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OCEAN REFLECTIONS

ELEVATING DISSOLVED OXYGEN—REFLECTIONS ON DEVELOPING AND USING LONG—TERM DATA

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Abstract: This prospectus took me about as long to generate as my 36—year record of working on the issue of northern Gulf of Mexico (nGOM) oxygen deficiency, or so I felt. There was so much to cover, but I focused on the issue of hypoxia on the Louisiana continental shelf from the early 1980s to present and my participation in the research and outreach. Not that I was ignoring other aspects of my academic research career (e.g., stone crab populations and their differences in physiology and larval development along the nGOM coast; settlement of crab megalopae, especially blue crabs, on artificial substrates and their timing with tidal events; oil and gas pollutant discharges in coastal waters of Louisiana, and as Director of the Coastal Waters Research Consortium (CWC) of the Gulf of Mexico Research Initiative (GoMRI), and marsh infaunal researcher. I must say, however, that the journey through the documentation of low dissolved oxygen on the Louisiana continental shelf, and its linkage to the changes in the Mississippi River nutrient loads to the coastal waters of the nGOM, marked a dominant part of my career. This prospectus follows my research and outreach career from my first journey offshore in an outboard to set stations for the transect off Terrebonne Bay in early summer of 1985 to now.

Key words: Gulf of Mexico, Mississippi River, eutrophication, nutrients, dead zone

Acknowledgments

Most publications end with the acknowledgments. Not this one. The accomplishments that I will outline in this review would not have been possible without the input of many individuals. I first acknowledge Dr. Donald F. Boesch, the first executive director (1979—1989) of the Louisiana Universities Marine Consortium (LUMCON), who pushed for the funds from the National Oceanographic and Atmospheric Administration (NOAA) for our first several cruises into the northern Gulf of Mexico (nGOM) to measure bottom—water low oxygen, a serious sign of symptoms of a coastal ecosystem in distress. As director, Don also funded some of the early cruises until we secured programmatic funding through competitive research programs.

There were other scientists in those 'early days,' pre—1985, that recognized the importance of GOM low oxygen conditions as a phenomenon to be studied more deliberately. These included: (1) Professors Ragan, Harris, and Green of Nicholls State University (Ragan et al. 1978), who risked their safety to work offshore in a 20—ft outboard, but detected hypoxic waters in July and September 1975, and August 1976 in the Louisiana Bight and west of the Atchafalaya delta; and (2) Professor R. Eugene (Gene) Turner of Louisiana State University (LSU) (Turner and Allen 1982) took advantage of NOAA's Southeast Area Monitoring and Assessment Program (SEAMAP) cruises on the RV *Oregon II* groundfish surveys in 1975 and 1976 from Mobile Bay to Atchafalaya Bay to document dissolved oxygen (hereafter DO) concentrations in the Louisiana Bight west of the Mississippi River.

Other occasional reports of low DO concentrations (≤ 2 mg/L) were reported as part of the hydrographic, chemical, and biological studies aimed at the influence of oil and gas production activities in the nGOM in 1972 to ~1984 (reviewed in Rabalais et al. 2002 and references therein). Several studies identified low DO concentrations (≤ 2 mg/L), eventually to be defined as "hypoxia," in summer months west of the Mississippi River delta to west of the Atchafalaya River delta. These occurrences were usually confined to a thin bottom layer. Unfortunately, the issue of low DO conditions on the nGOM did not get elevated to an issue of environmental significance at that time by federal and state agencies.

Then, there are the scientists involved over the years. Don Boesch brought me to the LUMCON Marine Center in Cocodrie, LA in the summer of 1983, when I was a 'fresh' Ph.D. Soon he introduced me to, as Don said, my 'aquatic ecologist,' Gene Turner, and my 'physical oceanographer,' Bill Wiseman, both of LSU and quite established in their careers, who would be working with me on a study of low oxygen conditions in the nGOM. Don fared from the Chesapeake Bay, knew the science of eutrophication and low DO there, as well as the increase in the nitrogen load in the Mississippi River (thank goodness for historical and more current Mississippi River water quality from the U.S. Geological Survey; *https://www.usgs.gov/ecosystems/toxic—substances—hydrology—program/data—tools)*, the results of environmental assessments that identified low DO concentrations, and earlier documentation of 'dead waters' by trawlers in the nGOM trying to capture brown and white shrimp (Boesch 1983, Renaud 1986). Many other scientific colleagues contributed to elevate the science of low DO in the nGOM.

I switch between first person singular "I" and plural "we" in this reflection, because I was seldom alone but joined by many collaborators. I reserve "I" for statements that I may or may not have uttered over the years. Gene Turner, the most dogged and scientifically engaged of all, was on board the RV *Pelican* from the beginning in 1985. These creative people are all part of the documentation of low DO conditions in the nGOM and the physical and biological processes that define them. Vessels' crews, students (secondary school to graduate students), research associates, lab managers, web site managers, and data managers rank highly in my praise. Without them, all this work could not have been envisioned or completed. Thank you.

MY EARLY CAREER

My humble academic career began with a love for biology classes in middle school and high school. The destination of biological sciences was appropriate, beginning with 2 years of community college, Del Mar College in Corpus Christi TX, followed by a BS and MS in Biology at a regional university, Texas A&I University, now Texas A&M University — Kingsville. I fell into a group of undergraduate and graduate students who were studying the fauna of Seven and One—Half Fathom Reef off Padre Island, TX under the direction of Alan H. Chaney. This was especially pleasing to me because of all the scuba diving it entailed. When it was my turn to choose a taxonomic group to work on for my MS, I chose the ascidians which formed part of the dense mat of polychaete tubes that covered the carbonate rock reef surface. I still wonder why, because they were difficult to identify. After graduating, I was employed as a seasonal naturalist at Padre Island National Seashore TX for 6 months in 1975. This was also pleasing because I loved being on Padre Island. I was fortunate to be hired as a taxonomist at the Port Aransas Marine Science Institute of the University of Texas in Port Aransas, TX. This was a dream job where I remained close to the marine environment with all the associated outdoor activities and honed my taxonomic skills for identification of benthic fauna for a pre—oil and gas development assessment survey covering the south Texas continental shelf. I was comfortable with my job and 'island life,' but the desire to work on a Ph.D. stopped the employment, and I became a graduate student at the University of Texas Austin in 1979 under the direction of Dr. James N. Cameron, but remained mostly in Port Aransas except for the first year where I spent time on campus as a graduate teaching assistant. Jim was a physiologist who worked on acid—base balance in fishes and invertebrates. This was not for me, but my good friend and colleague, Dr. Darryl Felder of Southwestern Louisiana University (now University of Louisiana – Lafayette) pointed me in the direction of an endemic fiddler crab in semi—arid coastal TX. Everything was different for this fiddler crab—morphology, physiology, behavior, microhabitat, and reproduction. When I approached Jim Cameron about this study, he asked me "Now why do you want to work on this?" At the completion of the Ph.D., he admitted "This turned out pretty well, right Nancy?" Once again it was time for an employment opportunity, and I took one as a Senior Research Associate (then professor series) at LUMCON in coastal Louisiana for 33 years, 11 years as the Executive Director. I moved to a tenured faculty and endowed chair position at LSU in 2016, where I remain. There was a lot packed into my first 15 years of academia, but the story now shifts to coastal Louisiana water quality problems.

