

Synthesis Report on Gulf of Mexico Hypoxia Biogeochemical Processing

**An output from the 3rd Annual Gulf of Mexico Hypoxia Research Coordination Workshop
to inform the Scientific Reassessment of Action 9 of the 2008 Gulf Hypoxia Action Plan**

Alan Lewitus (NOAA National Centers for Coastal Ocean Science))

Steve DiMarco (Texas A&M University)

Wayne Gardner (University of Texas)

John Lehrter (EPA Gulf Ecology Division)

Michael Murrell (EPA Gulf Ecology Division)

Nancy Rabalais (Louisiana Universities Marine Consortium)

Brian Roberts (Louisiana Universities Marine Consortium)

March 2013

Over the last three years, NOAA has convened Gulf Hypoxia Research Coordination Workshops (<http://www.ncddc.noaa.gov/activities/healthy-oceans/gulf-hypoxia-stakeholders/>) with objectives to (1) coordinate hypoxia monitoring and modeling research in preparation for the upcoming field sampling season; (2) provide a forum to discuss the state-of-knowledge on Gulf hypoxic zone research; and (3) inform activities of the Gulf Hypoxia Task Force (HTF) and other regional ecosystem management efforts. Outputs from the 1st and 2nd Annual Gulf Hypoxia Research Coordination Workshops guided development of the HTF's FY11 and FY12 Annual Operating Plans, respectively. Because the 3rd Annual Workshop coincided with the HTF reassessment process, NOAA decided to focus on two thematic areas where significant gaps in understanding existed when the 2008 Gulf Hypoxia Action Plan was produced – (1) Hypoxia Impacts on Living Resources to inform reassessment of Action 5 (see “Scientific Reassessment of Action 5”) and (2) Biogeochemical Processes to inform reassessment of Action 9, addressed here.

Action 9: Continue to reduce uncertainty about the relationship between nitrogen and phosphorus loads and the formation, extent, duration, and severity of the hypoxic zone, to best monitor progress toward, and inform adaptive management of the Coastal Goal.

Participants in the Biogeochemical Processes work group were asked to assess the state-of-knowledge and information gaps on the biogeochemical pathways that process and recycle nutrients and carbon and ultimately lead to generation and maintenance of hypoxia. This information is key to advancing development of, and validating results from ecosystem scenario based models that inform the nutrient reduction strategies central to the Action Plan Coastal Goal to reduce the size of the hypoxic zone. Research on the Gulf ecosystem since the last science reassessment (2005-2007) has led to a more comprehensive understanding of factors regulating hypoxia, and more explicit delineation of natural and anthropogenic drivers has reinforced the central tenet of the 2008 Action Plan mitigation strategy that “reducing nutrient loadings from the various sources in the Basin addresses the most critical and controllable cause of hypoxia”. At the same time, these advancements are leading to an enhanced ability of models to inform refinement of nutrient reduction targets and evaluate them in the context of additional ecosystem drivers.

[Caveat: this “scientific reassessment” is based largely on Workshop findings and therefore is limited to the attendees present at the meeting, and they are not necessarily informed by research conducted or published since the meeting.]

Summary of Main Points:

- Processing studies and statistical assessments reinforce the strong relationship between springtime nutrient loading, water column primary production, mid-water and benthic hypoxia, and hypoxic zone areal extent, thus validating watershed nutrient load reduction as the most effective management practice to mitigate hypoxia;
- Physical processes (local wind strength, wind duration, river discharge volume) are also correlated with hypoxic zone areal extent, and are important factors influencing spatial and temporal patterns in nutrient flux, water column stratification, and consequently hypoxic zone properties.
- N-limitation is generally more important than P-limitation in controlling primary production. When N and P co-limitation occurs, N typically has a greater effect than P on the co-limitation. These results validate the need to focus on N mitigation in the longer-term but to target both N and P in watershed nutrient reduction strategies;
- In plume waters, strong net autotrophy is observed, but further offshore (e.g., at > 15 m depths), photosynthesis and respiration are often balanced or net heterotrophy is observed, and nutrient regenerative processes are favored. Trophic dynamics driven by nutrient regeneration is consistent with prolongation of hypoxia into the summer (i.e., although the Mississippi River delivers > 5X more nutrients than needed to fuel offshore hypoxia, most of the surface net autotrophy needed to fuel hypoxia occurs in the winter/spring period).
- Sediment oxygen consumption accounted for 20-40% of sub-pycnocline respiration on average. Thus, the lower water column has higher integrated respiration rates than do the sediments, but the proportion varies seasonally.
- Water column nutrient availability is the predominant source for phytoplankton production – nutrient fluxes from sediment transformations supply only a minor fraction of N and P demand.
- Benthic microbial processes scavenge phosphate from bottom waters, which may accentuate P limitation on the continental shelf. During severely hypoxic conditions, P release from sediments is likely.
- Coupled nitrification/denitrification is a strong driver of sediment/water N dynamics under hypoxic conditions; anammox and DNRA are less important. Denitrification causes apparent N limitation of microbial processes in bottom waters of hypoxic area.
- However, one study observed net release of ammonium from sediments during hypoxic conditions, which can support primary production (and oxygen production) in the lower

water column if sufficient light is available, which may ameliorate hypoxia. The excess ammonium may also promote enhanced nitrification (and oxygen consumption), which may exacerbate hypoxia. (but inconsistent with next bullet).

