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We describe emerging capabilities to understand physical processes and biogeochemical cycles in coastal waters through the use of satellites, numerical models, and ship observations. Emerging capabilities provide significantly improved ability to model ecological systems and the impact of environmental management actions on them. The complex interaction of physical and biogeochemical processes responsible for hypoxic events requires an integrated approach to research, monitoring, and modeling in order to fully define the processes leading to hypoxia. Our efforts characterizes the carbon cycle associated with river plumes and the export of organic matter and nutrients form coastal Louisiana wetlands and embayments in a spatially and temporally intensive manner previously not possible. Riverine nutrients clearly affect ecosystems in the northern Gulf of Mexico as evidenced in the occurrence of regional hypoxia events. Less known and largely unquantified is the export of organic matter and nutrients from the large areas of disappearing coastal wetlands and large embayments adjacent to the Louisiana Continental Shelf. This project provides new methods to track the river plume along the shelf and to estimate the rate of export of suspended inorganic and organic particulate matter and dissolved organic matter form coastal habitats of south Louisiana.

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Bradley Penta, Richard W. Gould, Robert A Arnone, R. Greene, J. Lehrter, James Hagy, B. Schaeffer, M. Murrell, J. Kurtz, B. Herchenroder, R. Green, P. M. Eldridge

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Using Coupled Models to Study the Effects of River Discharge on Biogeochemical Cycling and Hypoxia in the Northern Gulf Of Mexico

B. Penta[1], D. Ko[1] R. Gould[1], R. Arnone[1], R. Greene[2], J. Lehrter[2], J. Hagy[2], B. Schaeffer[2], M. Murrell[2], J. Kurtz[2], B. Herchenroder[3], R. Green[1], and P. Eldridge[4]

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Abstract- **We describe emerging capabilities to understand physical processes and biogeochemical cycles in coastal waters through the use of satellites, numerical models, and ship observations. Emerging capabilities provide significantly improved ability to model ecological systems and the impact of environmental management actions on them. The complex interaction of physical and biogeochemical processes responsible for hypoxic events requires an integrated approach to research, monitoring, and modeling in order to fully define the processes leading to hypoxia. Our effort characterizes the carbon cycle associated with river plumes and the export of organic matter and nutrients from coastal Louisiana wetlands and embayments in a spatially and temporally intensive manner previously not possible. Riverine nutrients clearly affect ecosystems in the northern Gulf of Mexico as evidenced in the occurrence of regional hypoxia events. Less known and largely unquantified is the export of organic matter and nutrients from the large areas of disappearing coastal wetlands and large embayments adjacent to the Louisiana Continental Shelf. This project provides new methods to track the river plume along the shelf and to estimate the rate of export of suspended inorganic and organic particulate matter and dissolved organic matter from coastal habitats of south Louisiana.**

I. Introduction

Along the Louisiana coast, the annual spring to summer episodes of bottom water hypoxia ($[O_2] < 2$ mg l^{-1}) cover an areal extent on the order of 15,000 - 20,000 km^2 (Fig. 1). This region of the northern Gulf of Mexico is strongly influenced by outflow from the Mississippi and Atchafalaya rivers and the many estuaries and embayments that constitute the coastal wetlands of the Mississippi River watershed. This outflow carries dissolved inorganic nutrients, particulate and dissolved organic matter, and suspended inorganic particulate matter, which, through complex interactions with the physical regime and biogeochemical processes of the region, affect the onset and duration of hypoxic events.

The goals of our project are: 1) to assess and predict the relationships between nutrient loads and hypoxia, 2) quantify the errors and uncertainties of nutrient load reduction scenarios, and 3) to provide tools to support nutrient management decisions. The complex physical and biogeochemical processes involved require an integrated approach to research, monitoring, and modeling in order to fully define the processes responsible for hypoxic events.