INTRODUCTION TO HYPOXIA

The theme of this retrospective is "elevating dissolved oxygen (DO)." From the beginning of my involvement in studies of eutrophication and oxygen deficient waters, I was focused on elevating the science of better understanding the processes involved in the formation, maintenance, and complexities related to oxygen deficiency on the nGOM continental shelf. The science flourished over the years with the contributions of multiple colleagues and provided a sound understanding of the nGOM 'dead zone' and others around the world. I provide quotation marks around the idea of 'dead zone,' because the ecosystem is not 'dead' (Levin et al. 2009, Rabalais et al. 2010), but altered in detrimental ways that do not support living resources as valuable components of a socio—economic ecosystem. The overall umbrella of this retrospective is "elevating dissolved oxygen" as verification of the science supporting the understanding of the relevant processes. I also have a mantra of 'elevating dissolved oxygen' in public awareness, meaning citizens, school kids, college students, policy makers, resource managers, and legislators with clear, understandable messages of the linkages of science to policy.

The focus of our long—term data is the area of DO deficiency in the nGOM adjacent to the discharge from the Mississippi River watershed. The sequence of changes in this land—ocean ecosystem, over the last 70 years and annually on a seasonal basis, is an increase in Mississippi River inorganic nutrient loads (particularly nitrogen and phosphorus), an increase in nutrient—enhanced primary production, flux of more organic carbon to the lower water column and the seabed, and a decrease in DO through bacterial respiration of the organic matter in a seasonally stratified water column (Figure 1). The area of DO $\leq$ 2 mg/L on the Louisiana shelf is the second largest human—caused hypoxic area of the world's coastal oceans, averaging 14,000 km^2 of the bottom over a 35 y period, ranging from minimal to at least 22,000 km^2. The numeric description is based on the fact that demersal fish, shrimp, and crabs are not captured in a bottom trawl below the numeric limit. Some organisms are affected at a higher DO level and others at a lower level. Organisms that cannot escape the low DO concentrations are stressed or may die. Oxygen deficiency occurs in the spring during high river discharge and nutrient loads as long as the water column is stratified for an extended period, but is most widespread and severe in May through September.

FIGURE 1. *The plume of the Mississippi River, sediment-laden and nutrient-enriched, as it enters the oligotrophic Gulf of Mexico off Southwest Pass, LA. The sediments fall out fairly quickly or become entrained in the Louisiana coastal current, but the dissolved inorganic nutrients move mostly down current to the west and support the growth of phytoplankton along the Louisiana continental shelf.*

Elevating Dissolved Oxygen Science

The oceanographic fleet of LUMCON provided another humble beginning to our offshore expeditions in the form of a 20 ft outboard and an aged (to be polite) donation from Louisiana State University of the RV *R. J. Russell*. [An aside: The vessel was named for the well–known geologist R.J. Russell of LSU, who adamantly stated several times that LSU should never own a research vessel.] Cruises on the *Russell* were more than a little rocky and more than a little leaky (Rabalais 2010). An outboard was used to define eventual transects offshore of Terrebonne Bay and Bayou Lafourche and Barataria Bay west of the Mississippi River delta that were to be used for monthly transects with a distance up to 25 mi outside the barrier islands. The unusual curvature of these transects was dictated by being near offshore oil production platforms in case of foul weather or emergencies. It became clear to me that taking water samples over a long day so far offshore was not safe, and I requested (also considered a polite term) use of the RV *R. J. Russell* (Figure 2). It served our initial purposes.

The RV *Pelican* (109 ft, now 116 ft) arrived at the LUMCON dock in early summer of 1985 followed by the 58 ft RV *Acadiana* in 1986 (Figure 2). Our initial efforts in the study of low DO concentration in coastal waters of the nGOM began in 1985 with what has come to be called a "shelfwide hypoxia" cruise in mid–summer. This 1985 cruise was the second in a long sequence of research cruises for the RV *Pelican*, which we used mostly for our mid–summer cruises. Stand–ins included the RV *Longhorn*, RV *Acadiana* (for a portion of a shelfwide cruise), and the RV *Tommy Munro*, when mechanical problems or the time of mid–life refit of the RV *Pelican* prevented its use. The number of offshore trips increased substantially in 1989–2007 when we deployed and serviced oxygen meters in 20 m water depth off Terrebonne Bay (via outboard or the RV *Acadiana*). With better funding, we were able to use the RV *Pelican* to cruise monthly or bi–monthly in 2001–2012, so that the data were not collected just during 'fair weather' in summer. These monthly cruises provided better temporal coverage for an area closer to the Mississippi River delta off Terrebonne Bay and the shelf off of the Atchafalaya River, which carries about one third of the total Mississippi River discharge. While these cruises have often been identified as "monitoring" cruises, I have always, and rightfully, considered them as "research cruises" that identified integrated features of hypoxia and tested hypotheses concerning the physical and biogeochemical processes relative to the what, when, and where of hypoxia in the nGOM. The observations cover temporal ranges of seconds (deployed oxygen meters, 15 s data) to centuries (palaeoindicators), and differing spatial and temporal scales of the nGOM continental shelf. These include annual differences across the Louisiana continental shelf (annual cruises), stations off Terrebonne Bay (monthly cruises 1989–2017), and stations off the Atchafalaya (bimonthly cruises) and TerrebonneBay (monthly) closer to the Mississippi River (1990–1991, 2007–2013) as well as stations from Terrebonne Bay, LA to Matagorda Bay, TX as part of the Louisiana–Texas (LATEX) study, and a cruise east of the Mississippi River in 2011 (Figure 3). We deployed oxygen meters in 20 m off Terrebonne Bay (1989–2017) and off Barataria

