



Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters: Interactive effects of human and climatic perturbations

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Abstract

Estuaries are among the most productive, resourceful, and dynamic aquatic ecosystems on Earth. Their productive nature is linked to the fact that they process much of the world's riverine and coastal watershed discharge. These watersheds support more than 75% of the human population and are sites of large increases in nutrient loading associated with urban and agricultural expansion. Increased nutrient loading has led to accelerated primary production, or eutrophication; symptoms include increased algal bloom activity (including harmful taxa), accumulation of organic matter, and excessive oxygen consumption (hypoxia and anoxia). While nutrient-enhanced eutrophication is a "driver" of hypoxia and anoxia, physical–chemical alterations due to climatic events, such as stormwater discharge, flooding, droughts, stagnancy, and elevated temperatures are also involved. The complex interactions of anthropogenic and climatic factors determine the magnitude, duration, and aerial extent of productivity, algal blooms, hypoxia, and anoxia. Using the eutrophic Neuse River Estuary (NRE), North Carolina, USA, as a case study, the physical–chemical mechanisms controlling algal bloom and hypoxia dynamics were examined. Because primary production in the NRE and many other estuaries is largely nitrogen (N) limited, emphasis has been placed on reducing N inputs. Both the amounts and chemical forms of N play roles in determining the composition and extent of phytoplankton blooms that supply the bulk of the organic carbon fueling hypoxia. Biomass from bloom organisms that are readily grazed will be readily transferred up the planktonic and benthic food chain, while toxic or inedible blooms frequently promote sedimentary C flux, microbial mineralization, and hence may exacerbate hypoxia potential. From a watershed perspective, nutrient input reductions are the main options for reducing eutrophication. Being able to distinguish the individual and cumulative effects of physical, chemical and biotic controls of phytoplankton productivity and composition is key to understanding, predicting, and ultimately managing eutrophication. Long-term collaborative (University, State, Federal) monitoring, experimental assessments, and modeling of eutrophication dynamics over appropriate spatial and temporal scales is essential for developing realistic, ecologically sound, and cost-effective nutrient management strategies for estuarine and coastal ecosystems impacted by both anthropogenic and climatic perturbations. © 2005 Elsevier B.V. All rights reserved.

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1. Introduction

1.1. Eutrophication, hypoxia and anoxia dynamics in hydrologically variable estuaries

Estuaries are among the most productive, diverse, economically important, and hydrologically variable ecosystems on Earth (Neilson and Cronin, 1981; Hobbie, 2000). A bulk of the world's commercial and recreational fish stocks depend on estuaries as nurseries, refuges, and feeding grounds. Estuarine and coastal watersheds support approximately 75% of the world's human population and the number of coastal residents continues to rise (Vitousek et al., 1997). As such, they receive and process a large share of land-based nutrients and other pollutants entering via surface runoff, atmospheric deposition, and groundwater discharge, much of it delivered via rivers draining urban centers and agricultural watersheds (Howarth et al., 1996; Paerl, 1997; Jaworski et al., 1997; Paerl et al., 2002). The productive nature and resourcefulness of estuaries depend to a large extent on externally supplied or "new" nutrient inputs. Anthropogenic new nutrient inputs have increased dramatically; it is estimated that nitrogen (N) inputs alone have increased 10-fold in the past century (Howarth et al., 1996). Current nutrient loading rates often exceed those needed to sustain desirable production (Vollenweider et al., 1992; Jørgensen and Richardson, 1996; Boesch et al., 2001). Many estuaries are now facing nutrient-over-enrichment, or "too much of a good thing", in the form of nutrient-enhanced primary production (D'Elia, 1987; NRC, 2000). This condition, which often leads to excessive production of organic matter in the form of algal blooms (Fig. 1), is referred to as eutrophication (Nixon, 1995). Unused or partially degraded organic matter settles to the sediments, where it serves as "fuel" for microbial decomposition, converting organic matter to CO₂ and inorganic nutrients (Fig. 2).

Decomposition is an oxygen (O₂)-demanding process. Therefore, waters enriched with readily degraded or "reactive" organic matter tend to consume large amounts of O₂. If the affected waters are vertically stratified, slowly flushed, and/or stagnant, consumption of O₂ may exceed its re-supply from either atmospheric or in-stream photosynthetic (i.e., O₂ evolution) sources. The imbalance between relatively high rates of O₂ consumption and low rates of O₂ re-supply causes

dissolved oxygen (DO) content to drop to levels that are low enough to adversely affect oxygen-requiring animal and plant life. DO concentrations of less than 4 mg O₂ L⁻¹ are commonly referred to as hypoxic and are frequently stressful to higher life forms, while no detectable O₂ concentrations are termed anoxic and potentially fatal to finfish, shellfish and invertebrate species (Renaud, 1986; Pihl et al., 1991; Diaz and Rosenberg, 1995).

In addition to experiencing man-made nutrient enrichment (i.e. cultural eutrophication), estuarine and coastal ecosystems are also under the influence of natural (climatic) perturbations such as droughts, hurricanes, and flooding. Distinguishing and integrating the effects of natural and anthropogenic stressors is a difficult but essential challenge for understanding and managing coastal biotic resources.

The effects and manifestations of human and natural perturbations are readily detected and consequential at the microbial level, where a bulk of ecosystem energy and nutrient flow is mediated. Microbes have rapid growth rates, and respond to low levels of pollutants and environmental perturbations. These features make them sensitive, meaningful, and useful indicators of ecological change. In this paper, the response of suspended microalgae or phytoplankton, the dominant primary producers in many estuaries, to nutrient and climatic perturbations will be examined. The focus will be on how anthropogenic stressors interact with natural forcing features to determine the composition, distribution, and activities of phytoplankton communities.

