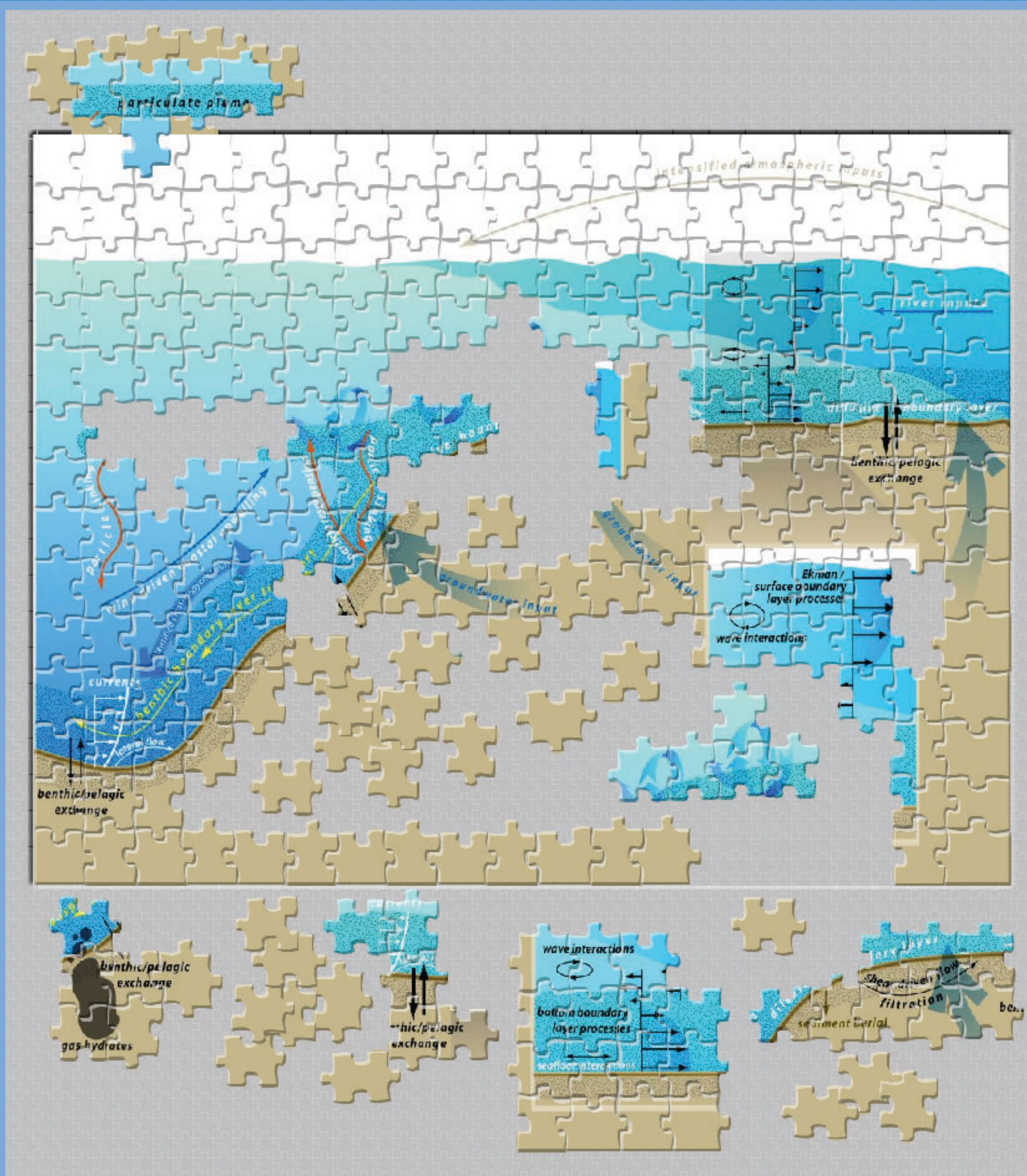
Coastal Benthic Exchange Dynamics



CoOP Report Number 10

October 2004

Clare Reimers, Carl Friedrichs, Brad Bebout, Peter Howd,
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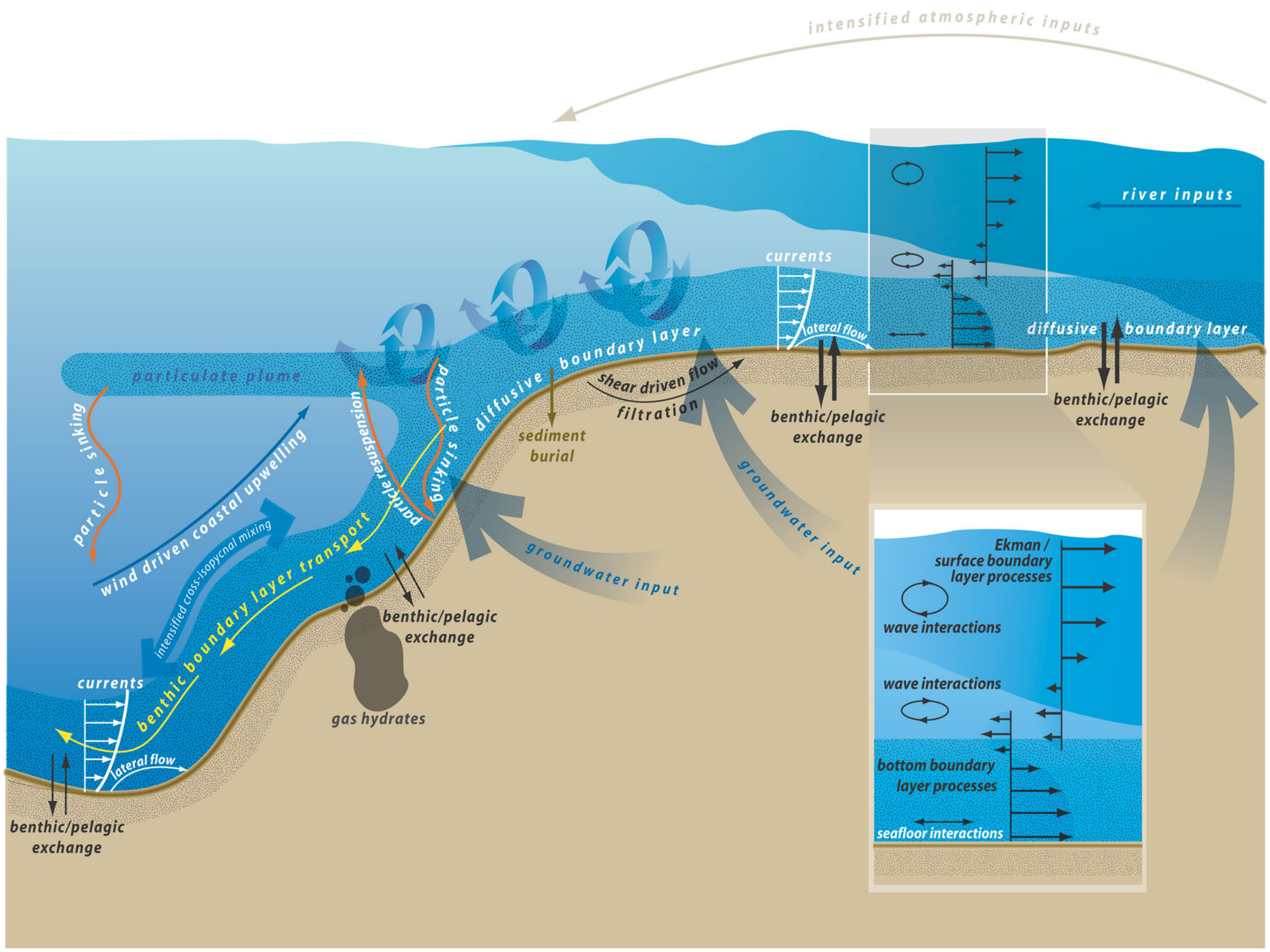
"The benthic boundary layer (BBL) constitutes those portions of sediment and water columns that are affected directly in the distribution of their properties and processes by the presence of the sediment - water interface." (Boudreau and Jørgensen 2001)



