The Chesapeake Bay-Mid-Atlantic Bight (CMAB): A Proposed NACP Coastal Ocean Field Intensive Site

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December 3, 2003

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Intensive field experiments within several carefully selected coastal ocean regions are essential for improving our understanding of C fluxes and inventories throughout North America and the world. The potentially large fluxes of carbon, production and carbon sequestration in the coastal ocean underscore the significance of the coastal ocean to the global carbon cycle. Globally, rivers export ~0.43 Pg organic carbon yr^{-1} (Schlünz & Schneider 2000; Ludwig et al. 1996) and ~0.4 Pg inorganic carbon yr^{-1} to the ocean (McKee 2003 & refs therein). The coastal ocean accounts for >20% (~9 Pg C yr^{-1}) of the ocean's primary production (Knauer 1993). Burial of organic carbon within coastal sediments sequesters ~0.1 Pg C yr^{-1} (Schlünz & Schneider 2000). An array of measurement and modelling approaches will be needed to achieve the objectives of the NACP. Developing carbon budgets for coastal ocean regions will require high resolution observations from ships, moorings, aircraft and satellites as well as integrated modelling techniques. Although we support the establishment of multiple coastal ocean domains such as the Mississippi River continental margin, we propose that the Chesapeake Bay and the adjacent coastal ocean margin would comprise an excellent site for NACP intensive field experiments. The complex biogeochemical processes and exchanges taking place within the largest estuary in the U.S. and across the extensive shelf and slope waters adjacent to the bay along with the massive anthropogenic alteration in land use, industrialization, and urbanization combine to provide an ideal setting to test key hypotheses, evaluate methodological approaches, and address issues that are critical to the overall NACP. Additional consideration is drawn from the situation of the site at the end of the across-continent advection of air masses with terrestrial contributions both anthropogenic and natural, its pronounced seasonal changes in both terrestrial and marine environments, and the effects of strong episodic weather events such as hurricanes and northeasters.

The proposed Chesapeake Bay-Mid-Atlantic Bight (CMAB) region (Fig. 1) has been the site of a number of field studies both past and present that can be utilized along with an array of additional field programs, refinement in methodology and improved modelling that are more focused on resolving carbon-specific questions facing the NACP. These additional activities are required due to the very complex nature of the CMAB site which contains varied land use, dynamic circulation patterns, lengthy residence times, altered sedimentation processes, multiple water mass types, and variable meteorology that have not to date been satisfactorily encompassed by previous or contemporary field programs and models. A long range objective of an intensive NACP study in the CMAB should be to put into place the capability to establish, track, and continue our understanding of the carbon-related processes and net export and distribution within the CMAB without the need for continuous high intensity field programs. This will require strategic planning for where ship cruises, moorings, and aircraft observations are essential and in particular will require considerable refinement of approaches in satellite remote sensing technology in particular if future advantage is to be derived from ocean color satellite (OCS) sensors. The primary goal of this field intensive program is to distinguish the impacts of seasonal, interannual and decadal climate variability, including ocean dynamics and river discharge, on the regional carbon inventories, fluxes and biogeochemical processes that could be scaled-up to continental carbon budgets.

Background

Estuaries along the Atlantic coast of the U.S. and throughout the world have been heavily impacted over the past several centuries from human activity such as deforestation, expansion of agriculture and industry, overfishing and urbanization of watersheds. These changes have ramifications for production, processing, transport, and fate of carbon in estuaries and adjacent waters of the coastal margin. Anthropogenic perturbations have resulted in increased land erosion, higher sediment loads in rivers, inputs of heavy metals and organic contaminants, eutrophication and increased hypoxia/anoxia within estuaries such as Chesapeake Bay (Cooper & Brush 1991; 1993). As a result, estuaries such as Chesapeake Bay have experienced a dramatic ecological shift from benthic based ecosystems dominated by submerged aquatic vegetation and oyster reefs to planktonic ecosystems which are dominated by phytoplankton (Cooper & Brush 1993; Harding & Perry 1997). Historical and recent changes in the

