

Executive Summary

The Atlantic Coast Ecological Indicators Consortium (ACE INC: www.aceinc.org), a component of the EPA-STAR Estuarine and Great Lakes Indicator Program (EaGLE), developed and tested broadly applicable, integrative indicators of ecological condition, integrity, and sustainability in four representative estuaries on the U.S. Atlantic coast. These estuaries encompass a range of hydrologic forcing and habitat types. Each has been impacted by human perturbations. All are highly sensitive to weather events and climatic variability. Included are the nation's two largest estuaries, Chesapeake Bay, MD/VA and Albemarle-Pamlico Sound, NC. Also included are a relatively small suburban estuary in New England, the Parker River, site of an NSF Long-Term Ecosystem Research (LTER) program, and a river-dominated estuary in the southeast Atlantic Bight, the North River Inlet, SC. The sites are distinguished by three dominant types of primary producers that typify U.S. estuaries: intertidal marsh – Plum Island and North Inlet; plankton dominated – Chesapeake Bay and Pamlico Sound; and sea-grass-dominated portions of Chesapeake Bay and Pamlico Sound.

ACE INC developed indicators based on geomorphological, hydrodynamic, and bio-optical attributes, biological community structure, ecological and trophodynamic processes, and ecosystem structure to address the following objectives:

Objectives

- Develop and evaluate indicators of estuarine and coastal water quality and ecosystem health that can be used to assess present status and long-term trends;
- Test the applicability of indicators in estuaries that encompass a range of primary producer bases, bio-geographic provinces, chemistry, circulation, hydrology, and geomorphic characteristics;
- Resolve effects of climatic forcing on indicators to differentiate effects of anthropogenic and natural stresses on ecosystem function;
- Use remote sensing and observing systems to augment monitoring data and provide a regional to coast-wide context for indicators;
- Provide indicators to managers leading to their use for specific applications, including setting numerical water quality criteria.

We developed indicators based on analysis and modeling of extensive archival and newly-collected data, guided by the belief that understanding how strong climate forcing imparts variability to temperate estuarine ecosystems is required for development of indicators that are useful and broadly applicable. This view was strongly supported in evaluating plankton and fish indicators for the two large estuaries, Pamlico Sound and Chesapeake Bay, where variability imposed by climate can, at times, obscure and complicate changes traceable to human activities and stresses. Specific plankton/fish indicators we developed include:

- Phytoplankton biomass (chl-a); primary productivity, community composition
- Microbial pathogens

- Zooplankton abundance/distribution (and climatology)
- Biomass size spectra – phytoplankton to fish
- Residence time
- Dissolved oxygen

Phytoplankton biomass, primary productivity, and community composition reflect nutrient loading in land-margin ecosystems exemplified by Chesapeake Bay and Albemarle Pamlico Sound. We developed indicators of these expressions of phytoplankton based on *in-situ* and remotely sensed observations spanning two decades. Statistical models were developed to quantitatively separate trends from variability. These models are the key to recognizing chl-a as a sentinel indicator for nutrient over-enrichment. Substantive progress was made to develop chl-a as a water-quality indicator in Chesapeake Bay, the Neuse River Estuary and Pamlico Sound. The chl-a criteria have been expanded by ACE INC scientists to support specific, numerical targets of acceptable concentrations (e.g., TMDLs). A product of ACE INC was extension of the time series of aircraft observations of chl-a and sea surface temperature (SST) in Chesapeake Bay to nearly two decades, providing highly resolved data to evaluate trends and responses to regulatory compliance.

Analyses of primary producers extended beyond chl-a to development of indicators that are major taxonomic groups based on concentrations of diagnostic photopigments in the Neuse River, Pamlico Sound, and Chesapeake Bay. High performance liquid chromatography (HPLC) quantified photopigment concentrations, and the computer program CHEMTAX was applied to reconstruct taxonomic composition from these concentrations. Indicators consisted of the proportions of total biomass (chl-a) represented by major taxonomic groups, expressed as time series and related to environmental variables for each system. Cell counts from monitoring confirmed the abundances of major taxa estimated using this method. We collected essential baseline data on photopigment indicators during ACE INC for a range of hydrologic conditions, supporting conclusions drawn from statistical analyses that climate was responsible for coincident forcing of biomass and composition.

