Project Description

<u>Introduction</u>

   Hypoxia, defined as occurring when the oxygen content of a body of water decreases below 2 mg·l^{-1} (1.4 ml·l^{-1} or 63 µmol·l^{-1}), occurs annually in late spring and summer in the northern Gulf of Mexico, west of the Mississippi delta. The decreased oxygen concentration can have a catastrophic effect on bottom-dwelling organisms and may severely affect the local shrimp and demersal fishing industry, although there is little hard evidence of this to date. The size of the region affected varies from year to year in response to floods; the mean area affected has increased from about 8000-9000 km^2 during 1985-1992 to about 15,000-17,000 km^2 from 1993-1997 (following the 1993 flood), about 19,000 km^2 during 1999 (Ferber, 2001, Battaglia and Goolsby, 2001), and to over 20,000 km^2 in 2001 and 2002. In 1998 and 2000 smaller areas were affected, as river flows were well below average, while in 2003 and 2005 tropical storms and hurricanes mixed the water column immediately before the monitoring cruise, reducing the area of hypoxia considerably.

   The NGOMEX Research Program "is directed toward the goal of developing a predictive capability for the Louisiana shelf ecosystem within an adaptive management framework that connects monitoring, data analysis, model predictions, and management actions with continuous feedback for improvement in each category." This proposal is directly relevant to these aims. We believe we have begun the necessary time-series data collection and modeling that will be required to describe and monitor the onset, development and decay of hypoxia in this region.

   In October 2002, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (henceforth Task Force) held a monitoring, modeling and research workshop in St. Louis, MO. The report of this workshop (USGS 2004), describes a framework for research activities that is expected to provide a sound scientific basis for future management actions. One of the major activities recommended by the workshop is the supplementation of existing monitoring efforts to describe the distribution and development of hypoxia across the shelf. During the period 1995-2003, there was only one annual shelf-wide monitoring cruise, in late July (Rabalais et al. 2002). During 2004 and 2005, several of the PIs of this proposal were funded through the NGOMEX program to conduct additional cruises and mooring deployments to determine the variability of the hypoxic zone and investigate its control functions. Three cruises were completed in 2004 (April, June and August) and five have been completed or are scheduled in 2005 (March, May, July, August, and October). We will refer to this funded program hence forth as MCHI [Mechanisms Controlling Hypoxia I]. The MCHI cruises were in addition to the regular cruises carried out by Rabalais and her co-workers.

   A second thrust of the Task Force report is the establishment of moored arrays and increasing the resolution of shelf-wide efforts. Three mooring sites were established (near 29°N, 92°W, 28.8°N, 90.5°W, and 29°N, 89.5°W) for these cruises, and grids of closely-spaced stations (separation ~10 km) were selected around each site (Figure 1). For technical reasons the only extended period of occupation was at site C (29°N, 92°W) during March – August 2005 (we hope to extend this through October 2005). However, the station grids were occupied on all cruises and additional stations were added along the 10m and 20m isobaths as time permitted.
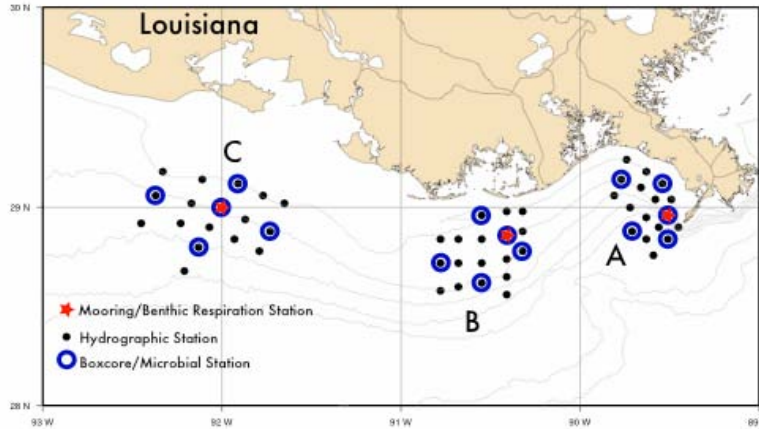
Figure 1. Typical sampling grid for MCHI cruises (2004-2005) showing hydrographic stations, benthic respiration and microbial stations, and mooring locations.