FIGURE 2. *The oceanographic fleet, other than outboards, that supported the research program defining the low oxygen area on the continental shelf off Louisiana. Upper center, RV* Pelican*; lower left, RV* R.J. Russell*; lower right, RV* Acadiana*.*

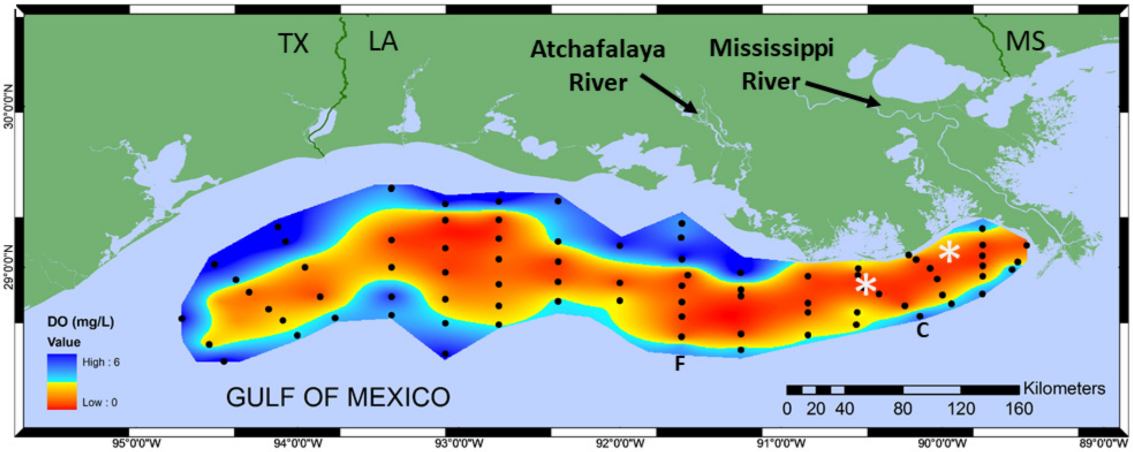

FIGURE 3. *Distribution of shelf wide stations and bottom-water dissolved oxygen (DO, mg/L), 21-27 July 2008. The yellow and orange shading represents DO < 2 mg/L and < 1 mg/L, respectively. Transects C and F are identified along with the continuously recording DO meters (*).*

Bay (1990–1991 and 2007–2013). Ultimately, during the course of these cruises from 1985–2021, we spent 350 days at sea and sampled about 4,000 unique stations.

Initial cruises focused on mapping the area of low DO in bottom waters and hydrographic data associated with DO concentrations, along with values of light quality and penetration, water column dissolved inorganic nutrients, water column chlorophyll *a* concentrations as indicators of phytoplankton biomass, and suspended particulates. The science expanded rapidly, both within our programs and with additional collaborating partners. The foci of questions and studied processes grew quickly. We 'swam up the river' to better understand the watershed and the land–ocean interactions. There were established competitive research programs that lasted for sufficient time to add to the long–term data.

Elevating the Need for Long–Term Data and Their Measurement

Some things never change, but many more do. There are often questions concerning the consistency, accuracy, and precision of data over a 30^{+} y period for our hypoxia studies. That is, we are often challenged by others who asked "can you compare data from 1987 to data from 2002 or 2010?" (Rabalais et al. 2018). Dissolved oxygen data were our primary focus over the years (along with the ancillary data), and we paid rigorous attention to its quality control.

The chemical basis of a Winkler DO titration or a fluorometric measurement of chlorophyll–*a* as an estimate of phytoplankton biomass remain the same measurements, although the instrument technology may have changed. Justić et al. (1987) used Winkler titration data to demonstrate clearly that DO content of bottom waters in the northern Adriatic Sea declined from 1911–1984). Water temperature measurements are reliable and consistent (Turner et al. 2017); salinity measurements can be calibrated against salinity standards (we relied primarily on an Auto–Sal). We moved from single burets for Winkler titrations to a refilling pipet looking for a color change for an end point, and now use a Mettler Toledo DL28 titrator with an easier and more precise potentiometric endpoint (Figure 4). Instruments are now available for a spectrophotometric end point.

Our cruises date back to the day of grinding phytoplankton sample filters to be digested in 90% acetone for 24 h (thank you Daiquiri Don Harper for all those grindings on multiple cruises). The 2 analog scales on our initial Turner fluorometer could be confusing, but could be back–tracked as needed. The current instrument for fluorometry is a Turner Model 10 AU fluorometer. The physics of optical changes with a Secchi disk depth remain solid as well, and the long–term data indicate decreases in Secchi depth that are correlated with increases in phytoplankton in surface waters and worsening oxygen conditions in the lower water column (Justić 1991, Rabalais 2002). However, there is now the addition of photosynthetically active radiation (PAR) sensors on the CTD unit (conductivity, temperature, and depth) as well as other probes.

Instrumentation progressed over the years for oxygen probes in CTD units, in profiling instruments, and as deployed meters. The CTD oxygen probes were always cross–calibrated with Winkler titrations. Our first oxygen meter for profiling was a Hydrolab, then the YSI 6820 for many years, which will be replaced with a YSI EXO3 for the 2021 cruise. To continuously measure DO, we used the Endeco T1184 beginning in 1989. [I know for sure that my research associate, Lorene Smith, disliked the T1184 and the difficulty in its calibration. I can still

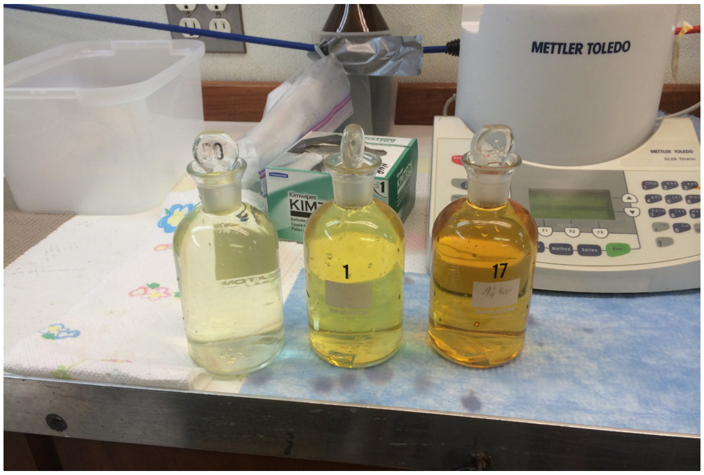

FIGURE 4. *BOD (biological oxygen demand) bottles with fixed Winkler samples to be titrated to determine the dissolved oxygen (DO) concentration in mg/L. From left to right, the color of the sample indicates low oxygen to high oxygen concentrations. The potentiometric titator is behind the BOD bottles.*

FIGURE 5. *Levels of biofouling on YSI 6600 deployed oxygen meters. Left: newly deployed meter, no fouling, clean probe guard, and taped sonde unit. Center: a deployed sonde to be retrieved; the probe guard is clean, but the sonde body is becoming covered with barnacles. Right: heavily fouled sonde unit, oil platform leg on left, upper sonde on right.*

hear her.] The T1184 was pre—calibrated at 25°C with analytical grade O_2 according to the manufacturer's guidelines. Our latest deployed instruments were YSI 6600s. Care was always taken in the calibration of oxygen units, cross—checked with Winkler titrations, and if data were deemed 'questionable,' they were post—calibrated or removed from the datasets (e.g., evidence of sensor decline due to biofouling or loss of battery life).