The linkage between nutrient loading, eutrophication, and hypoxia/anoxia dynamics is often non-linear and complex in estuarine and coastal systems (Cloern, 2001). This is because these systems are hydrodynamically and biogeochemically distinct and highly variable. Climatic and physiographic differences between these systems profoundly affect physical-chemical and biological processes mediating organic matter production and accumulation, oxygen dynamics, and nutrient cycling. The complex interplay between hydrologic discharge (i.e., flushing, residence time), vertical and horizontal thermal and salinity stratification, wind and tidal mixing, frontal passage (e.g., "nor-easters"), and even larger storm events (i.e., hurricanes), determines the frequency, spatial, and temporal extent of hypoxia events in estuaries. Here we will explore the interplay of anthropogenic (nutrient) and natural (climatic) forc-



Fig. 1. Examples of estuarine and coastal phytoplankton blooms symptomatic of nutrient-driven eutrophication. Upper left: a bloom of the nitrogen-fixing blue-green algae (cyanobacteria) *Nodularia* spp., *Aphanizomenon flos aquae* and *Anabaena* spp. in the Gulf of Finland, Baltic Sea (photograph courtesy of P. Moisander). Upper right: red tide dinoflagellate bloom, in coastal Japan (Courtesy of ECOHAB Program). Lower left: a mixed cyanobacterial bloom comprised of nitrogen fixers (*Anabaena* spp.) and a non-nitrogen fixing nuisance species, *Microcystis aeruginosa*, in the St. Johns River, a tidal estuary in Florida, USA. Lower right: a mixed algal bloom dominated by non-nitrogen fixing cyanobacteria (*Microcystis aeruginosa*, *Oscillatoria* spp.) and green algae (chlorophytes) in the upstream oligohaline segment of the Neuse River Estuary, NC.

ing features in the Neuse River Estuary (NRE), North Carolina. This estuary's watershed has experienced rapid population growth, and agricultural and urban development, accompanied by substantial increases in nutrient (N and P) loading. It has also been heavily impacted by tropical storm and hurricane-related flooding as well as droughts. Information from an intensive water quality modeling and monitoring program, ModMon (www.marine.unc.edu/neuse/modmon) is used to assess the relative roles and impacts of anthropogenic and natural stressors. The use of these data for formulating water quality criteria and nutrient management strategies aimed at controlling eutrophication is discussed.

1.2. Eutrophication dynamics in the Neuse River Estuary, North Carolina, USA

The NRE is a tributary of North Carolina's Albemarle-Pamlico Estuarine System (APES), the US' second largest estuarine complex. It drains a rapidly growing urban, industrial, and agricultural watershed and illustrates the plight of many coastal river systems under the influence of accelerating nutrient loading. This estuary is approximately 100 km long from its fresh headwaters to the mesohaline (15–25 psu) waters of Pamlico Sound (PS) (Fig. 3). Its physical, chemical, and biological characteristics have been intensively monitored and are the focus of mod-

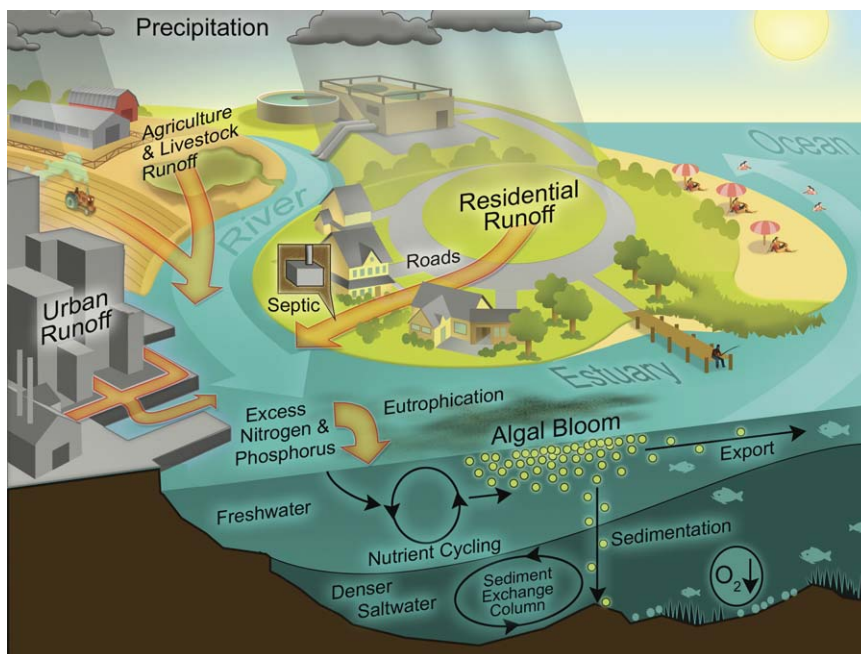


Fig. 2. Functional linkages between hydrology, anthropogenic nutrient inputs, eutrophication (phytoplankton blooms), and hypoxia/anoxia in estuarine and coastal aquatic ecosystems.

eling studies (www.marine.unc.edu/neuse/modmon, www.ferrymon.org/; Luetlich et al., 2000). Primary production in the NRE is strongly controlled by N inputs (Paerl, 1987; Rudek et al., 1991; Boyer et al., 1994), which have nearly doubled in the past three decades (Stanley, 1988; Dodd et al., 1993). Within this time frame, the NRE has experienced multiple symptoms of eutrophication, including nuisance (i.e., toxic and food web disrupting) dinoflagellate and cyanobacterial blooms, extensive bottom water hypoxia, and periodic shellfish and finfish kills (Christian et al., 1986; Paerl, 1987; Paerl et al., 1995). Non-point sources contribute ca. 75% of the external or “new” N loads, much of it from agricultural activities (NC Dept. of Environment and Natural Resources, 2002). Agricultural expansion, including creation of new farm land, widespread use of N fertilizers, proliferating livestock (swine, cattle) and poultry (chicken, turkey) operations, coastal urbanization, and increasing contributions from groundwater and atmospheric deposition have led to unprecedented increases in N loading (Paerl and Whitall, 1999). Industrial-style farms have increased the region’s hog population from approxi-

mately 1 million to over 12 million between 1989 and 1999 alone. As a result, land-applied and atmospherically deposited N inputs to this estuary constitute a large and growing source of externally supplied “new” N (Whitall and Paerl, 2001).

Eutrophication and algal bloom formation have been linked to enhanced deposition of organic matter (Clesceri, 2004), leading to growing frequencies, magnitudes, and aerial coverage of large-scale bottom water hypoxia and anoxia (Paerl et al., 1998; Fig. 4). Relatively long water residence times (from 30 to over 70 days), and persistent stratification exacerbate low DO conditions during summer, which can cover at least half the bottom of the estuary (Luetlich et al., 2000; Buzzelli et al., 2002). Finfish and shellfish kills have been linked to this chain of events (Lenihan and Peterson, 1998; Paerl et al., 1998; Fig. 4).