- Evidence for potential benthic photosynthesis exists, but no studies have adequately quantified the importance of the process. This area needs further research because of the implications for hypoxia formation and persistence.
- Organic matter in the sediment of the hypoxic area was relatively consolidated, suggesting that moderate or energetic storms would be required for mobilization. However, another study found spatial variability in the importance of sediment resuspension, and suggested that in these “patches”, buried organic matter may be mobilized with low physical forcing. The resolution of sediment mobility has important implications for the potential influence of organic matter burial as a source of stored carbon for hypoxia formation in subsequent years.

State of Knowledge

Relationship of primary production to nutrient loading: Historical accounts suggest that highest primary productivity is observed closest to the river source whereas less productive waters are observed at locations furthest from the source (Lohrenz et al. 1990, 1994, 1997, 1999). Prior studies also indicate that primary production and chlorophyll *a* (chl *a*) biomass peaks are related to nitrate-N load and concentration, and they occur at salinities of 15 to 25 where turbidity limitations for phytoplankton growth are reduced and sufficient nutrients remain to support elevated primary production (Lohrenz et al. 1997, Rabalais et al. 2002, Walker and Rabalais 2006). Recent studies have confirmed that chl *a* concentrations and primary production were significantly higher in surface waters of plume versus non-plume regions for the eastern shelf (Lohrenz et al. 2008, Lehrter et al. 2009, Quigg et al. 2011), but west of the Atchafalaya, primary production rates are similarly high in plume and non-plume waters (Lehrter et al. 2009, Quigg et al. 2011). Similar spatial patterns have been reproduced by recent modeling studies (e.g. Eldridge and Roelke, 2010; Fennel et al. 2011).

Primary production rates correlated most strongly with inorganic N concentration and loading, but also were related to P loading and freshwater discharge (Turner and Rabalais 2013). Nutrient-enhanced primary production and sinking of organic matter below the pycnocline are considered the main anthropogenic driver for benthic hypoxia. Mid-depth low oxygen concentrations are not only affected by the sources of the water controlled by physical factors but are also associated with the respiration of fluxed surface water organic matter to an upper water column pycnocline (Turner and Rabalais 2013).

The relationship between the input of terrestrially-derived nutrients into coastal ecosystems and coastal hypoxia is well documented (Diaz and Rosenberg 2008). Several studies have shown statistically-significant correlations between total nutrient loading from the Mississippi River and the mid-summer areal extent of hypoxia (Dale et al. 2007, Rabalais et al. 2007, Greene et al. 2009, Turner et al. 2012). Recent investigations (Forrest et al. 2011, Feng et al. 2012) indicate that physical processes related to local wind strength, wind duration, and river discharge volume were correlated with mid-summer hypoxic areal extent and that the strength of correlation is on

the order of that due to nutrient loading. This observation indicates that observed hypoxic area may be influenced by multiple, integrated processes. These processes influence the flux and distribution of nutrients into the coastal system, thus also the distribution of new carbon production that is available for oxidation. Further, these processes influence the distribution of freshwater and stratification, and thereby the ventilation of oxygen-poor subpycnocline water with relatively oxygen-rich surface water.

Light and nutrient limitation: Patterns of nutrient limitation are consistent annually and seasonally. Based on a series of nutrient bioassay experiments, water column primary production was most often limited by N alone or N+P shelfwide; P-limitation was observed less frequently (Turner and Rabalais 2013). A consistent definition of nutrient limitation was applied by Turner and Rabalais (2013) to other published studies of nutrient bioassay experiments, and resulted in similar findings. Studies examining shelf wide light and nutrient limitation indicated that P limitation of phytoplankton delays the assimilation of riverine dissolved inorganic N in the summer as the plume spreads across the shelf, thereby pushing primary production over a larger region (Sylvan et al. 2007, 2011, Quigg et al. 2011). Also, the mode of limitation varies temporally and spatially (Dortch and Whitedge 1992, Laurent et al. 2012, Turner and Rabalais 2013, Roberts et al. 2012, unpubl. data). The type of limitation changes along the salinity gradient, with transition from light limitation (salinity < 15, turbid waters), to N with some P (relatively nutrient-rich), and then to mostly N+P (most dilute) that may be synergistic (Quigg et al. 2011, Laurent et al. 2012, Turner and Rabalais 2013). However, Si limitation also may become important and ultimately influence hypoxia formation given the importance of diatoms (Turner et al. 1998, Dortch et al. 2001). Model generated 3-D nutrient limitation patterns indicates that at salinity < 25, N, P, or light was limiting, while at salinity > 25; mostly N was limiting (Eldridge and Roelke, 2010, Fennel et al. 2011, Laurent et al. 2012).

Strong DIC deficits occur in surface plume waters caused by net primary production (Cai 2003, Lohrenz and Cai 2006, Cai and Lohrenz 2010, Guo et al. 2012, Fry et al. unpubl. data). This observation provides evidence that mixed layer primary production dynamics are tied to river nutrient inputs, but the zone of high productivity is spatially restricted to near the river mouth. However, a well-documented lag occurs in river discharge, nutrient load, and formation of hypoxia, in which the high spring discharge and nutrient loads are most relevant to formation of hypoxia (Justić et al. 1993, 2002). Extreme flooding events, as seen in 2011, may lead to conditions in the northern Gulf that shift the continental shelf from a net sink to a net source of CO₂ to the atmosphere (Bianchi et al 2013).