Biofouling was always a problem with deployed instrumentation offshore. The goal was for an ~1—mo turnaround, but winds, waves, a suitable offshore vessel, and number of dive team members did not always align with the stars, and instruments went too long in fouled conditions, or insufficient battery life. We began with TBT (tributyl tin)—laced wax on the DO probe membrane. Eventually deployed oxygen meters were available with brushing mechanisms across the probe membrane face to keep down the fouling. Anti—fouling paint under plastic coverings and black tape for the sonde unit were helpful. Finally, we wrapped probes in copper tape to hinder biofouling (Figure 5). And, hallelujah, optical DO probes, with less biofouling and more consistent and accurate DO measurements became available. We ended the deployment of YSI 6600 meters with optical probes in 2017 for offshore DO measurements at near—surface, mid—water column, and near—bottom. The dive trips for instrument turn around could be grueling, but also could be amazing for the clear, calm water and things we saw while diving (Figure 6).

The hydrographic data were collected with a SeaBird/rosette CTD unit lowered from the surface to the bottom with bottom—water samples from a 5 L Niskin and at selected depths for other measurements and designated experiments (e.g., respiration rate determinations, $p\text{CO}_2$ determinations, stable isotope measurements, and denitrification and methanogenesis experiments). Up—casts were at the same rate as the lowering to provide adequate data for fired Niskins and for the ALIGN CTD post processing aspect of the SeaBird data. The CTD unit was raised 1 m above each triggered Niskin bottle to capture data that were most appropriate for the water collected there at the time of collection. This was extremely important for comparing electronic DO concentrations to those determined by the Winkler titrations in the stratified coastal waters and subsequently back calculating DO concentrations from the SeaBird, or a hand—held profiling oxygen meter, if necessary. A separate smaller profiling CTD allowed for very near bottom and near surface recordings to capture steep DO gradients.

The capabilities of the RV *Pelican* continued to increase with years of operation and success with proposals to the National Science Foundation for UNOLS—supported (University—National Oceanographic Laboratory System) improvements. This included a near—surface water flow—through system for % transmission, *in vivo* fluorescence, salinity, and temperature. This system and many others such as 3 ADCPs (Acoustic Doppler Current Profiler; 1200 kHz, 300 kHz, and 75 kHz) and dynamic positioning were integrated into a multiple data acquisition system with precision latitude/longitude, depth, meteorological data, and UTC (Coordinated Universal Time). We and other users of the RV *Pelican* call her the "Peli—Can—Do."

FIGURE 6. *Our buddy the barracuda on a clear water day, although green with phytoplankton.*

Elevating the Use of Long—Term Data

A more complicated and, unfortunately, more controversial issue than data quality, was the linkage of long—term Louisiana continental shelf oxygen deficiency to century—long changes in the Mississippi River watershed landscape use and flux of nutrients, particularly for nitrogen, phosphorus, and silicate. In the case of our hypoxia studies, it was impossible to develop experimental studies with a cause and effect design. This came back to us as "How can you prove that the Mississippi River is a major driver in the worsening of DO over time?" The beauty of long–term data is the ability to correlate appropriate data to develop plausible deductive relationships. Also, much of the long–term data serve to test hypotheses related to causative processes. The long–term data on the Mississippi River watershed and its water quality, nutrient–enhanced coastal ocean productivity, subsequent oxygen deficiency, and shifts in coastal sediment environmental indicators point to the linkage of the watershed and coastal ocean ecosystems in the larger land–ocean ecosystem. Other hypoxic coastal waters follow the same relationships and trajectories (Diaz and Rosenberg 2008, Breitburg et al. 2018, Rabalais 2019).

Nutrient–driven eutrophication and subsequent oxygen deficiency in estuarine and coastal waters usually follows an increase in nutrient loads from point (at the end of a pipe) and non–point (from direct landscape runoff or from atmospheric deposition) sources of phosphorus and nitrogen pollution, especially during the 1950s to 1970s (Cloern 2001, Rabalais 2004). These changes were evident globally at similar times (Diaz and Rosenberg 2008), and the relationships were also clear for the Mississippi River effluents and oxygen deficiency in the nGOM (Turner and Rabalais 2003).

Our research group pulled together and published initial observations among hypoxia and related ancillary data, including Mississippi River basin and discharge data (Rabalais et al. 1996). We confirmed increases and decreases of dissolved inorganic nutrients in the effluent of the Mississippi River since the beginning of the 20th century (Turner and Rabalais 2003) and phytoplankton community composition related to nutrient ratio shifts in river inorganic nutrients (Turner et al. 1998, Dortch et al. 2001). We further identified palaeoindicators of increased biological carbon and diatom biogenic silica remains as indicators of increased phytoplankton production (Turner and Rabalais 1994a; including a cover photograph for *Nature,* Rabalais et al. 1996, Rabalais et al. 2007, Rabalais 2014). Shifts in benthic foraminiferal community composition in dated sediment cores indicated an increase in eutrophication coupled with worsening oxygen deficiency with major shifts at the beginning of the 19th century and especially since the 1950s (Sen Gupta et al. 1996, Platon et al. 2005; Figure 7).

Water column phytoplankton communities shifted over the period of reduced silicate concentrations, including an increase in a harmful algal bloom diatom and potential effects on the diatom–based food web (Rabalais et al. 1996, Turner et al. 1998, Dortch et al. 2001, Parsons et al. 2002). The sediment indicators extended the long–term data with longer historical trends. These sediment indicators of ecosystem shifts correlated with Mississippi River increases in nitrogen. During the composition of the Rabalais et al. (1996) manuscript, I thought to myself that it might become a 'classic,' because of the strong relationships and implications. Eventually it was the second most cited paper in *Estuaries* from 1985 – 2005.