A third thrust of the Task Force is to improve the physical, chemical and biological modeling capability to better understand and quantify the rates of the particular processes that contribute to hypoxia. During MCHI, we developed a circulation model of the Texas/Louisiana continental shelf based on the Regional Ocean Modeling System (ROMS). ROMS is a hydrostatic circulation model that has become the community standard for coastal ocean modeling applications because of its robust numerical engine, which may be coupled with numerous extension modules, such as biological and sediment models. The model domain created for the MCHI project covers a region from the coast (with a minimum depth of 3 m) to the shelf break and extends from approximately 94.5˚W to 88˚W with a grid resolution of approximately 2-3 km. The model has 30 vertical *s*-layers, with resolution focused near the surface and bottom to resolve plume and benthic processes. The model is forced with regional winds and fresh water fluxes from the Mississippi and Atchafalaya Rivers. The statistics of the physical model variability have been analyzed using historical measurements from the LATEX program. Model data comparisons show that the model reproduces observed variability in the shelf currents. Also, a numerical nowcast performed while onboard the July 2005 hydrographic survey showed good agreement between the simulated and observed near surface salinity fields (Figure 2). This physical model will form the foundation of the proposed modeling work.
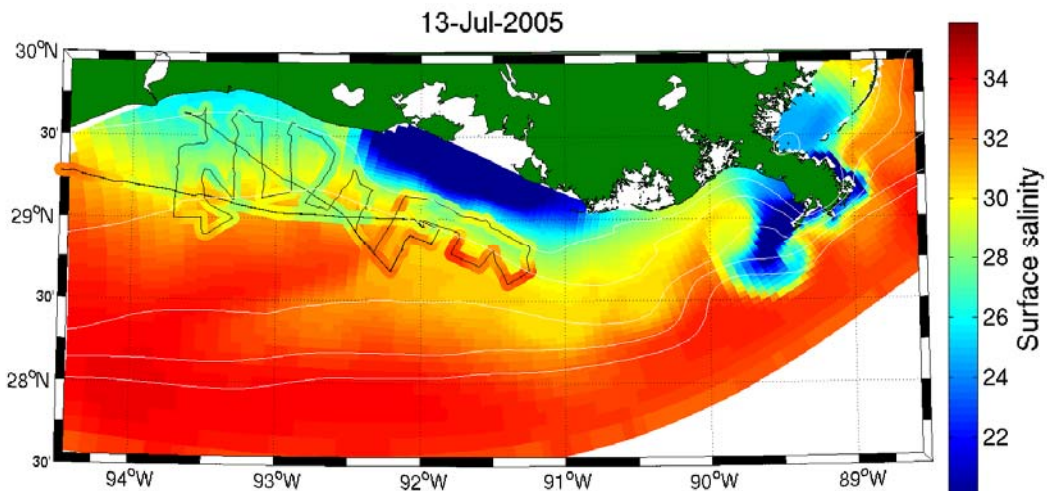

Figure 2. Comparison of observed 3-m salinity along cruise track (thin black line) during 7-14 July 2005 cruise by proposers and superimposed surface salinity field obtained from numerical circulation model (model day: 13 July 2005).

This proposed study will extend canonical ideas about the processes creating and controlling hypoxia on the Texas/Louisiana continental shelf. We believe that in locations where hypoxia is most variable (west of Terrebonne Bay) processes controlling hypoxia are sensitive to local winds, shelf-scale circulation features, and benthic biogeochemical processes in addition to inputs of nutrients and fresh water.
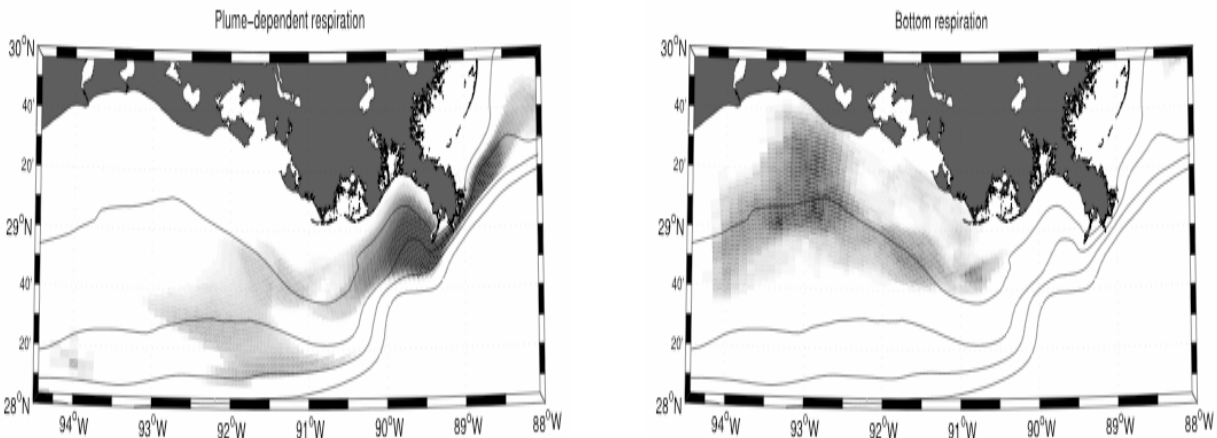

Figure 3.   Estimates from the ROMS model of the areas of the shelf where hypoxia is dependent on (a) plume respiration and (b) water column respiration. Note that the two controls affect different areas of the shelf.