The CBED report is the result of an open workshop intended to engage scientists actively involved in the interdisciplinary study of the coastal benthos. Interaction with the seafloor is a controlling characteristic of coastal environments, resulting in unique and intensified processes that define the coastal ecosystem. A comprehensive understanding of the coastal BBL will not come from the study of isolated processes in this complex environment. Rather, the physics, geology, chemistry and biology must be interpreted holistically.

SkIO TR-04-01
Coastal Benthic Exchange Dynamics

Report on the CoOP CBED Workshop
5-7 April 2004
St. Petersburg FL

Clare Reimers, Carl Friedrichs,
Brad Bebout, Peter Howd, Markus Huettel,
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Coastal Ocean Processes (CoOP) Program Report Number 10

October 2004

Technical Report

Funding provided by the National Science Foundation under
Grant No. OCE-0301872.

This report should be cited as:
Skidaway Institute of Oceanography Technical Report TR-04-01.

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Executive Summary

Coastal benthic exchange dynamics are linked to a variety of marine environmental issues of increasing ecological, economic and societal importance. Changes in climate, sea level, storm frequency, nutrient inputs, fishing effort, and utilization of shelf mineral resources are altering seafloor habitats and benthic feedbacks to essential marine food webs. Unfortunately, due to the responsiveness of seafloor processes to a wide variety of periodically varying external factors including solar irradiance, tides, and waves, there is at present a lack of quantitative data for measuring change and assessing the health of coastal environments worldwide. This lack of information is especially acute when scientists or resource managers are asked to predict short- and long-term benthic reactions to natural episodic (e.g., storm) disturbances and anthropogenic impacts (e.g., trawl or dredge fishing).

As a first step towards evaluating the role of benthic processes in maintaining healthy coastal ecosystems and in transporting biological, chemical and geological materials to deeper marine regions, the Coastal Ocean Processes (CoOP) Program sponsored an open workshop to gather community input on the leading questions being posed by researchers interested in coastal benthic exchange. The Coastal Benthic Exchange Dynamics (CBED) workshop was held from April 5 - 7, 2004 in St. Petersburg, Florida, and attended by 67 participants representing 37 academic and research institutions, government agencies and laboratories and private industry. A total of nineteen coastal US states and the District of Columbia were represented. Participants also attended from Denmark, England, Wales and Brazil, showing that strong interest from international partners can be expected for a CBED initiative.

After working groups discussed external factors that can force variation in benthic exchange processes on different time scales in the benthic boundary layer (BBL), the participants advocated new research focusing on the importance of:

Physical Disturbance in establishing, maintaining or altering benthic habitats;

Benthic - Water Column Exchange for understanding coastal biogeochemical cycles especially in regions of permeable sediments that may exhibit porewater advection and groundwater fluxes;

Benthic Community and Biological Activity as both a means to characterize habitats and a theme recognizing biological agents that affect material transport and transformation processes; and

Mechanistic Models of the BBL capable of predicting mass transfers and transformations associated with physical and chemical gradients across the sediment - water interface, while also representing processes at disparate scales that can be coupled or nested to describe ecosystem-wide responses.

There was strong consensus that timing is ideal for an integrated, interdisciplinary research initiative focused on linkages between external meteorological and hydrological forces and processes of particle and solute transformation, transport, and exchange in the coastal ocean BBL. The seafloor BBL was recognized as an integral component of coastal ecosystems, exerting considerable control over the biogeochemical and physical dynamics and biological communities that shape these environments. Furthermore, because seafloor - water column interactions are important in all coastal settings, BBL studies conducted in a number of contrasting regions of the US continental shelf were recognized as necessary before CoOP Program research can be considered complete and ready to provide a broad synthesis.

Additional scientific goals and recommendations endorsed during the CBED Workshop appear throughout this report. We highlight the major recommendations.

Future interdisciplinary projects should quantify the dynamics of the BBL system and its response, in the widest sense, to different forms of both natural and anthropogenic disturbance. Because BBL dynamics will vary with environmental characteristics such as bathymetry, sediment grain-size and permeability, studies should be distributed among contrasting coastal regions. Specific research examples include the need to further examine relationships among flow fields, entrainment, deposition and sediment biogeochemical processes in cohesive sediments, and the need to characterize the dynamics of porewater advection, filtration and particle mixing in coarse-grained sediments. Across diverse seafloor habitats, factors causing porewater and particle transport such as waves, groundwater flow, macrofaunal and meiofaunal abundance and composition as well as mobile fishing gear, need to be studied.

Because each measurement technique is associated with a limited range of spatial and temporal measurement scales, a multiplatform, holistic approach should be adopted in which ships, satellites, observatory moorings, autonomous vehicles, and other technologies are employed to optimize the range of space and time scales observed. Continued development of BBL sensors and deployment platforms is recommended, especially for those techniques that permit non-intrusive determinations of organism activities and populations, and seafloor solute and particulate exchange. Particularly promising, non-intrusive sampling techniques include acoustic scanning and eddy correlation with high-frequency concentration measurements of suspended and dissolved constituents.

Fluxes of oxidants, nutrients, essential trace metals and organic matter that determine relative roles of benthic and pelagic subsystems must be studied at key horizons, and in concert, to advance understanding of contrasting coastal ecosystems. The top of the Ekman layer, the sediment - water interface, and the base of the mixing zone are three critical horizons within the coastal ocean. Given the potential importance of benthic productivity in many coastal regions, projects that promise to establish new means to make widespread benthic productivity measurements as well as means to determine other critical fluxes in time-series mode should be supported.

Structure and function of BBL microbial communities catalyzing organic matter decomposition must be better understood, ideally across gradients in sediment characteristics, organic-matter loading, temperature, and other relevant environmental parameters. Continued development of molecular biological techniques for use in sediments is especially encouraged.

Experimental studies should be designed to improve understanding of process dependence on measurable system variables such as temperature, light, flow, particle concentration, wave height and ripple spacing, leading to reliable model parameterizations.

Comprehensive interdisciplinary mechanistic BBL models bridging the sediment - water interface are needed for incorporation into full ecosystem models that include larger-scale dynamics and link coastal models to global carbon and nutrient models. These models should represent processes at disparate scales, in a manner that is standardized (i.e., with a uniform set of exchange variables and interpolators), distributed (i.e., consisting of independent modules communicating through a central server), and coupled (i.e., including multi-model feedback with standard interpolators).