FIGURE 7. *Looking down at the top of a sediment core about to be sectioned on a precision core extruder. Note the black anoxic sediment and the white sulfur-oxidizing bacteria on the sediment surface.*

The long–term data are publicly available and used in peer–reviewed publications representing multiple aspects of oxygen–deficient conditions on the nGOM continental shelf. These data support our authored publications, along with many others who have studied this coastal ecosystem. The data are also used to develop and validate dynamic linked physical oceanography and eutrophication models that have transitioned into equally dynamic models for forecasting temporal changes in DO conditions. While much of the conclusions in these models and analyses were intuitive and sometimes documented on a more limited scale, the complex and dynamic models were a welcomed addition to the nGOM hypoxia understanding. The long–term research cruise data and metadata are archived in NOAA's National Centers for Environmental Information (NCEI, formerly the National Oceanographic Data Center). The mid–summer area of bottom–water hypoxia serves as the state and federal Hypoxia Task Force (2001) baseline data for defining progress in mitigating hypoxia (see *https://www.epa.gov/ms–htf* for references to all reports). The Hypoxia Task Force is co–chaired by NOAA and the U.S. Environmental Protection Agency (EPA) and includes 5 federal agencies, 13 states, and one tribal council. Not a bad list of accomplishments for 36 years. These are just a few examples of how important long–term data are for identifying trends in ecosystem health and legitimizing science–based management decisions.

CONTINUED ELEVATION OF DISSOLVED OXYGEN SCIENCE

We were always looking for able–bodied volunteers for our summer shelfwide hypoxia cruises. Our complement often numbered 14 of these new sea–going scientists. We worked 12 h shifts over a 24 h period. Volunteers included undergraduate students, graduate students, and science colleagues. [Our 2020 COVID complement was much smaller, only 6, then 5, when the chief scientist had an injury and was not able to attend.] We had already begun the training of a co–chief scientist, Dr. Cassandra (Cassie) Glaspie, who took over with a team of 4 that worked a 16 h shift to complete the cruise. “I” was with the “we” on almost all stations by way of video and telephone contact to help make decisions on cruise direction. They were an amazing, intrepid group of colleagues; the cruise was successfully completed. I continue to be amazed at the great groups of colleagues who joined us each summer (Figure 8).

Space on the RV *Pelican* was sufficient for additional science projects, and the summer cruises became an opportunity for interdisciplinary research projects among the primary funded scientists (with Drs. Quay Dortch, LUMCON, and Dubravko Justić, LSU, beginning in 1989 and 1991, respectively) and “tag along students and scientists.” “Tag along” is not a disparagement, but an acknowledgment of the great strides made by all our contributing sea mates and collaborators. The findings of other research on oxygen deficiency in the nGOM is not to be diminished, but this perspective is intended as my journey as we worked to elevate DO.

From initial data and understanding of the changes in expanse, location, and severity of summer hypoxia from year to year, we moved into processes involved in the offshore DO conditions. We began to forge hypotheses concerning the interactions of DO and biogeochemical processes in the Louisiana coastal ocean that were related to shifts in ecosystem conditions. We acquired data to better describe the hypoxia, but also collected data, including the long–term data, that supported many of our hypotheses.

Elevating Dissolved Oxygen into Policy – Swimming Upstream

At the same time we were documenting the dynamics of low DO on the continental shelf, Gene Turner was spending more time up in the watershed, locating and synthesizing long–term data on nutrient changes and other water quality parameters since at least the turn of the 20th Century. He began the engagement of non–profit groups, university scholars, and agriculture experts on water quality in the upper Mississippi River basin. The focus of these collaborations was to better understand the nutrient shifts, land use practices, agriculture policies, and sustainable agriculture practices to diminish nitrogen use for food, fuel, and fiber, now and into the future. He crawled among boxes of reports in the attic of the New Orleans Water and Sewerage Board, tracked down state environmental data, and found what seemed to be ‘forgotten’ federal data sets. Many of these he photocopied, photographed, transferred by hand, or located electronic files. He continues to find more Mississippi River data (Turner 2021), which will be important to our continued understanding of offshore hypoxia.

From the beginning of the 1950s, the rise in nitrogen constituents in the Mississippi River became apparent, and was closely related to landscape alterations in the watershed, tile drains, industrial agriculture, and increased use of artificial fertilizers (Turner and Rabalais 1991, Goolsby et al. 1999, Alexander et al. 2008). The total nitrogen (TN) and nitrate+nitrite–N (~70% of the TN) increased 3–fold from the early 1970s to present. The phosphorus record was not as complete, and a statistical increase is not clear, but there is an increasing trend. The concentration of silicate declined since the 1950s in tandem with the nitrate increase and triggered phytoplankton community shifts in the offshore waters (Turner and Rabalais 1994a, b). The major watersheds of the Mississippi River basin were dissected to examine trends in nutrients, suspended sediment, and discharge (Turner and Rabalais 2003, 2004). Besides the already mentioned nutrient shifts, the Mississippi River discharge since the early 1800s remained similar with variability among flow rates within a decade, but no long–term in increase and decrease, which could trend among decades. Suspended sediment loads dropped off in the 1950s after the completion of several dams and reservoirs on the Missouri River, the major source of suspended sediments from the basin. Despite the decreased sediment coming into Louisiana coastal waters that should improve water clarity, the upper mixed layer became more turbid due to the increase in phytoplankton biomass consistent with increasing nitrogen loading (Rabalais 2002). Thus, the quality and quantity of constituents discharged from the Mississippi River will change over time but there is a continued high load of nitrogen from the watershed.

Of course, timing of rainfall and the amount of discharge from the Mississippi River are related to the amount of nutrients entering the nGOM. However, the load (discharge concentration) of nitrogen, especially nitrate that makes up about 70% of the nitrogen load, is the single factor most correlated with the bottom–water area of DO concentration ≤ 2 mg/L in mid–summer since 1981 (Turner et al. 2005, 2012). Add phosphorus loading and discharge of the Mississippi River to the formula, and the regression becomes stronger. Various models use the May nitrogen load of the Mississippi River as the main driving force to predict the size of this hypoxic zone in late July, either as hindcasting, forecasting, or now–casting. The stability of these models, however, is not fixed, because the ecosystem is evolving. For example, the


FIGURE 8. *Shelfwide scientific crew with their 2017 t-shirt “Back to the Future.”*

size of the hypoxic zone for the same amount of nitrogen loading (as nitrite+nitrate) has increased about 3 times higher since 1981 (Turner et al. 2012). Models of hypoxia on the continental shelf and inputs from the Mississippi River began as correlational models (Turner et al. 2012). Additional models progressed in predictability and complexity to three–dimensional dynamic, coupled physical–biogeochemical process–based ecosystem models, incorporating 36 years of long–term DO and related data (e.g., Scavia et al. 2013, Justić and Wang 2014, Justić et al. 2017, Laurent et al. 2018, Del Giudice et al. 2020).