Chesapeake Bay ecosystem and its watershed have affected sources and sinks of carbon with ramifications for delivery of dissolved and particulate materials to the coastal margin. Deforestation cleared over 80% of the land surrounding the bay by the mid-19th century. Post-World War II increases in human population, fertilizer applications, atmospheric deposition, and animal husbandry further contributed to increased nutrient inputs that stimulated autochthonous production by phytoplankton. Furthermore, water column stratification and microbial decomposition of extensive algal blooms produce seasonal bottom water hypoxia/anoxia (in late spring and summer) in mid-bay waters of Chesapeake Bay (Smith et al. 1992). Migration of the oxic/anoxic boundary to the water column influences the amount of carbon preserved within the sedimentary record. Zimmerman and Canuel (2000) observed an increase in organic matter preserved within mid-bay sediments of Chesapeake Bay during the 20th century. The sedimentary record reveals an almost five-fold increase in sediment accumulation between pre-colonization and the modern bay (Bratton et al. 2003). Remobilized fossil carbon of terrestrial origin accounts for some of the increase, but over-enrichment has accelerated in the last 50 years, significantly affecting autochthonous production. Climate variability also drives seasonal, interannual, and multi-decadal fluctuations of freshwater flow and has a major impact on carbon processing and export.

Mid-Atlantic terrestrial ecosystem

The Chesapeake Bay lies totally within the Atlantic Coastal Plain. Its watershed includes parts of the Piedmont and the Appalachian mountain ranges (Fig. 2). These ecosystems are primarily temperate mixed deciduous (oak, hickory, beech) and pine forests (60% of the area within the watershed), although agriculture (28.5%), urban areas (3.6%; with a population >15 million) and wetlands (2.6%) are important components. Forested and tidal wetlands, dominated by nonwoody or herbaceous vegetation, are the two main types of wetlands found in the Bay watershed. Since its formation, the Bay's shores have undergone constant modification by erosion, transport and deposition of sediments. In this process, areas of strong relief, like peninsulas and headlands, are eroded and smoothed by currents and tides, and the materials are deposited in other parts of the Bay. Wetlands along shorelines are retreating inland as sea level rises. Many of the islands that existed in the Bay during colonial times are now submerged.

Mid-Atlantic marine environment

Chesapeake Bay is the largest and most productive estuary in the U.S. The drainage basin of the Bay (171,990 km^2) extends from New York to Virginia (Fig. 2). Chesapeake Bay discharges more freshwater (mean annual discharge of 2280 m^3 s^{-1}; 71.9 km^3 yr^{-1}; Schubel and Pritchard 1986) than any other river/estuary system along the U.S. Atlantic coast. Five major rivers, the Susquehanna, Potomac, Rappahannock, York and James, provide almost 90 percent of the freshwater to the Bay. The Susqhehanna River, which flows into the head of Chesapeake Bay, contributes about half of the total freshwater discharge within the estuary. Chesapeake Bay contributes about half the freshwater that flows into the Mid-Atlantic Bight (MAB), which extends from Cape Cod, Massachusetts to Cape Hatteras, North Carolina. Saline waters generally enter the Chesapeake Bay Mid-Atlantic Bight (CMAB) through the along-shore southerly flow of shelf waters from the northern and central regions of the MAB. During winter and early spring northerly winds (blowing to the south) and the along-shore current force the Chesapeake Bay plume to flow southward along the coast (Verity et al. 2002). As winds reverse later in spring the southerly along-shore flow weakens, and the Chesapeake Bay plume broadens and flows offshore, primarily to the south and east. This permits the surface heat flux to strengthen the water column stratification (Verity et al. 2002). At this point, saline waters from the South Atlantic Bight and the Gulf Stream also flow into the CMAB.