We developed indicators of heterotrophic bacteria and viruses that are potential pathogens, such as *Enterococcus sp.* and *E. coli*, in ACE INC. Outbreaks of these forms are often associated with storm water runoff, sewage effluent, animal operations, and agriculture. The focus was on factors that influence the delivery, growth, fate, and transport of these species and others. Of particular interest were bacteria of the genus *Vibrio sp.* as they are native to estuaries and include *Vibrio vulnificus* that is highly pathogenic. Virus probes were developed as indicators of pathogenic bacterioplankton and bloom-forming phytoplankton species in the Neuse River Estuary. We used these indicators to assess ecosystem condition and to identify the occurrence of species with a potential to disrupt estuarine ecosystems.

We discovered that zooplankton populations and taxa are sensitive indicators of climate forcing in Chesapeake Bay. Abundance and distribution of two key species of estuarine copepods, *Acartia tonsa* and *Eurytemora affinis*, that are major prey of fish and consumers of phytoplankton, are indicators of contrasting climate conditions manifested as ‘wet’ and ‘dry’

years (*Eurytemora* and *Acartia* years, respectively). Interannual variability in freshwater flow is predictive of abundance and spatio-temporal distributions of these indicator species. Statistical models evaluating effects of environmental factors and predominant weather patterns on zooplankton abundance developed by ACE INC have broad applicability to other estuaries where these common species reside.

Biomass size spectra (BSS) indicators spanning trophic levels from phytoplankton to fish delineate the abundance and distribution of organisms by size class and are broadly indicative of ecosystem structure and food-web relationships. We quantified BSS across trophic levels, developed statistical models of the spectra, and evaluated statistical properties as indicators of the structure and health of biological communities. Overall, BSS for Chesapeake Bay resembled those expected in unstressed aquatic communities, but specific regional-seasonal analysis indicated departures from spectral properties of a healthy ecosystem. Spectral properties were particularly effective in characterizing stressed conditions in mid-Chesapeake Bay during summer, corresponding to the season and region where deleterious water quality conditions, e.g., hypoxia and anoxia, prevail. Application of BSS may be most useful as decadal-scale indicators of the status and trends of estuarine biological communities.

Large-scale relationships between nitrogen export and residence time guided development of physical indicators to capture flushing characteristics of estuaries. We combined computational and modeling approaches to estimate residence times in several tributaries of Chesapeake Bay and the Neuse R. Estuary that encompass a range of geometries. Flushing times are sensitive to highly variable physical attributes of the systems including stratification, vertical exchange, and horizontal advection. Residence time is responsive to climate forcing on annual to interannual time scales and is largely driven by freshwater flow. This indicator is also applicable to other estuaries, provided appropriate data are collected to drive models. We also explored high-frequency variations in dissolved oxygen during Hurricane Isabel in September 2003. Isabel de-stratified the Bay leading to rapid ventilation of the lower layer and injecting significant nutrients into the surface layer, resulting in an unprecedented fall bloom. This event accentuated the need for highly resolved, continuous measurements to augment relatively infrequent monitoring of dissolved oxygen if it is to be used as an indicator.

Indicators were developed to evaluate and describe the status of seagrass communities and productivity for U.S. Atlantic Coast estuaries. Two primary indicators were developed; the first focused on habitat suitability, and the second on plant responses:

- Bio-optical model
- Light-limitation stress

The bio-optical model, developed in a two-year collaboration with the EPA EaGLe Atlantic Slope Consortium (ASC), uses water-quality data on bio-optically active constituents, including chl-a, total suspended solids (TSS), and chromophoric dissolved organic matter (CDOM), to compute the habitat suitability for seagrass based on the availability of light at a target depth. This tool is being developed into a software application for researchers and managers to determine causes of seagrass decline and to define strategies to improve water quality. It has been adopted as one of several water quality criteria in Chesapeake Bay focused on

restoration of submerged aquatic vegetation (SAV). A separate set of indicators was developed to quantify light-limitation stress wherein plant responses were characterized using morphological, physiological, and remote-sensing metrics. Application of these indicators to other sites would require quantification of regional differences of bio-optical properties that would affect calibration of the bio-optical model require quantification affect calibration of the bio-optical model. The methodology appears robust and implementation of this indicator in Chesapeake Bay may lead to its broader use at the national level. Useful indicators of light-limitation stress were developed for both a temperate species and a tropical species of sea-grass and proved applicable to both.