ELEVATING DISSOLVED OXYGEN AWARENESS

The initial funding for our early shelf wide hypoxia cruises came from NOAA's Coastal Ocean Program with the help of Don Boesch and his political connections with Senator John Breaux (LA). Don helped foot the cruise costs for a few more years. With Don's and other colleagues' efforts, NOAA sponsored a competitive research program for Nutrient–Enhanced Coastal Ocean Productivity program (1990–1996) for which we competed and received research funds that kept us afloat for cruises in the 1990s. The saga continued with more NOAA–funded research programs for which we were again successful recipients. These programs and others were fostered by political savvy of which I will unlikely know the full story and our dedicated efforts to raise attention through the media and policy relevant federal agencies.

Don Boesch was the spokesperson for the media while he was director of LUMCON until 1989. As he left for Maryland, *USA Today* wrote an article on the nGOM area of hypoxia. Shortly thereafter, Johnny Glover, owner of the neighboring marina near the LUMCON Marine Center and Representative in the Louisiana Legislature, called me over. With the centerfold story of Louisiana hypoxia in his hands, he asked me "why are you trying to destroy my charter fishing business?" We had a very cordial conversation where I explained that the Spotted Seatrout and Red Drum sought by many of his charters and visiting fishers were not affected, since the low oxygen area was further offshore (and, at that time, not as widespread as it eventually became). He relented and took up the "NO HYPOXIA" banner and became a relentless advocate of supporting the science. He also loved being in the limelight, and his excorticating television footage of why the 'dead zone' existed and his demonstrative appeal to fix it was seen many times.

Ah, the press—good friend, bad friend, unknown friend. I had limited experience working with the press, other than some environmental activism during my Port Aransas days, but it was time to bring on the press. I was fortunately chosen during the summer of Johnny Glover as one of the first cohorts of the Aldo Leopold Leadership Program and had a 2 week intensive on translating science to the public, and then 2 more weeks the next summer in Washington, D.C. These types of training continue to be offered by scientific societies at many of their meetings. Hint: take one or more.

We began bringing the research results to the public through press releases at the end of each summer shelf wide cruise that stated the size of the bottom–water area of low DO and the associated conditions. Don Boesch recommended that reporters from *The Baltimore Sun* (Tom Horton) and *The Washington Post* (Joby Warrick) should follow up on the low DO events in Louisiana and not just the Chesapeake Bay. We were also fortunate to have underwater photographers on our specialized summer cruises (1989–1991) to take photographs of our work and dead and decaying organisms on the seafloor. These friends were Don Harper of Texas A&M University Galveston and free–lance photographer Franklin Viola, Jr., a former Harper student. They accompanied us on a trip to use an ROV (remotely operated vehicle equipped with a DO sensor, nighttime) and diving operations (daytime) to define what organisms were found at what DO levels (Rabalais et al. 2001). The excellent photographs were used by the media and federal agencies, sometimes with permission, and displayed the conditions on the bottom at the seafloor (Figure 9). These photographs were used in our co–edited book on Gulf hypoxia as illustrations (Rabalais and Turner 2001).

The photograph of the 'smoked crab' (Figure 9D) was posted above the fold in a *Washington Post* article on Sunday by Joby Warwick. This caught the interest of Senator John Breaux (LA), who then wanted to dive in the 'dead zone.' This did not work out given the season, the lack of low oxygen, and poor sea state. At the same time, Senator Olympia Snowe (ME) was concerned with harmful algal blooms in the Gulf of Maine that were degrading coastal ecosystems and their natural resources. Breaux joined the Snowe effort with the condition that an 'H' for hypoxia be inserted into the Harmful Algal Bloom and '<u>H</u>ypoxia' Research and Control Act of 1998. I met with Senator Breaux ahead of my 1998 testimony before the U.S. Senate Subcommittee on Oceans and Fisheries, Senate Committee on Commerce, Science, and Transportation, and explained the issues. The legislation passed (it was bi–partisan). I now knew that GoM represented the Gulf of Maine, not just the Gulf of Mexico. The legislation set up the federal coordination for continued research on harmful algal blooms and hypoxia and improvements in watershed nutrient management that continue to this day under the federal/state/tribal task force (Hypoxia Task Force 2001,

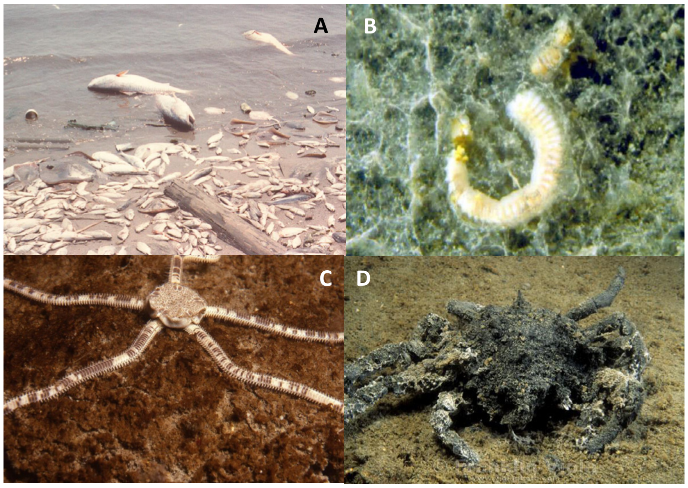

FIGURE 9. *Dead and stressed organisms as a result of low dissolved oxygen. A. Fish kill, Grand Isle, LA. B. Dead spionid polychaete and sulfur-oxidizing bacteria. C. Stressed brittle star at surface, reaching for oxygen; note the organic matter on the sediment surface. D. Dead spider crab.*

FIGURE 10. *A CNN film crew and reporter participated on a 2 day research cruise on the RV Pelican.*

2008, 2015). The authorizations continue to fund competitive research on harmful algal blooms and 2 programs on hypoxia (Northern Gulf of Mexico Ecosystems & Hypoxia Assessment (NGOMEX) and the Coastal Hypoxia Research Program (CHRP)).

