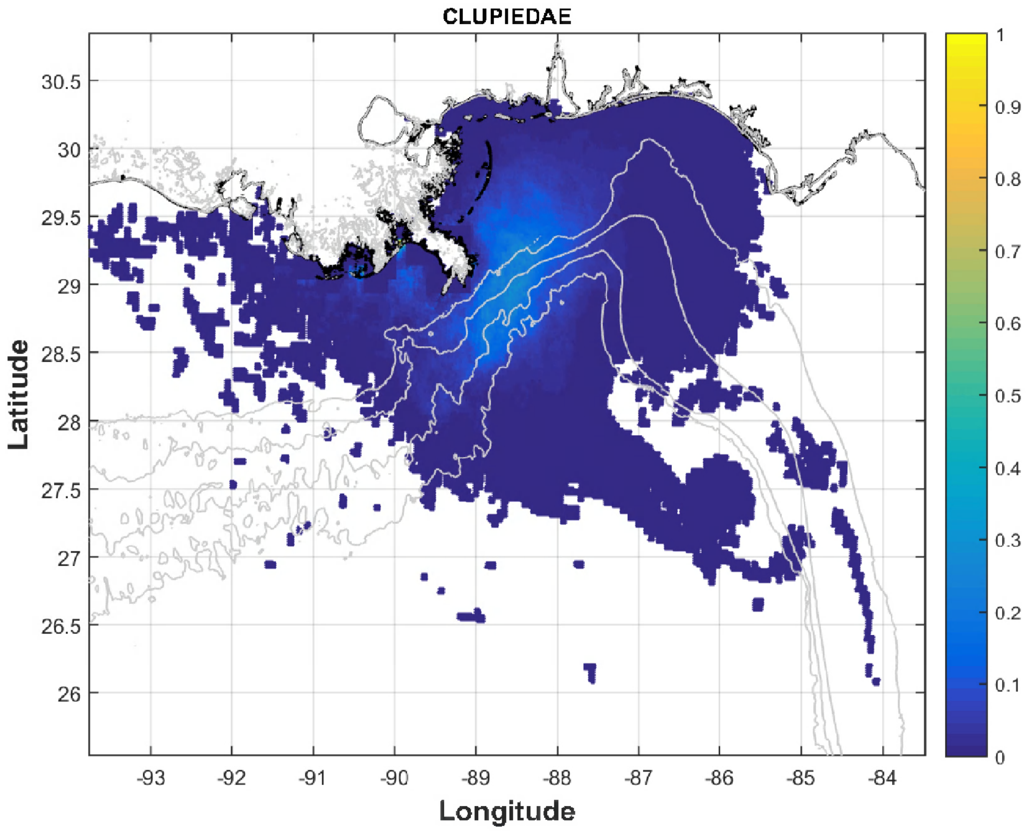

Figure 24 - Aggregated and normalized Clupiedae abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

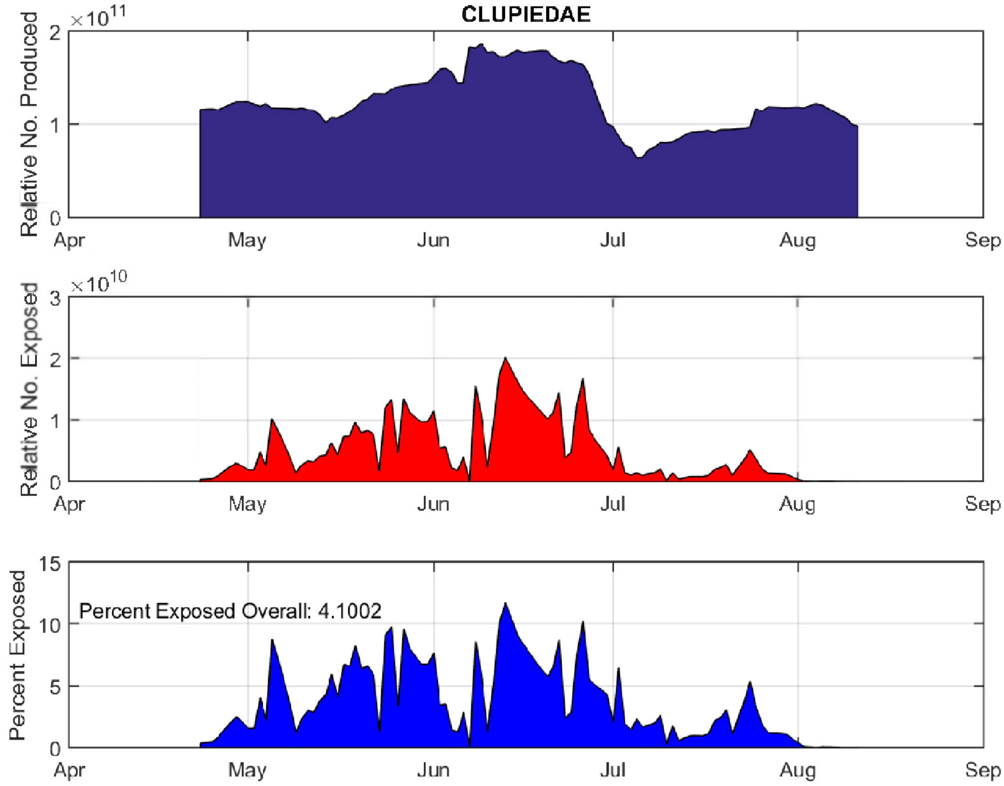

Figure 25 - Time series of Clupiedae relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Clupiedae in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

CLUPIEFORMES

The order *Clupieformes* includes herrings and anchovy families. The analyses show that potential injury to larval *Clupieformes* occurred over a broad diffuse area mostly inshore of the 400 m isobath. The production schedule during the spill exhibited peaks in June and early August. Daily percent potentially exposed ranged from near zero to about 20%. Overall, approximately 5.6% of the expected number of *Clupieformes* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

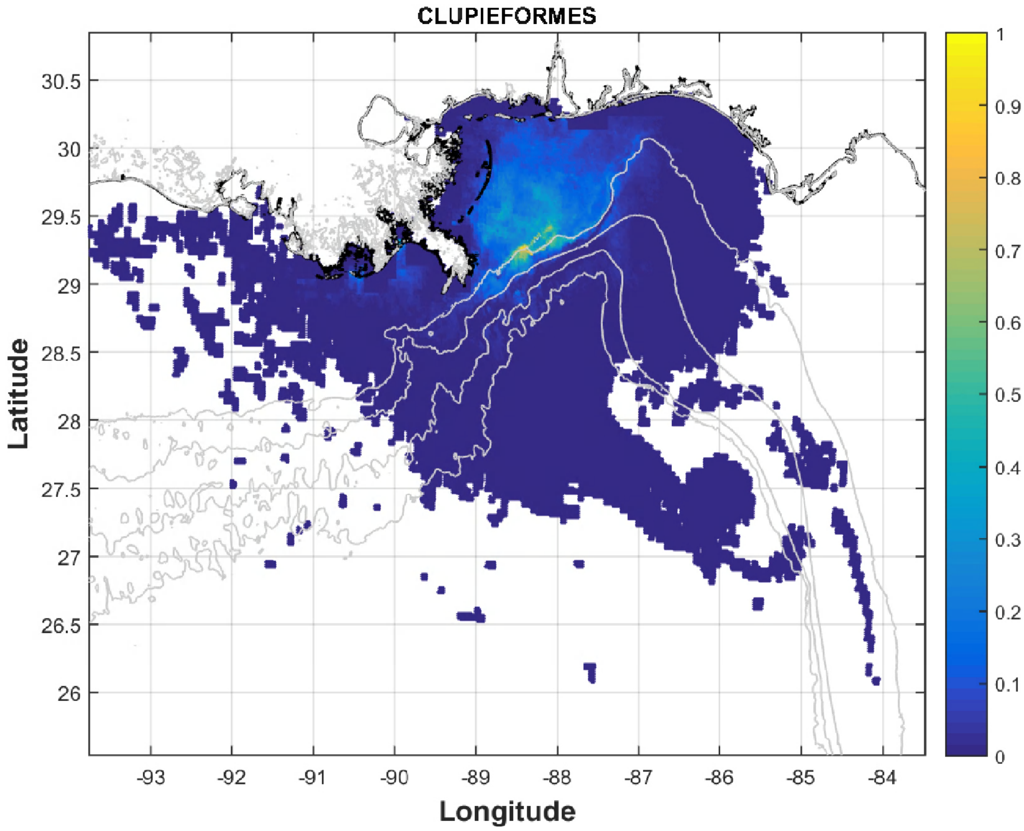

Figure 26 - Aggregated and normalized Clupieformes abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

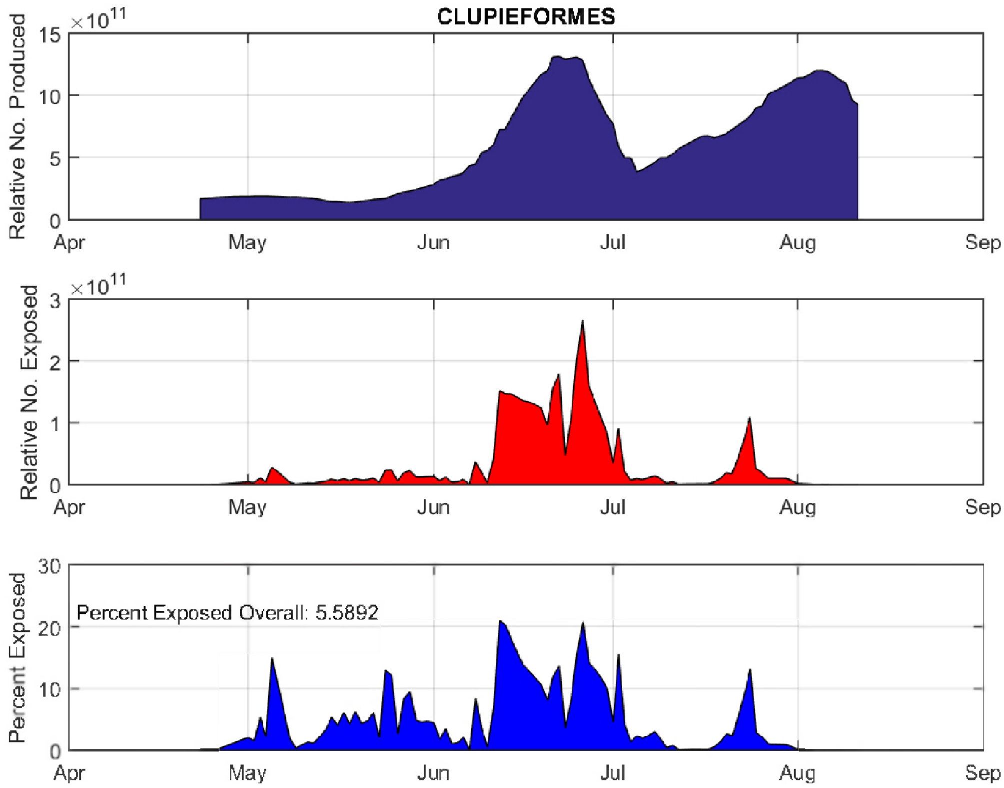

Figure 27 - Time series of Clupieformes relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Clupieformes in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

CYNOSCION

The genus *Cynoscion* are drums that include sea trouts. The analyses show that potential injury to larval *Cynoscion* occurred over a broad diffuse area mostly inshore of the 400 m isobath. The production schedule during the spill exhibited a minor peak in June and a larger peak in early August. Daily percent potentially exposed ranged from near zero to more than 20%. Overall, approximately 2.0% of the expected number of *Cynoscion* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

