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Satellite Optical Water Mass Classification to Map Coastal Hypoxia

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Abstract – We applied an optical water mass classification technique to estimate the areal extent of coastal hypoxia in the northern Gulf of Mexico. Partitioned absorption coefficients (phytoplankton, sediment/detrital, and CDOM) derived from satellite ocean color imagery are coupled with a stratification index (surface-to-bottom temperature difference) derived from a circulation model. Optical properties (relative and absolute absorption coefficients) were extracted from a 10-year climatology of monthly satellite composites to define expected optical conditions of hypoxic waters, which were delineated by mid-summer ship surveys (LUMCON, 2009). Then, for a given year, the satellite-derived optical properties are compared to the expected conditions and coupled with the model-derived water column stratification index, to provide a real-time spatial estimate of hypoxia.

Keywords: water mass, optical classification, hypoxia.

1. INTRODUCTION

The frequency, extent, and severity of coastal hypoxic events are increasing worldwide due to increasing eutrophication (Larsen, 2004). Hypoxia occurs when water column oxygen levels drop below 2 mg/l, and these low oxygen levels can potentially impact local fisheries and benthic organisms, with important ecological and economic consequences. This “dead zone” off the coast of Louisiana forms every summer and is the second largest hypoxic zone in the world. It is thought that agricultural fertilization upstream leads to the increased nutrient loading on the continental shelf, stimulating a phytoplankton bloom. As the bloom stimulated by this nutrient-rich discharge of the Mississippi and Atchafalaya Rivers sinks to the bottom and decays, oxygen levels are depleted in the process. In addition to the bloom decay, water column stratification is also a required condition for hypoxia development, to prevent mixing with surrounding oxygen-replete waters.

Typically, ship-based survey cruises are conducted to map the extent of bottom hypoxic waters. Each summer since 1985, monitoring cruises have been conducted by the Louisiana Universities Marine Consortium (LUMCON) to map the spatial extent of the Louisiana hypoxic zone. This measurement represents the officially-reported size of the hypoxic zone, which has varied from about 4,000 – 22,000 km², with the maximum size reported in 2002 (LUMCON, 2009). There is currently a national mandate to decrease the size of the hypoxic zone to 5,000 km² by 2015, mostly by a

proposed 40% reduction in annual nitrogen discharge into the Gulf of Mexico. A monitoring program is required to assess whether these goals are being met. However, ship sampling is expensive and is not spatially or temporally synoptic. So, the question is, can surface satellite imagery be used to map the spatial extent of bottom-water hypoxia?

2. METHODS

To estimate areas of possible hypoxia, we couple satellite ocean color imagery with a stratification index derived from a circulation model, in a three-tiered testing approach. The premise is that by comparing current optical properties to properties observed in past hypoxic events, we can “predict” where hypoxia is likely to occur in the current image. We first compare the relative optical composition, then we examine the absolute optical properties, and finally we assess the water-column stratification.

2.1 Satellite Imagery/Processing

NRL has collected, processed, and archived a 10-year time series of SeaWiFS ocean color imagery covering the northern Gulf of Mexico from 1998-2007. All imagery was processed using the NRL automated satellite processing system (Martinolich and Scardino, 2009). A near-infrared atmospheric correction tuned for coastal waters was applied.

2.2 Circulation Modeling

A real-time ocean nowcast/forecast system (ONFS) has been developed at the Naval Research Laboratory (NRL). The NRL ONFS provides short-term forecasts of ocean current, temperature, salinity, and sea level variation including tides. It is based on the NCOM hydrodynamic model, but has additional components such as data assimilation and improved forcing. A nested model with 2-km horizontal resolution and 40 vertical layers has been implemented in the northern Gulf of Mexico. The surface-to-bottom (or surface to 100 m in deeper waters) vertical temperature gradient from this model is used as our stratification index.