Coastal wetlands indicators focused on development of geomorphological metrics at a scale suitable for remote sensing, i.e. landscapes, and on physiological indicators at the scale of whole plants and single leaves. These indicators included:

- Marsh elevation relative to tidal elevation
- Bioassays of optimal elevation

In coastal wetlands, vertical elevation relative to tidal amplitude is a critical measure, affecting productivity and resiliency to storms and rising sea level. ACE INC results support the novel concept that resiliency or stability can be quantified by computing the frequency distribution of marsh elevation relative to tidal elevations. The distributions are of three types: (1) skewed against the lower vertical limit of the vegetation, which is characteristic of an ecosystem with little or no resiliency; (2) skewed against the upper vertical limit, signifying greatest resiliency; or (3) normally distributed in the middle of the species' range, indicating a system with moderate resilience, possibly in transition. This indicator of resilience can be obtained over large regions using remotely sensed LIDAR data paired with classified, high spatial resolution imagery such as ADAR to define plant community boundaries. We took this approach in the North Inlet salt marsh in South Carolina dominated by *Spartina alterniflora* using imagery classified using artificial neural network methods. The distribution of elevations of this salt marsh was statistically normal, which suggests that the marshes in this site have not kept up with sea-level rise during the last two decades. This indicator is applicable to any region to identify areas at risk of massive loss of wetlands, indicating where pre-emptive management could prevent losses due to erosion and rising sea level.

Indicators of the maximum, minimum, and optimum elevations of marsh vegetation were developed in ACE INC using in-situ bioassays. These bioassays consisted of a series of PVC pipes arranged vertically in rows in a terraced pattern, filled with sediment, and planted with the appropriate plant species. Growth and physiological properties of the plants respond to differences in 'hydroperiod'. Sensitivity of plants to differences in relative elevation and changes in sea level depends on tidal amplitude. The marsh vegetation of 'microtidal' estuaries exemplified by the U.S. Gulf Coast proved particularly sensitive to small changes in mean sea level. We also found above-ground and below-ground plant biomass respond differently to hydroperiod. Below-ground biomass was greatest when plants grew near the top of the tidal frame (near high tide), whereas above-ground biomass was greatest when the plants were lower in the tidal frame. This new indicator can be used to establish conditions for growth of

vegetation in coastal wetlands in any region, and complements the remote sensing application directed at elevation.

In summary, ACE INC has developed and applied quantitative indicators that are broadly applicable to the nation's estuaries. We have particularly addressed how climate forcing imposes high variability on candidate indicators. Quantitative analyses of ecosystem responses to climate are essential to distinguish change from variability, an essential step before instituting management measures. A wide range of candidate indicators was developed, ranging from physical characterizations of large ecosystems using residence time to explain differences among systems, biotic indicators including bulk properties, taxonomic properties, rates, size spectra, coupled bio-optical and physiological indicators of seagrass communities, and salt marsh indicators responsive to sea level change. Remote sensing was an integral part of ACE INC indicator development to "scale up" to ecosystem- and regional-level assessments of key biotic resources (e.g., phytoplankton, marsh vegetation, and seagrass). Our indicators are readily applied in other estuaries and potentially address both research and management needs. We have fostered collaborations with resource managers who are using our indicators in developing numerical criteria to promote joint development, evaluation, and implementation of specific indicators, particularly those to characterize and evaluate water quality. Predictive capabilities developed in ACE INC to characterize ecosystem responses to climate forcing have significantly enhanced our understanding of land-margin ecosystems and their sensitivity to dominant meteorological patterns. This new understanding is especially relevant as we are experiencing a period of elevated hurricane activity in the Atlantic and Gulf of Mexico coastal regions.