Water column photosynthesis vs. respiration: Most offshore stations at >15 m depth have surface mixed layers where photosynthesis and respiration are nearly balanced, with more stations slightly net heterotrophic than slightly net autotrophic (Murrell et al. 2013, B. Fry, unpubl. data). Surface mixed layers were primarily net autotrophic on an annual basis with some net heterotrophy observed in summer at a single 20 m deep station located 100 km west of the Mississippi River (C6 off Terrebonne Bay) (Justic et al. 1994). Based on patterns observed from other continental shelf systems, the deeper stations are likely nutrient limited, which would favor nutrient regenerative processes and nearly balanced photosynthesis and respiration (Fry et al. unpubl. data, Rabalais et al. Annual Report Year 2 NGOMEX09). Similar to the DIC patterns discussed above, where nutrients are higher in plume waters, strong net autotrophy is observed.

Calculations indicate that the Mississippi River delivers > 5x more nutrients than needed to fuel offshore hypoxia, but probably most of the surface net autotrophy required to fuel benthic heterotrophy occurs in the winter and spring at times of high river discharge (Fry et al. unpubl. data).

Water column respiration rates can span a wide range. Based on samples collected along the C and F cross-shelf transects in spring through summer of 2010 and 2011, water column rates ranged from 3.7 – 177 mmol O₂ m⁻² d⁻¹, with both mean and median surface water rates (38.0 and 23.3, respectively) being over twice those of bottom water rates (17.1 and 10.9, respectively) (Roberts et al. 2012). In that study, resource-limitation enrichment bioassays suggested primary limitation of respiration by C, with greatest stimulation when CNP were added but respiration only responded to N when both C and P were also added. Murrell et al. (2013) reported plankton community respiration measurements from ten cruises at sites distributed across the shelf. Volumetric respiration rates ranged from below detection to 99.3 mmol O₂ m⁻³ d⁻¹ and showed strongly coherent vertical and horizontal variability, being highest in shallow surface waters and declining offshore. Surface layer samples consistently had higher respiration than bottom layer samples collected at the same site, a pattern observed all across the shelf in both spring, summer and fall months. Water column integrated rates were strongly dependent on the integration depth, averaging 121 mmol O₂ m⁻² d⁻¹ at sites < 10 m deep to 239 mmol O₂ m⁻² d⁻¹ at sites > 40 m deep.

Vertical flux of primary productivity: Diatom flux into moored sediment traps is higher when diatom abundance dominates the surface water phytoplankton community (Dortch et al. 2001). Over a period from April to December, the carbon associated with fecal pellet flux into moored sediment traps exceeded the carbon contribution from diatoms (Qureshi 1995), but the traps were not deployed in the late winter when diatoms may have been more dominant in the settled material. There is likely an annual cycle of flux by diatoms, diatoms and fecal pellets, and fecal pellets as the source of organic matter reaching the lower water column and sediment surface, and this cycle varies by nutrient loading, availability of nutrients, geographic location, depth of water column, and a range of physical and biological factors. [See research need below.] Diagnostic pigments from HPLC analysis indicate that the ratio of dinoflagellates to diatoms decreased from 1.3 at the shallowest station to about 0.37 at the deepest station, but despite these differences, sequence analysis suggests that calanoid copepods across the Louisiana shelf were feeding mostly on diatoms (Sinclair et al. unpubl. data, Rabalais et al. Annual Report Year 2, NGOMEX09).

Benthic respiration: Temperature can help predict benthic respiration rates in the Atchafalaya River Delta Estuary (ARDE) and along a transect out to 30 m deep locations in the northern Gulf off of the Atchafalaya River (Roberts et al. 2012), in the 15-20 m depths on a transect off Terrebonne Bay within 100 km of the Mississippi River delta (Baustian 2011, Baustian et al. submitted), and across the Louisiana shelf area (Nunnally et al. 2013 and references therein). There is high variability (> 3-fold) in benthic respiration with distance offshore. The maximum benthic respiration along the “F Transect” extending cross-shelf off of the Atchafalaya River (greatest frequency of hypoxia observance) does not occur until ~60 km from the ARDE at the 20 m isobaths. This result is consistent with previous findings from the ARDE showing that despite high inputs of river nutrients and organic matter, ARDE benthic respiration rates as far as 20 km offshore of the river deltas were not higher than other published rates for the northern Gulf of Mexico due to “unstable” sediments high in sand and low in organic matter (OM)

content (Roberts et al. 2012). The spatial gradient of respiration on the inner continental shelf is inshore (higher rates) to offshore (lower rates) (Murrell and Lehrter 2011, Murrell et al. 2013).

Sediment oxygen consumption (SOC) rates in summer vary primarily as a function of bottom-water oxygen and are typical of other estuarine and coastal systems (Baustian 2011, Murrell and Lehrter 2011, Nunnally et al. 2013, Baustian et al. submitted). On average, SOC accounts for 20% of sub-pycnocline respiration, and SOC was a minor component of water-column respiration. Murrell and Lehrter (2011) found that most respiration occurs in the lower water column (~75%) vs. the sediment-water interface (~25%), in contrast to Quiñones-Rivera et al. (2010). Several factors may contribute to the differences among published studies quantifying relative respiration rates in the water column and the sediments, including the limited number of incubations that can be completed on a single cruise, the time of the year, geographic location of the stations, ambient physical and biotic conditions, methodology (change in oxygen concentration, isotopes, productivity:respiration), and assumptions in calculations. There is a great need for more work focused on improving our understanding of oxygen consumption dynamics on the Louisiana shelf where hypoxia occurs.