I.A. Workshop Rationale

The exchange of carbon and nutrients between the seafloor and the overlying water column of the coastal ocean has been implicated in sustaining high rates of biological productivity, maintaining abundant fisheries production, and exporting food and energy to the deep ocean. At the same time, scientists and ecosystem managers recognize that seafloor habitats are physiographically heterogeneous, so that the approaches used and the scales studied need to vary from region to region. Seventy percent of the global continental shelf has been classified as geologically relict, suggesting that most shelf deposits comprise non-accumulating sands (Fig. I.A.1). Other shallow-water environments are more varied and include deltas, rocky banks, reefs, and emergent marine terraces that capture ephemeral mud layers (Fig. I.A.2). Each of these habitat types is subject to unique, physically and biologically-forced solute and particulate exchange processes that may vary diurnally, seasonally and as a function of climatic steps or cycles. In recent years, some coastal regions have experienced changes in significant wave height and storm intensities that may be linked to global warming (Allan and Komar, 2000; Fig. I.A.3). Coastal regions have also been heavily impacted by altered fresh water inputs including groundwater-derived nutrient fluxes that can contribute to eutrophication and hypoxia. Concurrently, mobile fishing gear impacts are a form of ecological disturbance that is not evenly distributed. For example, all areas of the broad fishing grounds of the Gulf of Mexico and New England regions are trawled or dredged several times per year while other areas may be rarely fished (Steele et al. 2002; Table I.A.1). These regionally managed human activities can make it difficult to resolve the effects of natural sources of disturbance.

The Coastal Ocean Processes (CoOP) Program recognized at inception that comprehensive interdisciplinary studies of benthic processes would be needed to close shelf budgets of carbon, nitrogen and trace elements and to understand the particle transformations leading to the chemical and geological character of the seabed (Brink et al. 1990, 1992). Physical processes that drive benthic exchange include

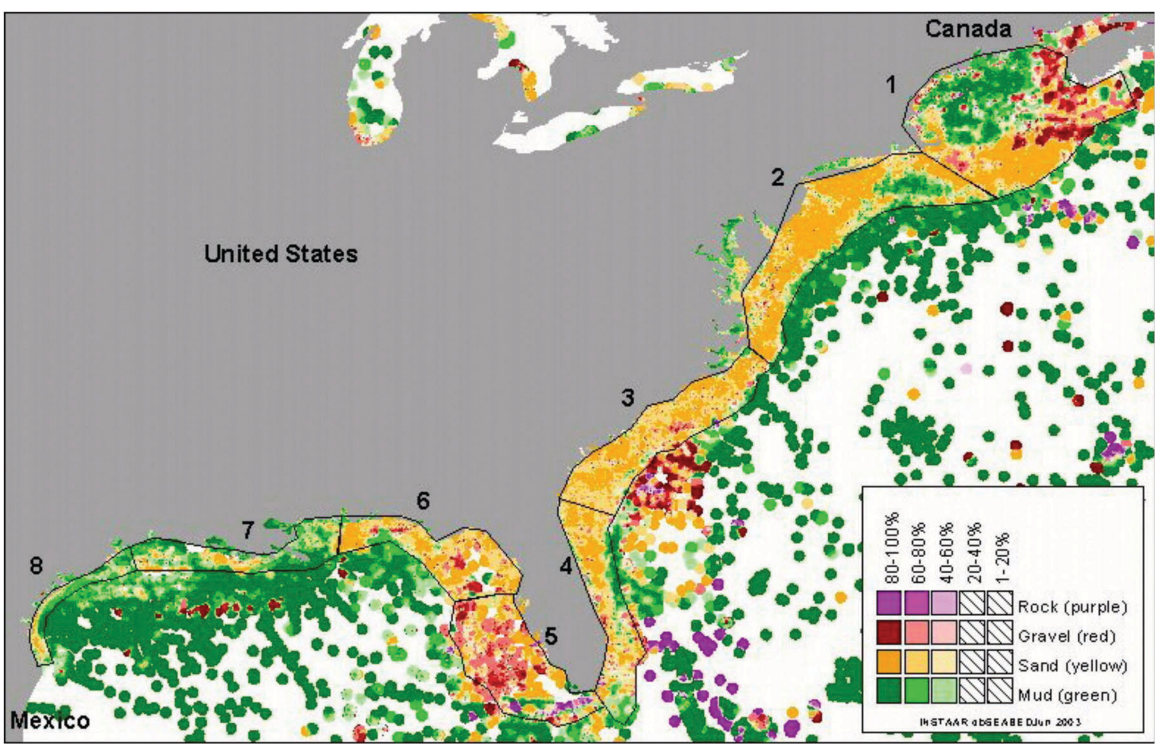


Figure I.A.1. Map showing textural distributions of sediments in eight regions of the Eastern US continental shelf. Like much of the global shelf, geologically relict sand deposits dominate and may act as filtering beds. (provided by P. Wiberg and C. Jenkins from dbSEABED).