As interest in the nGOM low—oxygen area grew among the press, so did the requests for time with me or my colleagues, and time on a research vessel to document the issues. I tried to accommodate as many of these as I could (Figure 10). Most did not have the time to accompany an 8 day research cruise, but I found space on shorter cruises to help them do their stories (either 2 day cruises on the RV *Pelican* or RV *Acadiana,* a 1 day cruise on the same vessels, or a smaller offshore dive boat). Some articles ended up as Pulitzer prize—winning articles (Mark Schleifstein, New Orleans *Times—Picayune* and Perry Beeman, *DesMoines Register*). These and all the others elevated the visibility of the low oxygen conditions in the nGOM. The Japanese videographers were the most precise and had me jump off the side of the RV *Acadiana* in SCUBA gear with an oxygen meter numerous times to make sure the shoot was perfect. They also had me walk into the reference collection room at the Marine Center many times and pick up a specimen jar with an animal that was usually affected by low DO. None of the Japanese filming made television. National media were more successful in taping shows for television.

All reporters ended up on my press release announcements, and many called. Mark Schleifstein with the *Times—Picayune* would find me on vacation after the shelfwide cruises to get a 'non—standard' quote and interviewed me on the road. Unfortunately, the area of low oxygen on the Louisiana shelf after our annual research cruise does not have the interest it one time did, because it keeps occurring year—after—year, with variability due to river discharge and nitrogen loading, and current meteorological conditions, but <u>not</u> due to nutrient mitigation within the Mississippi River watershed. Many of these reporters and others continue contacting me on stories about the Gulf of Mexico.

Of my many media experiences, I have hung up on only one reporter, warned only one reporter to identify his recording device early in the interview, almost drowned a single reporter who could not swim well, and did not make the appointment with a journalist who ran his sailboat into pipeline warning signs on the way to LUMCON in Cocodrie and sunk. Otherwise, they were all rewarding interactions (Figure 10).

I need to describe one more important interaction related to the press' description of the size of the low oxygen area being about equal to the size of the state of New Jersey. The National Academy of Science hosted a colloquium in 2000, led by Dan Walker of the Ocean Studies Board of the National Research Council and myself on their study of "Coastal Waters, Global Patterns of Cause and Effects" (National Research Council 2000). We pulled together an international panel of experts to help decipher the results for policy makers and the public. The plenary speaker was the Honorable Christine Todd Whitman, the former Governor of the state of New Jersey and the new Administrator of the US EPA. As she began her speech, she peered at the audience, I was assuming at me, and told us "No matter what you do, please, please, quit comparing the 'dead zone' as the size of the state of New Jersey! Any other state, just not New Jersey." She was obviously well informed. In the meantime, a group of NOAA—funded colleagues and others had completed 6 reports that fed into an Integrated Assessment of Hypoxia in the Northern Gulf of Mexico (CENR 2000), which led to a proposed Hypoxia Task Force (2001) plan to address increased nutrients in the Mississippi River and the low oxygen off Louisiana's coast. The Action Plan arrived on President Clinton's desk shortly before the inauguration of President George W. Bush where it languished. Bob Wayland, the Administrator of the Office of Water for the US EPA, also a crusader for more attention to the nGOM was soon to retire, and a celebration in his honor was held in Washington, D.C. I took the opportunity to fly up and back from Louisiana to honor his contributions for water quality improvement. The Administrator of the EPA, Christine Todd Whitman, was also present. I walked up to her, introduced myself, mentioned the 'dead zone' in the Gulf of Mexico, and then mentioned the size of the state of New Jersey. She got the point. Shortly thereafter President Bush released the Integrated Assessment from his desk to be implemented by NOAA and EPA.

Some of the best interchanges now between the Gulf of Mexico and mid—West communities take place in small group social events among shrimpers bringing their freshly caught shrimp to Wisconsin for sharing and likewise the mid—west farmers bringing corn—fed beef to the shrimping communities in Cocodrie, LA to share after a day out on the water capturing shrimp. This is one way to develop conversations among shrimpers and farmers, but more is needed on the federal policy front.

At the same time, the dynamic quartet of Don Goolsby (U.S. Geological Survey for nutrient conditions of the Mississippi River), Nancy Rabalais (for dynamics of the DO depletion in the Gulf of Mexico), Bill Mitsch (Ohio State University for mitigation measures), and Otto Doeringer (Purdue University for economic considerations) began a Mississippi River watershed instructional discourse. The goal was to show residents of the Mississippi River basin how they were connected to the communities of the nGOM and vice versa. The audiences were primarily receptive but not always, and not always polite. Don Boesch was present for one of these panels and reminded the audience to “not shoot the messenger” during a question/answer session with me.

You know that you have made an imprint on the public when the answer to a question on the game show “Jeopardy” is about the low oxygen in the Gulf of Mexico, not to mention a similar question on the game show “Cash Cab” on the streets of New York City. Also, “Forbes” magazine called out Gene Turner and I as “tree hugger environmentalists” with no evidence. As several people told us “It’s good to know who your enemies are.”

Unfortunately, some press on the subject was not positive. Citizen and industrial nay sayers could be quite vocal or more often silent behind the scenes. Others, including coastal scientists, should have understood the combination of physics and nutrient—enhanced productivity on a continental shelf with long water residence time. One group wrote a report for the Fertilizer Institute about the relevance, or lack thereof, of nutrients and their sources in the Mississippi River and their influence on coastal hypoxia (Carey et al. 1999). A different group of Texas and Louisiana marine scientists published commentaries on “it’s not just nitrogen,” to which our research team responded through similar venues that “it never was just nitrogen, but a combination of contributing drivers, physical and biogeochemical” (Rowe and Chapman 2002, Bianchi et al. 2008, 2010, Boesch et al. 2009, Cowan 2009). The antagonists’ comments, in my opinion, could have been more professional (good to have a thick skin). I think that the science and modeling publications that have accumulated over the years support a data— and evidence—based sound basis for the interconnected complexities of DO processes and guide for nutrient reduction.

ELEVATION OF DISSOLVED OXYGEN INTO POLICY – MORE SWIMMING UPSTREAM

An Interagency Working Group of President Clinton’s National Science and Technology Council convened a science panel in 1997 to understand the causes and effects of eutrophication in the Gulf of Mexico; coordinate activities to reduce the size, severity, and duration; and ameliorate the effects of hypoxia. The Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) of 1998 called for an integrated assessment of causes and consequences of hypoxia in the GOM (CENR 2000). As a foundation for the assessment, 6 interrelated reports that examined various aspects of the hypoxia issue were developed by 6 teams with experts from academia and within the federal government. HABHRCA also called for a plan of action to reduce, mitigate, and control hypoxia. With the help of the EPA Office of Water and NOAA’s National Ocean Service, the Task Force released the Hypoxia Action Plan (2001), a national strategy to reduce GOM hypoxia based on the science in the Integrated Assessment.