Autochthonous production of particulate organic carbon (POC) in Chesapeake Bay and the coastal margin is dominated by phytoplankton. A spring bloom consisting of large, centric diatoms develops on the coastal margin in March to April, and in the mid- to lower Bay from April to May. Diatoms support annual peaks of phytoplankton biomass that reach integrated, water-column *chl a* 0.5-1 g C m^{-2} (Malone et al. 1988; Harding et al. 1999). The magnitude of freshwater flow carrying nutrients and suspended particulate matter regulates the timing, position and magnitude of the spring bloom in the Bay proper by modulating the interplay of light- and nutrient- limitation along the salinity gradient (cf. Fisher et al. 1988; Harding et al. 2002). The lower Bay and coastal margin are highly sensitive to nutrient inputs, particularly N, expressed both as historical increases of *chl a* since World War II, and seasonal/ interannual increases in *chl a* and autochthonous production of POC in years of high freshwater flow (Harding 1994; Harding & Perry 1997). Mean, annual *chl a* in the lower Bay is currently ~5 mg m^{-3}, representing at least a doubling during the last 50 years, and primary production in the lower Bay and shelf is >250 g C m^{-2} yr^{-1} (Harding et al. 2002). POC export, stimulated by diatom production in the mid- to lower Bay and coastal margin, occurs when grazer populations are not well developed, and the spring bloom biomass and suspended sediments are exported from the surface mixed layer.

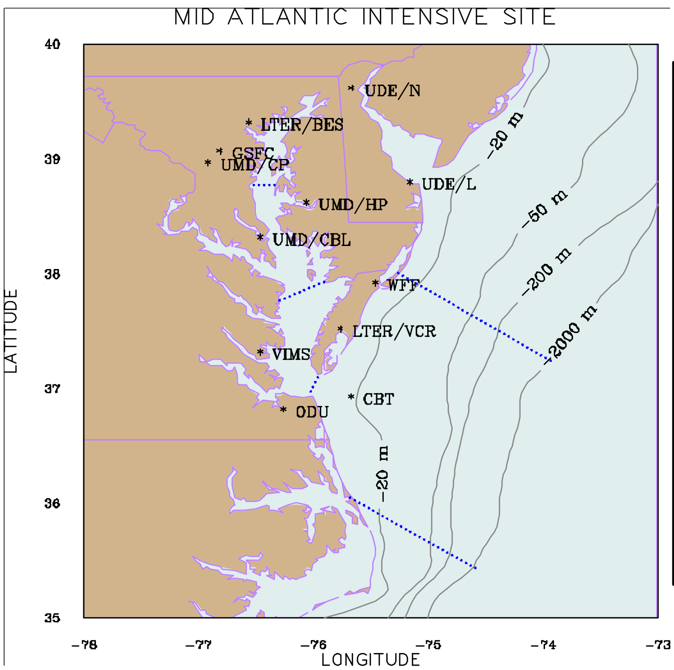

Fig. 1. Proposed Chesapeake Bay-Mid-Atlantic Bight NACP Intensive field site. See Appendix for acronyms.

Fig. 2. Chesapeake Bay watershed.

Major field studies conducted over the past 2 decades in Chesapeake Bay (e.g., LMER [Land Margin Ecosystem Research], TIES [Trophic Interaction Ecosystem Studies], LTER [Long-Term Ecological Research programs]) and the Mid-Atlantic Bight offer a wealth of information on the physics, ecology and biogeochemical processes of this region. The Shelf Edge Exchange Processes experiments (SEEP I & II) and the Ocean Margins Program (OMP) in particular focused on carbon flow within the MAB (summarized by Verity et al. 2002). From the SEEP experiments, primary production in the MAB was estimated at 7.5×10^{13} g C yr^{-1} (Falkowski et al. 1994). Falkowski et al. (1988) and Anderson et al. (1994) estimated that <20% of the spring bloom (<1% of annual primary production; ~5×10^{12} g C yr^{-1}; Biscaye et al. 1994) from MAB shelf waters was exported off the shelf as POC. As part of OMP, Vlahos et al. (2002) estimated the inventory of dissolved organic carbon (DOC), which was not measured in the SEEP experiments, at ~6×10^{12} g C with an export flux of ~19×10^{12} g C yr^{-1} from the MAB. However, flux estimates of carbon (organic and inorganic) from Chesapeake Bay to the MAB are rather limited. The MAB appears to be a modest sink for atmospheric CO_2, on the order of ~1×10^{6} g C yr^{-1}, with ~70% of the sink occurring on the mid-shelf region (DeGrandpre et al. 2002). With the exception of winter measurements, the mid-shelf measurements used by DeGrandpre et al. (2002) to estimate the atmospheric CO_2 sink are based on a local study off the coast of New Jersey (Boehme et al. 1998). Relatively few air-sea CO_2 gas exchange measurements have been made in Chesapeake Bay. Raymond et al. (2000)