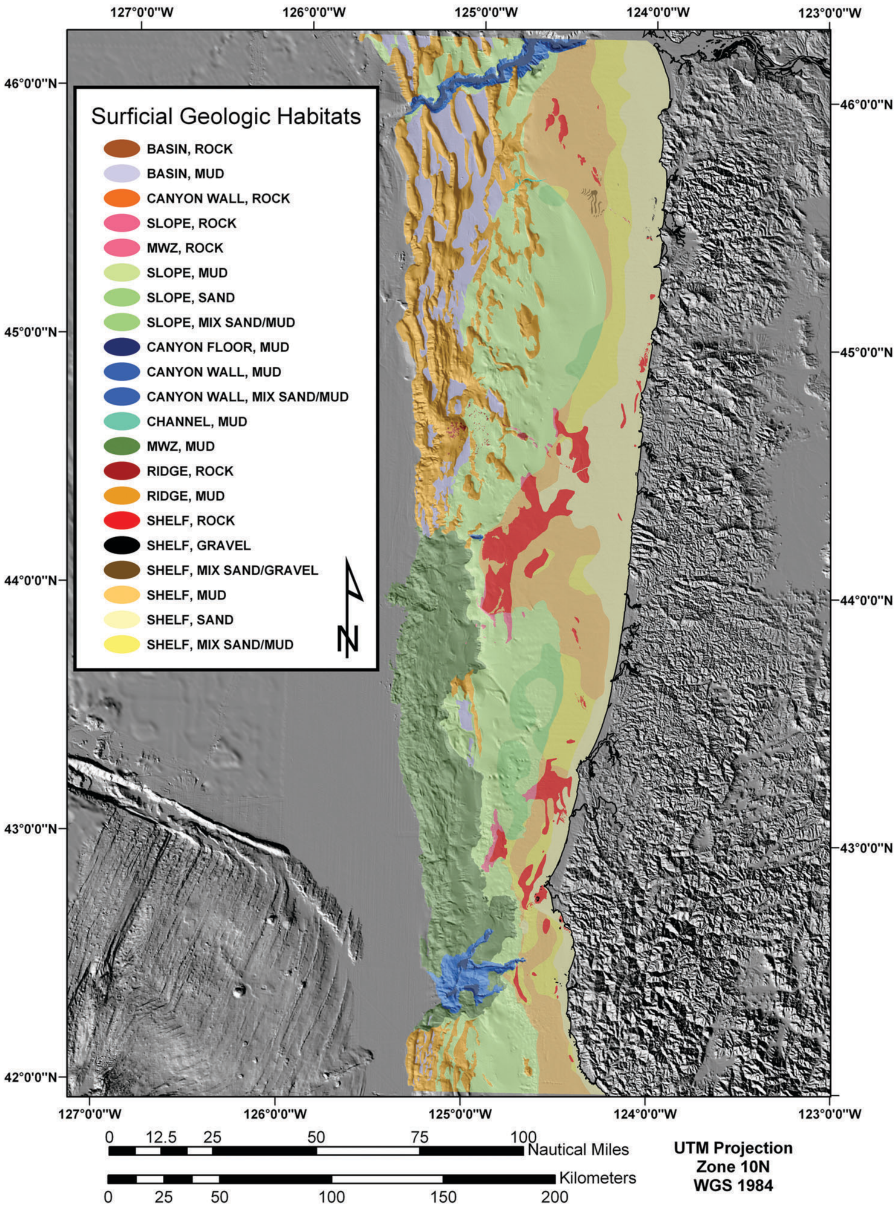


Figure I.A.2. Map of surficial geologic habitats on the Oregon Margin. This region exhibits a high degree of seafloor heterogeneity related to local river inputs, tectonics and physical conditions. Figure provided courtesy of C Goldfinger (OSU).

shear-driven flows associated with bottom currents, advective and dispersive exchange due to pressure variations created by the passage of gravity waves, and migration of bedforms. Resuspension driven by widely variable conditions of turbulence can regulate bottom turbidity, light attenuation and benthic primary production. Sand filtration and the capture of small particulates within sediments may couple peak periods of water-column productivity with benthic microbial metabolism. All of these processes may change in character and importance depending on the sequence and magnitude of meteorologically-generated events such as coastal upwelling or storms.

The biological processes that affect solute and particulate transport from surficial coastal deposits and rocky banks may be structured by physical and chemical factors, geological substrates and topography. Benthic microbial populations can influence solute and particle transport with the development of bacterial mats or the armoring of surficial sediments by the secretions of benthic diatoms. Many benthic

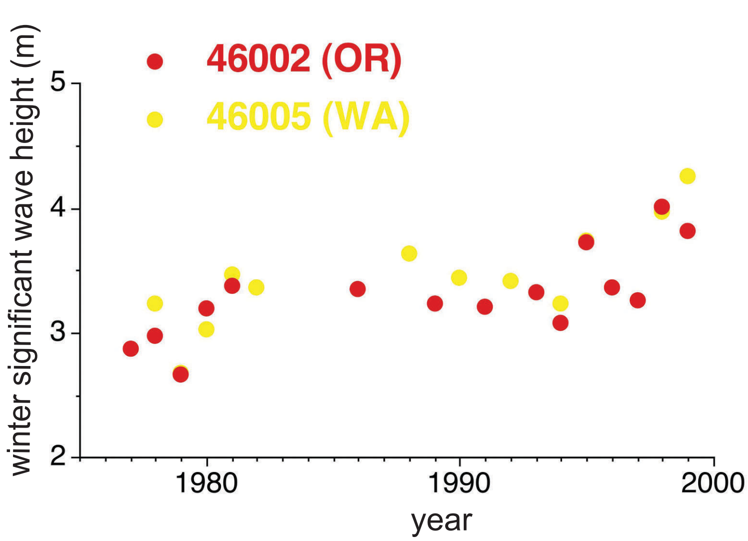


Figure I.A.3. Record of significant wave heights off Oregon and Washington suggests a trend of increasing storm intensities. From Allan and Komar (2000).

Table I.A.1. Estimated Fishing Density by Region (from Steele et al. 2002).

region	total area fished (TAF, nm²)	total tows	swept area (nm²)	% TAF swept/yr	gear type[i]	observed years
New England[a]	40,168	NA	46,193	115	BT	1993
Mid-Atlantic[b]	31,007	NA	11,925	38	BT	1985
Southeast US	NA	NA	NA	NA	NA	NA
Gulf of Mexico[c]	78,629	902,885	200,588	255	ST	1998-1999
Alaska						
Bering Sea[d]	27,632	17,688	15,274	57	BT	1998-2000
Aleutian Islands[e]	5,168	3,650	2,974	58	BT	1998-2000
Gulf of Alaska[f]	11,320	8,640	5,120	45	BT	1998-2000
West Coast						
California[g]	20,671	15,535	6,902	33	BT	1994-1996
Oregon & Washington[g]	26,744	11,487	5,104	19	BT	1998-1999
Oregon & Washington[h]	10,253	10,108	2,246	22	ST	1997-1999
Oregon & Washington	26,744	21,595	7,350	27	BT & ST	1997-1999

[a]Data from Pilskaln et al. (1998) and NMFS data from 1991-1993.
[b]Data from Churchill (1989) and NMFS data from 1991-1993.
[c]Assumes 5 tows/fishing day, door spread of 150 ft, and 9 nm/tow.
[d]Assumes observed tows equal 0.75 actual tows, door spread of 600 ft, 9 nm/tow,total tow distributed proportionally to observed tows.
[e]Assumes observed tows equal 0.75 actual tows, door spread of 550 ft, 9 nm/tow,total tow distributed proportionally to observed tows.
[f]Assumes observed tows equal 0.40 actual tows, door spread of 400 ft, 9 nm/tow, total tow distributed proportionally to observed tows.
[g]Assumes door spread of 300 ft and 9 nm/tow.
[h]Assumes door spread of 150 ft and 9 nm/tow.
[i]BT=bottom trawl, ST=shrimp trawl.
Note: Relative intensity of trawling between regions based on assumptions regarding area swept, estimated total fishing area, and total number of trawl tows (used with permission from Natural Resource Consultants). NA indicates data not available.

macrofauna are effective filter feeders and/or bioturbators and may enhance solute exchange through burrowing and burrow irrigation and alter resuspension through particle repackaging. Losses of benthic macrofauna due to mobile fishing gear impacts have been suggested to be partially responsible for higher incidence of algal blooms (Steele et al. 2002). Composition and migration behavior of pelagic communities including zooplankton, fish and marine mammals, may also be dependent on food foraged from benthic communities.

The goal for a workshop on Coastal Benthic Exchange Dynamics was to gather community input on the leading questions being posed by benthic researchers and to assess whether new technologies were sufficient to advance our understanding of the complex and dynamic interactions connecting atmospherically and tidally-generated forces with benthic exchange, benthic communities and rates of metabolism. The opportunity emerging from evolving observational technologies is to perform regional studies that simultaneously incorporate the spatial and temporal variability of the important external forcing with experimental studies and modeling of the mechanics of boundary layers and seabed transformations. While tidal and irradiance variations across a shelf region can be reasonably predicted, interactions with waves generated locally or remotely require constant monitoring of atmospheric and oceanic conditions. Designing this monitoring network and learning how varied benthic systems will respond remain the challenge for understanding benthic - pelagic coupling in the coastal ocean.