The NRE is also under the influence of elevated tropical storm and hurricane activity, possibly reflecting a larger-scale Atlantic basin trend predicted to last 10–40 years (Goldenberg et al., 2001). At least seven major hurricanes have impacted the NRE watershed in the past 8 years alone. During the fall of 1999, three

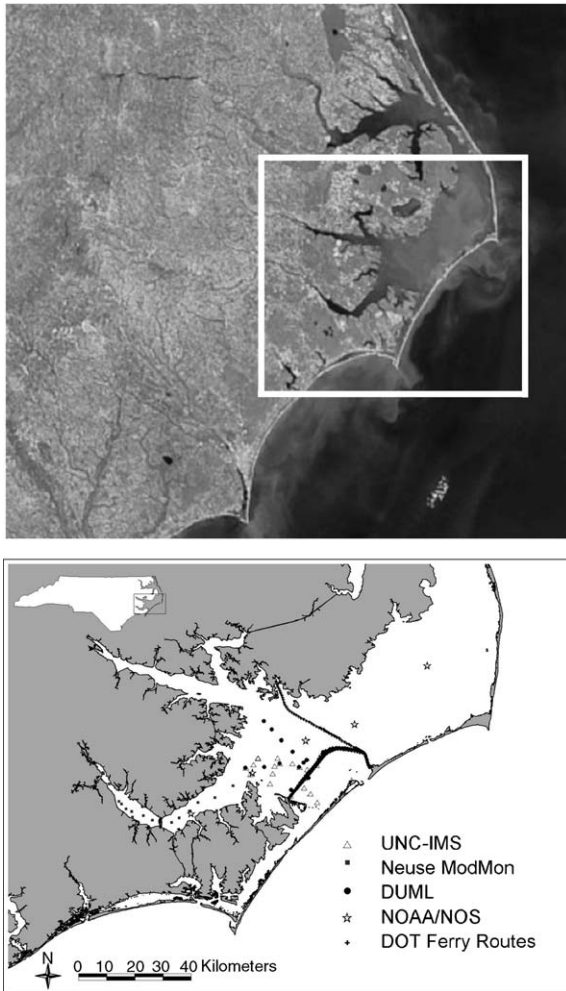


Fig. 3. Upper frame: remote sensing (NASA Sea WiFS satellite-mounted color sensor) view of Eastern North Carolina, showing the location of the Pamlico Sound system. The Neuse River Estuary, which is the southern-most major tributary of this system, is delineated with a red box. Lower frame: Map of the Neuse River Estuary and Pamlico Sound, showing the various monitoring programs used for assessing water quality and habitat condition. Key sources of data used in this contribution include: (1) UNC-Chapel Hill's Institute of Marine Sciences Neuse River Bloom Project (see www.marine.unc.edu/Paerllab for details), (2) the Neuse River Modeling and Monitoring Study, ModMon (www.marine.unc.edu/neuse/modmon), (3) NC Ferry-based Water Quality Program, FerryMon (www.ferrymon.org), (4) Duke University Marine Laboratory (courtesy J. Ramus and L. Crowder), and (5) the NOAA-NOS Beaufort Laboratory, Beaufort, NC.

sequential hurricanes, Dennis, Floyd and Irene, inundated the NRE watershed with up to a meter of rain during a 6 week period. This caused a 100–500 year flood (depending on location) in the NRE watershed. Floodwaters turned the NRE and other tributaries of the Pamlico Sound completely fresh, and accounted for more than half the annual N load to this N-sensitive system (Paerl et al., 2001). Biogeochemical and ecological effects included hypoxic bottom waters, altered nutrient (N, P, C) cycling, a three-fold increase in algal biomass, shifts in microbial community structure and function, altered fish distributions, catches, and an increase in fish disease (Paerl et al., 2001; Peierls et al., 2003).

Numerous estuarine studies throughout the world clearly demonstrate that interactions between the sediment and the water column play an important role in regulating phytoplankton production and the extent of bottom water hypoxia/anoxia (e.g., Matson et al., 1983; Nixon and Pilson, 1983; Kemp and Boynton, 1992; Jørgensen, 1996). Estuarine sediments are rich in organic matter (typically 3–10% organic carbon) and represent vast storage reservoirs for nutrients and oxygen demand. For example, the upper 10 cm of sediment in the NRE contains 500 times more N than the entire water column (Alperin et al., 2000). Likewise, the benthic oxygen flux in the Neuse ($20\text{--}40\text{ mmol m}^{-2}\text{ d}^{-1}$) is capable of depleting the bottom water of oxygen in just 10 days (Alperin et al., 2000).

Sediment biogeochemical processes are driven by the flux of organic matter from the water column. The quantity of organic matter deposited at the sediment surface depends on productivity in the overlying water (internal loading), the flux of organic matter from the watershed (external loading), and the efficiency with which the organic matter is exported from the estuary by either physical processes or consumption by grazers. Since, on an annual basis, external organic matter constitutes less than a third of the total load to the NRE (Paerl et al., 1998), primary productivity and export are the major controls on the flux of organic matter reaching the sediment surface. While estuarine productivity is largely controlled by the supply of combined N, the export of organic matter from the estuary will depend on phytoplankton community structure and food web dynamics. Taxonomic groups that contain certain species that are poorly grazed (e.g., cyanobacteria, dinoflagellates) or that flocculate and settle as