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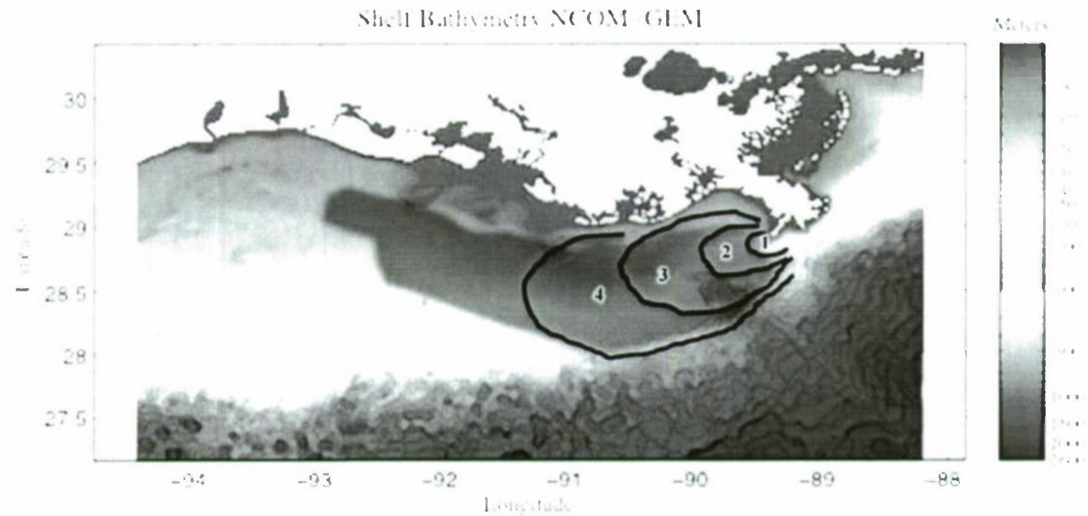

Fig. 1 Bathymetry of the Louisiana Shelf (m) with the hypoxia region depicted in gray. The four regions used in the 'box model' version of the biogeochemical model (see text) are also shown (1-4). This is the domain of the physical and coupled biogeochemical models.

II. Data

A. In situ Sampling

The EPA Gulf Hypoxia Monitoring and Modeling Program has collected data during offshore and inshore surveys on the Louisiana shelf and coastal embayments (Barataria, Terrebonne, and Atchafalaya Bays). *In situ* biological, optical, physical, and chemical measurements were collected during multiple cruises over several years. Measurements included: primary productivity; water-column and sediment respiration; sediment nutrient and dissolved gas fluxes; water-column nutrients; chlorophyll a; high performance liquid chromatography (HPLC) pigment analysis; particulate organic carbon and nitrogen (POC and PON); dissolved oxygen; dissolved inorganic carbon (DIC); CO_2; pH; temperature; salinity; surface and underwater irradiance; ADCP horizontal and vertical current velocities; and *in situ* optical measurements (absorption and scattering coefficients and partitioned filter pad absorptions).

B. Satellite

The Louisiana coastal region comprises various environments - river plumes, streams, marshes, swamps, wetlands, and shallow embayments. These sources of water, nutrients, and inorganic and organic matter impart a complex array of optical signatures to the shelf. Techniques employed for the analysis and interpretation of satellite-derived time-series data allow us to distinguish these signatures and thus investigate the sources and fates of different water masses [1]. Multi-spectral algorithms allow for the extension of remote sensing capabilities to coastal ocean (case 2) waters where the optical signal is not necessarily chlorophyll-dominated. Calibrations of satellite sensors with accurate atmospheric corrections and ground-truthing with *in situ* measurements were used to develop a quasi-analytical algorithm [2] to separate unique optical components (Fig. 2) of absorption (phytoplankton and non-living material (CDOM + detritus)) and spectral backscattering. These components have also been used to characterize distributions of particulate organic and inorganic matter (POM, PIM) [3], both of which are important in shallow river-dominated regions where sediment resuspension plays an important role.