Sediment/water boundary N transformation: Some nutrient fluxes are strongly coupled to oxygen concentrations (Rabalais and Turner 2006, Baustian 2011, Lehrter et al. 2012, Roberts et al. 2012, Nunnally et al. 2013, Baustian et al. submitted). Silicate, phosphate and ammonium fluxes from the sediment to the overlying water are higher under lower oxygen conditions and concentrations of these inorganic nutrients are relatively high in bottom water. Nitrate is mostly taken up by sediments year-round. Nutrient flux measurements suggest that sediments supply only a minor fraction of water-column N and P demand by phytoplankton (Lehrter et al. 2012). Fluxes were potentially a more significant source beneath the pycnocline.

Nunnally et al (2013) found that during summer hypoxia, benthic microbial processes resulted in net consumption of nitrate and nitrite and production of ammonium. Elevated sediment community oxygen consumption and nutrient remineralization occurred near terrestrial river inputs associated with the Mississippi and Atchafalaya rivers. Net release of dissolved inorganic N, in the form of ammonium, peaked during late summer. The authors suggested that released ammonium may be a source of nutrients for primary production in bottom waters, and can also provide reduced N for nitrification and microbial respiration, both of which may reinforce the intensity and duration of hypoxia. Based on chamber results, benthic microbes actively scavenged phosphate from the bottom waters and released silicate. The results of Nunnally et al. suggest that addition of reactive N and removal of P due to benthic community metabolism could potentially be accentuating P limitation on the continental shelf.

Denitrification occurred primarily through coupled nitrification-denitrification; mean denitrification rate = $1.4 \text{ mmol N m}^{-2} \text{ d}^{-1}$. If extrapolated to the area of the shelf (to the 200-m contour), this N sink represents 39% of the River TN load (Lehrter et al. 2012). The nitrification/denitrification cycle dominates the sediment/water N dynamics under hypoxic conditions; Anammox and DNRA are less important than denitrification (Gardner and McCarthy 2012). Sediment ammonium demand (“SAD”) is often high at the sediment-water-interface, implying that microbial processes are often N-limited due to nitrification/denitrification, even though excessive nutrient input led initially to the high primary production that, in turn, caused the high respiration and hypoxia in bottom waters (Lin et al. 2011). Thus, denitrification causes apparent N limitation at times in bottom waters of the hypoxic region.

Subpycnocline and benthic photosynthesis: Light attenuation was correlated with wind, discharge, and nutrients (Schaeffer et al. 2012). Estimated euphotic depths (as defined by the 1% light depth) were often greater than the bottom depth (Lehrter et al. 2009, Schaeffer et al. 2012). However, differing levels of light penetration occurred in different years of shelfwide and seasonal oxygen isotope studies (Quiñones-Rivera et al. 2007, 2010). The seasonal abundance and biomass of microphytobenthos along one frequently-hypoxic transect ~ 100 km west of the Mississippi River delta were correlated with relatively higher photosynthetically active radiation (PAR) levels, warmer temperatures, and the higher salinity of the bottom water (Baustian et al. 2011). Thus, light may be a significant factor regulating bottom-water oxygen in this system. The light availability beneath the pycnocline allows for substantial sub-pycnocline water-column primary production, averaging 25 to 50% of the total water-column production during spring and early summer (Lehrter et al. 2009). Baustian et al. (submitted), however, found little evidence for bottom generated oxygen in benthic incubations at ambient light levels and by isotopic uptake indicating primary production. They suggested that any oxygen generated under extremely low oxygen conditions is likely consumed immediately through sediment oxygen demand or chemical oxygen demand. Schaeffer et al. (2012) also determined that the euphotic depth was correlated to the depth at which the water column turned hypoxic on the shelf. Thus, the development of hypoxic waters may be influenced by decreased light availability below the pycnocline in addition to other physical and biological forcing. In summary, these results suggest that freshwater and nutrient inputs are important regulators of shelf-wide light attenuation and, consequently, the vertical distribution of primary production. The incidence of below-pycnocline primary production has potentially important implications about the formation and persistence of hypoxia on the Louisiana continental shelf and warrants further study.

An organic layer of particles occurred in the bottom waters at some sites distant from the river mouth, suggesting that, once out of the more turbid plume waters, there is enough PAR to penetrate down 15 m or so to possibly support a low light phytoplankton community (Baustian et al. 2011, 2013). The sediment algal community (cells > 3 μm) found during hypoxia differed from those in the water column and were primarily benthic (58 to 88%) (Baustian et al. 2011). The abundance of benthic cells was correlated with light levels at the seafloor and with sediment chl *a* values. The presence of a viable community of microphytobenthos during hypoxia indicates that the potential for photosynthetic oxygen production exists and may influence the oxygen dynamics in the hypoxic zone (Grippo et al. 2009, 2010; Baustian et al. 2011, 2013).

Sediment resuspension, erodibility: Based on field measurements, Xu et al. (2011a) concluded that sediment under the hypoxic water in the northern Gulf of Mexico was fairly consolidated whereas muds next to the Mississippi Delta and Atchafalaya Bay mouth were more mobile, and therefore seemed to be more recently deposited or reworked. Additionally, Xu et al. (2011a) found sediment in the northern Gulf of Mexico to be more consolidated and less erodible than that measured at other locations, such as the Adriatic Sea (Stevens et al. 2007) and in the turbidity maxima at the York River, Chesapeake Bay (Dickhudt et al. 2009). This result may indicate that organic matter buried in sediment in the northern Gulf of Mexico requires moderate or energetic storms to be mobilized.