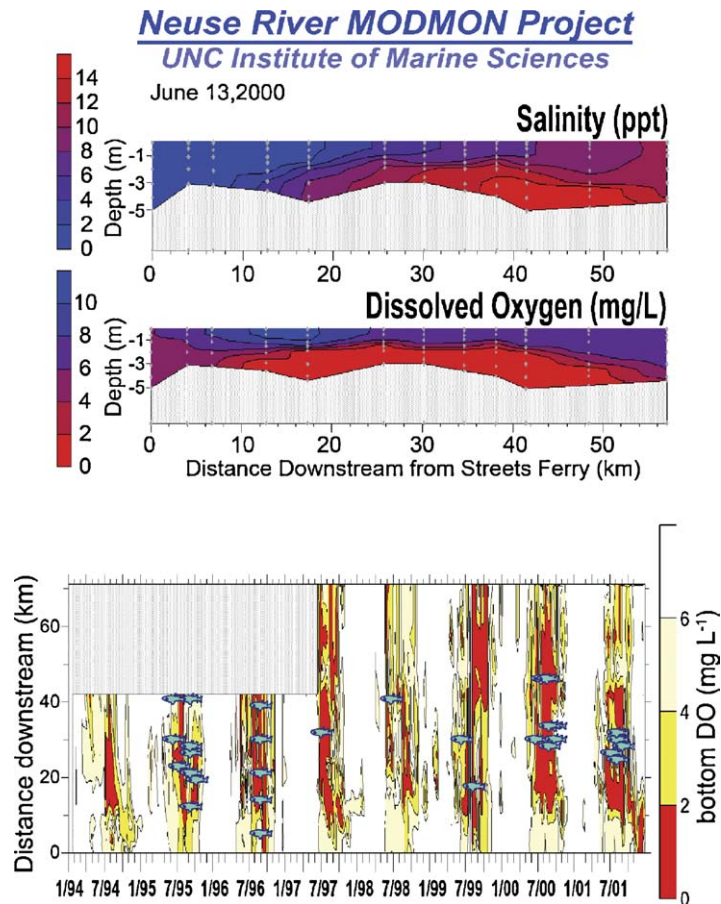


Fig. 4. Hypoxia dynamics of the Neuse River Estuary. Upper frame: two-dimensional plot, showing the vertical distribution of salinity and dissolved oxygen along the main axis of the estuary from the freshwater riverine region (left hand side) to the mesohaline entrance to Pamlico Sound. Data are from the ModMon sampling program. Salinity stratification, shown for 13 June, 2000, persists from late spring into fall. Strong vertical salinity stratification in this poorly flushed estuary is a key factor promoting extensive hypoxia. This pattern is only disrupted by large storm events (i.e., “nor-easters”, tropical storms, and hurricanes). Bottom frame: spatio-temporal relationship between bottom water hypoxia and fish kills, plotted for 1994–2001 in a mesohaline segment of the Neuse River Estuary between New Bern and a location midway between Minnesott Beach and the entrance to Pamlico Sound (see Fig. 3). Dissolved oxygen data were obtained by the ModMon program (www.marine.unc.edu/neuse/modmon). The fish kill events (each representing at least 500 dead fish) were recorded by the North Carolina Dept. of Environment and Natural Resources, Division of Water Quality. The fish kill data-base can be accessed at: <http://www.esb.enr.state.nc.us:80/Fishkill/fishkillmain.htm>.

their blooms “crash” (e.g., some diatom species) have a greater tendency to contribute to water column or sediment oxygen demand (Fig. 5).

Hydrology and nutrient enrichment play key interactive roles in determining phytoplankton community composition and activity. Discharge delivers nutrients to the coastal zone and determines hydrologic properties (flushing or residence time), vertical stratification, turbidity, and color of the water column, all of which

mediate productivity, nutrient cycling, DO, and habitability in an interactive manner (Fig. 2). The rate of water discharge to estuarine and coastal embayments controls their hydraulic residence time. Residence time, in turn, strongly mediates the availability and rate of use of nutrients by phytoplankton and higher plants. Because discharge strongly impacts transport of phytoplankton through these systems, it plays an interactive role with nutrient supply in controlling growth,

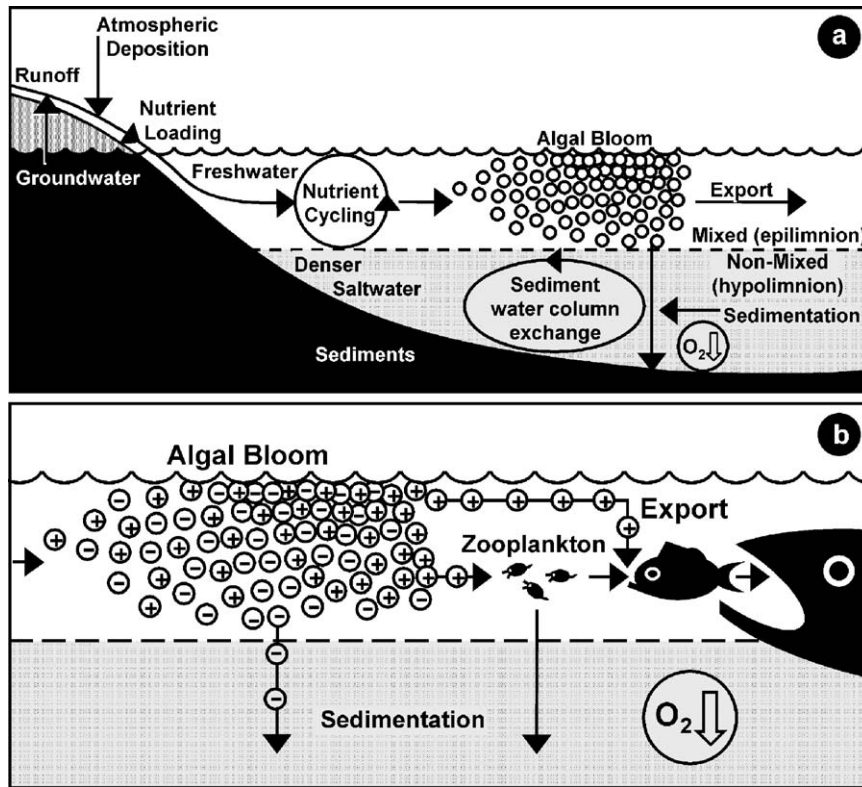


Fig. 5. Upper frame: conceptual diagram showing the linkage between watershed nutrient inputs, nutrient cycling within the estuary, nutrient enhanced eutrophication, and algal bloom formation and hypoxia under salinity-stratified estuarine conditions. Lower frame: differential impact on hypoxia of phytoplankton species that are readily consumed (labeled +) vs. species that are not (–). Species that are not consumed form a larger share of sedimented organic matter and therefore represent a larger burden on the hypoxia potential of the estuary (also see Fig. 9).

competition, and succession among members of the phytoplankton community.

1.3. Phytoplankton community dynamics as an indicator of environmental perturbations in the Neuse River Estuary

The interactive effects of anthropogenic (nutrient enrichment) and hydrologically driven changes of phytoplankton community composition and activity have been studied intensively in the NRE and less frequently in PS. High performance liquid chromatography (HPLC), coupled to photodiode array spectrophotometry (PDAS), was used to determine phytoplankton composition based on diagnostic photopigments. Pigments include specific chlorophylls (*a*, *b*, *c*), carotenoids and phycobilins. A statistical procedure, ChemTax (Mackey et al., 1996), partitions

chlorophyll *a* (Chl *a*; i.e. total microalgal biomass) into the major algal groups, based on ratios of carotenoid accessory pigments to chlorophyll *a*, to determine the relative and absolute contributions of each group. In the NRE, key photopigment markers include Chl *b* and lutein (chlorophytes), zeaxanthin, myxoxanthophyll, and echinenone (cyanobacteria), fucoxanthin (diatoms), peridinin (dinoflagellates) and alloxanthin (cryptomonads).