Ternary plots [4] of the components of total absorption are used to 'fingerprint' water masses using surface ocean color imagery. These techniques provide the capability to define the seasonal cycles of the water masses, residence times, and dispersion rates in the surface waters. Green and Gould [5] developed a multiple linear regression model with ocean color time series (2002-2004) to identify the importance of various physical forcing mechanisms, such as discharge and wind stress, in determining optical variability on the shelf. Riverine nitrate concentration and wind stress were found to best correlate with the phytoplankton absorption in nearshore waters, indicating that stratification and vertical mixing are of primary importance to phytoplankton dynamics in the hypoxic areas. Further offshore, solar radiation and sea surface temperature (SST) were the dominant components, suggestive of upwelled nutrient sources. These satellite-derived products are also used for development and evaluation of our model system.

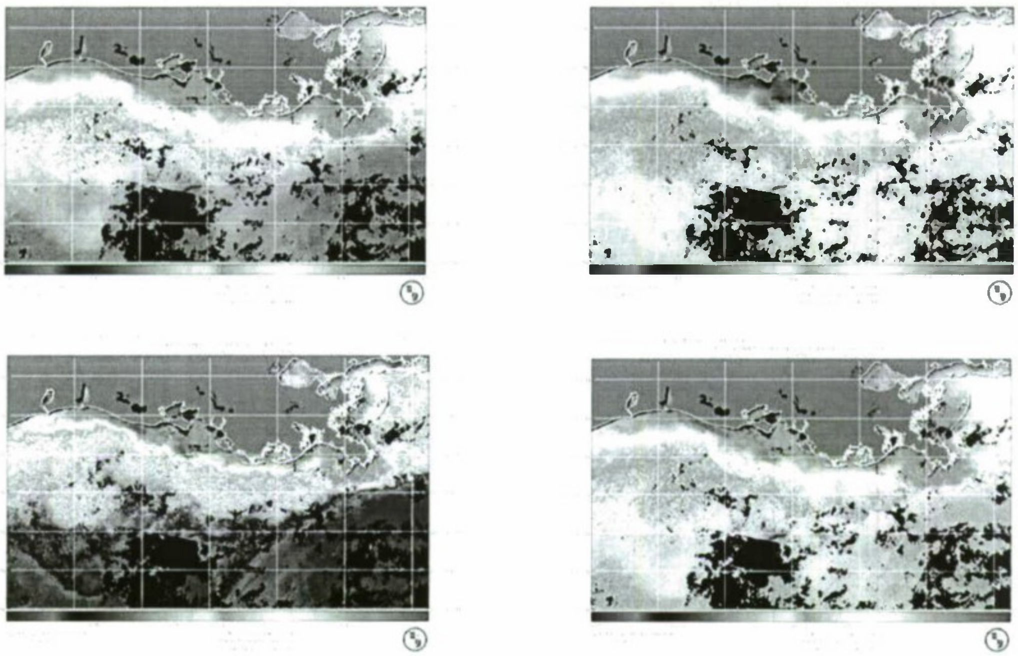

Fig.2 Satellite-derived (SeaWIFs) products: Weekly composites (week of June 18, 2003) of chlorophyll (OC4), TSS (total suspended solids), CDOM (gelbstuff), and absorption of phytoplankton (A_{ph}).

III. Models

A. Physical Model

Our model domain encompasses the area from 88 to 95 degrees West Longitude and 27 to 30.5 degrees North Latitude (Fig. 1). Over this domain we run a high-resolution physical circulation model, with 1/64-degree horizontal resolution and 36 layers in the vertical (with 19 sigma layers on the continental shelf). The model is forced with high-resolution surface fields (wind, air pressure, and shortwave radiation) from the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS™). This high-resolution domain receives boundary information from the larger scale NRL IASNFS (Naval Research Laboratory Intra-Americas Seas Nowcast/ Forecast System) [6] model with tidal forcing and assimilation of satellite altimetry and sea-surface temperature and salinity (SST/SSS). The discharge of 103 rivers and river outlets are included.

The model does an excellent job of simulating the observed temperature structure (Fig. 3). In the freshest inshore waters, the model is less adept at simulating the observed salinity. We are exploring methods for adjusting the vertical distribution of freshwater input as a function of river flow-rate in order to improve the inshore salinity in the model.