A three-dimensional hydrodynamic and sediment-transport model represented dispersal of fluvially delivered sediment on the Louisiana shelf (Xu et al. 2011b). Within the one year time-

scale modeled, much of the modeled fluvial sediment accumulation was localized with deposition focused near sediment sources. Little fluvial sediment could be transported into the vicinity of the hypoxic zone within the seasonal or annual timeframe considered. During storm conditions, strong winds helped mix the water column vertically over the entire shelf (up to the 100-m isobath), and wave shear stress dominated total bed stress. In other storm conditions, e.g. Hurricane Katrina, the water column at some stations west of the storm center were only mixed to 15 m of the 20 m water column (Rabalais unpubl. data). The ability for a tropical storm to disrupt hypoxia and/or resuspend sediments depends on the size of the storm, the transit speed, the pressure of the system, and the quickness of transit across the shelf (Rabalais et al. unpubl. data for bottom oxygen series). During fair-weather conditions, however, the freshwater plumes spread onto a stratified water column, and combined wave-current shear stress only exceeded the threshold for suspending sediment in the inner-most part of the shelf. Based on a long-term record of sediment samples compiled by Williams et al. (2006), a mud band that was formed probably during the late Holocene exists on the Louisiana-Texas shelf between the 10 and 50 m isobaths, and centered along the 20 m isobaths. During a storm event in March 1993, the model indicated that this mud band experienced enhanced erosion depths relative to sediment seaward and shoreward of it (Xu et al. 2011b). On its shallow boundary, sediment texture played a key role; the shoals offshore of Atchafalaya Bay resisted erosion because of the higher critical shear stress assumed by the model for the sands there. Seaward of 50 m, wave energy attenuated, decreasing the frequency and magnitude of erosion. The boundaries of the mud band followed the landward and seaward boundary of hypoxia, especially along the sand-mud boundary south of the sandy shoals, implying that resuspension may impact the formation and duration of hypoxia on the Louisiana-Texas shelf (Xu et al. 2011b).

Modeling work with hi-resolution oxygen profiles suggests that respiration sources shift with depth in the water column, with resuspended sediments becoming more important with depth in the water column than at the surface (B. Fry, unpubl. results, Rabalais et al. Annual Report Year 2, NGOMEX09). These results suggest that more attention should be given to how sediments are resuspended, as this process may be critically important for hypoxia and could occur in patches and with low physical forcing. The findings also suggest that buried organic matter can store “memory” in the sea floor that would support respiration in a subsequent year (as modeled by Turner et al. 2012). Water and nutrient discharge from the Mississippi River play a role in the formation of hypoxic water, but the discharge from several previous years may be important as well.

Research/Information Needs [as identified by workshop attendees]

Processes related to production and respiration

- Better understanding of how controls on oxygen consumption vary in space and time.
- Role of phytoplankton sinking, fecal pellet flux, and marine aggregates in the transfer of surface water organic matter to the lower water column and sediments over a broad geographic area within the hypoxic zone.
- Rates of surface and bottom water respiration rates, sediment oxygen consumption and their controls.
- Integration of water column and sediment rates of oxygen production and consumption into coupled physical and biological models of hypoxia dynamics.

- Continued examination of benthic photosynthesis and associated physical and biotic variables.
- Role of benthic micro-algae in sediment carbon, oxygen, and nutrient cycling dynamics.

Nutrient limitation

- Spatial and temporal limitation of phytoplankton growth by multiple nutrients, inorganic and organic.
- Shifts in stoichiometric ratios of nutrients and loads and concentrations of nutrients on phytoplankton community composition and subsequent flux of materials.

Biogeochemical pathways

- Better spatial and temporal measurements of N cycling in sediments and the benthic boundary layer.
- More small-scale mechanistic studies of the interactions of C, O, and N at the sediment-water interface and overlying water; e.g. the relationship between potential and net NH_4 uptake.
- Better understanding of cycling of N, P, C and elements such as Fe, Hg, Mn between sediments and water column.
- Benthic remineralization and timescales of benthic cycles.
- Carbon cycling—burial, remineralization, transformation—in sediments
- Release of H_2S , CH_4 , NH_4 , Fe(II) from the sediments as oxygen sinks.
- Importance of benthic fauna as bio-irrigators in mediating the sediment exchanges of O_2 -consuming chemical species.

Physical and geological processes

- Role of vertical mixing and stratification in dynamic, 3-D physical models.
- Role of internal waves at the pycnocline and with regard to sediment resuspension and transport.
- Role of vertical mixing and lateral and horizontal transport across the area of the shelf that is subject to hypoxia.
- Importance of inner shelf sandy shoals to circulation patterns.
- Influence of physical processes on biogeochemical processes.
- Role of resuspended sediments in oxygen dynamics.

Potential effects of climate change (conceptually modeled in Rabalais et al. 2009, 2010)

- Changes in hydrology related to IPCC predictions for the Mississippi River watershed; changed hydrograph of the Mississippi River; extreme events.
- Effects of higher water temperatures on stratification, solubility of dissolved oxygen, pH, biological rates, floral and faunal communities, winds and currents.
- Effects of apparent sea-level rise on coastal landscape subsequent effect on dynamics of hypoxia.
- Ocean acidification interactions with hypoxia (Cai et al. 2011).