HPLC pigment analyses have been adapted to routine monitoring programs (Pinckney et al., 2001) including ModMon. Data from ongoing studies in the NRE (1994–present), PS (1999–present), and Chesapeake Bay (1993–present) indicate that these estuarine systems have experienced the combined stresses of anthropogenic nutrient enrichment, droughts (reduced flushing combined with minimal nutrient inputs), and in the NRE/PS since 1996, elevated hurricane activ-

ity (high flushing accompanied by elevated nutrient inputs). These distinct perturbations have allowed us to examine impacts of both anthropogenic and natural stressors on phytoplankton community structure. Seasonal and/or hurricane induced variations in river discharge, and the resulting changes in flushing rates and hence, estuarine residence times, have differentially affected phytoplankton taxonomic groups presumably as a function of their contrasting growth characteristics. For instance, the relative contribution of chlorophytes (Fig. 6), cryptophytes, and diatoms (not shown) to the total Chl *a* pool appeared strongly controlled by periods of elevated river flow in the NRE. It is hypothesized that these effects are due to the efficient growth rates

and enhanced nutrient uptake rates of these groups. Cyanobacteria, on the other hand, showed greater relative biomass when flushing was minimal (i.e., longer residence times) during the summer (Fig. 6).

Further evidence that hydrologic changes have altered phytoplankton community structure is provided by the observed historical trends in dinoflagellate and chlorophyte abundance in the NRE. Both decreases in the occurrence of winter-spring dinoflagellate blooms and increases in the abundance of chlorophytes coincided with the increased frequency and magnitude of tropical storms and hurricanes since 1996 (Fig. 6). The relatively slow growth rates of dinoflagellates may have led to their reduced abundance during these high

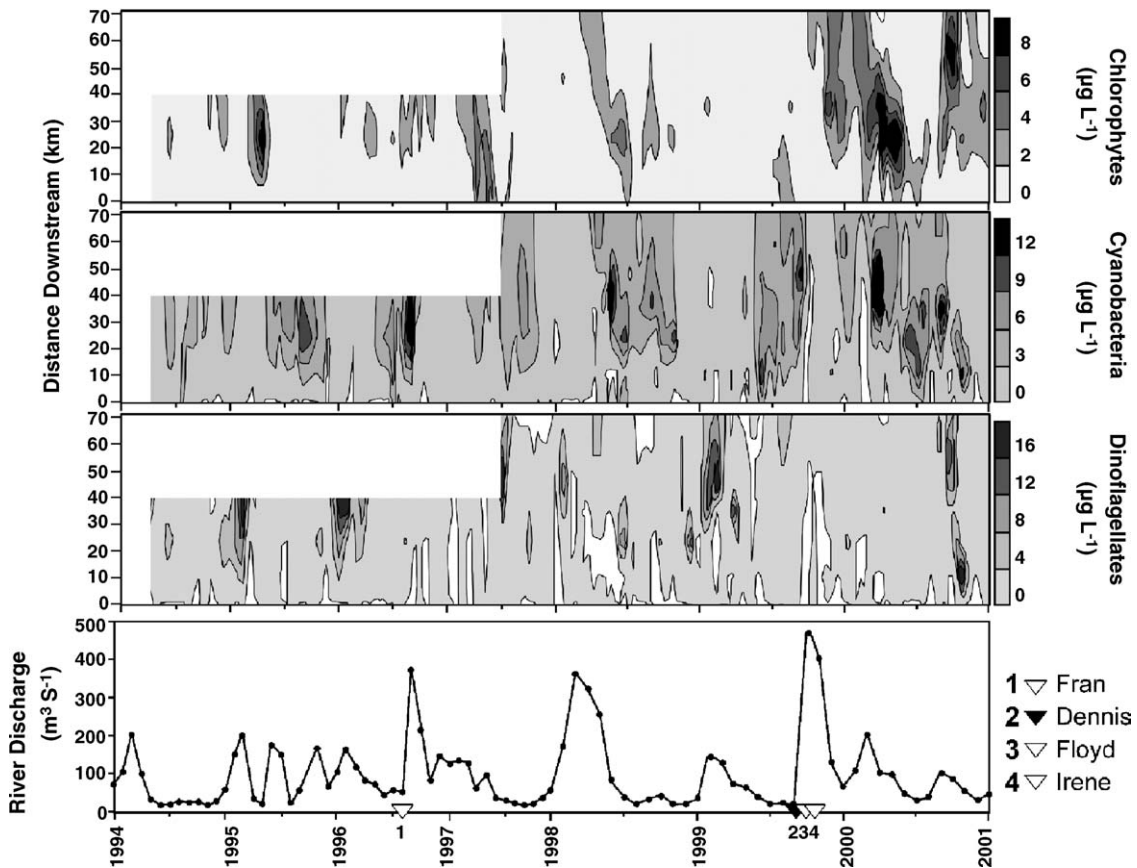


Fig. 6. Distributions, in time and space, in the Neuse River Estuary of chlorophyll *a* ($\mu\text{g Chl } a \text{ L}^{-1}$) contributed by several key phytoplankton functional groups contributing to estuarine primary production during 1994–2000. Groups shown here are chlorophytes, cyanobacteria, and dinoflagellates. Values were derived using ChemTax for surface water at mid-estuarine mesohaline locations sampled by the ModMon program (see Fig. 3 for station locations). Data were collected bi-weekly and were temporally extrapolated. White areas indicate instances where data were not collected. ChemTax data were plotted along with freshwater discharge at the head of the estuary. The dates of landfall of the four major hurricanes that have significantly affected flow since mid-1996 are shown.

river discharge events. Clearly, phytoplankton composition has been altered since 1994 in conjunction with major hydrologic changes, most likely floods following hurricanes. These phytoplankton community changes could have potentially altered trophodynamics and nutrient cycling in the NRE during these years.