I.B. CoOP Background

The overall goal of the Coastal Ocean Processes (CoOP) Program is to advance understanding of the physical, biological, chemical, geological and meteorological dynamics of continental margin systems and in particular the processes controlling cross-shelf exchange (Brink et al. 1990, 1992; Roman 1998). The initial CoOP workshop report (Brink et al. 1990) identified primary factors controlling shelf exchange as air-sea interaction, wind-driven processes, buoyancy effects, tidal transport and mixing, coastal-open ocean connections such as western boundary current impacts, benthic processes, and biogeochemical transformations. These factors were developed further in subsequent publications (Brink et al. 1992; Roman 1998).

The CoOP Program is based on the central hypothesis that the small set of fundamental processes and factors listed above control transport on continental shelves and that shelf ecosystems are thereby distinguished by the relative importance of these processes. The overall strategy of CoOP has been to focus multidisciplinary, process-oriented research efforts at locations where individual factors, such as wind-forcing, freshwater inflow, and episodic events, impact transport processes and the local biogeochemistry and ecology to different extents. Comparison of results from individual studies can then provide improved fundamental understanding of material exchange and margin dynamics.

The first two CoOP projects were relatively small, 3-year-long, focused studies of inner shelf larval transport and air-sea gas exchange. Subsequent research projects have employed larger interdisciplinary teams and have been funded for 5-year periods, including a 2-year synthesis and modeling period after the field studies, to facilitate full integration of results. Studies of regions affected by episodic and seasonally varying events in Lake Michigan and Lake Superior (Episodic Events Great Lakes Experiment - EEGLE and Keweenaw Interdisciplinary Transport Experiment in Superior - KITES, respectively) were completed in 2000. Projects currently underway include studies of the California and Oregon margins where wind-induced transport is a major controlling factor (Coastal Ocean Advances in Shelf Transport - COAST and Wind Events and Shelf Transport - WEST) and systems impacted by freshwater inputs (River Influences on Shelf Ecosystems - RISE and Lagrangian Transport and Transformation Experiment - LaTTE). In late 2003, the CoOP Scientific Steering Committee (SSC) decided that the goal of the next CoOP research effort should be to advance understanding of the dynamics of exchange processes at and within the benthic boundary layer.

The vast range of relevant spatial and temporal scales at which important coastal processes operate has long presented significant challenge. CoOP has worked, therefore, to advance new technologies and instrumentation in coastal research that expand the temporal and spatial scales at which observations can be made. For example, the recently-funded RISE project will employ arrays of moored sensors and long-range HF radar arrays, as well as AVHRR and SAR to follow buoyant plume dynamics in the Columbia River plume, while the LaTTE project will employ the ECOshuttle, Slocum gliders, a nested CODAR grid and XBAND-derived satellite products as a part of the Hudson River buoyant plume study.

Since many of these are the same technologies that would be incorporated into coastal observatories, CoOP has actively participated in the planning process of coastal research observatories. In 2002, CoOP sponsored a workshop to examine the scientific opportunities of developing coastal ocean observatories. The workshop report (Jahnke et al. 2002) recommended a nested, three-component coastal observatory design consisting of multiple, permanent observation nodes installed in widely-distributed regions; additional, individual nodes where necessary to maximize observations of specific important regional features and processes; and relocatable, high-density clusters of moorings (Pioneer Arrays, Fig. I.B.1) that could be adapted to each deployment environment and research question.

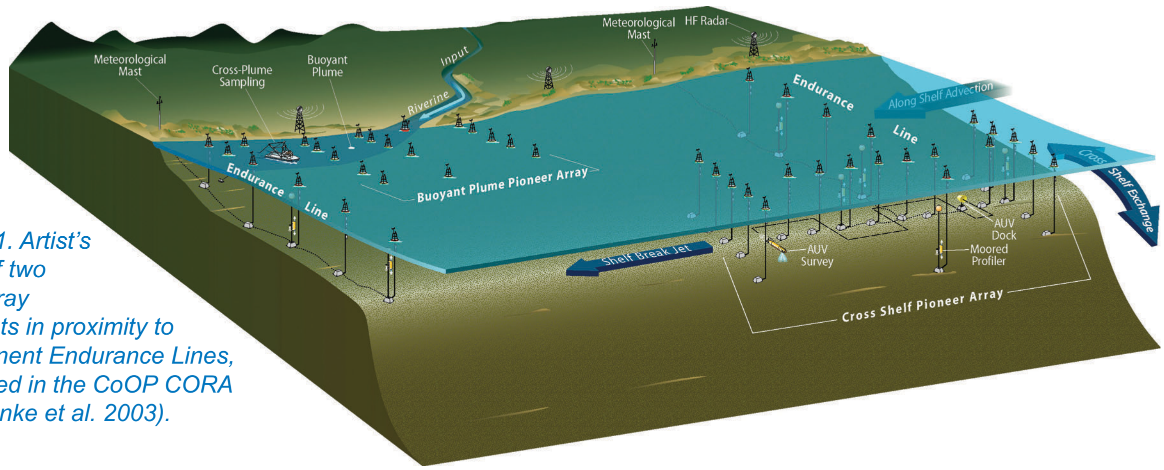


Figure I.B.1. Artist's rendition of two Pioneer Array deployments in proximity to two permanent Endurance Lines, as discussed in the CoOP CORA report (Jahnke et al. 2003).

In preparation for the ORION (Ocean Research Interactive Observatory Network) workshop in Puerto Rico in January 2004, a second coastal observatory workshop was convened by CoOP to establish the mix of permanent and relocatable observatory assets required for coastal observatory research. The Coastal Observatory Research Array (CORA) workshop participants again articulated the need for both distributed, permanent and relocatable observatory components (Jahnke et al. 2003). The regionally-distributed permanent observatory, referred to as the Endurance Array (Figure I.B.2), comprises cross-shelf transect lines of 3-6 sensing stations supported by individual moorings at critical locations. Endurance Lines are intended to provide sustained observations and high observational frequency, with sufficient infrastructure, bandwidth and power to support a wide range of interdisciplinary sensors and to support sensor development. Pioneer Arrays can be located and scaled to optimize the study of specific processes, thereby complementing the Endurance Array. Strawman science plans presented in the report for each US coastal region demonstrate potential research applications and the adaptability of the nested array design. The combination of permanent, relocatable, distributed and high-bandwidth observing sites is anticipated to greatly expand the range of spatial and temporal scales at which critical coastal measurements can be made, thereby contributing significantly to future CoOP research efforts.

Figure I.B.2. Potential locations of Endurance Line components in the Endurance Array, as discussed in the CoOP CORA report (Jahnke et al. 2003).

I.C. Workshop Charge

Just as previous CoOP workshops and projects have wrestled to define the spatial and temporal scales for observations of fundamental processes within different coastal settings, the CBED workshop began with the charge to formulate and prioritize research questions that focus on temporal variability of important external factors or forces in coastal regions; linkages of dynamic conditions to fluxes into and out of the benthic boundary layer; benthic biological, chemical and geological patterns; and biogeochemical processes and rates within the benthic boundary layer. First-day Working Groups were asked to direct their thinking to forcing factors operating at specific time scales. These Working Groups/time scales/forcing factors were:

- *Group 1: up to hours (e.g., turbulence, waves, biological pumping, a trawling event)*
- *Group 2: several hours to a few weeks (e.g., diurnal cycles of light, tides, storm and flood events, biological blooms)*
- *Group 3: month to year (e.g., seasonal cycles in physical forcing, fishing effort)*
- *Group 4: years to decades (e.g., climatic cycles, groundwater discharge, burial)*

In addition, Working Groups were asked to identify at least four major categories of processes or themes that must be central to any future CoOP project designed to understand roles of coastal benthos. The plan was that these categories would lead to new working groups on the second day of the workshop and focal areas for a workshop Science Prospectus. Deliberations of the first-day Working Groups are included verbatim in SectionVI.A. Second-day Working Group deliberations provided the basis for Sections II.B. through II.F.