Basic numerical experiments illustrate the importance of the location of respiration in the water column in determining the vertical structure of oxygen (Hetland et al. 2005, in preparation). A tracer representing oxygen was added to the basic physical model. Oxygen was initialized using saturated oxygen values (in turn dependent on the local temperature and salinity), and saturation concentrations were maintained at the surface and for the inflowing river water, while being nudged toward saturation along the open boundaries. Two types of respiration were then applied that reduced the oxygen in the model. First, benthic respiration was applied, based on measurements by Rowe et al. (2002). Second, respiration was applied throughout the water column, higher where surface salinities were lower. The second scenario was based on the idea that the organic material necessary for respiration, and ultimately hypoxia, is highest near the fresh water sources due to enhanced nitrogen introduced to the coastal ocean through the river water. Both cases created hypoxic conditions within the model (see Figure 3). Water column respiration produced hypoxia east of Terrebonne Bay, where hypoxia is observed often. Benthic respiration produced hypoxia west of Terrebonne Bay, where the presence of seasonal hypoxia is more sporadic. Comparisons with vertical profiles of oxygen in this region also suggest that benthic respiration appears to be the driving factor controlling the western limb of seasonal hypoxia.

The Conceptual Model of Hypoxia on the Louisiana Shelf

Rowe and Chapman (2002) suggested as a simple model that hypoxia development is controlled by three different mechanisms, depending on distance from the Mississippi or Atchafalaya. Close to the mouths of the rivers the main driver is the sediment loading and the associated chemical reactions between reducing compounds in the nearshore sediments (Morse and Rowe, 1999; Rowe, 2001). Further away, the sediment load drops and light penetration increases. This is enough to encourage phytoplankton growth, fueled by the high dissolved nitrogen concentrations (N < 120 $\mu mol \cdot kg^{-1}$, Si < 200 $\mu mol \cdot kg^{-1}$; Turner and Rabalais, 1991; Hitchcock et al., 1997) in the low-salinity surface plume (e.g., Rabalais et al., 1991). Further

away still, however, dissolved nitrogen concentrations are very low at the surface, and hypoxia is controlled by the local stratification, which is highly dependent on both the local wind field and the amount of freshwater coming down the rivers. While the exact details of this simple model are still a matter of conjecture (Boesch, 2003), the idea of different regions having different controlling factors remains sound (Rowe and Chapman, 2003). *The logical outcome of this model is that since the regions controlled by chemical and biological activities become hypoxic almost every year (Rabalais et al., 1999) it is the annual changes in the area of the region controlled by stratification that determines the total area of the hypoxic zone.* This is borne out by the fact that in wet years such as 1993, with sustained high flow during the summer, the hypoxic zone is much larger than in dry years such as 1987, 1988 and 2000 (USGS 2004). Carey et al. (1999) have shown that there has been a steady increase of river flow of about 30% since the 1950s, suggesting one possible reason for the expansion of the hypoxic zone since its first observation in the 1980s. It is known that hypoxia occurs primarily at the bottom, associated with the base of the pycnocline (see Figure 4, where the salinity isopleths can be considered as analogous to density). The layer can be very thin, as here, but may also grow to more than 10 m in thickness (Rabalais et al., 1999).
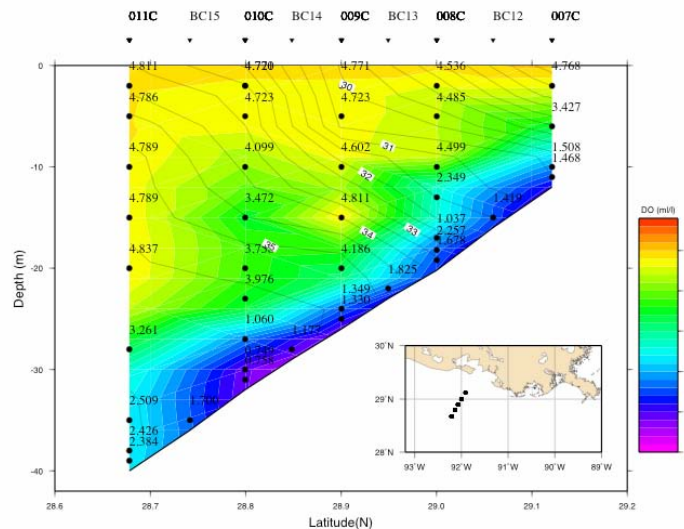

Figure 4.   Vertical section of dissolved oxygen concentration (color) and salinity (black lines) along cross-shelf transect in Zone Z south of Atchafalaya during MCH1 August 2004 cruise. Inset shows geographical locations of stations.