Hypoxia monitoring

- The Hypoxia Monitoring Implementation Plan (found at <http://www.ncddc.noaa.gov/activities/healthy-oceans/gulf-hypoxia-stakeholders/>) has a strategy for tiers of information needed to address the needs of the Hypoxia Task Force

- Basic need for the Hypoxia Action Plan is the mid-summer baseline condition of hypoxic zone area. Additional spatial and temporal resolution has been recommended.
- Additional tiers of information can be addressed through improved understanding of biogeochemical processes and integration into 3-D, dynamic physical-biological coupled models.
- Better understanding of the distribution of hypoxia east of Mississippi River delta, which is complicated by multiple freshwater inputs and interaction with shelf edge processes.
- Consideration of AUVs and gliders for some aspects of hypoxia monitoring; proof of concept needed.
- Additional measures of hypoxia other than bottom area (as outlined in Rabalais et al. 2007), such as volume, oxygen deficit, duration, intensity, and application of different values of oxygen stress (e.g., less than 1 mg/l, less than 2 mg/l), use of oxygen saturation values rather than concentration.
- Additional Data management needs.

Other issues

- Implications of coastal restoration projects in Louisiana with regard to river diversions, changes in hydrology.
- Integration of remote sensing products into observations relevant to oxygen dynamics and hypoxia dynamics models.
- Response to extreme events, such as storms, droughts, floods with regard to hypoxia dynamics.

References

Baustian, M.M. 2011. Microphytobenthos of the northern Gulf of Mexico hypoxic area and their role in oxygen dynamics. Ph.D. Dissertation, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA

Baustian, M.M., N.N. Rabalais, W.L. Morrison and R.E. Turner. 2011. Seasonal microphytobenthos on the hypoxic northern Gulf of Mexico continental shelf. *Mar. Ecol. Prog. Ser.* 436:51-66.

Baustian, M.M., N.N. Rabalais, W.L. Morrison and R. E. Turner. 2013. Microphytobenthos along the Louisiana continental shelf during mid-summer hypoxia. *Cont. Shelf Res.* online, pp. 108-118 DOI information: 10.1016/j.csr.2012.10.014

Bianchi, T.S., F. Garcia-Tigreros, S.A. Yvon-Lewis, M. Shields, H.J. Mills, D. Butman, C. Osburn, P. Raymond, G.C. Shank, S.F. DiMarco, N. Walker, B.K. Reese, R. Mullins-Perry, A. Quigg, G.R. Aiken, and E.L. Grossman. 2013. Enhanced transfer of terrestrially derived carbon to the atmosphere in a flooding event. *Geophys. Res. Lett.* 40, doi:10.1029/2012GL054145.

Cai, W.-J. 2003. Riverine inorganic carbon flux and rate of biological uptake in the Mississippi River plume. *Geophys. Res. Lett.* 30:1032, doi:10.1029/2002GL016312.

Cai, W.-J., X. Hu, W.-J. Huang, M.C. Murrell, J.C. Lehrter, S.E. Lohrenz, W.-C. Chou, W. Zhai, J.T. Hollibaugh, Y. Wang, P. Zhao, X. Guo, K. Gundersen, M. Dai, and G.-C. Gong. 2011. Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience* 4:766-770.

Cai, W.-J. and S.E. Lohrenz. 2010. The Mississippi River plume and adjacent margin in the Gulf of Mexico. In: Liu, K.-K., L.P. Atkinson, R. Quinones and L. Talaue-McManus (Eds.), *Carbon and nutrient fluxes in the continental margins*. Springer, Berlin, pp.406-422

Dale, V., C. Kling, J.L. Meyer, J. Sanders, H. Stallworth, T. Armitage, D. Wangness, T.S. Bianchi, A. Blumberg, W. Boynton, D.J. Conley, W. Crumpton, M. David, D. Gilbert, R.W. Howarth, R. Lawrence, K. Mankin, J. Opaluch, H. Paerl, K. Recknow, A.N. Sharpley, T.W. Simpson, C. Snyder, and D. Wright. 2007. Hypoxia in the northern Gulf of Mexico: An update by the EPA Science Advisory Board, EPA-SAB-08-003, 333 pp.

Diaz, R.J. and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321:926-928.

Dickhudt, P.J., C.T. Friedrichs, L.C. Schaffner and L.P. Sanford. 2009. Spatial and temporal variation in cohesive sediment erodibility in the York River estuary: a biologically-influenced equilibrium modified by seasonal deposition. *Mar. Geol.* 267:128-140.

Dortch, Q. and T.E. Whitledge. 1992. Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions? *Cont. Shelf Res.* 12:1293-1309.

Eldridge, P.M. and D.L. Roelke. 2010. Origins and scales of hypoxia on the Louisiana shelf: importance of seasonal plankton dynamics and river nutrients and discharge. *Ecol. Mod.* 221:1028-1042.

Feng, Y., S.F. DiMarco and G.A. Jackson. 2012. The relative role of upwelling favorable wind and Mississippi River forcing of the northern Gulf of Mexico hypoxia, *Geophys. Res. Lett.* 39, doi:10.1029/2012GL051192, L09601.

Fennel, K., R. Hetland, Y. Feng and S. DiMarco. 2011. A coupled physical-biological model of the Northern Gulf of Mexico shelf: Model description, validation and analysis of phytoplankton variability. *Biogeosciences* 8:1881-1899.

Forrest, D.R., R.D. Heltand and S.F. DiMarco. 2011. Multivariable statistical regression models of the areal extent of hypoxia over the Texas-Louisiana continental shelf. *Environ. Res. Lett.* 6, 045002 (10pp). doi:10.1088/1748-9326/6/4/045002

Gardner, W.S. and M.J. McCarthy. 2012. Nitrogen transformation and respiration rates in the water-column and sediments of selected NGOMEX sites. Presentation at the 3rd Annual Hypoxia Coordination Workshop, March 27-28, 2012, Bay St. Louis, Mississippi.

Greene, R.M., J.C. Lehrter, and J.D. Hagy. 2009. Multiple regression models for hindcasting and forecasting midsummer hypoxia in the Gulf of Mexico. *Ecological Applications* 19:1161-1175.