I.D. Workshop Structure

The workshop was planned with input from the CoOP Program Office, the CoOP Scientific Steering Committee, the co-chairs, and the organizing committee. The workshop was open to all interested participants and announced via the CoOP Newsletter and website, an evening forum at the AGU 2004 Ocean Sciences Meeting in Portland, OR, and e-mailings of an announcement poster. Demonstrating the widespread interest in benthic science, the workshop attracted 67 participants representing 37 academic and research institutions, government agencies and laboratories and private industry (see Appendix VI.B). A total of nineteen coastal US states and the District of Columbia were represented. Participants also attended from Denmark, England, Wales and Brazil.

The workshop opened with a plenary session including a brief welcome and introduction to CoOP, a reminder that the benthic boundary layer should be viewed as *"those portions of sediment and water columns that are affected directly in the distribution of their properties and processes by the presence of the sediment - water interface"* (Boudreau and Jørgensen, 2001), the charge to participants, and five keynote talks (see Appendix VI.D.). Keynote speakers were asked to present background material and developing research related to broad disciplinary themes such as "animal-sediment interactions in the seafloor and implications for biogeochemistry". First-day working groups organized by time scale were structured to be multidisciplinary. These groups met throughout the afternoon of the first day and Working Group Chairs or Rapporteurs reported on their discussions at a plenary session beginning the second day.

Based on overarching themes, research questions, and focus areas emerging from the first day, new working groups were formed on the second day. These working groups were charged to focus on *Physical Disturbance and Sediment Dynamics; Benthic - Water Column Exchange; Benthic Habitat, Community, and Activity, or Modeling the CBED-defined BBL*. They were also asked to describe example process studies, coastal regions, and technologies suited for future multidisciplinary projects related to their theme. Workshop participants were free to attend any of the second-day working groups, but members of the organizing committee were asked where possible to serve as Chairs or Rapporteurs in the groups they attended.

Discussions and recommendations of the second-day working groups were reported in a plenary session followed by group discussion the morning of the third day. One discussion point was whether there would be value in recommending a study aimed at comparing methodologies for estimating benthic fluxes from permeable sediments influenced by surface gravity waves. No agreement was reached, but it was suggested that comparative methods should be considered as much as possible in future research projects.

After adjourning the workshop, the organizing committee outlined the workshop report and assigned writing responsibilities. Specific recommendations stressed at this meeting were that:

- *the occurrence of specific transport and transformation processes in the benthic boundary layer should drive the domain selection(s) for future CoOP research projects (in other words, there is no optimal coastal site or sites);*

- *a CoOP Coastal Benthic Exchange Dynamics project should complement the Ocean Research Interactive Observatory Network (ORION) Program and emerge as an example of science-driven observatory science; and*

- *emerging non-intrusive technologies such as high-frequency chemical samplers for eddy correlation and range-gated, multi-frequency acoustic scanning should be supported so they are more capable and can be used widely.*

II. A. Science Prospectus - Overview

The coastal ocean is the boundary zone between terrestrial and oceanic realms. Within this interfacial region, transport processes, biological interactions and chemical reactions are intensified. As a result, coastal systems play disproportionately important roles in the ecology and biogeochemistry of the oceans. Additionally, as the intersection between the human-occupied terrestrial environment and the oceans, coastal systems dominate human-marine interactions.

Distributed as an initial focal point for the CBED workshop, Figure II.A.1 schematically represents many of the transport and exchange processes that are either intensified within or unique to the coastal ocean. These phenomena exert considerable influence on the structure, composition and characteristics of coastal habitats. Depicted in this figure are freshwater inputs (1), groundwater exchanges (2), atmospheric inputs which while not unique to coastal systems are generally heightened due to the proximity to terrestrial sources of airborne materials (3), benthic solute exchange (4), sediment resuspension (5), wind-driven coastal upwelling (6), particulate plumes (7), near-bottom density flows (8), sediment accumulation (9), hydrates and gas fluxes (10), intensified water-column mixing due to friction with the sea floor (11), internal wave - sea floor interactions (12), turbulent interactions with the surface and benthic boundary layers (13 and 14) and water-column and benthic interactions with surface gravity waves (15). These processes are driven by both local and external conditions that are temporally variable, and many depend directly on the geomorphology of the coastal seafloor. Magnitudes and interactions of these processes and timing of responses are not well known.

Previous CoOP research projects have focused on inner-shelf transport processes, coastal air-sea chemical fluxes, cross-margin transport in large lakes, wind-driven coastal upwelling, and buoyancy-driven processes near rivers. As can be recognized from Figure II.A.1, many of the other important processes unique to coastal systems or responsible for focusing or intensifying exchange processes involve interactions with the seafloor and have not been

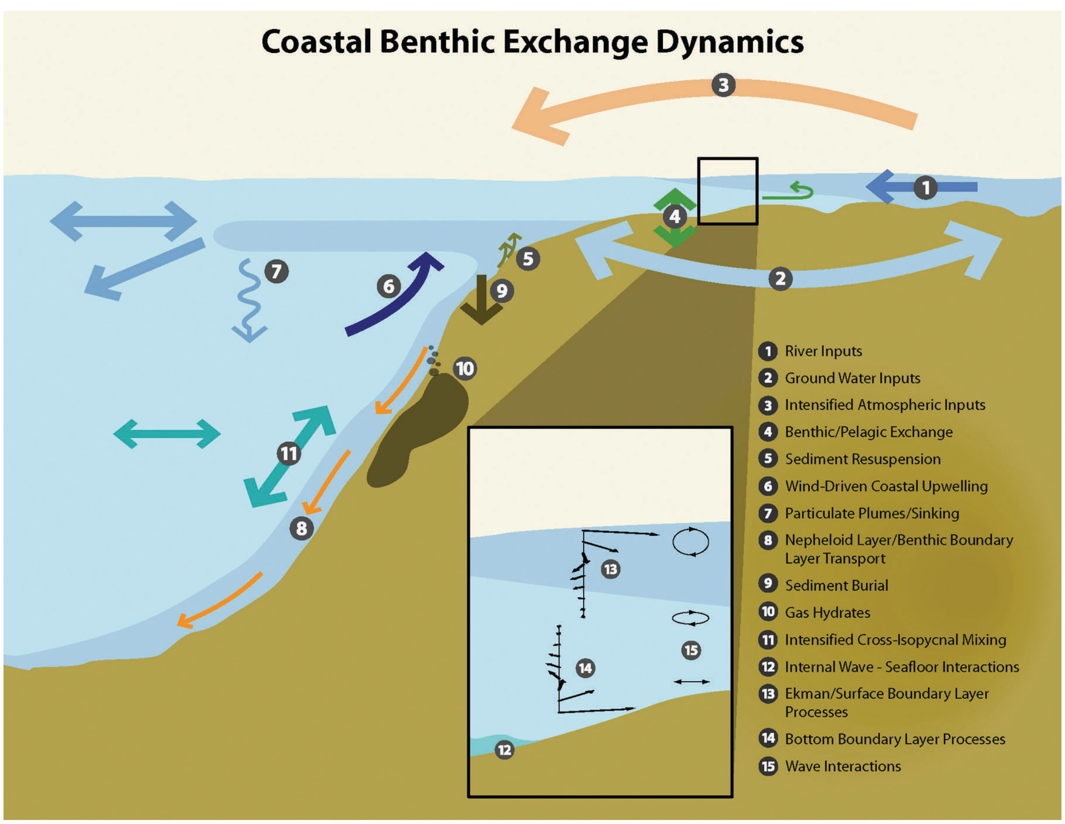


Figure II.A.1. Schematic of selected transport processes that are either unique to or intensified at the ocean - continental margin boundary as described in the text. In response to complex interactions between physical forces and local topography, it is important to recognize that these exchanges vary significantly spatially and temporally.