The reconstructed taxonomic composition for Chesapeake Bay (Fig. 7) also shows strong contrasting responses between dominant phytoplankton groups during spring and summer due to the variability of freshwater flow and nutrient loading. This pattern is strongest in the spring-early summer during which high flow alleviates N limitation of the mid- to lower estuary and supports diatom blooms in the spring. Low flow produces improved photic conditions but causes an expanded zone of N limitation in the main stem of the Bay during the summer, thereby changing phytoplankton dominance to those groups that can grow efficiently under these conditions (L. Harding, Personal communication).

Pinckney et al. (1998) have shown that phytoplankton bloom dynamics and community structure in the NRE vary in time and space. Typically, total productivity is highest in the spring, coincident with a peak in N loading associated with maximal river discharge. The NRE spring bloom is dominated by dinoflagellates, which grazers find less palatable than diatoms and chlorophytes, allowing a greater portion of the production to escape export and settle to the sediment (Pinckney et al., 1998). This sedimentation process is an important mechanism for retaining C and N fixed during the spring since high flow during this period would tend to flush the suspended organic matter from the estuary in <1.5 months (Christian et al., 1991). Secondary blooms – composed of cyanobacteria, cryptomonads, chlorophytes and occasionally diatoms – typically occur during the summer. These blooms coincide with the period of minimal external N loading (Paerl et al., 1998), implying that recycled N released from the sediment plays a significant role in fueling productivity. The oxygen demand associated with organic matter from the summertime bloom combined with warm temperatures (up to 30°C in the summer), low flow rates, fewer mixing events, and persistent water column stratification can result in pervasive hypoxia and anoxia.

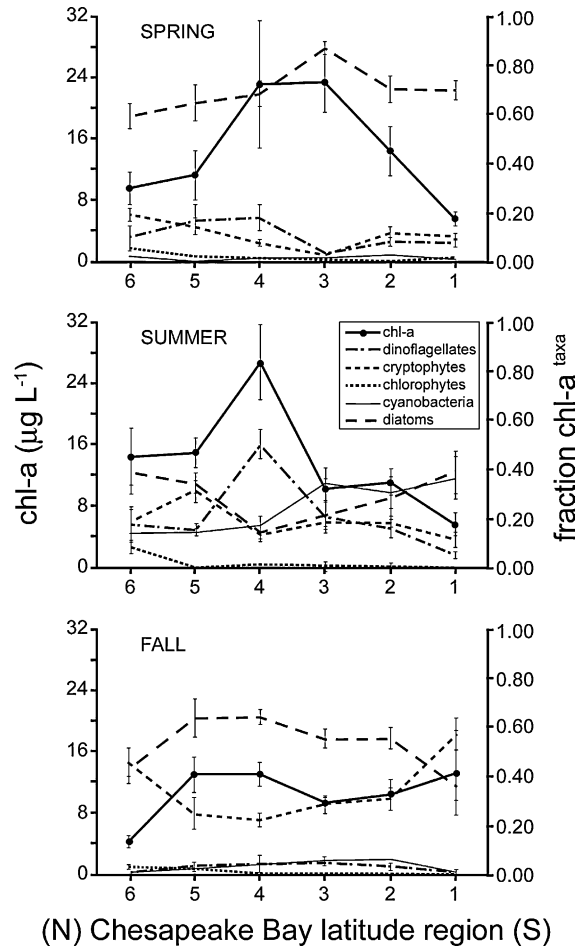


Fig. 7. Regional mean \pm S.E. (1995–2000) for Chl *a* (mg m^{-3} or $\mu\text{g L}^{-1}$) and the relative abundance (fraction Chl *a*_{taxa}) of phytoplankton groups determined by ChemTax for Chesapeake Bay (mid-Bay location). One approach to developing indicators from measurements of phytoplankton biomass and composition is to define the ‘average’ conditions, as shown above, and then conduct analyses of deviations (seasonal, regionally, inter-annually) in relation to differences in environmental forcing functions and patterns of primary production. Data courtesy L. Harding, Univ. of Maryland Horn Point Laboratory, Cambridge, Maryland.

1.4. Estuarine hypoxia dynamics: underlying processes and their management

In the NRE, summertime long residence times, low flushing rates, persistent vertical stratification, and elevated temperatures exacerbate hypoxic conditions that can persist for weeks and cover large areas (Luettich et al., 2000). Non-motile (sessile) fauna are unable to

escape these conditions and subsequently large areas of the benthos are subjected to periodic defaunation events (Lenihan and Peterson, 1998). In addition, these conditions overlap with critical fish nursery/refuge habitats (Luettich et al., 2000). The ecosystem-level trophic implications are that a large component of the estuarine food web may be negatively impacted or removed, altering both the structure and function of the system until benthic and nektonic communities are reestablished. Hypoxia and anoxia also influence biogeochemical cycling processes in affected habitats. Benthic nutrient release, especially of NH_4^+ and PO_4^{3-} , is enhanced under low DO concentrations (Rizzo et al., 1992). These nutrients, critical for supporting phytoplankton productivity and biomass, are present in high concentrations during and following anoxic events. Further, periodic pulse nutrient loading from storm events throughout the watershed as well as point and non-point source discharges near the estuary help sustain phytoplankton blooms, and perpetuate hypoxic conditions (Fig. 8). As the frequency, duration, and aerial coverage of these perturbations increase, both the structure and function of the estuarine ecosystem may experience long-term change.

Key variables controlling hypoxia include vertical salinity and/or temperature stratification, flushing, wind or tidal mixing and oxidizable organic matter to support net O_2 consumption (Paerl et al., 1998; Buzzelli et al., 2002). As a rule, estuarine or coastal waters that exhibit periods of vertical stratification and/or are sufficiently deep have a natural propensity to develop hypoxia. Conversely, well-mixed, non-stratified and rapidly flushed estuarine or coastal waters rarely exhibit water column hypoxia. From a management perspective, these physical forcing features are seldom controllable. Notable exceptions include small systems such as aquaculture ponds, which may lend themselves to artificial destratification, or larger water bodies and wetlands impounded by water flow control structures, such as large floodplain reservoirs and spillways where pulsed discharges of fresh river water may flush the system at high enough volumes to “freshen” and destratify them, thus preventing hypoxia. River diversions such as those present in the lower Mississippi basin have the capacity to do so. These diversions can also dilute nutrients and increase turbidity; the combined effect which would be a reduction in primary production in downstream waters. Hydrologic manip-