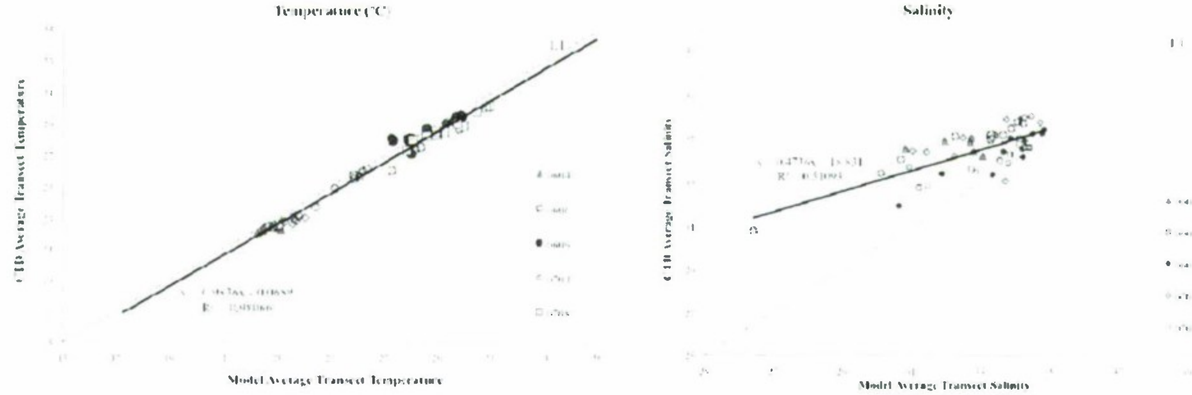

Fig. 3 Regression of modeled temperature (°C; left) and salinity (PSU; right) vs. *in situ* temperature and salinity over four cruise transects.

B. Biogeochemical Model

We employed the Eldridge and Roelke [7] biogeochemical 'box model' in four regions along the salinity gradient off the mouth of the Mississippi River (Fig. 1); the regions are roughly defined as salinity 0-18 PSU, 18-27 PSU, 27-32 PSU, and 32-34.5 PSU. Each region (1-4) in the model consists of a surface mixed-layer, four bottom water layers, and a sediment layer (Fig. 4). The surface layer exchanges O_2 and CO_2 with the atmosphere. Within the surface layer, multiple phytoplankton species compete for nitrogen, phosphorus, and light. Six phytoplankton types (P1-P6) are defined on a range of edibility, growth rates, and sinking rates. A cell quota model allows luxury consumption of nutrients (and nutrient starvation) by the phytoplankton. Diel zooplankton vertical migration across the pycnocline allows nighttime grazing in the mixed layer that is influenced by prey edibility and stoichiometry. The zooplanton then migrate downward, to avoid predation in the sunlit waters, and excrete and respire in the sub-pycnocline waters. The sub-pycnocline aggregate water-column metabolism is also influenced by sinking fecal pellets and dead (or dying) algal cells. A simplified version of the multi-element sediment diagenesis model of Eldridge and Morse [8] is included in the bottom sediment layer. In addition, CDOM has also been added to the model (not shown). This model formulation predicts the temporal onset and duration of hypoxic and anoxic events in the four regions, but cannot (in this form) characterize the spatial extent of hypoxia.