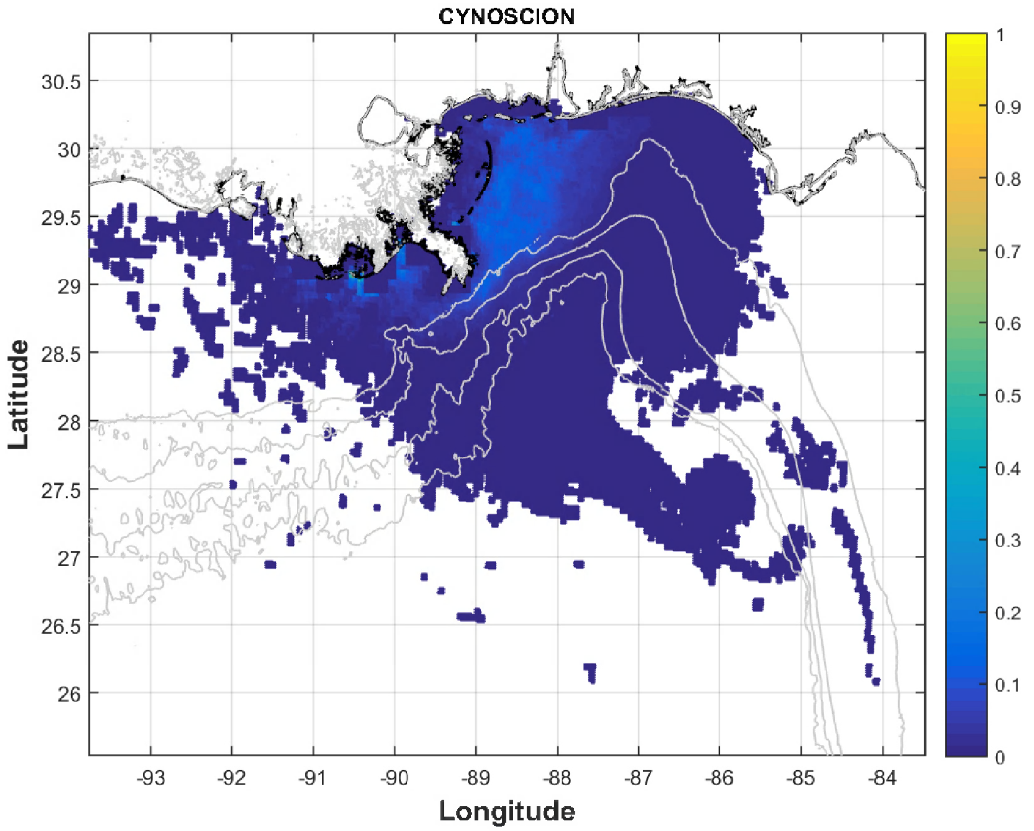

Figure 28 - Aggregated and normalized Cynoscion (trouts) abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

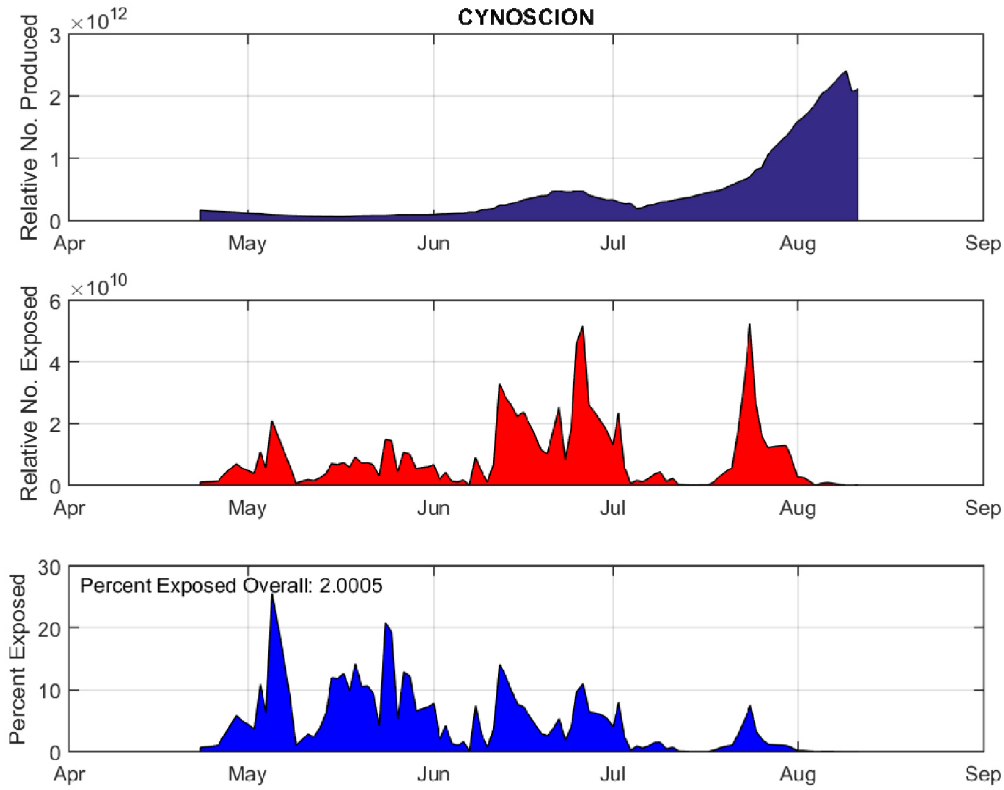

Figure 29 - Time series of Cynoscion relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Cynoscion in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

EPINEPHELINI

The *Epinephelini* are groupers and are economically important, slow growing fishes. The analyses show that potential injury to larval *Epinephelini* occurred over a broad area mostly offshore of the 100 m isobath with increased incidence between the 100 and 400m isobaths. The production schedule during the spill was broadly flat. Daily percent potentially exposed ranged from near zero to nearly 15%. Overall, approximately 1.7% of the expected number of *Epinephelini* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

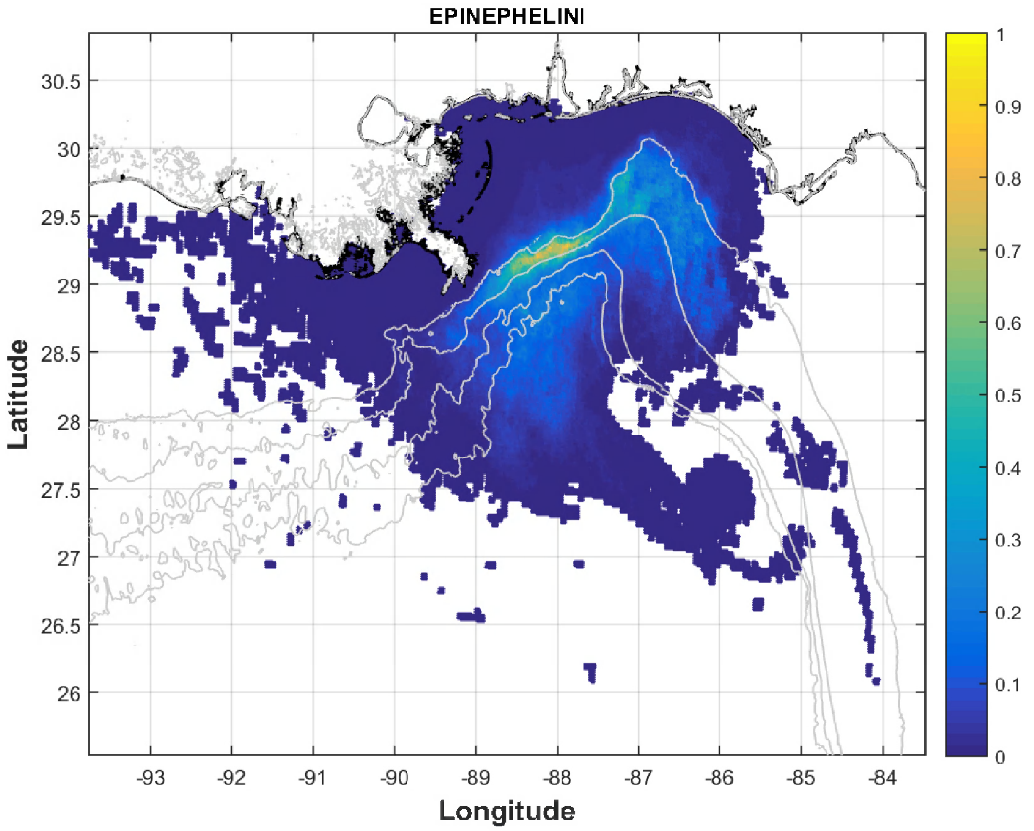

Figure 30 - Aggregated and normalized grouper abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

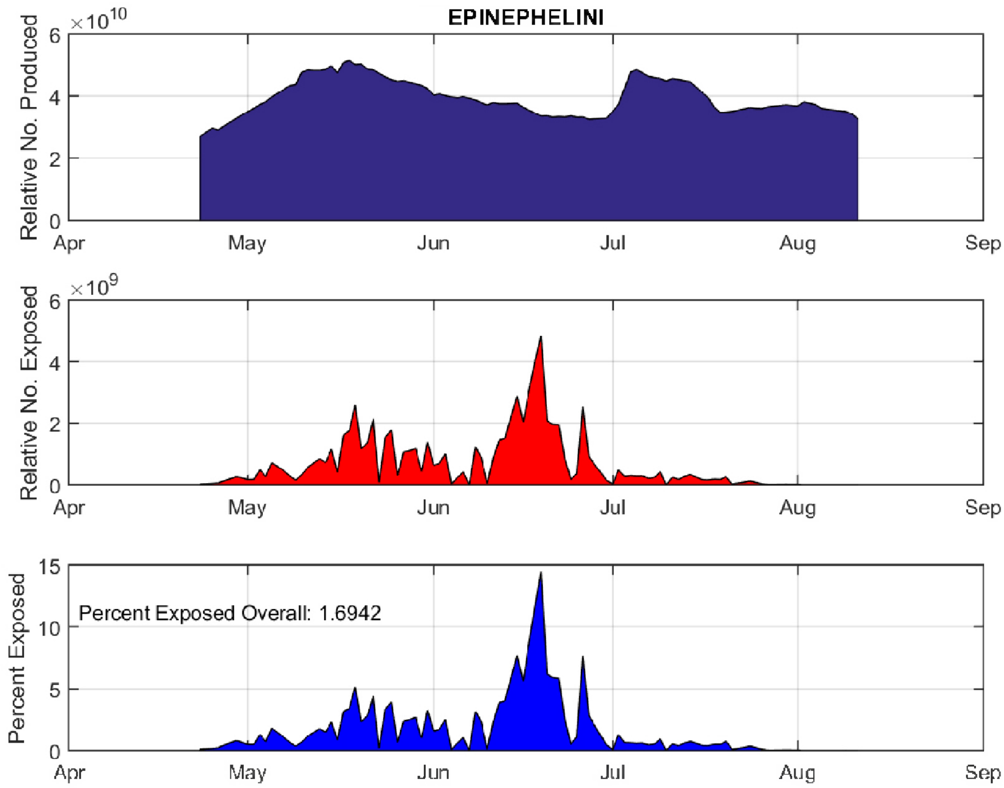

Figure31 - Time series of grouper relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of grouper in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

EUTHYNNUS_ALLETTERATUS

The species *Euthynnus alletteratus* is the little tunny, a recreationally important fish. The analyses show that potential injury to larval little tunny occurred over a broad diffuse area seaward of the 100 m isobath. The production schedule during the spill ramped from low in April to a peak in mid-July. Daily percent potentially exposed ranged from near zero to about 10%. Overall, approximately 3.1% of the expected number of little tunny larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

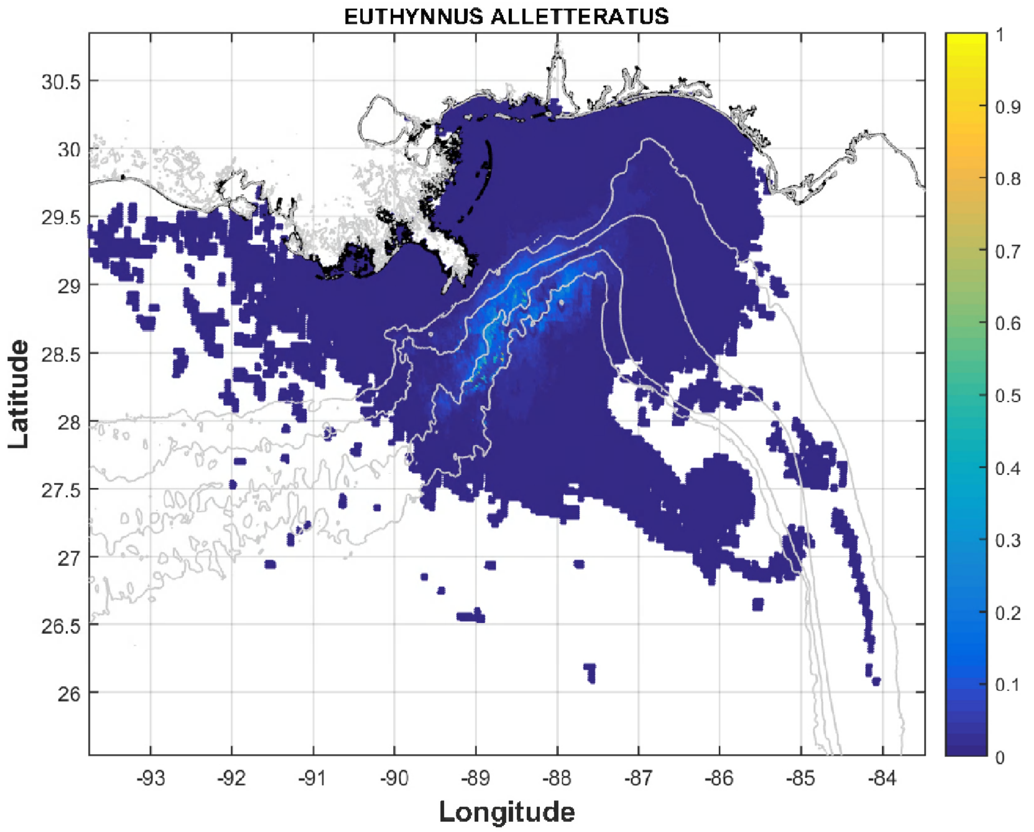

Figure 32 - Aggregated and normalized little tunny abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