- Grippo, M.A., J.W. Fleeger, R. Condrey and K.R. Carman. 2009. High benthic microalgal biomass found on Ship Shoal, north-central Gulf of Mexico. *Bull. Mar. Sci.* 84:237-256.
- Grippo, M.A., J.W. Fleeger, N.N. Rabalais, R. Condrey and K.R. Carman. 2010. Contribution of phytoplankton and benthic microalgae to inner shelf sediments of the north-central Gulf of Mexico. *Cont. Shelf Res.* 30:456-466.
- Guo, X.-H., W.-J. Cai, W.-J. Huang, Y.-C. Wang, F.-H. Chen, M.C. Murrell, S.E. Lohrenz, L.-Q. Jiang, M.-H. Dai, J. Hartmann, Q. Lin and R. Culp. 2012. Carbon dynamics and community production in the Mississippi River plume. *Limnol. Oceanogr.* 57:1–17.
- Justić, D., N.N. Rabalais and R.E. Turner. 1994. Riverborne nutrients, hypoxia and coastal ecosystem evolution: Biological responses to long-term changes in nutrient loads carried by the Po and Mississippi Rivers. In: Dyer, K.R and R.J. Orth (Eds.), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Olsen & Olsen, Fredensborg, Denmark, pp. 161-67.
- Justić, D., N.N. Rabalais and R.E. Turner. 2002. Modeling the impacts off decadal changes in riverine nutrient fluxes on coastal eutrophication near the Mississippi River Delta. *Ecol. Mod.* 152:33-46.
- Justić, D., N.N. Rabalais, R.E. Turner and W.J. Wiseman, Jr. 1993. Seasonal coupling between riverborne nutrients, net productivity and hypoxia. *Mar. Poll. Bull.* 26:184-189.
- Laurent, A., K. Fennel, J. Hu and R. Hetland. 2012. Simulating the effects of phosphorus limitation in the Mississippi and Atchafalaya River plumes. *Biogeosciences* 9:4707-4723.
- Lehrter J.C., D.L. Beddick, R. Devereux, D.F. Yates and M.C. Murrell. 2012. Sediment-water fluxes of dissolved inorganic carbon, O₂, nutrients, and N₂ from the hypoxic region of the Louisiana continental shelf. *Biogeochemistry* DOI 10.1007/s10533-011-9623-x.
- Lehrter, J.C., M.C. Murrell and J.C. Kurtz. 2009. Interactions between freshwater input, light, and phytoplankton dynamics on the Louisiana continental shelf. *Cont. Shelf Res.* 29:1861-1872.
- Lin, X., M.J. McCarthy, S.A. Carini and W.S. Gardner. 2011. Net, actual, and potential sediment-water interface NH₄⁺ fluxes in the northern Gulf of Mexico (NGOMEX): Evidence for NH₄⁺ limitation of microbial dynamics. *Cont. Shelf Res.* 31:120-128.
- Lohrenz, S.E. and W.-J. Cai. 2006. Satellite ocean color assessment of air-sea fluxes of CO₂ in a river-dominated coastal margin. *Geophys. Res. Lett.* 33, L01601, doi:10.1029/2005GL023942.
- Lohrenz, S.E., M.J. Dagg and T.E. Whitledge. 1990. Enhanced primary production at the plume/oceanic interface of the Mississippi River. *Cont. Shelf Res.* 10:639–664.
- Lohrenz, S.E., G.L. Fahnenstiel D.G. Redalje. 1994. Spatial and temporal variations of photosynthetic parameters in relation to environmental conditions in northern Gulf of Mexico coastal waters. *Estuaries* 17:779–795.

- Lohrenz, S.E., G.L. Fahnenstiel, D.G. Redalje, G.A. Lang, X. Chen and M.J. Dagg. 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. *Mar. Ecol. Prog. Ser.* 155:45–54.
- Lohrenz, S.E., G.L. Fahnenstiel, D.G. Redalje, G.A. Lang, M.J. Dagg, T.E. Whitledge and Q. Dortch. 1999. Nutrients, irradiance, and mixing as factors regulating primary production in coastal waters impacted by the Mississippi River plume. *Cont. Shelf Res.* 19:1113–1141.
- Lohrenz, S.E., D.G. Redalje, W.-J. Cai, J. Acker and M. Dagg. 2008. A retrospective analysis of nutrients and phytoplankton productivity in the Mississippi River plume. *Cont. Shelf Res.* 28:1466–1475.
- Murrell, M.C. and J.C. Lehrter. 2011. Sediment and lower water-column oxygen consumption in the seasonally hypoxic region of the Louisiana continental shelf. *Estuaries and Coasts* 34:912–924.
- Murrell, M.C., R.S. Stanley, J.C. Lehrter and J.D. Hagy. 2013. Plankton community respiration, net ecosystem metabolism, and oxygen dynamics on the Louisiana continental shelf: implications for hypoxia. *Cont. Shelf Res.* 52:27–38.
- Nunnally, C.C., G.T. Rowe, A. Quigg and D. Thornton. 2013. Oxygen consumption and nutrient regeneration from shipboard core incubations in the northern Gulf of Mexico hypoxic zone. *J. Coastal Res.* 63:
- Quigg, A., J.B. Sylvan, A.B. Gustafson, T.R. Fisher, S. Tozzi and J.W. Ammerman. 2011. Going west: Phosphorus limitation of primary production in the Northern Gulf of Mexico and the importance of the Atchafalaya River. *Aquatic Geochemistry* 17:519–544.
- Quiñones-Rivera, Z.J., B. Wissel, D. Justić and B. Fry. 2007. Partitioning oxygen sources and sinks in a stratified, eutrophic coastal ecosystem using stable oxygen isotopes. *Mar. Ecol. Prog. Ser.* 342:69–83.
- Quiñones-Rivera, Z.J., B. Wissel, N.N. Rabalais and D. Justić. 2010. Effects of biological and physical factors on seasonal oxygen dynamics in a stratified, eutrophic coastal ecosystem. *Limnol. Oceanogr.* 55:289–304.
- Qureshi, N.A. 1995. The role of fecal pellets in the flux of carbon to the sea floor on a river-influenced continental shelf subject to hypoxia. Ph.D. Dissertation, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA.
- Rabalais, N.N., R.J. Díaz, L.A. Levin, R.E. Turner, D. Gilbert and J. Zhang. 2010. Dynamics and distribution of natural and human-caused coastal hypoxia. *Biogeosciences* 7:585–619.
- Rabalais, N.N. and R.E. Turner. 2006. Oxygen depletion in the Gulf of Mexico adjacent to the Mississippi River. In: Neretin, L.N. (Ed.), *Past and Present Marine Water Column Anoxia*. NATO Science Series: IV-Earth and Environmental Sciences, Kluwer, pp.225–245.