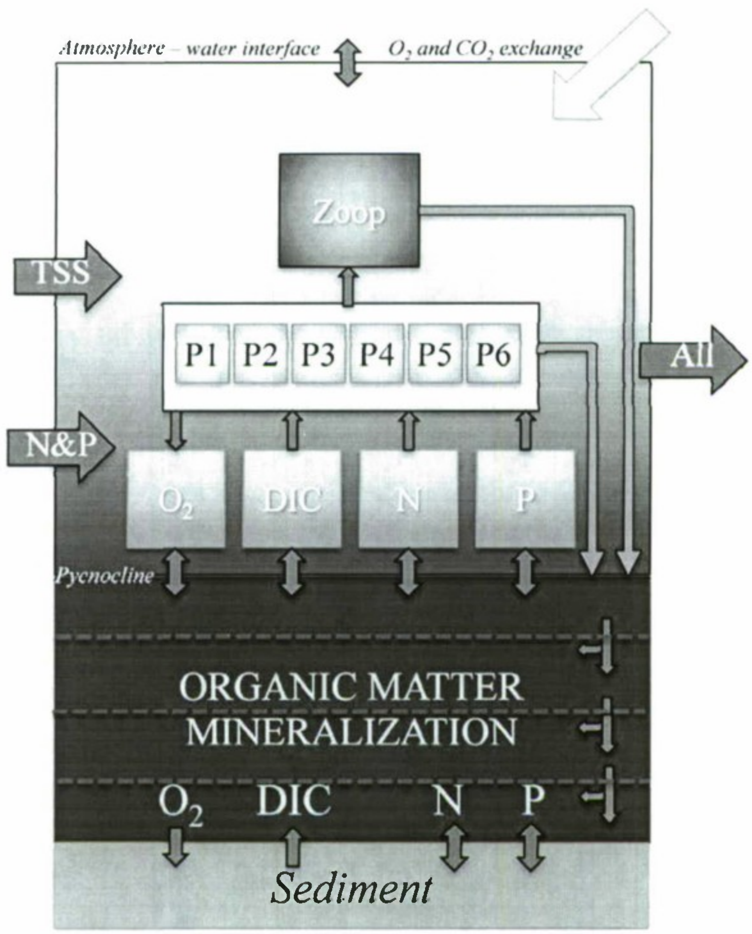

Fig. 4 Schematic diagram of the 'box model' version of the biogeochemical model.

C. *Coupled Model*

By coupling the circulation and ecological models, we provide a new, improved management tool to simulate the impact of various environmental scenarios (changing discharge, nutrient, stratification, etc...) on the extent, development, maintenance, and dissipation of hypoxic events. The 'box model' has been altered such that all of the water column (mixed layer and sub-pycnocline) processes are included in each of the 19 sigma layers of the physical model. The same advection-diffusion equations are used along with output from the physical model (offline coupling) of the three-dimensional currents (u, v, w) and the vertical mixing coefficient (k_h) to drive the biogeochemistry. The coupled model was first used to advect and diffuse inert tracer (no biogeochemical reactions) input from the rivers and bays (Fig. 5).

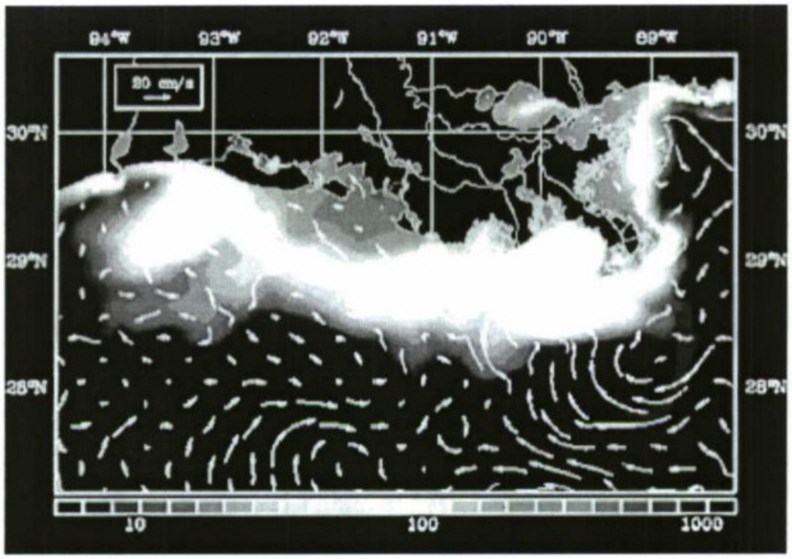

Fig. 5 The physical model (white arrows represent currents) with inert tracer input from rivers (colors).