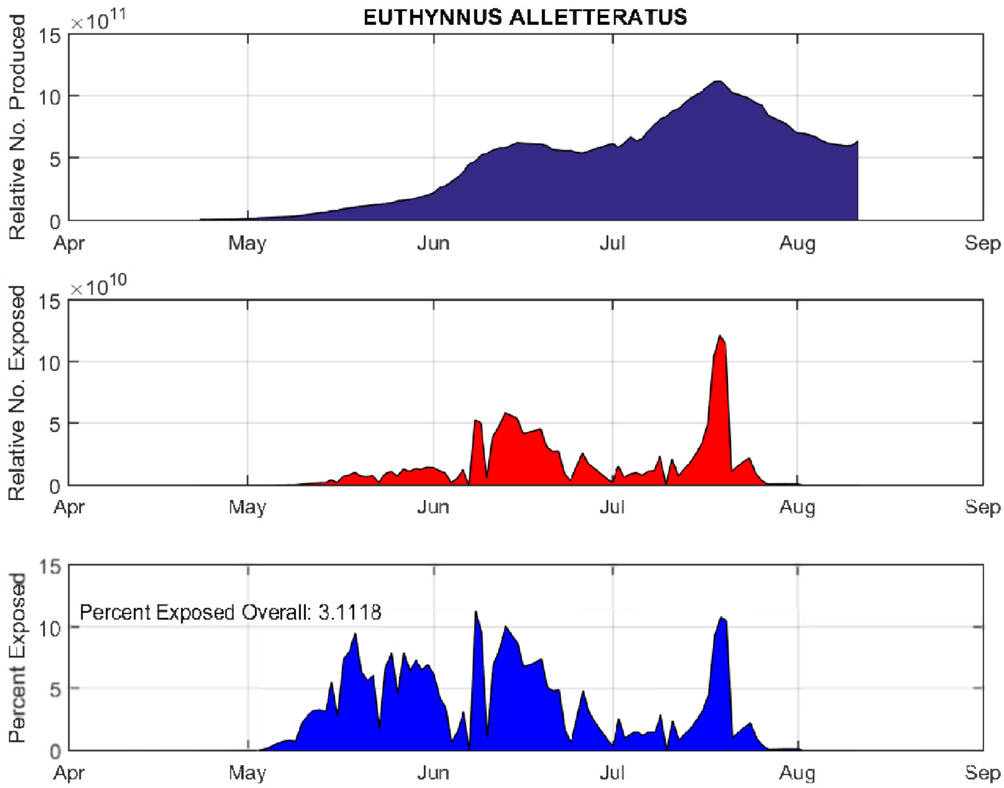

Figure 33 - Time series of little tunny relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of little tunny in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

EXOCOETOIDEA

The family *Exocoetoidea* are the ecologically important flying fishes. The analyses show that potential injury to larval flying fishes occurred over a broad diffuse area. The production schedule during the spill peaked in early July. Daily percent potentially exposed ranged from near zero to about 5%. Overall, approximately 1.1% of the expected number of flying fish larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

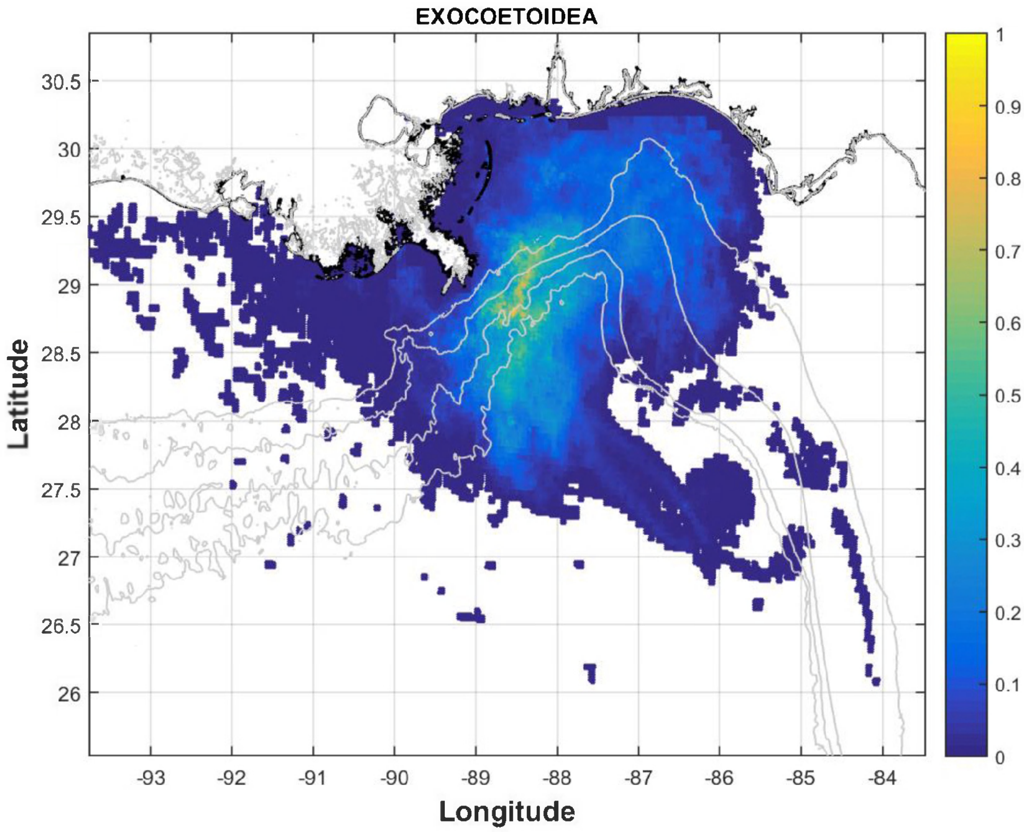

Figure 34 - Aggregated and normalized flying fishes abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

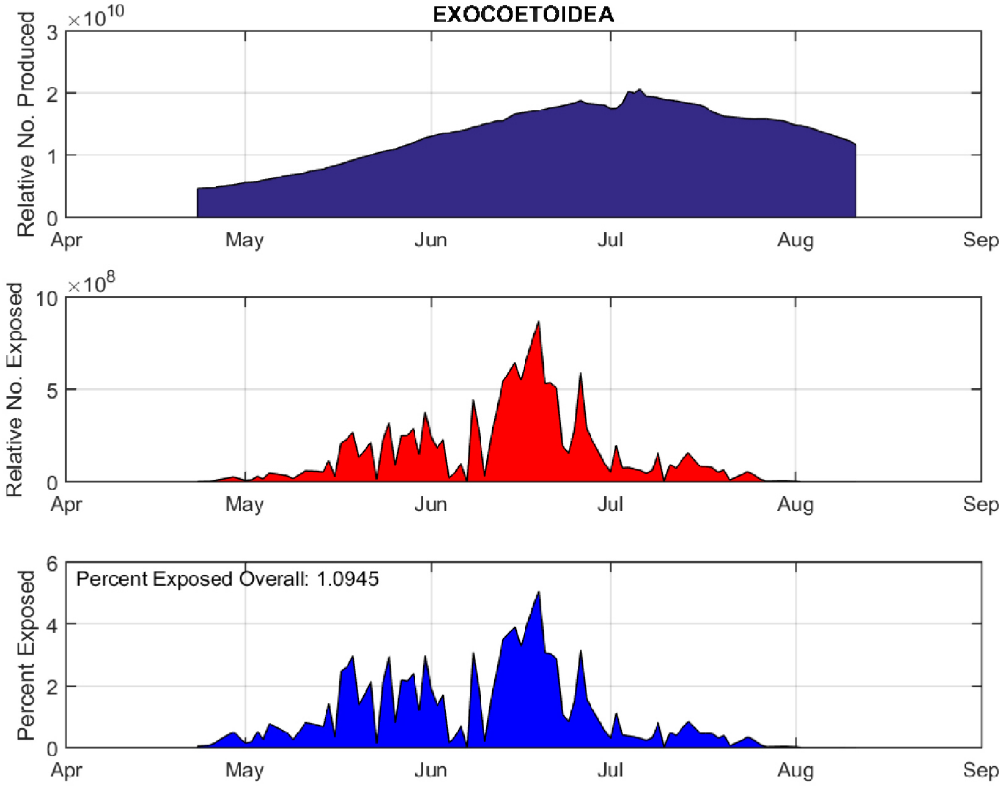

Figure 35 - Time series of flying fishes relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of flying fishes in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

GOBIIDAE

The family *Gobiidae* is large, diverse and fairly ubiquitous. The analyses show that potential injury to larval *Gobiidae* occurred over a broad diffuse area centered between the 100 and 400m isobaths near the wellhead. The production schedule during the spill ramped from a low in April to a peak in early August. Daily percent potentially exposed ranged from near zero to nearly 6%. Overall, approximately 1.1% of the expected number of *Gobiidae* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

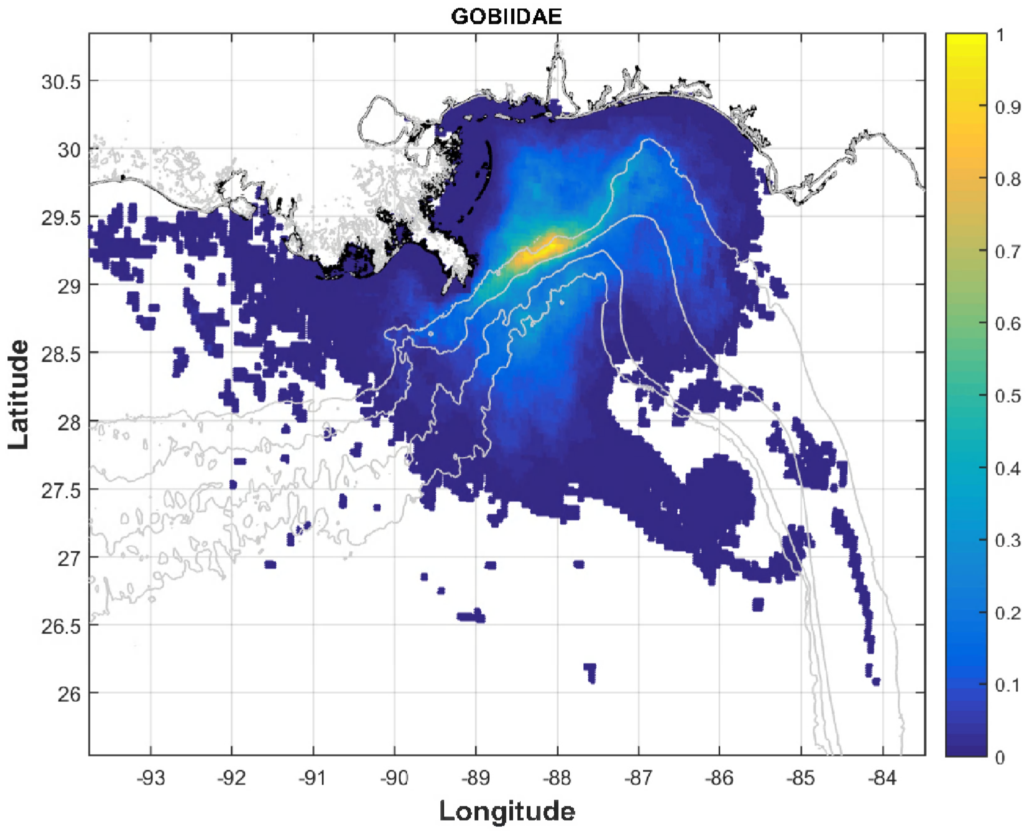

Figure 36 - Aggregated and normalized Gobiidae abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