2.3 Mapping Hypoxia

First, we apply an optical water mass classification (OWMC) system developed at NRL to the imagery (Gould and Arnone, 2003). The OWMC can help identify and track oceanographic features, similar to the approach employed by physical oceanographers using temperature/salinity diagrams. The total absorption coefficient is partitioned into individual absorption components, due to phytoplankton at 443 nm (a_{p443}), sediment/detritus at 443 nm (a_{s443}), and CDOM at 443 nm ($a_{CDOM443}$). We then

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calculate the percent of the total absorption coefficient due to each of the three components, and produce pseudo-color RGB images of the optical patterns, by loading % a_d into the red channel, % a_p into the green channel, and % a_b into the blue channel. Thus, areas dominated by relatively high detrital loads appear red in the image, areas of high phytoplankton absorption appear green, and areas of higher CDOM absorption appear blue.

For each year from 1998-2007, we created monthly composite OWMC image covering coastal Louisiana for June and July. Also for each year, we digitized the hypoxia map produced by the LUMCON group. Figure 1 shows an example OWMC image for July 2007, a year with one of the largest measured hypoxic zones (20,500 km²). The cruise-mapped hypoxic area is indicated in red. Using the digitized hypoxia map, we then extracted the absorption percentages for all of the image pixels falling in the "hypoxic zone" from the OWMC composite image, and plotted these on a ternary diagram. This procedure was repeated for all 10 years, and a frequency ternary plot was generated (Figure 2).

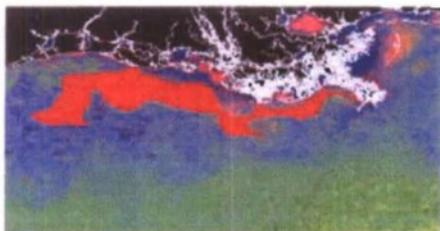


Figure 1. OWMC image for July 2007 (SeaWiFS). Pixel colors indicate relative optical characteristics, as described in the text. Area delineated by red pixels indicates the hypoxic region for summer 2007 as determined from the LUMCON regional survey cruise.

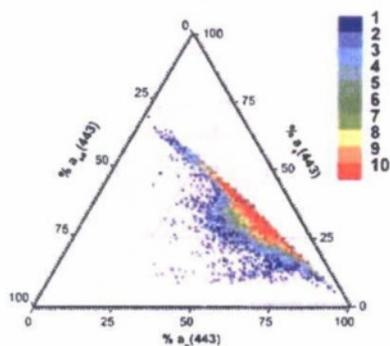


Figure 2. Frequency ternary diagram showing the optical characteristics of hypoxia pixels. Axes are the partitioned absorption percentages. The colors represent frequency (the number of years at least one hypoxia pixel exhibited the specific optical characteristics indicated).

In addition to the frequency plots based on the number of years, similar plots were created based on total number of pixels. This approach only represents changes in the relative optical composition across an image; to more completely characterize the water masses, similar analyses were performed using the absolute magnitudes of the partitioned absorption coefficients, and frequency ternary plots (based on years and total pixels) were generated from these results as well.

3. RESULTS

To test the approach, we estimated hypoxic pixels in the July 2007 OWMC image, and compared these to the actual hypoxia distribution as determined by the cruise sampling. A three-tiered test was applied: first, pixels were marked as possibly hypoxic if their relative optical properties matched the historical properties in at least 9 years and occurred at least 500 times (i.e., in at least 500 pixels over the 10 years); next, if their absolute optical properties matched the historical properties in at least 9 years and 500 times; and finally, if the surface-to-bottom temperature gradient from the model was positive (temperature increased with depth). The intersection of these three regions determined the final prediction (Figure 3). Note the close correspondence with the actual hypoxic region in Figure 1. We calculate areas of estimated hypoxia and comparison statistics for all 10 years.

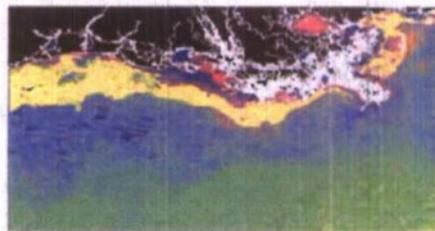


Figure 3. Predicted hypoxic region for July 2007 (yellow).

4. CONCLUSION

Satellite ocean color imagery can be used to augment ship surveys and delineate areas of expected hypoxic conditions in near-real time, providing coastal managers with a new monitoring tool.

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