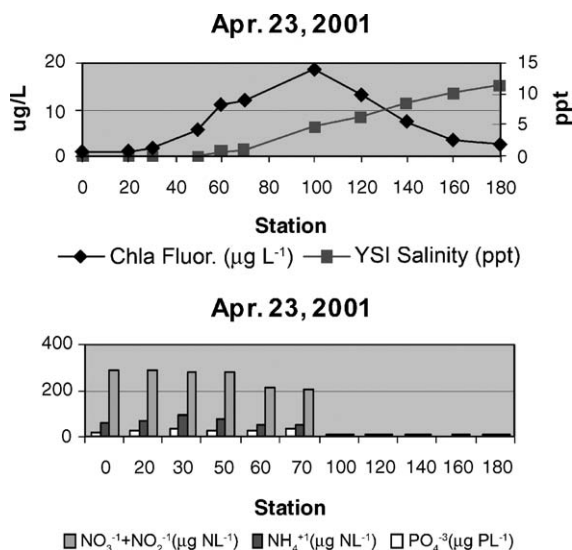


Fig. 8. Spatial relationship between chlorophyll *a* concentrations, salinity, and concentrations of the essential phytoplankton nutrients nitrate, ammonium, and phosphate along the axis of the Neuse River Estuary. Data are from near-surface depths collected during a ModMon sampling run on 23 April 2001. These data show the characteristic development of a zone of maximum chlorophyll *a* concentration, commonly referred to as the “chlorophyll maximum”, which is established along a region of the longitudinal salinity gradient where phytoplankton have ready access to limiting nutrients (in this case N as nitrate) and salinity conditions are optimal for phytoplankton growth. Seasonally, the “chlorophyll maximum” migrates longitudinally depending on the interactions of freshwater discharge (residence time), nutrient loading (availability), and growth optima for specific phytoplankton functional groups that show strong successional patterns (see Fig. 6).

ulations offer some options in reducing hypoxia and excessive production in the Mississippi Delta region. However, in most other watersheds, the luxury of having enough freshwater to physically disrupt and destroy stratification-induced hypoxia is not a hydrologically or economically feasible option.

Manipulating the production of organic matter, the “fuel” for hypoxia, is often the most achievable and hence realistic option. Organic matter (OM) arises from two main sources, externally supplied OM derived from the watershed, and internally supplied OM, derived from primary production within the system. A vast amount of watershed-based OM input is attributable to natural processes, including leaching of decomposing plant and animal OM materials from soils, forests, wetlands and swamps. Leaching

is often enhanced in agricultural soils through tilling and the application of organic fertilizers (i.e., animal wastes, manures). Therefore, land management practices that minimize OM losses from these sources can help reduce OM losses to downstream estuarine and coastal waters.

As mentioned above, estuarine and coastal OM inputs are dominated by in situ primary production, either originating from phytoplankton, macroalgae, or rooted higher aquatic plants (Nixon, 1986; Valiela, 1995; Paerl et al., 1998; Hobbie, 2000). Therefore, controlling the rate of primary production is a direct approach to minimizing OM loading and potentially reducing hypoxia. Because estuarine and coastal primary production is at least in part controlled by nutrient (i.e., N and P) supply, nutrient input constraints are the prescribed approaches for minimizing the hypoxia potential of sensitive waters (Nixon, 1995; Paerl et al., 1998; Boynton and Kemp, 2000). As to what, how much, when and where to reduce nutrient inputs are site-specific questions that require answers intimately tied to the interactive effects of physical, chemical and biological forcing features. Demonstrating a linkage between phytoplankton and O₂ dynamics within the framework of annual variability requires a process-based understanding of the combined effect of individual factors. Synoptic measurements of the major variables at relevant time scales are a critical first step in developing data useful for formulating, validating, and testing realistic conceptual/mathematical models describing environmental controls of this process on the ecosystem scale.

The linkages between nutrients, phytoplankton, and hypoxia/anoxia are usually viewed in a simple conceptual manner that translates biomass into carbon deposition and decomposition (c.f. Fig. 2). However, this approach needs to incorporate the complex interactions of changing nutrient sources and chemical forms (e.g., nitrate versus ammonium versus organic N) associated with human and climatic perturbations in coastal watersheds, which impact phytoplankton community structure and functional responses. We now know that these responses impact trophic transfer and C deposition rates, both of which affect hypoxia potentials (Fig. 9). Amounts, forms, and rates of delivery of watershed-discharged nutrients should be the primary targets of management strategies aimed at reducing estuarine hypoxia potentials. In most instances, the

focus should be on N controls, since productivity of receiving waters is largely N limited (Nixon, 1995). However, N and P co-limitation occurs in some estuaries, in which case both nutrients should be included in management strategies (Jonge, 1990; Elmgren and Larsson, 2001; Paerl et al., 2004). Modeling efforts should be focused on determining naturally occurring “background” hypoxia potentials, i.e., the tendency of a system to develop hypoxia independent of man-made nutrient inputs. Models able to predict the difference in hypoxia potentials between “natural” and anthropogenically enriched nutrient conditions will help management devise approaches to control estuarine hypoxia using quantifiable, ecologically sound, and cost-effective nutrient input reduction strategies. Modeling efforts under way in the NRE to distinguish the relative importance and roles of physical and chemical drivers of hypoxia (Borsuk et al., 2001; Buzzelli et al., 2002) may prove useful for other, hydrologically and biogeochemically variable estuaries.

In any case, it should be recognized and kept in perspective that hypoxia is a natural phenomena that frequently takes place in strongly stratified, productive waters. Therefore, it is unlikely that management efforts will entirely eliminate the tendency of these waters to periodically exhibit localized oxygen depletion. However, there is evidence that excessive organic matter loading, most commonly as nutrient-enhanced eutrophication, can increase hypoxia potentials in these waters (cf., Rabalais and Turner, 2001). As such, steps taken to reduce the unwanted symptoms of eutrophication will also help mitigate, but not necessarily eliminate, hypoxia potentials. Management strategies and approaches for reducing hypoxia will most likely need to be site and ecosystem specific (e.g., Mississippi Delta versus Neuse-Pamlico Sound versus Chesapeake Bay).