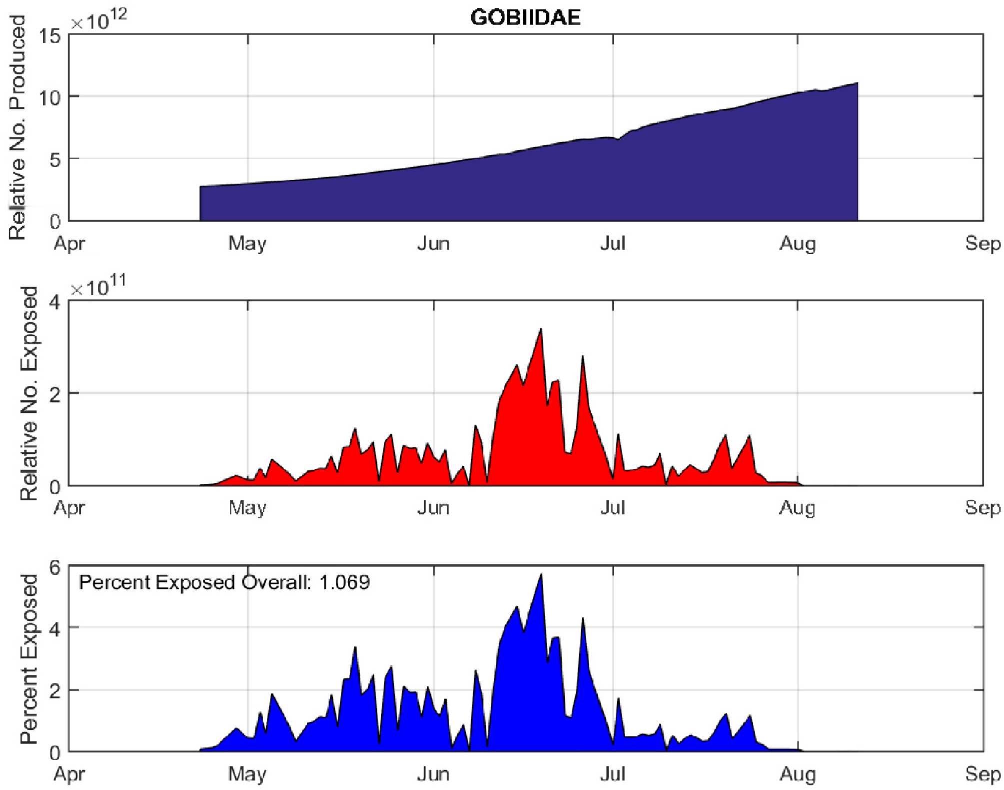

Figure 37 - Time series of Gobiidae relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Gobiidae in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

KATSUWONUS PELAMIS

Katsuwonus pelamis is the skipjack tuna. The analyses show that potential injury to larval skipjack tuna occurred over a broad diffuse area seaward of the 100m isobath. The production schedule during the spill was broadly flat with a peak in late June. Daily percent potentially exposed ranged from near zero to about 4%. Overall, approximately 1.0% of the expected number of skipjack tuna larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

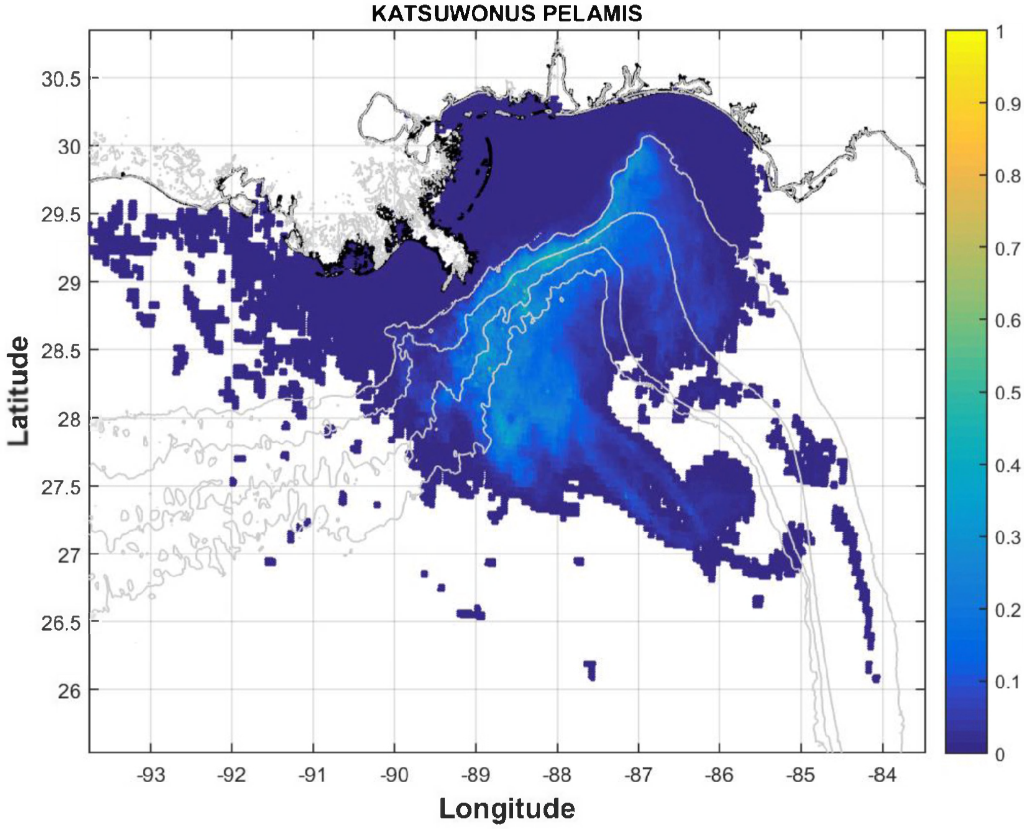

Figure 38 - Aggregated and normalized skipjack tuna abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

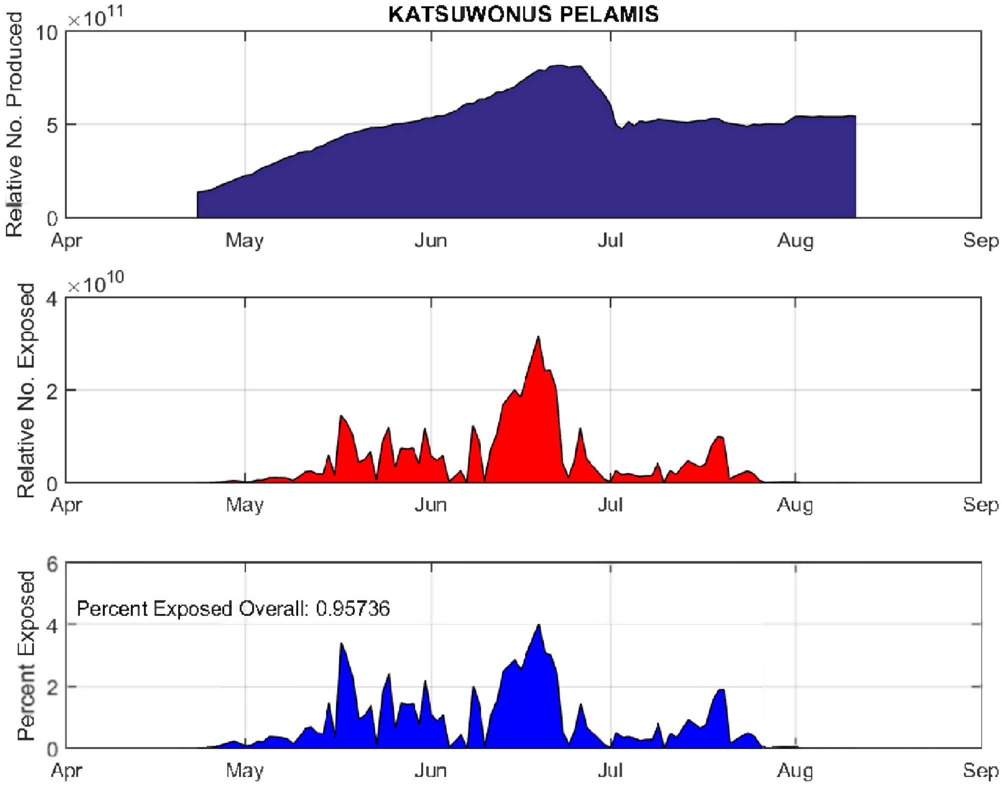

Figure 39 - Time series of skipjack tuna relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of skipjack tuna in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

LUTJANUS CAMPHECHANUS

Lutjanus campechanus are the economically important red snapper. The analyses show that potential injury to larval red snapper occurred over a broad area centered between the 100 and 400m isobaths. The production schedule during the spill ramped up to a minor peak in June and a larger peak in early August. Daily percent potentially exposed ranged from near zero to nearly 10%. Overall, approximately 2.3% of the expected number of red snapper larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

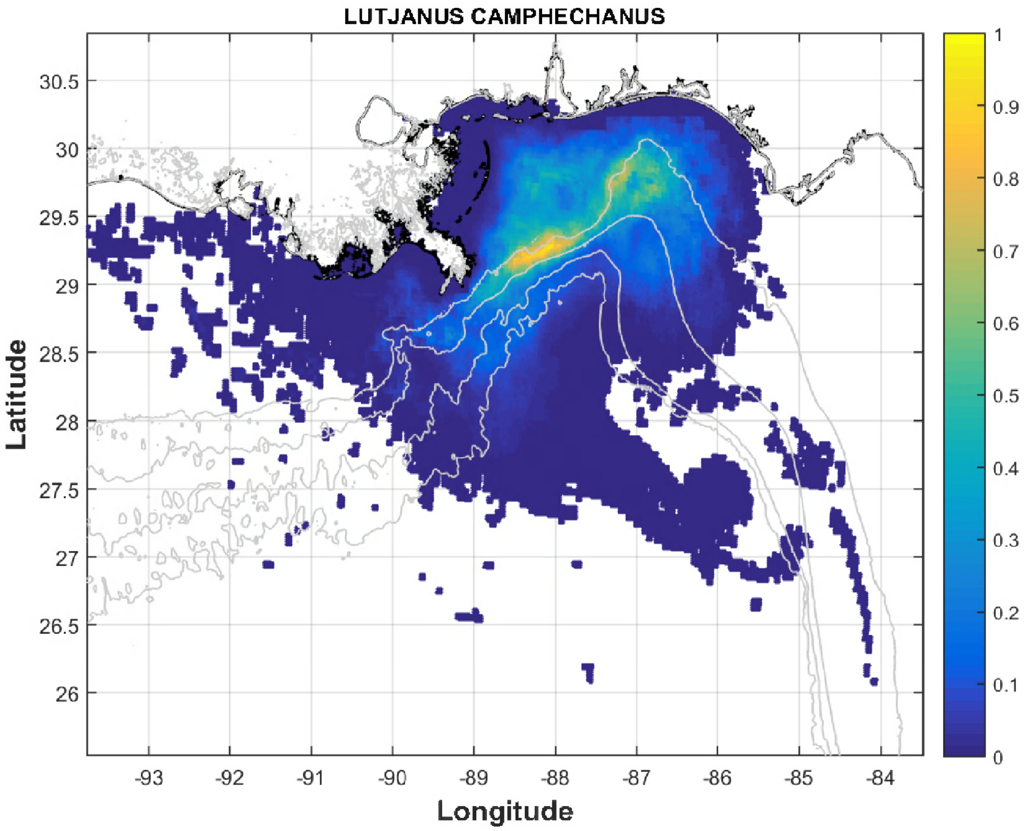

Figure 40 - Aggregated and normalized red snapper abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