determined that the York River estuary was a net source of CO_2 to the atmosphere. On a transect from the Chesapeake Bay mouth to Bermuda during early autumn, Bates and Hansell (1999) observed supersaturated CO_2 levels in surface waters near the bay mouth, slightly undersaturated within a small region of the bay plume and generally saturated levels throughout the MAB. Although these programs and numerous field studies provide valuable insight into carbon flow within the CMAB, the temporal and spatial sampling frequency of these previous measurements are insufficient to derive the accuracy and precision in carbon balances necessary to achieve the objectives of the NACP.

Rationale for the CMAB coastal ocean domain

The Chesapeake Bay-Mid-Atlantic Bight domain offers many advantages. The NACP teams that will work on the CMAB field site can leverage off existing activities and expertise. Numerous coastal and oceanographic institutions and associated resources (facilities, ships, aircrafts, moorings, etc.) are located on or near CMAB (Fig. 1). Current and past research activities within CMAB provide a foundation on which to build an intensive field program for the development of regional scale carbon budgets and also provide the initial baseline data for evaluating decadal changes in carbon flow. Chesapeake Bay is the largest and most productive estuary in the U.S. and contributes half the freshwater discharge entering the MAB. The Chesapeake basin drains a large area of northern temperate forests ($1x10^5$ km^2), which purportedly account for a significant fraction of the atmospheric CO_2 land sink (Fan et al. 1998; Schimel et al. 2001), although with some debate (e.g., Fung 2000; Bousquet et al. 2000). One significant unknown is the amount of terrestrial carbon entering estuaries such as Chesapeake Bay and the fate of this carbon. How much of this terrestrial carbon is remineralized to CO_2, buried in sediments, or exported to the ocean as DOC or POC? The higher flux of particles to continental slope sediments in the southern MAB (3-4 orders of magnitude greater) compared to the northern MAB (Biscaye and Anderson 1994) indicates that slope sediments within CMAB may represent a region of considerable carbon burial. A significant portion of shelf waters from the MAB are advected offshore from the region between Cape Hatteras and Chesapeake Bay (Verity et al. 2002), which suggests that this region is an important site for carbon export to the open ocean.

Suggestions on experimental plan

For the purpose of developing a regional carbon budget, the Chesapeake Bay is divided into 3 sections: 1) upper bay (oligohaline region from the Susquehanna River mouth to north of the Choptank River), 2) mid-bay (mesohaline region from the upper bay to south of the Potomac River), and 3) lower bay (polyhaline region) (Fig. 1). The adjacent Mid-Atlantic Bight (from ~36° to 38° N orthogonal to the 2000m isobath from the coast; Fig. 1) is also divided into 3 sections: inner shelf (<20m depth), outer shelf (20-200m depth), and continental slope (200-2000m depth). The major tasks for each of the 6 sections of the CMAB will be to measure the carbon inventories, fluxes, and transformations.