the focus of previous CoOP studies. Indeed, it may be argued that the defining measure that distinguishes coastal systems from the open ocean is proximity to the seafloor. Because of interactions with the seafloor, many of the lessons learned from open-ocean studies cannot be applied directly to coastal ecosystems. To further our understanding of coastal systems, they must be directly studied, and - in particular - we must improve understanding of processes within the benthic boundary zone.

The study of seafloor processes and their interactions with the water column presents significant intellectual and technological challenges. The need for integrated studies of the major coastal ecosystems surrounding the US has been confirmed by the report from the US Ocean Commission on Ocean Policy (2004). At the CBED workshop, participants recommended emphasizing research related to physical disturbance and sediment transport, benthic - water column exchange, benthic habitat, community and activity, and modeling. These four themes are expanded upon in sections II.B-E. Since technology issues were common to all, *Technologies - Opportunities and Challenges* is the topic of Section II.F.

Perhaps the greatest challenge is to develop a strategy by which observations and models integrate at several spatial scales. Such models can be expanded to include a greater portion of the large range of temporal scales at which many of the transport and biological processes and interactions occur. Coastal ecosystems in general and benthic habitats specifically are changing in response to variations in global systems and through local anthropogenic pressures. Of particular concern in coastal areas are the long-term impacts of sea level rise, variations in freshwater and nutrient inputs, and the long-term variations in fishing pressures and techniques. In many regions of the coastal ocean, 100% of the sea floor area is scraped by benthic trawl nets one or more times per year. Imposed on these trends, seasonal and multi-year cycles (such as ENSO and NAO) may modulate the occurrence of periods of hypoxia, storms and other events. On the other end of the temporal spectrum, short-term events and processes such as sediment resuspension or irrigation by dense concentrations of megafauna often dominate exchange and biogeochemical transformation rates. Indeed, many of the longer-term trends may be accurately represented as variations in the frequency and intensity of short-term events. Elucidation of short-term events is therefore critical to improving understanding of the shelf system in total.

To fully expand the range of space and time scales observed, multiple observational approaches, each of which may be suited for only a narrow range of temporal or spatial variability, will be required. It will be critical that new non-intrusive approaches are developed and that vigorous comparisons are run when new methods challenge established techniques. Ship-board measurements and samplings with in situ and remote, fixed and mobile sensor measurements should be well coordinated and overlapped to maximize the utility of observations.

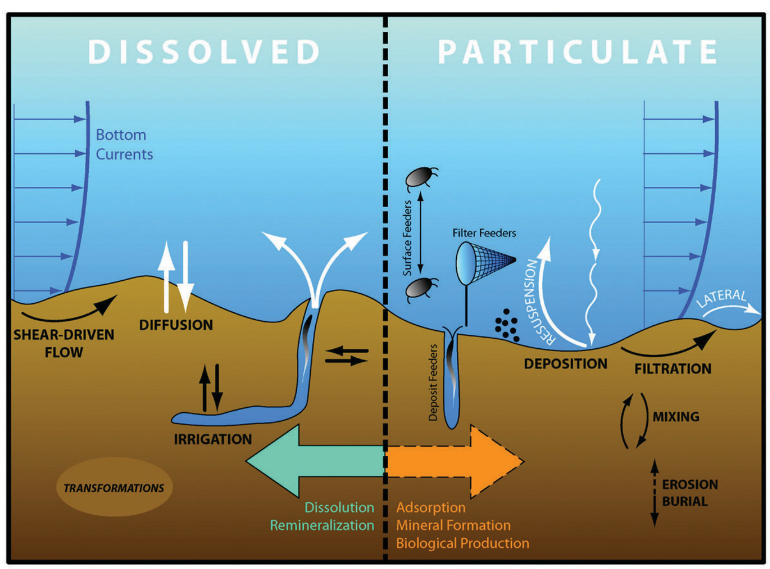


Figure II.A.2. Schematic representation of the important processes controlling the distribution and transport of both particulate and dissolved materials in the benthic boundary layer zone.

Spatial and temporal scales associated with many coastal features will require high-resolution, sustained techniques to be an important component of the remote-sensing strategy. This is especially important in studies of sediment transport where there are distinct thresholds for particle movement and single events may dominate annual transport. Satellites, possibly including geostationary satellites, and aircraft-based sensors may provide important synoptic observations of surface features. However, because the benthic layer is subsurface and generally invisible to satellite or aircraft-mounted sensors or land-based radar systems, in situ ‘observatory-type’ sensor installations are expected to play an important role in advancing understanding of BBL processes. Of particular importance in this context will be the use of coastal observatory measurements to identify short-term, episodic phenomena and long-term trends in the frequency of events, both of which are mostly missed by shipboard observations. Research array-based measurements will permit broader spatial comparison and, over time, extrapolation of results to other margin settings, significantly expanding our understanding of specific processes in a broader context.

In addition to the technical challenge of expanding observations to cover a wide range of temporal and spatial scales, there is a fundamental intellectual challenge of advancing understanding of the physical, biological, chemical, geochemical and meteorological interactions within this complex spatial and temporal context. Because many of the linkages between hydrographic, biogeochemical and ecological processes have not been identified or quantified, detailed, ship-based process studies and laboratory studies will also remain important components in overall research strategies for coastal systems. Cross-shelf and along-shore transects should be studied to examine the three dimensional complexity of dynamics and transports and occupied at appropriate frequencies to quantify major temporal variations. Many potentially important transport features such as offshore advective filaments, and particulate layers at specific density surfaces, may extend seaward hundreds of kilometers from the shelf/slope region. Holistic regional studies must include this spatial domain. Throughout these studies, models will play an important role in the design of the field observation program and in extrapolating processes and their interactions to the regional scale.

II.B. Physical Disturbance and Sediment Dynamics

Physical interactions shape the sea bed and benthic ecosystems. High temporal variability is a distinguishing characteristic of the coastal benthos, setting shallow environments apart from the generally quiescent deep sea. Benthic fluxes in coastal habitats, such as major muddy river deltas (Aller 1998) or sandy nearshore environments (Scapini 2003), are often dominated by physical disturbance and may play an important role in the maintenance of diversity and productivity in coastal ecosystems (Dernie et al. 2003; Hérnandez-Arana et al. 2003). Identifying causes and consequences of bottom sediment - fluid interactions is central to understanding the role of physical forcings in coastal environments.