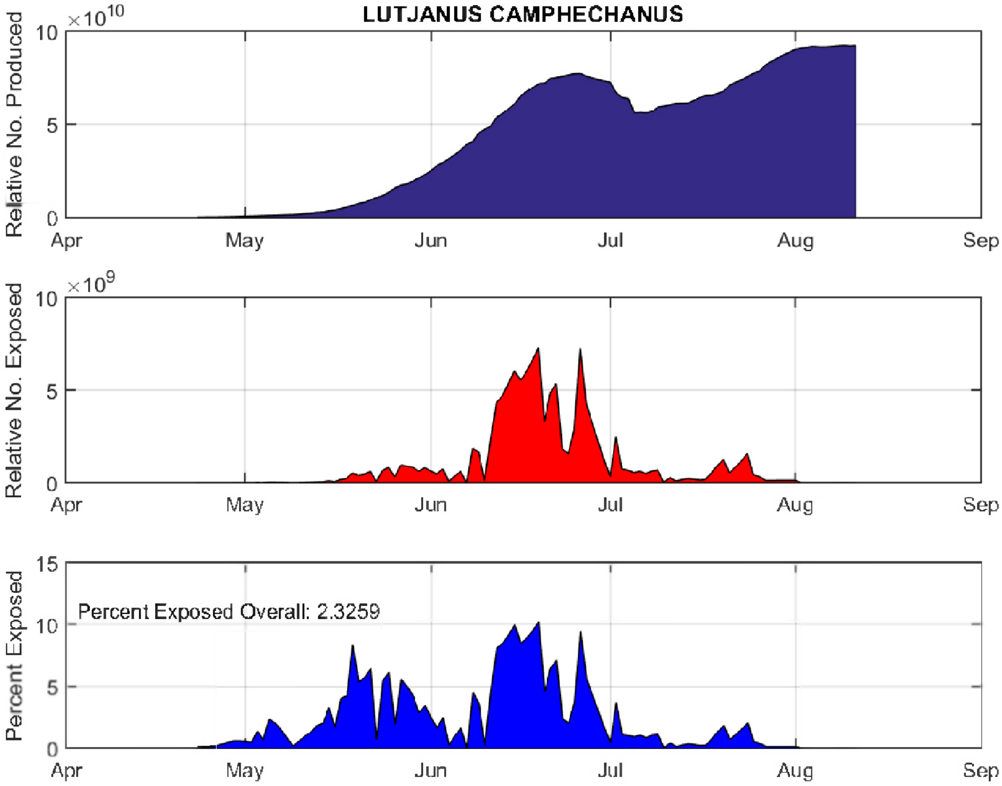

Figure 41 - Time series of red snapper relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of red snapper in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

MYCTOPHIDAE

The family *Myctophidae* are the lanternfishes and represent one of the more numerous groups of fishes in the ocean. During day they are typically at depth, but rise to the surface waters at night and *Myctophidae* eggs have been identified in surface plankton samples. The analyses show that potential injury to larval *Myctophidae* occurred over a broad area mostly seaward of the 100m isobath and centered along the 1500m isobath. The production schedule during the spill is irregular but broadly flat. Daily percent potentially exposed ranged from near zero to about 6%. Overall, approximately 1.3% of the expected number of red snapper larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

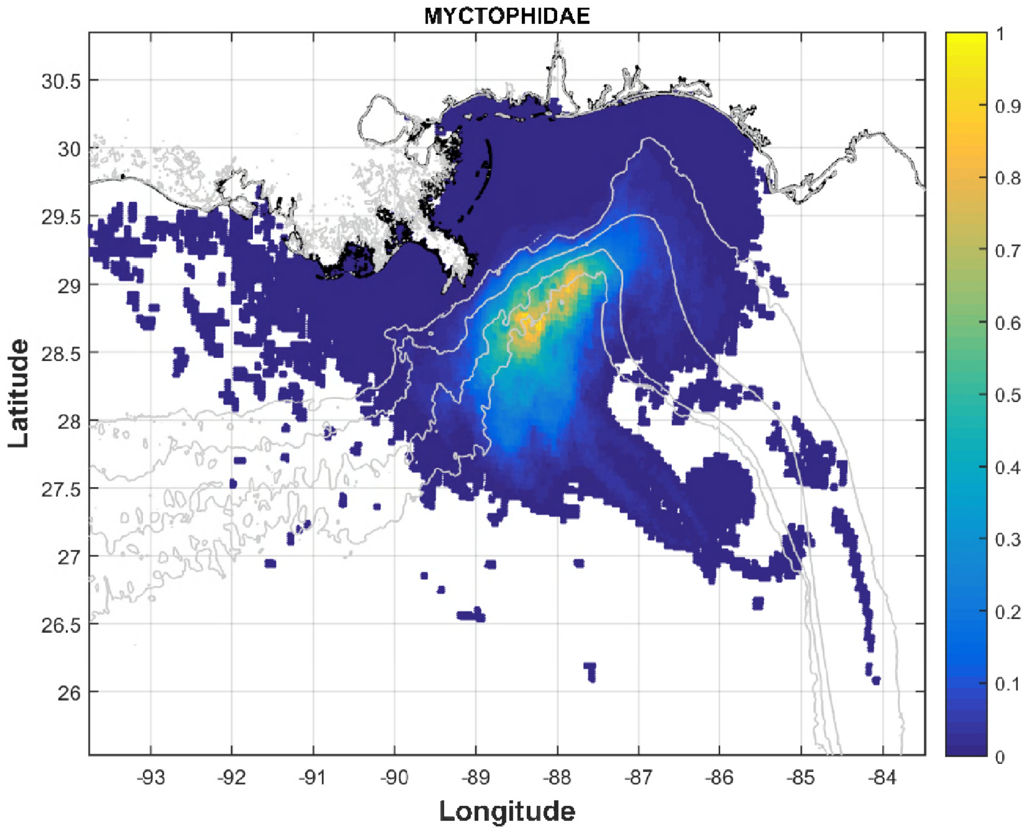

Figure 42 - Aggregated and normalized Myctophidae abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

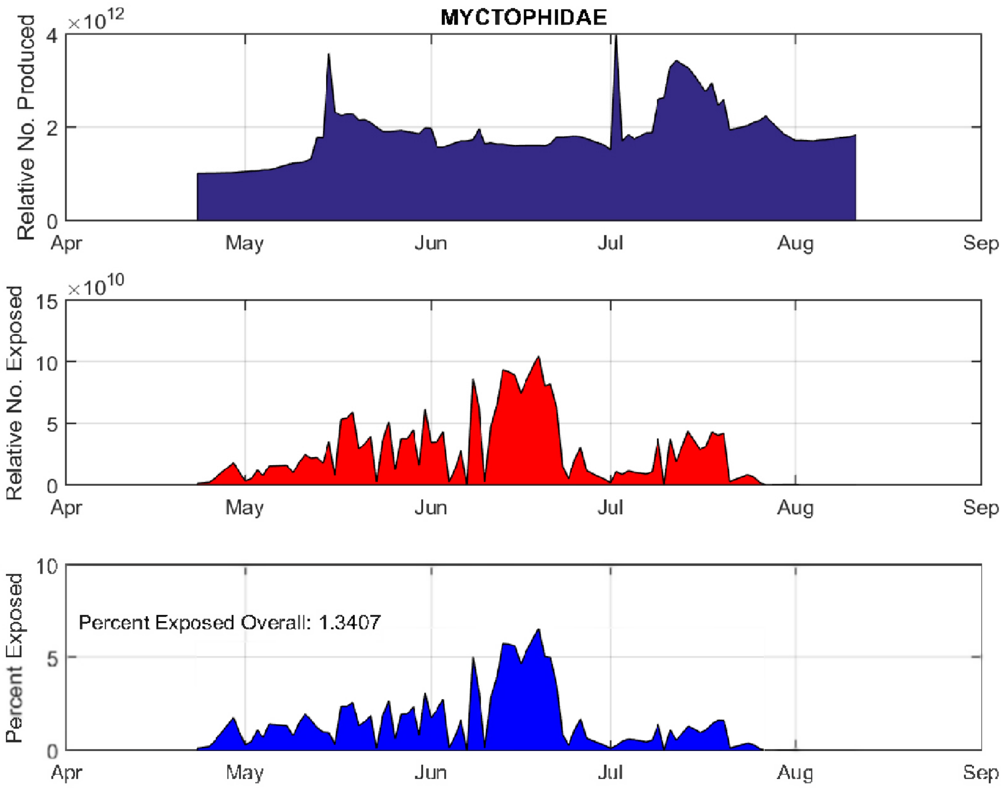

Figure 43 - Time series of Myctophidae relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Myctophidae in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

PEPRILUS BURTI

Peprilus burti is the ecologically and economically important Gulf butterfish. The analyses show that potential injury to larval Gulf butterfish occurred over a broad area mostly inshore of the 400m isobath and especially near the head of the Desoto Canyon. The production schedule during the spill was high in late April, declined, and then peaked in mid-June. Daily percent potentially exposed ranged from near zero to more than 10%. Overall, approximately 2.2% of the expected number of Gulf butterfish larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

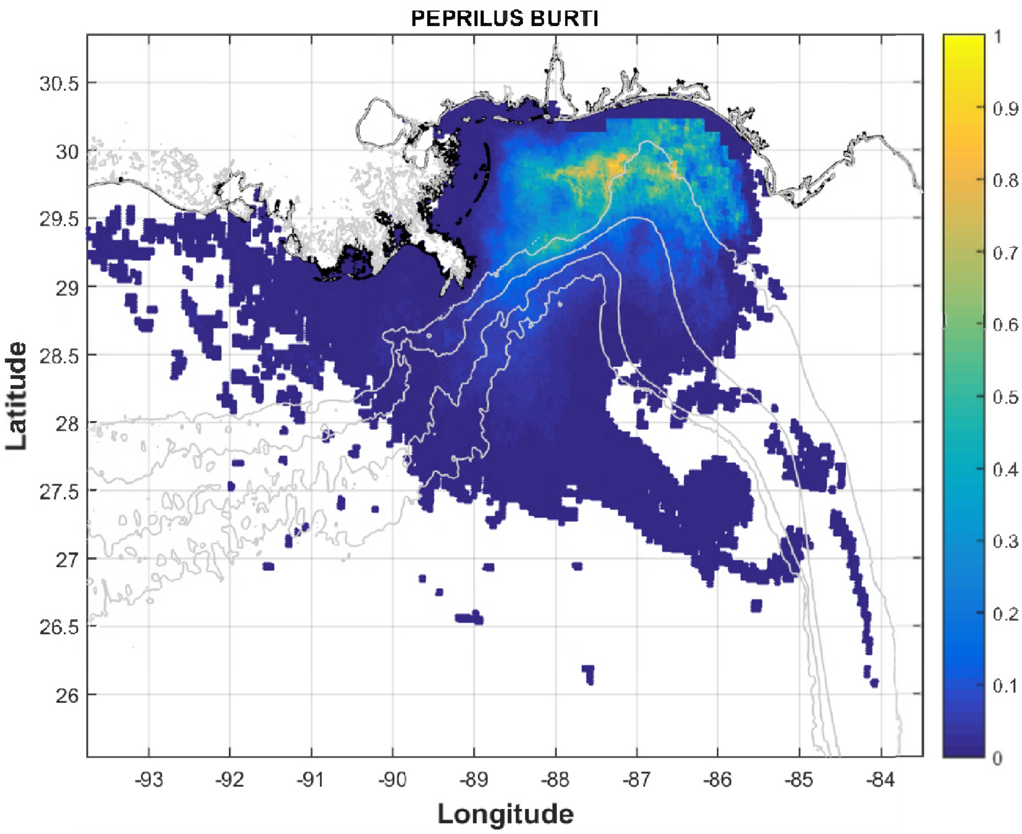

Figure 44 - Aggregated and normalized Gulf butterfish abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