Carbon inventories: POC, DOC, sedimentary OC (SOC), pCO_2, dissolved and particulate inorganic carbon (DIC; PIC), CH_4, CO, terrestrial and autochthonous OC

Carbon fluxes: a) land/river-bay, b) air-sea, c) water-sediment, d) tidal wetlands-bay/ocean, e) bay-inner shelf, f) inner-outer shelf, g) outer shelf-continental slope, h) continental slope-abyssal ocean, i) CMAB-central MAB, and j) CMAB-South Atlantic Bight

Carbon Transformations: a) primary production, b) microbial remineralization, c) photo-oxidation, d) grazing, e) other physical/chemical processes, and f) other benthic processes

Long-term Field Measurements

Bay & Ocean – Monthly cruises should be conducted to collect discrete and underway samples on transects along the main-stem of Chesapeake Bay to the edge of the continental margin as well as lateral transects across the bay and along the shore of the coastal ocean. Samples should also be collected at the mouths of major tributaries to Chesapeake Bay. In addition to carbon components, other relevant measurements include wind speed, currents, salinity, temperature, density, dissolved oxygen, nutrients, *chl a*, HPLC pigments, dissolved and particulate organic nitrogen and phosphorus, alkalinity, pH, ocean optics, radiocarbon and stable (C, N and S) isotopes, total suspended solids, primary production (PP), community respiration, and bacterial production. Higher frequency measurements of key parameters will be made from autonomous in situ sensors on moorings, remote vehicles, aircrafts and satellites (see below). Biomarkers such as lignin phenols and lipids and stable isotope measurements can be used to quantify terrestrial and autochthonous POC and DOC. Development of in situ sensors is critical to reduce the dependency on ships for long-term monitoring.

Air-sea fluxes of CO_2 are an important component of the carbon budget in coastal regions; however, the magnitude and sign of the CO_2 flux appears to be highly variable (Crawford et al. 1993). Direct measurements are difficult, scarce and uncertain (Fairall et al. 2000; McGillis et al. 2001). Flux measurement by eddy correlation is the most direct method to determine CO_2 air-sea exchange. Eddy correlation measurements will be implemented at fixed sites where possible. In addition, eddy correlation measurements for CO_2 air-sea flux from aircraft are feasible with current instrumentation. Airborne flux measurement affords the potential to map fluxes over large regions of the ocean unconstrained by fixed measurement locations. This capability would be a great advantage for the NACP coastal budget intensives. Airborne eddy correlation is subject to uncertainties related to statistical flux determination (Lenschow & Kristensen 1985) and these measurements should be carefully intercompared to those from the fixed sites. Given confidence in the airborne methods, the fluxes over the study region can be mapped by a limited set of flights in the intensive phase. The eddy correlation fluxes will be used to determine the best parameterization for CO_2 fluxes based on bulk aerodynamic methods and these can be used in conjunction with the fixed sites for continuous monitoring and extension to larger scales. Airborne eddy correlation measurements of dimethyl sulfide (DMS) have been used to determine marine boundary-layer exchange processes (Stevens et al. 2003), and can be used to calculate air-sea surface exchange coefficients, which can be applied to CO_2. Thus, measurements of concentrations and fluxes of DMS from ships, fixed sites, and aircraft are highly desirable.

Land-Water interface – (see process studies) Over a gauged watershed measure precipitation, evapotranspiration, runoff, water chemistry, stream flow, vegetation type, structure (e.g. cover, leaf area index), soil data (texture, depth, carbon content, etc.) and topographic data. For croplands, crop type and cropping practice (fertilization, irrigation no-till, seasonal rotation schemes, etc.) is needed.

Intensive Process Studies

Bay & Ocean – Cruises for intensive process studies should occur in spring (during high river discharge and phytoplankton blooms), summer (high biological and photochemical activity), fall (low river discharge and sporadic phytoplankton blooms), and winter (low biological activity and high capacity for air-sea gas exchange). Process studies would occur at multiple sites within each of the bay and continental margin sections (Fig. 1). In addition to measurements listed as long-term measurements, other process-related measurements would include grazing activity, sedimentation, photo-oxidation of DOC, phytoplankton and zooplankton taxonomy, remineralization rates of POC and DOC, benthic studies (e.g. remineralization of SOC, gas fluxes [CO_2 & CH_4], PP in shallow areas) and other physical/chemical processes (e.g. flocculation, desorption, resuspension of sediments). Intensive studies should also examine the impact of tidal flow on carbon inventories, fluxes and transformations.