We have recently begun running the coupled model with the water column biogeochemical reactions. To validate the functionality and internal consistency of the model, an initial test simulation was run for 2003. The results indicate that the model performs in an ecologically stable manner; e.g., phytoplankton bloom and decline within reasonable concentrations and time frames. The surface chlorophyll concentration of the model is computed from the sum of all six phytoplankton (algae) groups (cell numbers times internal nutrient concentration). A snapshot (Fig. 6) of model surface chlorophyll for June 18, 2003 can be compared to the satellite-derived (Fig. 2) chlorophyll and the *in situ* measurements (the colored circles overlain on Fig. 6) for the same day. It is evident that, while the model generates chlorophyll concentrations of the correct order of magnitude nearshore, it does not simulate the offshore gradient properly. The surface chlorophyll concentrations of the six model phytoplankton groups are shown individually in Fig. 7. Phytoplankton group 6 is responsible for most of the total surface chlorophyll signal. In the model, this group is the least edible – causing the zooplankton to shift their grazing away from this group and onto the other groups. By increasing the zooplankton grazing on group 6 (increasing edibility), we may improve the model outcome.

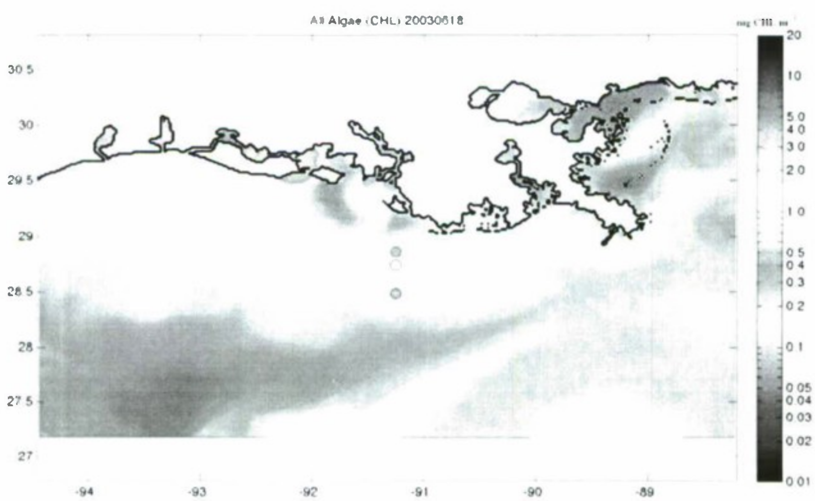

Fig. 6 Results for total phytoplankton chlorophyll (mg CHL m^{-3}) from our initial test run of the coupled model (x-axis is degrees longitude and y-axis is degrees North latitude). Colored circles represent *in situ* measurements. The date is June 18, 2003 for comparison with Fig. 2.

