What is the Impact of Light on Ocean Primary Production and Hypoxia?

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Introduction: The magnitude and distribution of solar radiation incident at the sea surface impacts the physics, chemistry, and biology of the ocean. From a physical perspective, it penetrates into the water column and heats the upper layer of the ocean, driving stratification and thermohaline circulation, and through ocean-atmosphere coupling and feedback mechanisms, influences air/sea heat exchange, winds, and climate. Biologically, a portion of the shortwave (SW) radiation, the photosynthetically available radiation (PAR), drives oceanic primary production.

In the northern Gulf of Mexico, nutrients from upstream agricultural fertilization and river runoff are delivered to the Louisiana Continental Shelf (LCS) via the Mississippi-Atchafalaya river basin. This increased nutrient loading stimulates a phytoplankton bloom; as the resulting phytoplankton biomass sinks to the seafloor and decays, oxygen levels in the water can be reduced to very low levels, causing hypoxia (dissolved oxygen levels below 2 mg/l). This "dead zone" develops seasonally every year from mid-April through September, and is the second largest hypoxic zone in the world (only the Baltic Sea hypoxic zone is larger). Hypoxia can impact local fisheries and benthic organisms, causing important ecological and economic consequences.

Our goal is to develop a modeling approach to better understand how interactions between biotic and abiotic factors affect primary production and oxygen dynamics on the LCS. Specifically, we are interested in how light variability (PAR) can impact the magnitude, distribution, and duration of hypoxia. Working together, the U.S. Naval Research Laboratory (NRL) and the U.S. Environmental Protection Agency (EPA) have developed a coupled hydrodynamic/ecosystem model. With our three-dimensional model, we can perform simulations with different, realistic input light conditions, such as those that might be expected to result from various climate change scenarios, and compare results to assess the impacts.

Model Development: The Navy Coastal Ocean Model–Louisiana Continental Shelf (NCOM-LCS) provides the hydrodynamic components of the coupled model system (horizontal and vertical transport and mixing, temperature, and salinity at 2-kilometer horizontal resolution for 20 equally-spaced sigma depth layers at a 5-minute time step). Land-sea forcing is through observed river discharges to the domain. The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) and the Navy Operational Global Atmospheric Prediction System (NOGAPS) provide atmospheric forcing (air pressure, temperature, wind stress, and SW radiation). Open-ocean boundary conditions are from the 6-kilometer regional NCOM. The hydrodynamic forcing is supplied to the Coastal General Ecosystem Model (CGEM), which provides the ecosystem components of the coupled model system. CGEM[1] computes a suite of biogeochemical properties, such as phytoplankton and zooplankton biomass, nutrients, and oxygen concentration, at each model time step and grid location; it was applied to the LCS for a 1-year period (2006).

Estimating PAR Magnitude, Distribution, and Variability: Accurate estimates of sea-surface PAR (and its attenuation with depth) are required as input to the ecosystem model (CGEM), from which we then can derive accurate estimates of phytoplankton biomass and primary production. Such estimates are available from satellite ocean color imagery and atmospheric model predictions. Because the PAR values could come from either source, it is important to understand the variability and accuracies of each. We compare values derived from the imagery to those from the models, and to in situ measurements in the Gulf of Mexico, to assess PAR variability based on source. Spatial and temporal analyses covering multiple years and seasons as well as clear/cloudy conditions indicate that PAR estimates can vary up to 10%, depending on the source.

In addition, climate change could alter cloud coverage, thereby impacting the amount of PAR reaching the sea surface and its spatial distribution.[2] Furthermore, future river discharge patterns could change as a result of changing precipitation patterns,[3] which would lead to associated regional increases or decreases in nutrients and colored dissolved organic matter (CDOM) in coastal areas, thereby impacting phytoplankton production and the horizontal and vertical distribution of PAR. Thus, the many interacting processes affecting water column and benthic light levels and primary production are difficult to separate, but coupled bio-physical ecological modeling provides an effective approach for doing so.

Impact of PAR on Primary Production and Hypoxia: Based on the PAR comparisons and a potential climate change scenario, we performed eight ecosystem (CGEM) sensitivity simulations using scaled PAR values, to assess the impact of PAR on oxygen production and hypoxia development. The NOGAPS-derived input PAR values were scaled by a constant factor (± 2, 5, 10, 50% of original values) at each 3-hour time step for 1-year model runs (2006). Other parameters were held constant. The "baseline" run, for comparison to the scaled runs, used the original NOGAPS PAR values without any changes. Only results for a 10% increase in PAR are shown here (for a single day, 2 August 2006).

Based on the model results, PAR variability can impact the magnitude and distribution of simulated primary production and hypoxia. For example, a 10% increase in PAR can lead to higher water-column integrated primary production (IPP) over a large area (Fig. 7), with a 6–10% increase in IPP in offshore waters and a smaller impact in coastal waters. For bottom water oxygen concentration, slightly smaller differences from the baseline run are observed (generally ~2 to 5%, but up to 20%). However, the differences can be observed over much of the model domain and can extend 5–35 meters into the water column from the bottom (depending on water depth and location on the LCS; Figs. 8 and 9). These increases in oxygen concentration can lead to decreases in daily bottom hypoxic area of 200–400 km^2 from June through September, and such decreases can be important locally.

Summary: Our research enables us to assess the impact of biotic factors, such as phytoplankton growth rate/mortality and zooplankton grazing, and abiotic factors, such as light and nutrients, on oceanic primary production and hypoxia development. We can separate the impacts of individual factors, as we did here, enabling us to focus on just the effect of light variability. The model simulations combine complex biogeochemical, ecological, and physical interactions, and this approach can be extended to examine a variety of applications, such as climate change scenarios, ocean acidification, and other processes that impact both navy and civilian operations. Model hindcasts and forecasts provide coastal managers with valuable analysis and predictive tools.