Land-Water interface – One component of this intensive study would be a relatively small (~20-30 km^2) gauged watershed on the Chesapeake to develop model and remote sensing techniques to compute carbon and other chemical transport from non-urban terrestrial ecosystems into the Bay. An example might be the head waters of the Rappahanock. The focus of this small intensive study is to characterize the runoff field and its chemistry as a function of land cover type, structure and change, soil type, spatial and temporal precipitation patterns, and topography. The characteristics of the watershed must be such that it is representative of watersheds on the Chesapeake, where accurate input data (precipitation, topography and soil properties) for a hydrological model can be obtained. The model(s) will compute the temporal and spatial runoff fields and total runoff. The chemistry of the streamflow as well as lateral transport within the watershed would also be measured. The final product of this intensive study would be developed and validated using remote sensing driven models to compute carbon transport from similar watersheds as a function of precipitation, topography, soils land cover and change. Remote sensing data would consist of aircraft lidar data for vegetation structure, as well as seasonally integrated land cover maps from Landsat or EO-1 ALI data. These could provide the data for estimating organic matter accumulation and removal, and susceptibility of specific areas to soil erosion and nutrient losses during severe weather events. Topography could be obtained from standard sources and combined with seasonally integrated land cover data in an appropriate hydrological runoff model to estimate carbon and nutrient transport from land to water. Locations of chicken farms must be known and treated as point sources for nitrogen and nutrient outflow, determined from flow patterns of local hydrology. A network of ground water lysimeters for chemistry, stream flow gauges, and monthly water samples are needed.

In Situ Autonomous Measurements

A long-term ocean observing system for both the Chesapeake Bay and coastal ocean regions of the MAB are essential for the success of the coastal ocean field intensive. The system would include current observational moorings such as the Chesapeake Bay Observing System (CBOS) and additional moorings. NOAA and NASA are developing a coastal ocean observation laboratory off the Delmarva Peninsula, which will have long-range Coastal Ocean Radar (CODAR), and an autonomous vehicle called the Ocean-Atmosphere Sensor Integration System (OASIS). OASIS will be remotely controlled and will collect data on the following ocean-atmosphere parameters: air temperature, surface wind velocity, relative humidity, atmospheric pressure, sea surface temperature, sea surface salinity, ADCP current profiles and phytoplankton fluorescence spectra. Additional sensors are in development for air-sea CO_2 flux, delta-pCO_2, alkalinity and nutrients.

Remote Sensing

Aircraft instrumented with laser spectrometers and passive hyperspectral spectroradiometers can play an important role in the intensive sampling within the CMAB site. The high speed of the aircraft (12–15X ship) can provide wide coverage of events that are otherwise not possible. Airborne laser spectrometers have shown excellent agreement with ship-derived measurements of phytoplankton biomass, CDOM fluorescence and absorption (Hoge et al. 1999; 2001), and sea surface temperature and are therefore surrogates for extending these measurements over wide areas. Moreover, recently published results using pump and probe LIDAR technology (Chekalyuk, et. al. 2000) have shown the potential for measuring phytoplankton physiology and primary productivity and recently for phytoplankton taxonomy to some useful level. The utilization of aircraft remote sensing in the CMAB is therefore viewed as a critical component to be strategically utilized surrounding ship experiments to extend surface layer measurements and between cruises to allow observation of intra-seasonal changes.