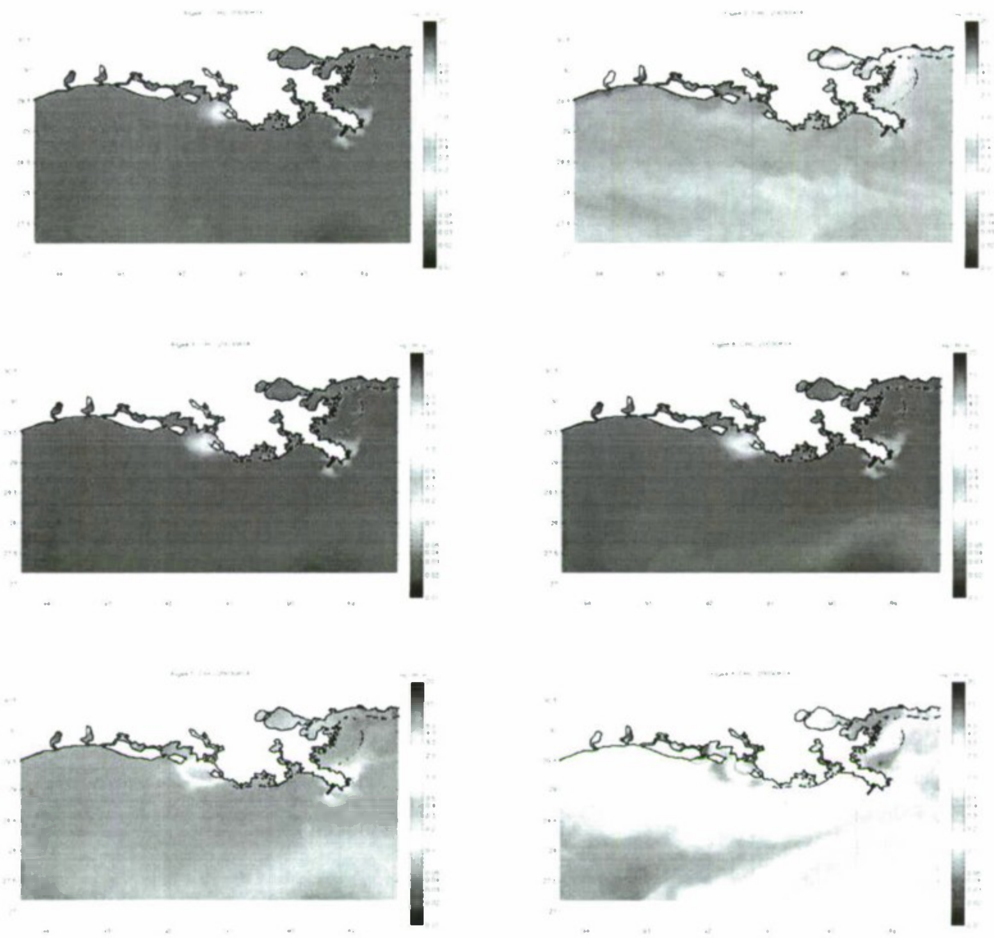

Fig. 7 Results for each of the phytoplankton (Algae 1-6) groups (mg Chl m^{-3}) from our initial test run of the coupled model (June 18, 2003). The x-axis is degrees longitude and the y-axis is degrees North latitude.

The distribution of riverine CDOM input to the shelf (Fig. 8) needs to be adjusted, but the dynamics appear sound. Suspended particulate matter [SPM (TSS)] sinks out of the model too quickly (Fig. 8) and currently there is no model mechanism for resuspension. We recognize the importance of sediment resuspension and mobility to the hypoxia problem and are implementing an empirical wave model to account for these processes.

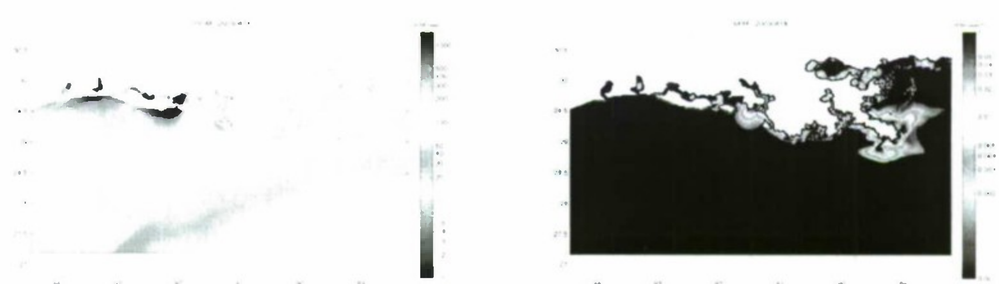

Fig. 8 Initial test run results for CDOM and suspended particulate matter (SPM) for June 18, 2003. The x-axis is degrees longitude and the y-axis is degrees North latitude.

IV. Future Work

We continue to analyze the results from our first coupled model run. In addition to the modifications mentioned above, we are currently implementing the sediment diagenesis component of the biogeochemical model into the coupled system. Another important enhancement will be the inclusion of a more accurate light propagation scheme [9] in the model. Our irradiance measurements have shown photosynthetically active radiation (PAR) penetrating deeper into the water column (occasionally to deep benthic layers) than the 'standard' light model replicates. A more accurate depiction of the euphotic zone may have important effects on the hypoxia simulations.

Ultimately, the goal is for these components to become a forecasting model and management tool. In order for the tool to be useful, we need to understand and quantify the uncertainties and errors inherent in our simulations. We can then investigate various nutrient-loading scenarios and determine their impact on the area of hypoxia.

Acknowledgment

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