Local currents in the region vary considerably throughout the year. During winter and spring, currents flow west along the Louisiana coast parallel to the isobaths, forced both by the Coriolis effect and by the prevailing easterly (downwelling) winds. This flow extends as far as southern Texas (see surface salinity distributions in Li et al. (1997), which parallel the bathymetry). In late spring/early summer, however, the coastal wind system changes to westerly (upwelling). This causes a flow reversal along the TX shelf and results in cross-shelf flow south of the Atchafalaya (Cochrane and Kelly, 1986; Li et al., 1997). At this time, the Mississippi plume may be forced offshore or to the east so that the Atchafalaya is the major source of fresh water west of 91°W (see Li et al., 1997). Flow below the pycnocline is reduced to 1-3 cm·s^{-1} (Wiseman et al., 1997; Murray et al., 1998), and because gas exchange is almost zero, little in situ respiration is required to induce hypoxic conditions. The varying freshwater input not only supplies more or less nutrient, but local stratification also controls oxygen transfer between the pelagic and benthic layers. A non-linear relationship between runoff, light and currents thus provides the physical control on the system (Justic et al., 1993; Chen et al. 1997, 2000; Lohrenz et al., 1999). The situation is exacerbated during flood years, when the

area affected is larger than usual, or when higher than normal runoff occurs after the spring freshwater peak, causing strengthening of the pycnocline later in the season.

Data on respiration rates (Morse and Rowe, 1999; Rowe et al., 2002; Childs et al., 2002) suggest both water-based and sediment-based respiration rates are fast enough to cause hypoxia within a season. The ratio between the two is likely to change considerably during the year, depending on the changing river flow, nutrient supply, and phytoplankton distributions. Nutrient regeneration rates also vary considerably across the area (Bode and Dortch, 1996; Nelson and Dortch, 1996; Morse and Rowe, 1999; Gardner et al., 1993). For example, carbon burial rates varied by a factor of three, while phosphate regeneration rates varied by a factor of fifty, with the highest phosphate regeneration occurring in an hypoxic area (Morse and Rowe, 1999).

There have been several attempts to use box models to estimate the extent and intensity of hypoxia and its dependence on nitrate input (e.g., Brezonik et al., 1999; Justic et al., 2002, 2003; Scavia et al., 2003). These simple models are one- or two-dimensional, and tend to neglect horizontal oxygen transport or the local effects of winds. Thus, while they can apparently reproduce the interannual variability at a point (Justic et al., 2002, 2003) or provide estimates of the total area likely to be affected by hypoxia (Scavia et al., 2003), they tell us little about where it actually occurs or how it moves in response to physical forcing. However, they do agree in suggesting that widespread hypoxia was not likely before the mid-1970s, when organic carbon accumulation rates also began to increase. Their potential use is in allowing us to make estimates of likely scenarios following changes to either nitrate loading or water flow; decreasing the nitrate flux by 30%, as recommended by the Nitrate Reduction Action plan (Rabalais et al., 2002), may not be enough to reduce the area affected by hypoxia to below 5000 km^2 because of annual variability (Justic et al., 2003, Scavia et al., 2003).

A simpler model (Turner et al., 2005) relates the area of the hypoxic zone to the total nitrogen input measured at the Louisiana Offshore Oil platform (LOOP). While a simple polynomial regression appeared to give good agreement for "normal" years, the passage of storms disrupts the relationship and results in over-estimates (e.g., in 2005). The model did, however, agree with the results of Justic et al. and Scavia et al. cited above in suggesting only patchy hypoxia before the mid-1970s.

While box models of the sort used in the above studies are common in work on rivers, it is not clear how they relate to the dynamics of the buoyant river plume; for instance, neither the changing dimensions of the plume itself nor wind forcing were included in the model. Thus, we believe that the results of these studies are limited. *The need for a more realistic model incorporating local forcing functions was specifically recommended by Brezonik et al.* (1999). Our ROMS model provides three-dimensional capability that can follow changes in local forcing functions.