Ultimately, any cost effective solution to remotely sensing the CMAB will have to rely on satellite observations. Chlorophyll concentration, diffuse attenuation, photosynthetically available radiation, aerosol optical thickness, and a number of carbon related quantities, e.g., primary production, are operationally available from SeaWiFS, AQUA and TERRA MODIS, and eventually VIIRS. However, current OCS products are not sufficiently accurate within the inner shelf and estuarine regions for routine and reliable utilization, due to problems in sensor operation as the image is swept from land to the Chesapeake Bay and the inner shelf as well as poor performance of the product algorithms in the complex estuarine and inner shelf settings. Remote sensing of coastal areas with turbid waters and absorbing aerosols will require refined bio-optical and atmospheric correction algorithms. Thus, the refinement of current algorithms is a high priority of the NACP intensive in the CMAB. Noteworthy success in radiative transfer inversion of SeaWiFS reflectances in the MAB (Hoge et al. 2001) yields the absorption coefficient of chromophoric dissolved organic matter (CDOM). Using an MAB ship-derived CDOM-to-DOC algorithm (Vodacek et al. 1997), it has been recently demonstrated DOC retrievals very comparable to the Chesapeake-to-Bermuda ship values of Bates and Hansell (1999) are possible; thus strongly suggesting the potential of satellite quantification and temporal monitoring of the MAB coastal/shelf surface layer. The feasibility of airborne LIDAR mapping, monitoring and validation of the CDOM absorption coefficient has previously been demonstrated (Hoge et. al. 1999; 2001) concurrently with chlorophyll biomass. The development of a forward scattering coefficient algorithm would allow the POC to be retrieved from satellite reflectances, since POC is retrievable from the beam attenuation coefficient (Bishop 1999). Periodic underflights of OCS imagery with airborne laser spectroscopy and passive hyperspectral sensors to validate and improve OCS products are strongly recommended for the CMAB.

Modelling Techniques

Finite-difference 3D, high spatial resolution (<1km) coastal ocean circulation models can be developed to simulate the advective and diffusive processes along the coastal zone. The Regional Ocean Modeling System (ROMS) is presently configured to simulate the circulation processes along the entire coastal regions of the east and west coasts of the U.S. Freshwater and associated nutrient fluxes are prescribed using USGS data compiled at NASA for the time spanning 1950-2002. Additional model forcing fields use satellite and observational data for wind stress and heat fluxes at the surface. The circulation fields are used to analyze the heat and momentum budgets for the coastal regions of the U.S. Data assimilation capabilities are presently being tested.

Coupled models will need to be developed that link 3D circulation models, such as that described above, to a complete biogeochemical model for the coastal zone. Presently, the majority of these models are nitrogen-based and have simple model configurations (Phytoplankton-Nutrient-Zooplankton “PNZ”, Phytoplankton-Nutrient-Zooplankton-Detritus “PNZD”, etc). These models will need to be modified considerably in order to resolve the full carbon cycle system in coastal zones. In coastal regions, nitrogen and phosphate are intimately folded into carbon cycle dynamics. Also, both dissolved and particulate organic materials are important. Sources of nutrient inputs vary greatly in space, time and stoichiometry. For instance, fluvial sources have higher P:N ratios than atmospheric sources and the deposition and time evolution of these sources differ. In addition to this, benthic processes and unquantified sources of nutrients (groundwater) need to be addressed in the path to a fully developed biogeochemical model capable of addressing carbon cycle questions. In addition to this, the method used to characterize the inorganic carbon system should be carefully considered. In the global ocean modelling community, an agreement has been reached as to the manner in which the system equations are calculated. This standardized solution (Ocean Carbon-Cycle Model Intercomparison Project, OCMIP) is used to allow for direct intercomparison of the various model results being made by different modelling groups. A similar effort will need to be undertaken for the CO_2 system of equations appropriate for the coastal ocean.

Appendix

Figure 1 labels

CBT – Chesapeake Bay Tower
GSFC – NASA Goddard Space Flight Center
LTER/BES – Long Term Ecological Research network /Baltimore Ecosystem Study
LTER/VCR – Long Term Ecological Research network / Virginia Coast Reserve
ODU – Old Dominion University
UDE/N – University of Delaware Newark
UDE/L – University of Delaware College of Marine Studies at Lewes
UMD/CP – University of Maryland at College Park
UMD/CBL – University of Maryland Center for Environmental Science (UMCES)/ Chesapeake Biological Laboratory
UMD/HP - University of Maryland Center for Environmental Science/ Horn Point
VIMS – Virginia Institute of Marine Science

WFF – NASA GSFC Wallops Flight Facility

Other Chesapeake institutions:
ANSERC – Academy of Natural Sciences Estuarine Research Center (St. Leonard, MD)
SERC – Smithsonian Environmental Research Center (Edgewater, MD)

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