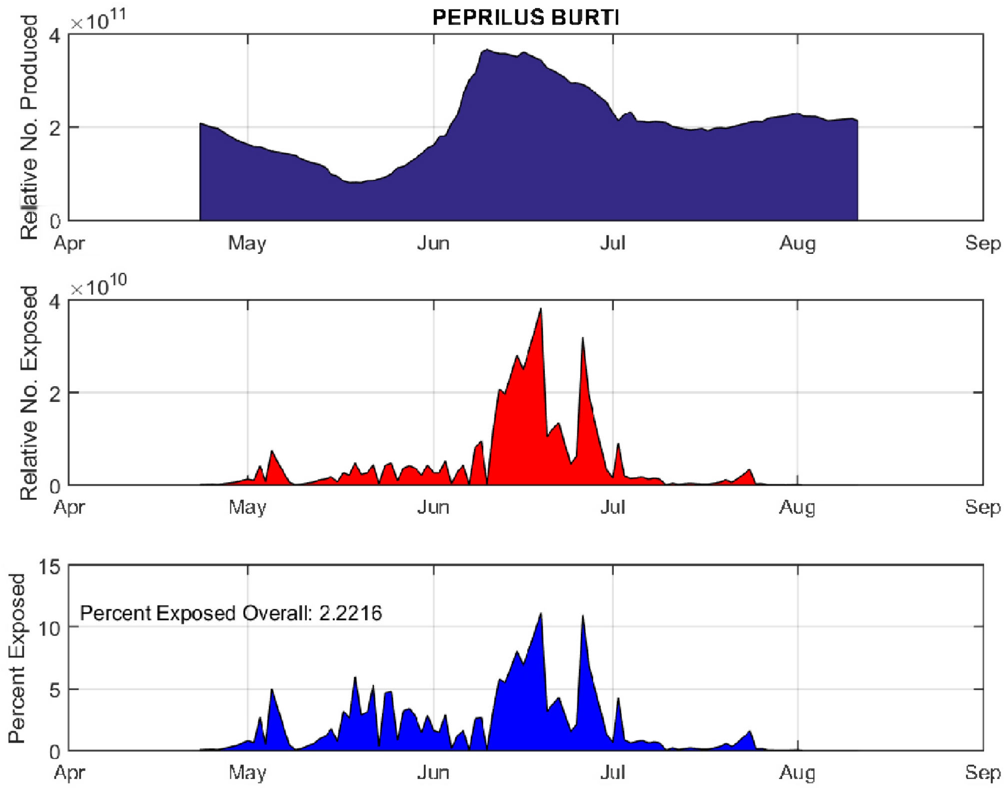

Figure 45 - Time series of Gulf butterfish relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Gulf butterfish in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

SARDINELLA_AURITA

The species *Sardinella aurita* are commonly known as round sardinella. The analyses show that potential injury to larval *Sardinella aurita* occurred over a broad area mostly inshore of the 100m isobath. The production schedule during the spill exhibited a single peak in early June. Daily percent potentially exposed ranged from near zero to about 0.5%. Overall, less than approximately 0.1% of the expected number of *Sardinella aurita* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

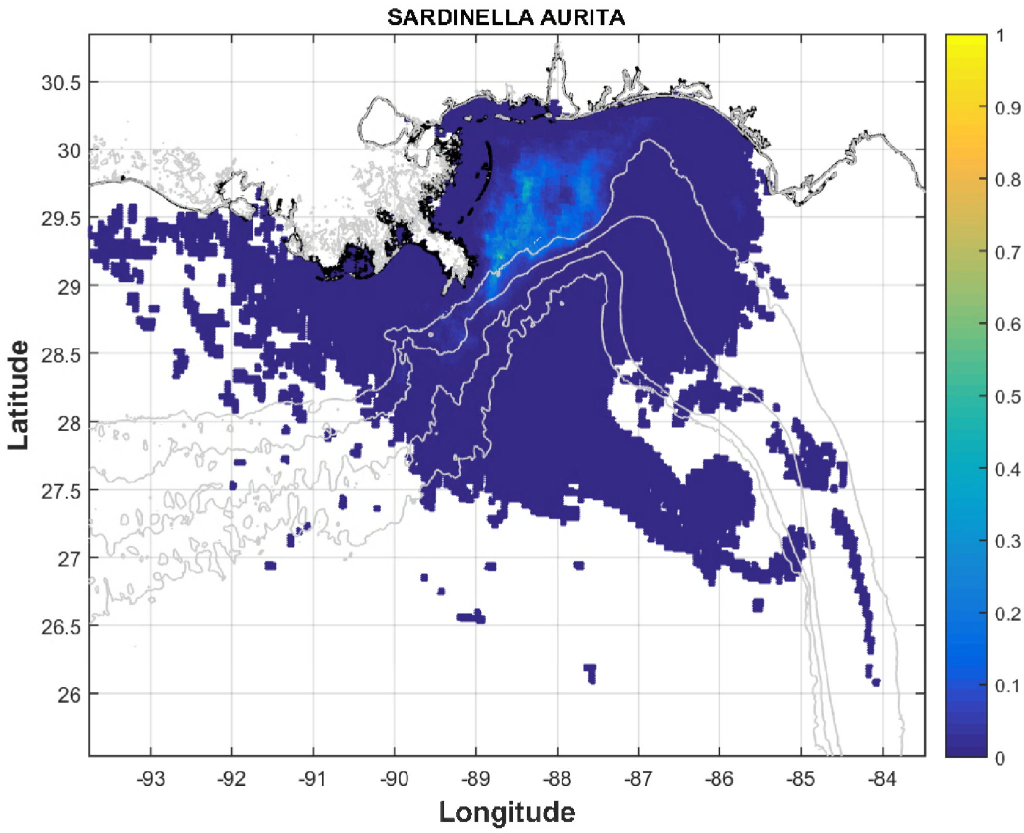

Figure 46 - Aggregated and normalized round sardinella abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

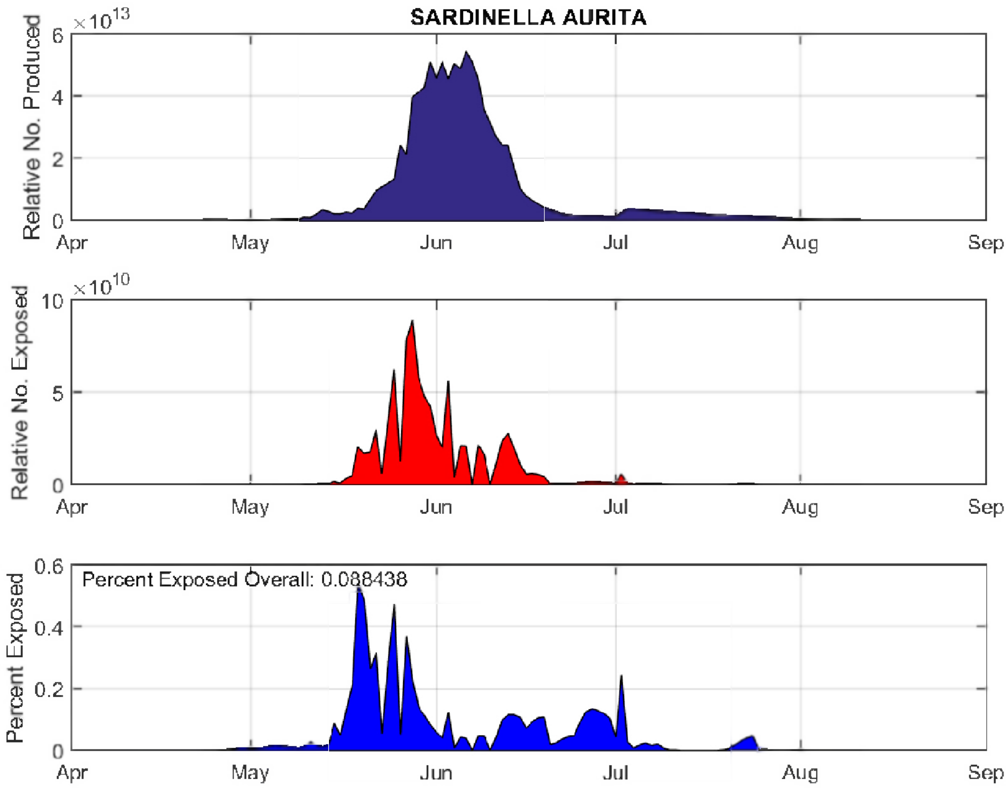

Figure 47 - Time series of round sardinella relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of round sardinella in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

SCOMBEROMORUS CAVALLA

The species *Scomberomorus cavalla* is commonly known as king mackerel. The analyses show that potential injury to larval *Scomberomorus cavalla* occurred over a broad area with a peak centered near the 400m isobath. The production schedule during the spill exhibited a shallow peak in June and was climbing to a larger peak by early August. Daily percent potentially exposed ranged from near zero to about 5.0%. Overall, approximately 1.3% of the expected number of *Scomberomorus cavalla* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

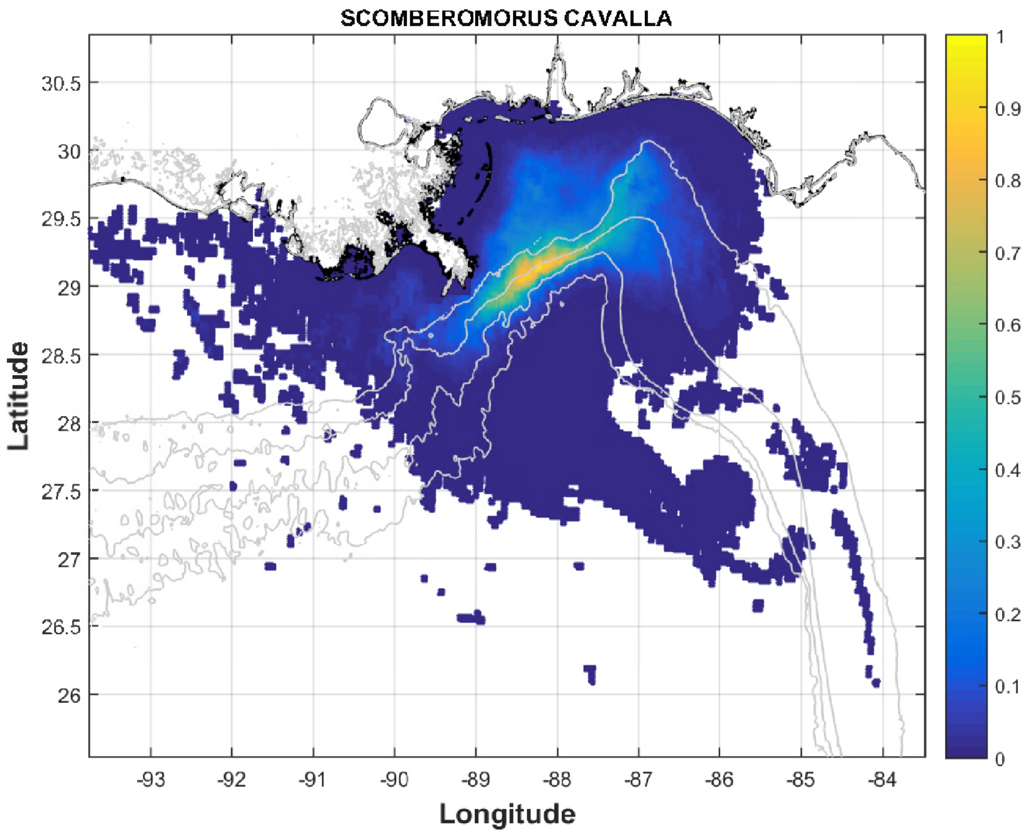

Figure 48 - Aggregated and normalized king mackerel abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

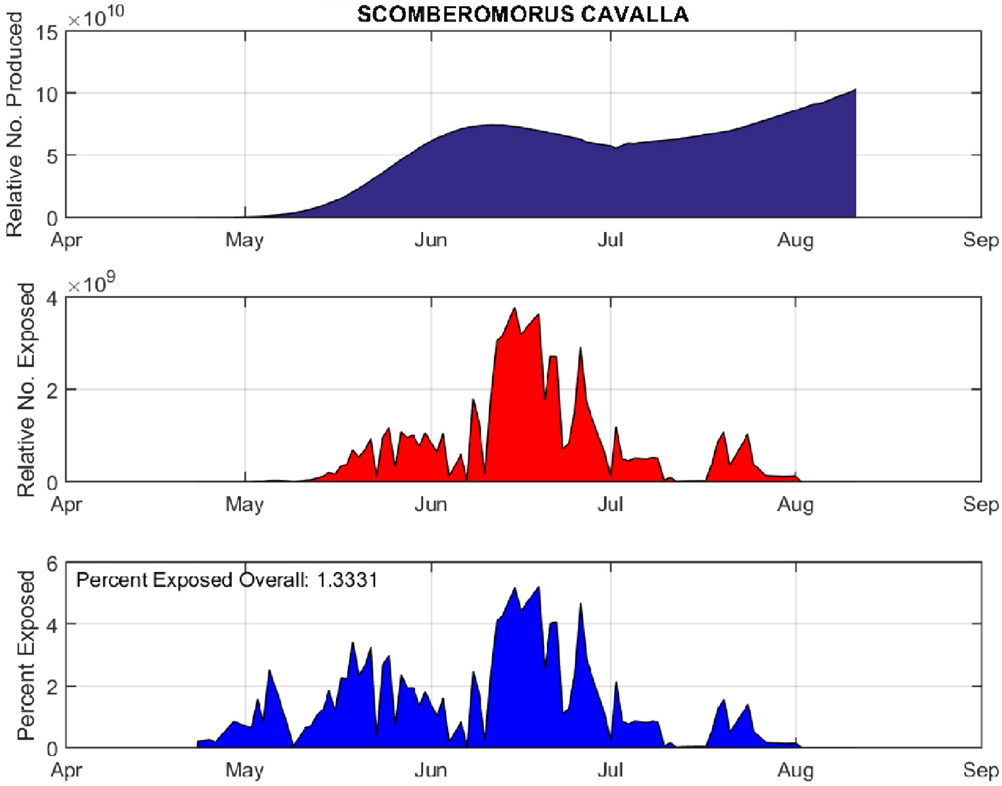

Figure 49 - Time series of king mackerel relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of king mackerel in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