The results of the MCHI cruises in 2004 and 2005 and of our modeling experiments have shown clearly that hypoxia development and decay depend on three factors, the local wind regime, the stability of the water column, and the amount of water coming down the Mississippi and Atchafalaya Rivers. Several particular items of interest are:

1. The hypoxic layer can be very thin and associated with the bottom nepheloid layer. Frequently we have observed that the hypoxic layer is only 1-2 meters thick or less, thus sampling very close to the bottom is required. In the near-liquid mud that is found over parts of the Louisiana shelf, it is not always clear where the bottom is. The proposed mooring systems will include 2-3 dissolved oxygen sensors in the lower 8 m of the water column.

2. The hypoxic region can vary in area and position on short time and space scales. The local winds control the position of the freshwater plume; particularly that coming out of Southwest Pass, and this varies over periods of a day or less. The ROMS model results clearly reflect this, with pulsing occurring depending on the wind forcing. Similarly, the hydrographic data show large changes in oxygen concentration at the bottom over short length (<10 km) and time scales (see Figures 5 and 7). The proposed mooring system will

include reporting of several variables (temperature, salinity, velocity, dissolved oxygen, and others) at hourly intervals at three locations.

3. Major atmospheric fronts can cause large changes in stratification over large areas very quickly, but once the front has passed, restratification can occur within a few (O < 5) days depending on the amount of freshwater coming down the rivers. This was found in March 2005 when restoration of the pynocline along the 10-m isobath took less than two days. The proposed observing system will distribute observations over the entire water column to monitor vertical variability as well as temporal.

4. There is a clear separation for much of the year between the hypoxic zones that are close to the sources of the Mississippi and Atchafalaya, except for very close inshore along the 10m isobath. This separation is equally clear in the model outputs.

5. "The Wave." We have observed a locally trapped shelf wave with wavelength (O 50 km). It is not clear if this wave acts to amplify or dampen hypoxia across the shelf (DiMarco et al., 2005, in preparation). The oxygen maxima and minima are inversely correlated with the salinity (density) gradient and associated with onshore/offshore flow regimes as measured by shipboard ADCP. The placement along the shelf of the proposed moorings would be able to provide phase information of propagating shelf waves.
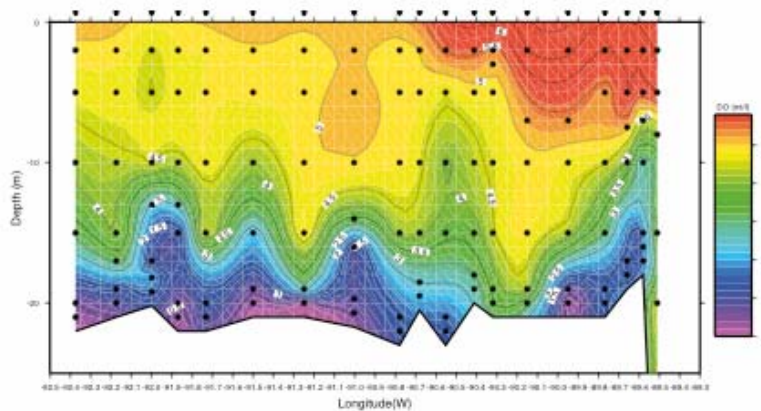

Figure 5.   Vertical profile of dissolved oxygen along the 20-m isobath between Southwest Pass, LA (right) and 92.4°W (left) during MCHI August 2004 cruise.

6. It is possible that the volume of fresh water, rather than the amount of nitrogen it contains, determines the maximum extent of the hypoxic zone, although of course nitrogen is required for phytoplankton production and the subsequent flux of carbon to the bottom. Thus, the maximum extent of the hypoxic region will be found when a late flood coincides with calm weather in summer. This will maximize the area subject to a stable pycnocline, minimize oxygen transfer to the benthic layer, and maximize bottom respiration and hence hypoxia. The proposed moorings will be deployed from March through September to cover the peak discharge and hypoxic seasons.

7. We observed during MCHI that sediment community oxygen consumption (SCOC) rates are similar across the Louisiana Shelf from Southwest Pass to Atchafalaya confirming results in Rowe and Chapman (2002). During the onset of hypoxia, SCOC resembles healthy rates seen prior to hypoxia. In July and August, sediments are depleted of metabolic substrates for oxic consumers resulting in a noticeable decrease in total sediment respiration. This appears to be accompanied by a switch from oxygen to sulfate as the terminal electron acceptor. We propose to continue benthic respiration experiments begun in MCHI and extend the spatial coverage west of Atchafalaya.