- Rabalais, N.N., R.E. Turner, Q. Dortch, D. Justić, V.J. Bierman, Jr. and W.J. Wiseman, Jr. 2002. Nutrient-enhanced productivity in the northern Gulf of Mexico: past, present and future. *Hydrobiologia* 475/476:39-63.
- Rabalais, N.N., R.E. Turner, D. Justić and R.J. Díaz. 2009. Global change and eutrophication of coastal waters. *ICES Journal of Marine Science* 66:1528-1537.
- Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, D.F. Boesch, P. Chapman and M.C. Murrell. 2007. Characterization and long-term trends of hypoxia in the northern Gulf of Mexico: Does the science support the Action Plan? *Estuaries* 30:753-772.
- Roberts, B.J., W. Morrison, N.N. Rabalais and R.E. Turner. 2012. Spatial and temporal patterns in carbon, oxygen, and nutrient cycling in the northern Gulf of Mexico hypoxic zone. Presentation at the 3rd Annual Hypoxia Coordination Workshop, March 27-28, 2012, Bay St. Louis, Mississippi.
- Schaeffer, B.A., G.A. Sinclair, J.C. Lehrter, M.C. Murrell, J.C. Kurtz, R.W. Gould and D.F. Yates. 2012. An analysis of diffuse attenuation in the northern Gulf of Mexico hypoxic zone using the SeaWiFS satellite data record. *Remote Sensing of the Environment* 115:3748-3757.
- Stevens, A.W., R.A. Wheatcroft and P.L. Wiberg, 2007. Seabed properties and sediment erodibility along the western Adriatic margin, Italy. *Cont. Shelf Res.* 27 (3-4):400-416.
- Sylvan, J. B., A. Quigg, S. Tozzi and J.W. Ammerman. 2007. Eutrophication induced phosphorus limitation in the Mississippi River Plume: Evidence from fast repetition rate fluorometry. *Limnol. Oceanog.* 52:2679-2685.
- Sylvan, J. B., A. Quigg, S. Tozzi and J.W. Ammerman. 2011. Mapping phytoplankton community physiology on a river impacted continental shelf: testing a multifaceted approach. *Estuaries and Coasts.* 34:1220-1233.
- Turner, R.E., N. Qureshi, N.N. Rabalais, Q. Dortch, D. Justić, R.F. Shaw and J. Cope. 1998. Fluctuating silicate:nitrate ratios and coastal plankton food webs. *Proceedings National Academy of Science, USA* 95:13048-13051.
- Turner, R.E. and N.N. Rabalais. 2013. N and P phytoplankton growth limitation, northern Gulf of Mexico. *Aquatic Microbial Ecology* 68:159-169.
- Turner, R.E., N.N. Rabalais and D. Justić. 2012. Predicting summer hypoxia in the northern Gulf of Mexico: Redux. *Marine Pollution Bulletin* doi:10.1016/j.marpolbul.2011.11.008
- Walker, N.D. and N.N. Rabalais. 2006. Relationships among satellite chlorophyll a, river inputs and hypoxia on the Louisiana continental shelf, Gulf of Mexico. *Estuaries and Coasts* 29(6B): 1081-1093.
- Williams, S.J., M.A. Arsenault, B.J. Buczkowski, J.A. Reid, J.G. Flocks, M.A. Kulp, S. Penland and C.J. Jenkins. 2006. Surficial sediment character offshore of the Louisiana Continental Shelf region: a GIS Compilation. U.S. Geological Survey Open-File Report 2006-1195, online at <http://pubs.usgs.gov/of/2006/1195/index.htm>.

Xu, K.H., K.B. Briggs, G.M. Cartwright, C.T. Friedrichs and C.K. Harris. 2011a. Spatial and temporal variations of sea bed sediment erodibility on the Texas-Louisiana shelf and their implications to the formation of hypoxic water, 21st Biennial Conference of the Coastal and Estuarine Research Federation Societies, Daytona Beach, FL.

Xu, K., C.K. Harris, R.D. Hetland and J. Kaihatu. 2011b. Dispersal of Mississippi and Atchafalaya sediment on the Texas–Louisiana shelf: Model estimates for the year 1993. Cont. Shelf Res. 31(15):1558–1575.