The Hypoxia Action Plan (2001) was a compromise among the members of the Task Force, but did develop an environmental goal to reduce the size of the summer hypoxic zone to 5000 km^2 over a 5 y running average by 2015, to protect the integrity of watershed and coastal habitats, and to do so through voluntary actions with no regulations. The Hypoxia Task Force (2008) continued the environmental water quality goal from the Hypoxia Task Force (2001) for a 5000 km^2 size, over a 5 y average by 2015.

An independent review of hypoxia in the nGOM was undertaken by the U.S. EPA Science Advisory Board (SAB 2007). Their findings affirmed the major findings of the *Integrated Assessment* (CENR 2000), namely that contemporary changes in the hypoxic area in the nGOM were linked to enhanced nutrient loads from the Mississippi—Atchafalaya system. The SAB also determined that a dual nutrient strategy was needed that achieved at least a 45% reduction in both riverine nitrogen and phosphorus loads in order to reach the 2001 Action Plan bottom areal goal of 5000 km^2. The SAB (2007) called for a 5 y Report to Congress delivered by the Hypoxia Task Force (2015). The report stated that it was evident that reduction of nutrients would be difficult but still advised actions. It also became evident that the original target year of 2015 was unrealistic, and it was extended to 2035, with an interim target of a 20% nutrient load reduction in the Mississippi River by 2025. There continues to be little progress in nutrient reduction, and the nitrate—N load is not decreasing. This is discouraging to those of us who have worked so hard on the research and science that supports mitigation of Mississippi River nutrients. We will continue our efforts at translating the science into useful information for nutrient load reductions to resource managers, but we fear there will be insufficient progress within the states and watershed to deter the development of seasonal hypoxia on the Louisiana shelf.

ELEVATING DISSOLVED OXYGEN WITHIN GLOBAL CHANGE

Global change includes changing climate, warming seas, shifts in timing and location of precipitation, and shifts to more extreme conditions in storms, floods, and droughts. Further changes are predicted with human population increases and dependence on fossil fuels, as well as over—consumption of resources, and over—use and mis—use of the landscape. A larger incongruity is the global system of poor, marginalized populations and those able to have a better sustained life. This is a huge discrepancy that may seem out of proportion to our individual human domains. So, let's pull it back into the Mississippi River watershed and the GOM. Climate models for the Mississippi River indicate higher and earlier snowfall and melting and increased precipitation in the upper watershed, while the lower watershed will have less precipitation. The increase in runoff from the upper watershed will lead to more fresh water on the continental shelf, stronger stratification, and greater loads of nutrients (Justić et al. 2003, Rabalais et al. 2009). All will have a negative impact on hypoxia. It seems reasonable that coastal waters will warm, strengthening stratification and limiting exchange of DO from surface waters to the bottom. Surface waters, to date, have not and, therefore, would not be a factor in increased strength of stratification. Warmer waters also hold less DO. Water temperatures have increased in the bottom—waters of the Louisiana shelf where hypoxia occurs (Turner et al. 2017). The change in solubility of DO in the warmer bottom—waters, so far, does not contribute to the hypoxia because of the volume of bottom water affected and the small decrease in solubility. However, nutrient mitigation and reduction will be more difficult under several climate scenarios.

We cannot forget people when considering ways to reduce nutrients in the watershed. Dietary choices can reduce the use of N overall (Scavia 2019). Eating less meat is healthy and requires less N, via less fertilization for corn crops. Choice of grain products other than corn or corn—based products will reduce an individual's N footprint. Proper wastewater treatment is implicit for human health, but also for reducing N loss into streams and rivers. Fossil fuels generate NO_x emissions, and croplands and manure generate ammonium, which will volatilize to the atmosphere to return as atmospheric nitrogen in precipitation. There are some obvious solutions with respect to generation of NO_x. Less consumption of fossil fuels and use of non—ethanol gasoline avoids many processes that contribute to increased reactive N in the landscape and airshed. A deliberate and stronger social and political resolve is necessary to decrease nutrient inputs to aquatic ecosystems and alleviate the associated ecosystem, human health, and economic difficulties.

Closing Thoughts

Who would have thought? I never thought about being where I am today as a satiated and whole coastal scientist with so many rewarding experiences, opportunities, and accomplishments. I just kept thinking, working, and doing. I found a side of me that wanted to generate research that supported wise use of our environmental resources. And, I did it! I grew up in coastal ocean science, in some ways when it was 'easier' with sufficient funding. I also had a great group of science collaborators, the 'village' that accomplished so much. And, the hypoxia problem in the nGOM was a necessary research and policy focus for state and federal agencies. My advice to young scientists learned through my journey.....

Professionalism. Always be **p**rofessional, even if it becomes difficult to keep negative thoughts and actions in place. Also, you never know who may be affected by you or how you may affect them.

Persistence. I was awarded the John D. and Catherine T. MacArthur award in 2012, sometimes called the 'Genius Award.' In my alphabet the 'G' stands for **P**ersistence. If nothing else, I am persistent in my goals, direction to accomplish them, and desire to keep my mind in the right direction.

Produce science that you can translate to the **p**ublic, and be effective in that public outreach. Seek opportunities to become involved in science community—directed activities through public outreach that informs the public or entrains them in citizen science activities (Figure 11).

Press. Ah, do not be afraid of the press, but be prepared. There are several good communication skills workshops offered by our professional organizations. Use them, learn from them, **P**ractice, be **P**atient and respectful.

Politics. You may get to this point. This is where your professionalism and ability to translate science to the public come to the forefront in trying to influence public policy for the public good (Figure 12).

Hope. I know this word does not begin with a **P**. I often say my middle name is 'Hope,' but it is not really. [My parents did not give me a middle name.] I try to maintain my optimism that good efforts can produce good results. It is more satisfying than dwelling in pessimism or fear of failure.

Fais toujours de ton mieux meme si personne ne regarde.
"Always do your best, even if no one is watching."

FIGURE 11. *Nancy Rabalais working with students from Lower Little Caillou elementary school on water quality measurements.*

FIGURE 12. *Nancy Rabalais (third from right) in Washington DC for a Congressional committee meeting.*

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