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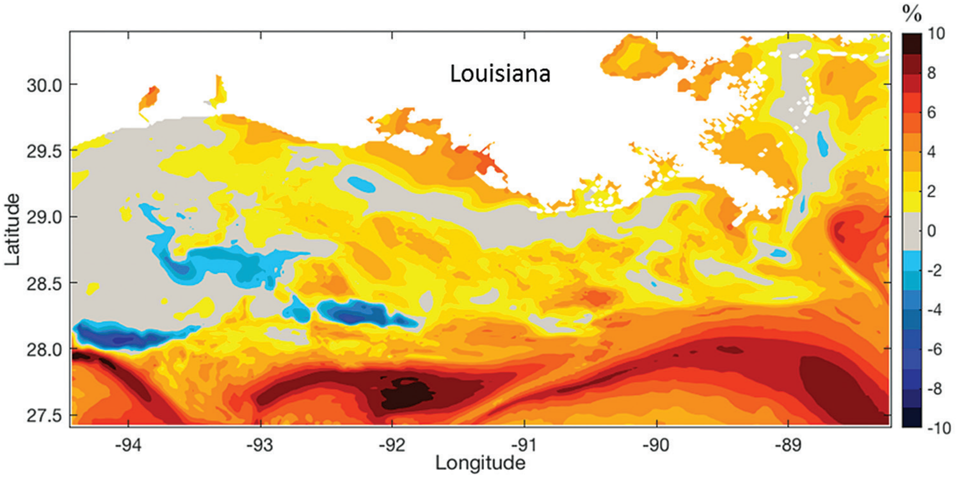

FIGURE 7
Simulation results showing the % difference between the "baseline" model run and the +10% PAR run, for integrated water column photosynthesis on 2 August 2006. Gray pixels indicate very little difference between the two model runs (see color scale).

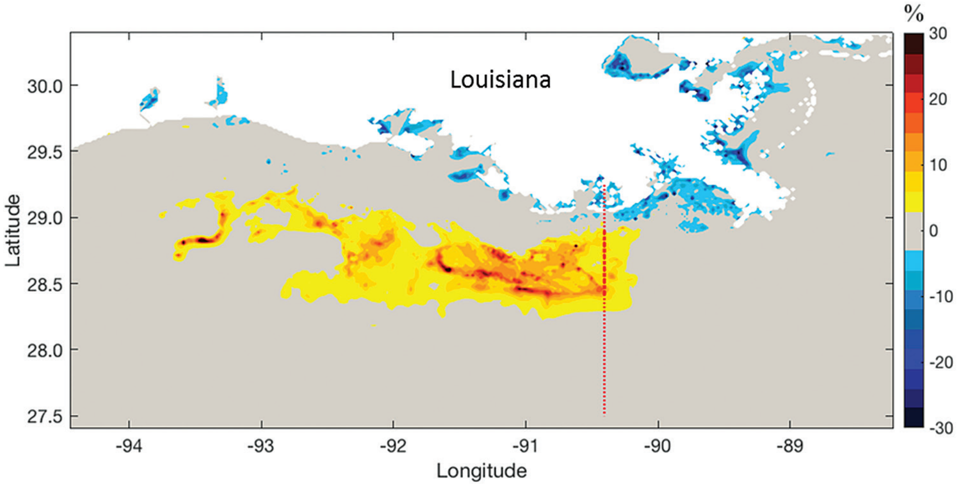

FIGURE 8
Simulation results showing the % difference between the “baseline” model run and the +10% PAR run, for bottom water oxygen concentration on 2 August 2006. Gray pixels indicate very little difference between the two model runs (see color scale).

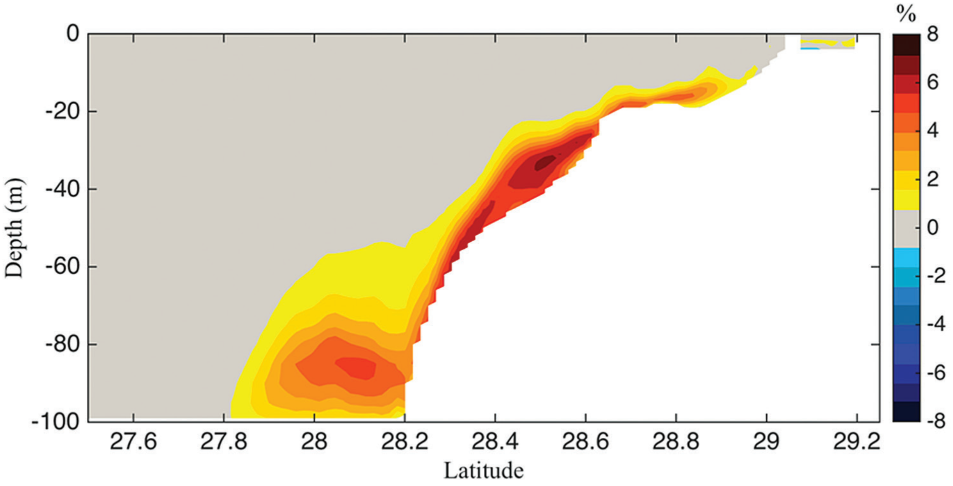

FIGURE 9
Simulation results showing the % difference between the “baseline” model run and the +10% PAR run, for water column oxygen concentration on 2 August 2006. North/South vertical transect through the water column, at the location indicated by the red dotted line in Figure 8. White pixels indicate the bottom and gray pixels indicate very little difference between the two model runs (see color scale).

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