SELENE

The genus *Selene* includes lookdowns and moonfishes. The analyses show that potential injury to larval *Selene* occurred in broadly but with small peaks inshore of the 400m isobath and to the north and east of the wellhead. The production schedule during the spill exhibited a small peak in June and was climbing to a much larger peak by early August. Daily percent potentially exposed ranged from near zero to as much as about 50%. Overall, approximately 7.5% of the expected number of *Selene* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

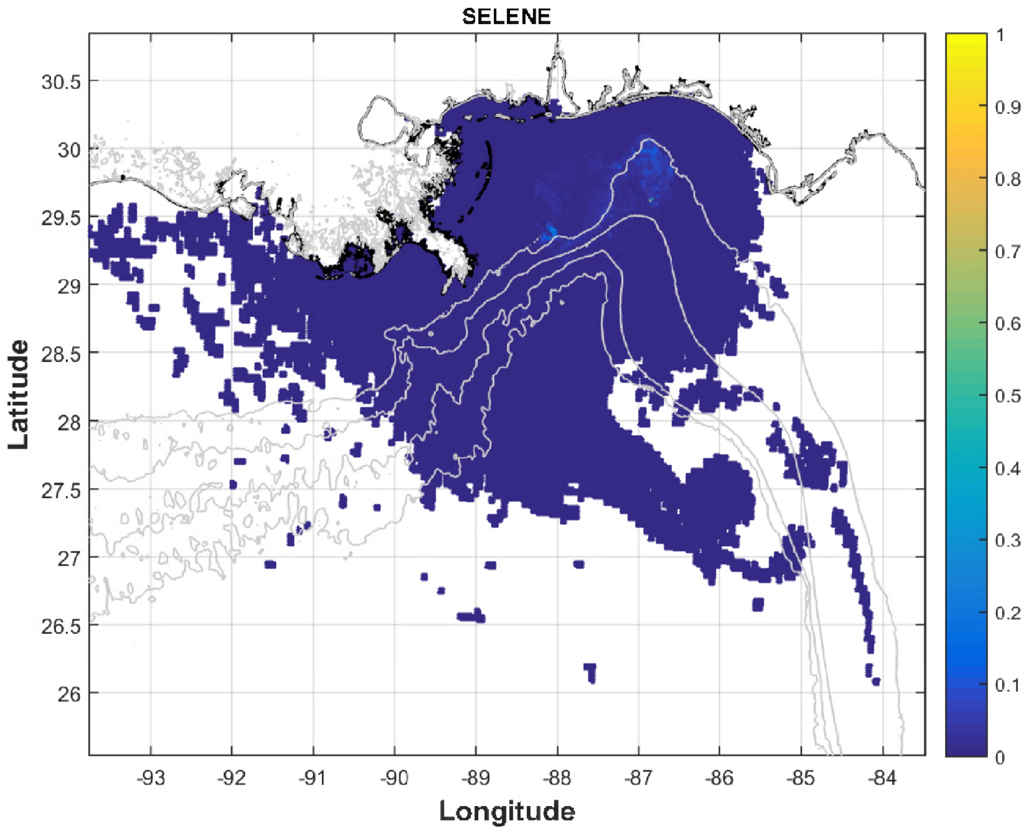

Figure 50 - Aggregated and normalized Selene abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

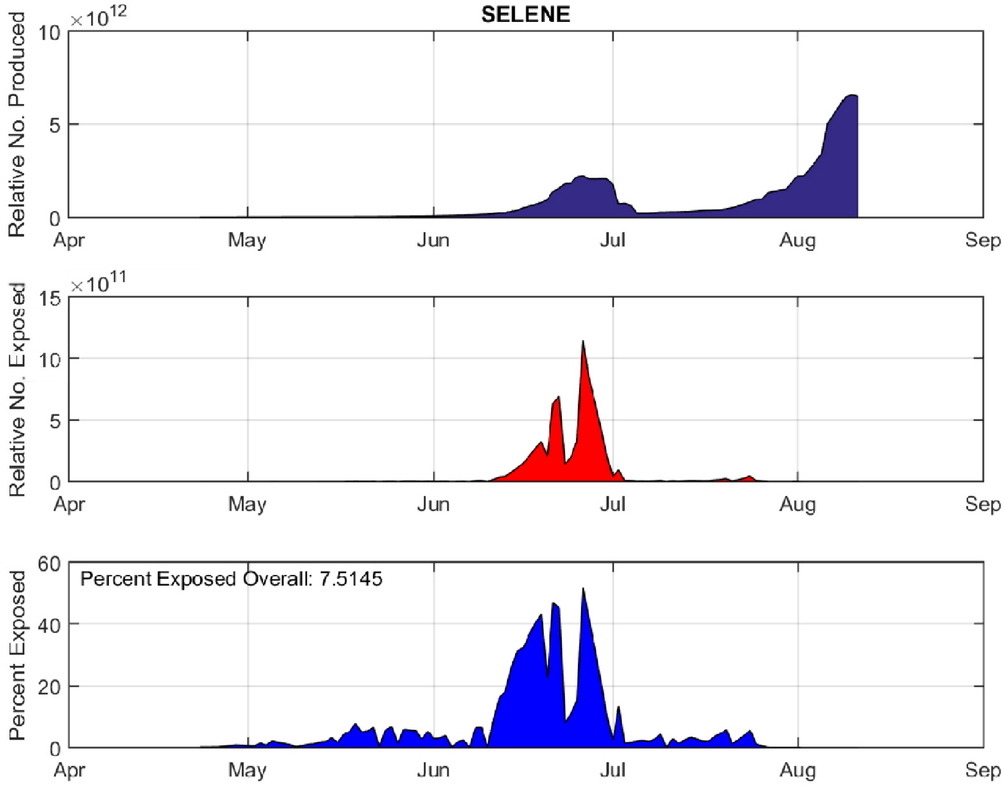

Figure 51 - Time series of Selene relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Selene in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

TETRAODONTIDAE

The family *Tetraodontidae* are commonly known as puffers or pufferfishes. The analyses show that potential injury to larval *Tetraodontidae* occurred over a broad area with a peak mostly shoreward of the 100m isobath. The production schedule during the spill exhibited was broadly flat with a peak in late May. Daily percent potentially exposed ranged from near zero to about 2%. Overall, approximately 0.4% of the expected number of *Tetraodontidae* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

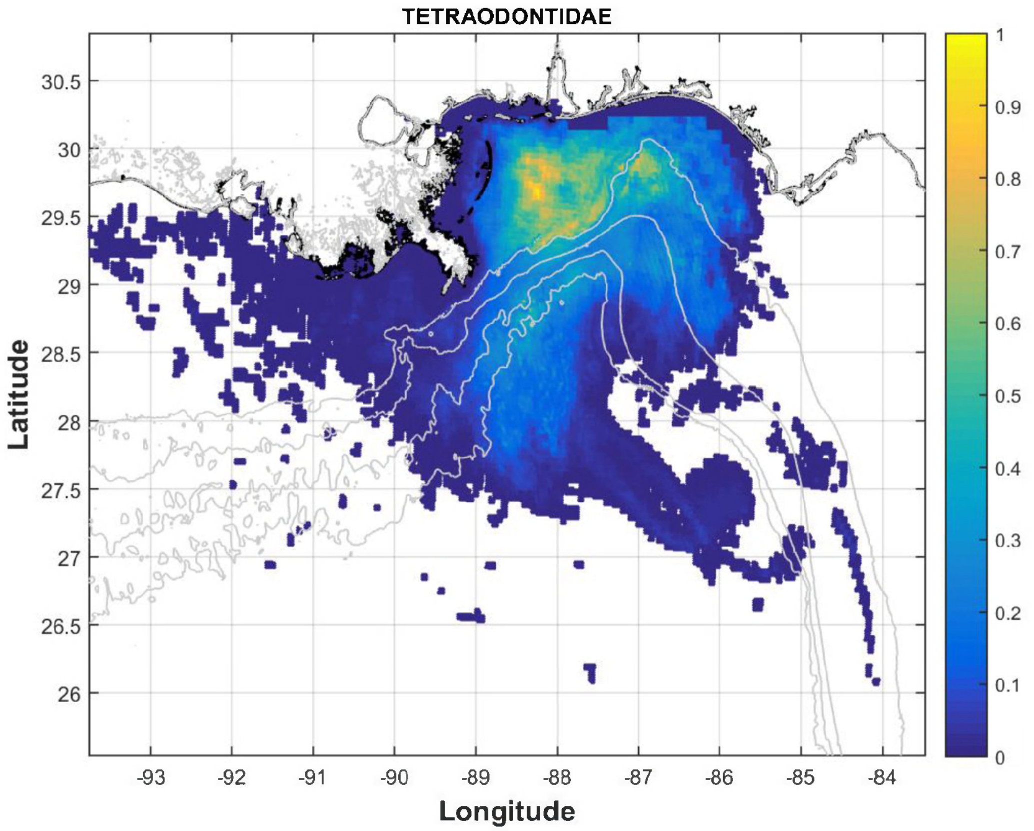

Figure 52 - Aggregated and normalized Tetraodontidae abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

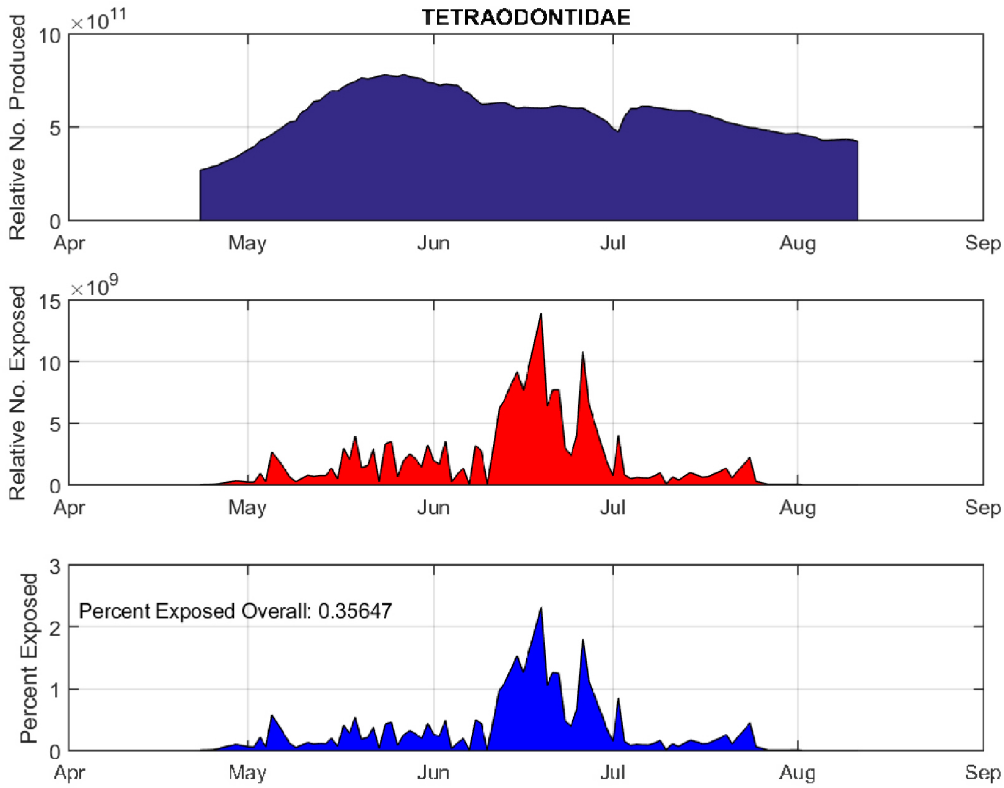

Figure 53 - Time series of Tetraodontidae relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Tetraodontidae in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