1.5. Managing coastal eutrophication under hydrologically variable conditions

The North Carolina “experience” has taught us that integrated (watershed-airshed-receiving waters) monitoring, research, and assessment are essential ingredients for nutrient management programs in estuarine and coastal systems affected by large-scale climatic, hydrologic, and (as a result) nutrient variability. These

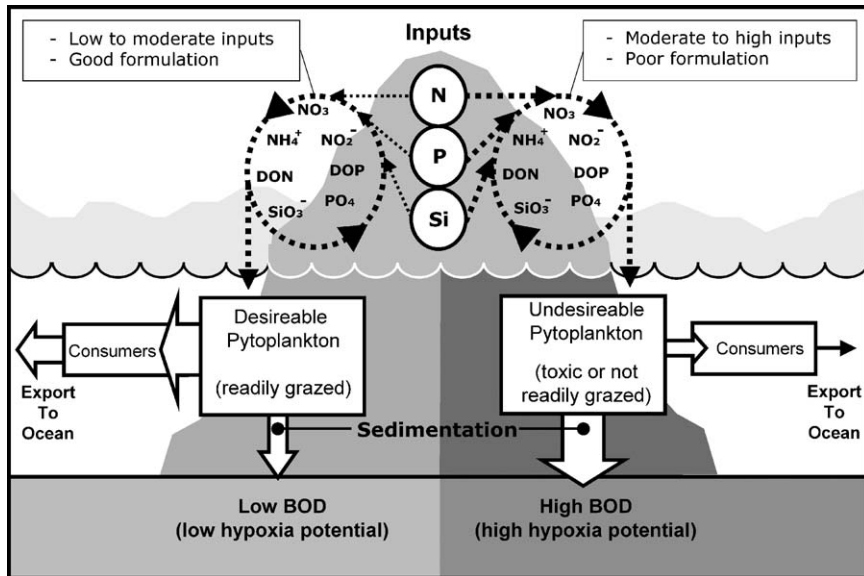


Fig. 9. Conceptual diagram showing the linkage of nutrient loading regimes (both types and amounts) to selective growth of different algal functional groups (each one having specific nutrient requirements) and hypoxia potentials in a stratified estuary. According to this scenario, both the amounts and ratios of nutrient influence the composition and amount of phytoplankton that constitute the base of the estuarine food web. Certain nutrient regimes (left hand side) will favor the growth of readily utilized (by filter-feeding zooplankton and ultimately fish) phytoplankton taxa, promoting efficient trophic transfer and minimizing losses of “unused” phytoplankton to the sediments, which in turn would minimize hypoxia potential. In contrast, the favoring of less edible or toxic phytoplankton by a different nutrient regime reduces trophic transfer in the water column and enhances loss of unused phytoplankton to the sediments, thus promoting hypoxia.

programs should consider the following questions:

- What type of assessment program is necessary and sufficient to adequately address the full range of ecosystem nutrient and habitat impacts resulting from major hydrologic perturbations, such as droughts, tropical storms, hurricanes, and floods?
- What are the specific issues that are unique to monitoring on the short-term episodic and longer-term chronic event scales?

Monitoring and assessment should be able to answer the following questions:

- How far away from “normal” conditions was the system changed by climatic events?
- To what extent do these systems recover? What conditions are required for recovery?
- Are there permanent changes to the ecosystem, and what are they?
- How do human activities affect recovery?
- Are any of the changes (short-term or permanent) detrimental to human use and resources?

Lessons learned from the 1996, 1999, and 2003 hurricanes that struck coastal North Carolina stress the need for long-term monitoring and assessment. These assessments must be able to detect and quantify these events over appropriate spatial and temporal scales, have realistic and sustainable efforts and financial resources, and achievable assessment criteria and goals. Important features of a long-term monitoring and assessment program include:

- Sampling to detect (1) trends, (2) changes in state equivalent through a step function, and (3) consequences of infrequent, but large-scale events.
- Routine monitoring and event-response components.
- Spatially and temporally extensive monitoring of key environmental variables, using continuous and time-integrative sampling of water quality, productivity, and turbidity, possibly making use of satellite- and aircraft-remote sensing, and large-scale, long term, real time monitoring using existing infrastructure such as bridges, platforms, commercial and gov-

ernment vessels, and ferries (Buzzelli et al., 2003; www.ferrymon.org).

- Measurement of water quality and habitat responses using meaningful, sensitive, and easily deployed indicators of environmental stress. Here, I have illustrated the use of phytoplankton community structure and function as diagnostic indicators of the occurrence and impacts of nutrient and hydrologic stresses. There are many other useful indicators, ranging from the molecular to biotic community level in scale, that can serve as diagnostic indicators of ecological, biogeochemical, and trophic change in response to these and other stresses. Readers are advised to consult EPA's-STAR's website for the Estuarine, Coastal and Great Lakes Ecological Ecological Indicators (EaGLE: <http://eagle.nrri.umn.edu/pubprojdescript.htm>).
- Assessment of sediments. Sediments contain a wealth of paleo-climate and paleo-sea level information for the past 10,000 years of coastal history. Recent paleo-sediment studies using indicators aimed at elucidating the history of cultural eutrophication of the Chesapeake Bay (Brush, 1984, 1986), and the Baltic Sea (Bianchi et al., 2000) are examples of the applicability of this approach.
- Aggregation of meteorological data on storm paths, winds, rainfall, and flooding to provide a quantitative context for large-scale storm events and consequent environmental perturbations.
- Assessment of effects of hydrologic, chemical, and sediment loading on biotic communities impacting production, nutrient cycling, finfish and shellfish habitats, including water column (planktonic), salt marsh, seagrass, and sediment habitats.
- Behavioral, physiological, and health responses of higher trophic levels (i.e. fish) to variation in water depth, salinity, temperature and dissolved oxygen.

A vital component of an effective and broadly utilized integrated assessment program is cooperation and coordination among state, federal, and private research and monitoring entities. The North Carolina 1999 hurricane experience proved that a strong working relationship among these entities was essential for sharing resources and expertise and utilizing research aimed at understanding and managing a large system impacted by interacting human and climatic forcing features. Cross-cutting, multi-disciplinary, multi-

agency approaches and analyses provide the necessary broad perspective that is needed to assess ecological change in a system that is simultaneously affected by human and economic, cultural activities and values.

Synthesis and modeling of watershed, water quality, habitat and fisheries effects of large storm events is a key component of an integrated assessment program and is an important tool for synthesizing information and providing options for environmental management. Extension of model predictions to cover a wide range of infrequent and extreme conditions and validation of those predictions is both a challenge to, and requirement of, an effective assessment program. In lieu of that, models become minimally applicable for understanding these macro-events. The challenge to simulating effects of large-scale events is to find ways to quickly integrate the results of various independent models to aid in scientific and management responses to these events.

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