THUNNUS

The genus *Thunnus* represents several species of tunas not otherwise included in the analyses. The analyses show that potential injury to larval *Thunnus* occurred over a broad area mostly seaward of the 100m isobath. The production schedule during the spill ramped toward a peak in July. Daily percent potentially exposed ranged from near zero to about 4%. Overall, approximately 1.0% of the expected number of *Thunnus* larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

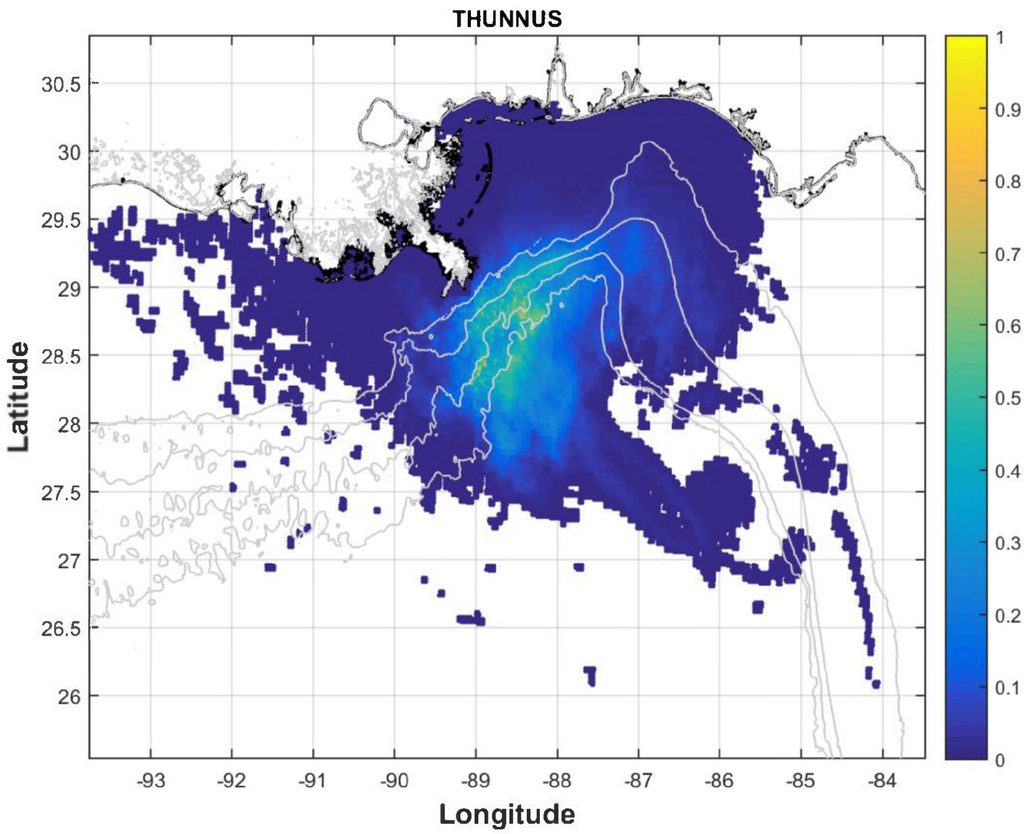

Figure 54 - Aggregated and normalized Thunnus abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

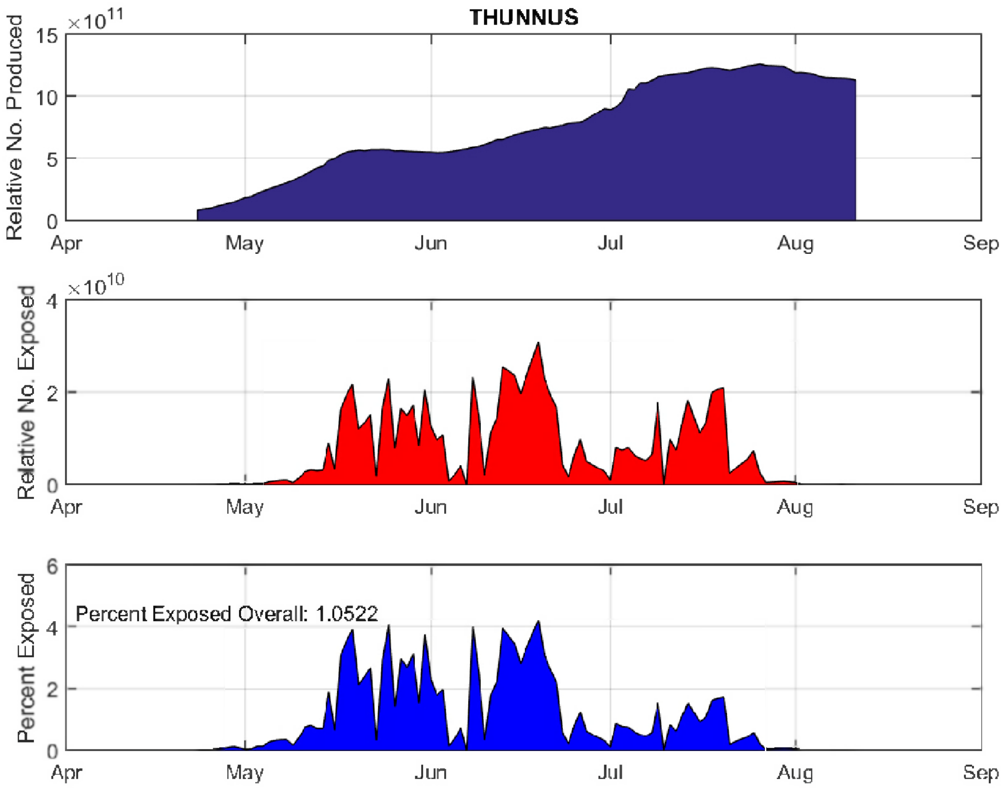

Figure 55 - Time series of Thunnus relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of Thunnus in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).

THUNNUS THYNNUS

The species *Thunnus thynnus* is the economically important bluefin tuna. The analyses show that potential injury to larval bluefin tuna occurred over a broad area mostly seaward of the 100m isobath and centered beyond the 1500m isobath. The production schedule during the spill was unimodal with a peak in mid- to late May. Daily percent potentially exposed ranged from near zero to slightly more than about 2%. Overall, approximately 0.8% of the expected number of bluefin tuna larvae in the EEZ were potentially exposed to Deepwater Horizon surface oil.

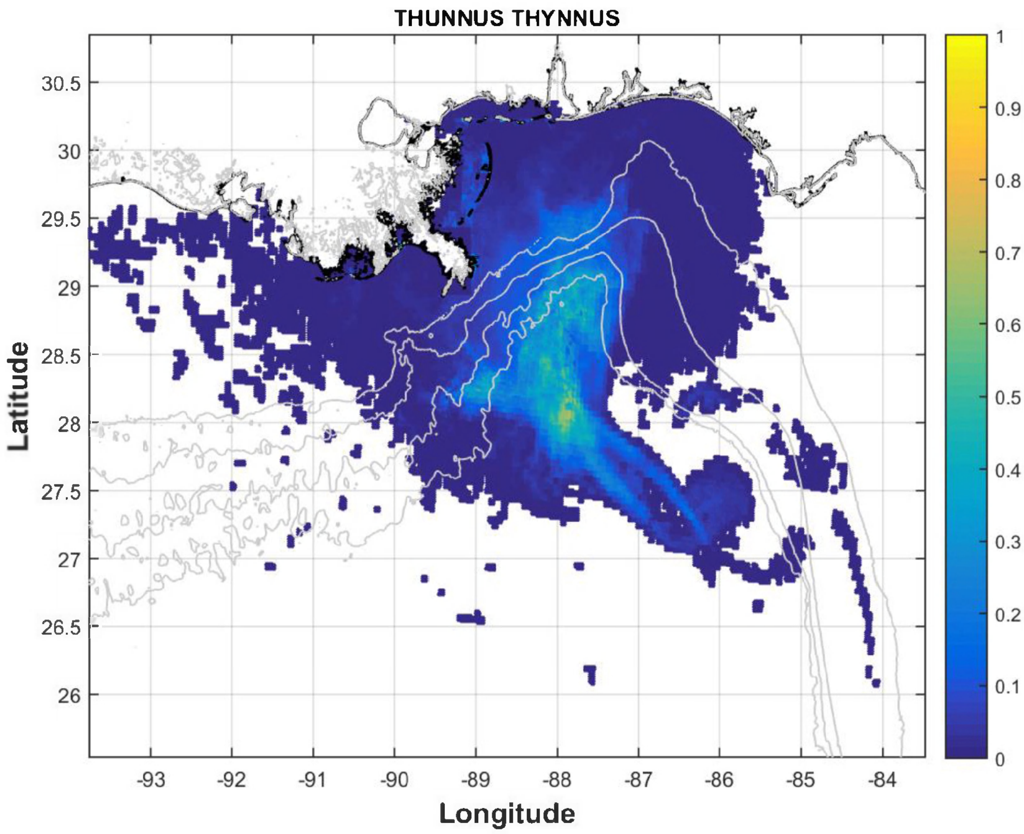

Figure 56 - Aggregated and normalized bluefin tuna abundance data under the footprint of the surface slick. A larger number of organisms were exposed to surface oil in areas with warmer colors. Grey contours depict the 100, 400, 1000 and 1500 meter isobaths.

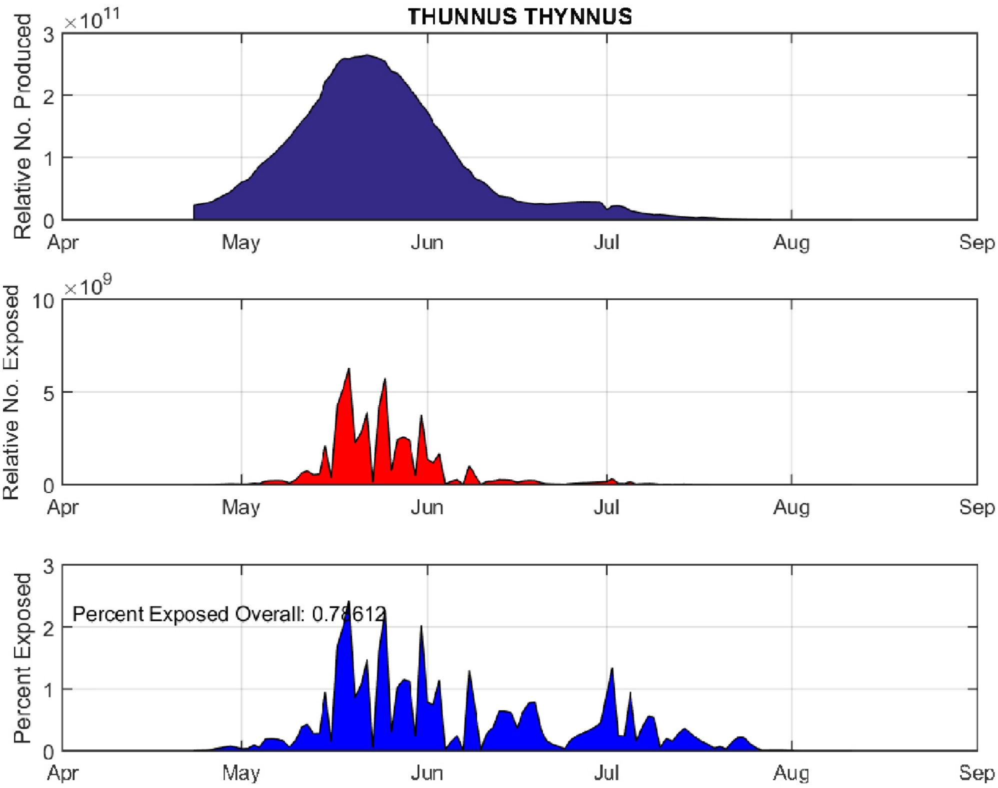

Figure 57 - Time series of bluefin tuna relative abundance in the study area. Top panel represent the 'production schedule' or total relative number of bluefin in the EEZ each day from April 23 to August 11, 2010. Middle panel represents the relative number that occurred under the foot print of the oil on each day. Bottom panel represents the percent of total daily production that was under the oiled footprint on each day. The percent exposed overall is the total number exposed (area under red curve) divided by the total number in the system during the time period (total area under the dark blue curve).