The study of benthic processes is highly relevant to environmental management. Since many nutrients and anthropogenic pollutants are adsorbed onto and transported by suspended sediments, knowledge of how this material is transported is required to accurately model the behavior of these materials. Rapid respiration of carbon associated with overturning of muds along energetic deltaic coasts initiates return of massive amounts of greenhouse gases to the atmosphere (Aller 1998). On a smaller scale, low macrobenthic diversity and occurrence of opportunistic species may be consequences of persistent physical perturbation or anthropogenic contamination (Diaz et al. 2003). Widespread impacts of trawling on benthic communities are a potentially destructive form of physical perturbation (see Section I.A; Ocean Studies Board 2002).

However, logistical difficulties of studying episodically disrupted environments and the impact of occasional extreme disturbance on instrumentation and observational platforms have led to under-sampling relative to quiescent conditions, especially in evaluating the potential role that physical disturbance may play in driving habitat structure and biochemical cycling (Fig. II.B.1).

General causes, types and effects of physical disturbance

Common causes of benthic physical disturbance include major storms, density currents associated with river floods, and groundwater emanating from the coastal ocean floor. River floods and groundwater in turn depend on precipitation amounts and extent of flooding over the near-coast landmass. Characteristics of this atmospheric forcing necessary for diverse physical benthic disturbances are unknown. How are duration and magnitude of atmospheric events expressed in benthic dynamics and habitat disturbance? Does a long, moderate storm have the same impact as a short, intense storm?

Figure II.B.1. Waves overtop the 8 m tall research pier at Duck, NC, on September 18, 2003, during Hurricane Isabel. Because of the permanent coastal observing system maintained at Duck, continual records of bottom boundary layer currents are available during major storms. However, highly energetic, episodic conditions are generally under-sampled worldwide. Photo courtesy of the US Army Corps Field Research Facility.

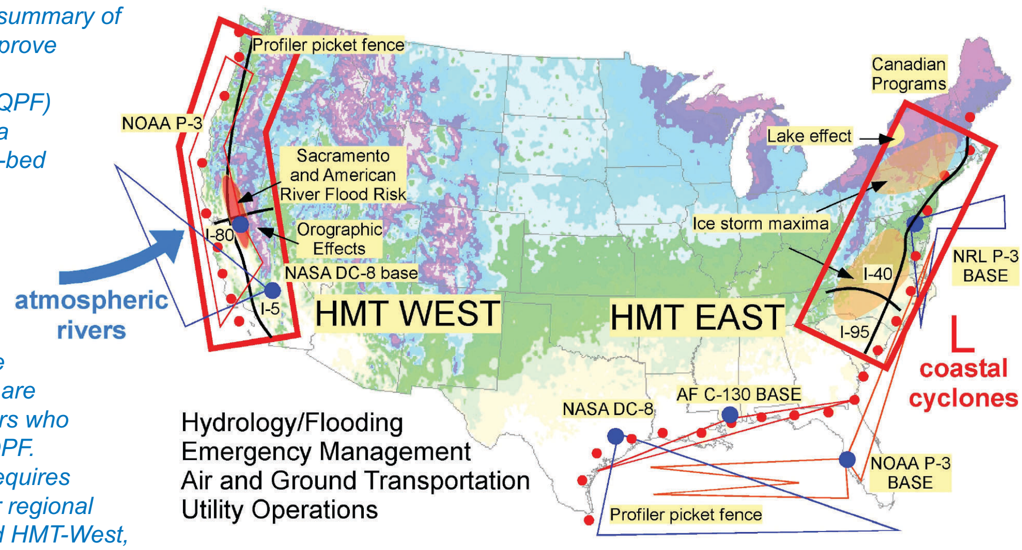


Figure II.B.2. Schematic summary of the primary strategy to improve cool-season quantitative precipitation forecasting (QPF) through establishment of a Hydrometeorological Test-bed (HMT) approach that will foster both the research needed as well as its testing and transition to operations. Successful implementation requires addressing an appropriate range of phenomena that are critical to the forecast users who depend on cool-season QPF. Accomplishing this goal requires development of two major regional efforts, i.e., HMT-East and HMT-West, which focus on differing phenomena, forecast issues and user needs. This implementation involves developing both a long-term core infrastructure for HMT that supports efforts nationally, and conducting episodic intensive regional field studies needed to address certain key research and forecasting challenges. Modified from Ralph et al. (2004) in review.

To address these questions, atmospheric and benthic observations must be made in concert. Collaboration with proposed coastal zone atmospheric observatories may provide an important strategy for advancing understanding of atmospheric - benthic interactions. An example of the distribution of a proposed coastal atmospheric observing system that would be part of the National Hydrometeorological Test-bed (HMT) is provided in Fig. II.B.2.

Tidal currents can also be highly energetic, causing the seabed of macrotidal coastal regions to be dominated by physical disturbance (Schaffner et al. 2001; Fig. II.B.3). On some shelves, strongly non-linear internal waves play an important role in suspending sediment and organisms. Mean currents associated with wind-driven flows, storm surges, river floods, plumes, coastal currents and other density-driven flows can also impact the seafloor and benthic ecosystem (Okey 1997). Mechanical anthropogenic activities (Fig. II.B.4) such as trawling and dredging elicit benthic responses similar to natural disturbance (Collie et al. 2000). Physical perturbation can also come from below, in association with groundwater movement, mud volcanoes, gas venting and other physical processes triggered by seismic events.

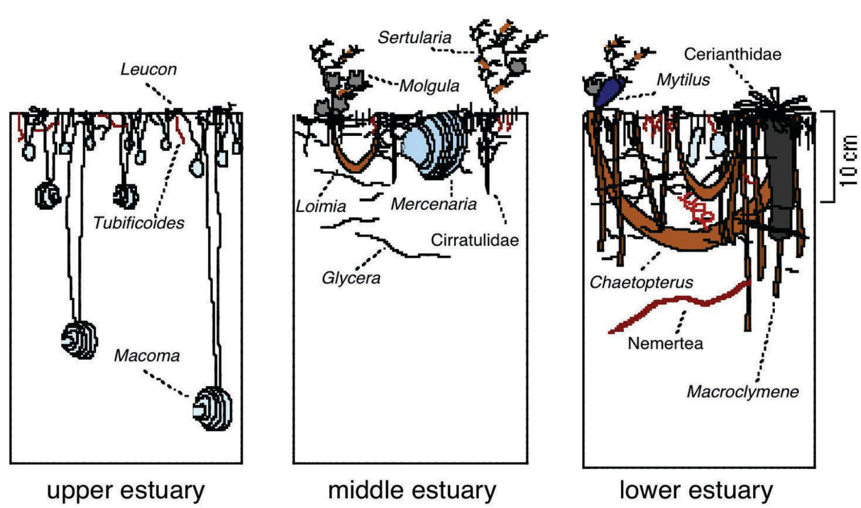


Figure II.B.3. A generalized illustration depicting the reduction in macrobenthic diversity and reduction in abundance of suspension feeders associated with persistent physical disturbance by sediment transport near the turbidity maximum in the upper portion of the York River, VA, tidal estuary. From Schaffner et al. (2001).

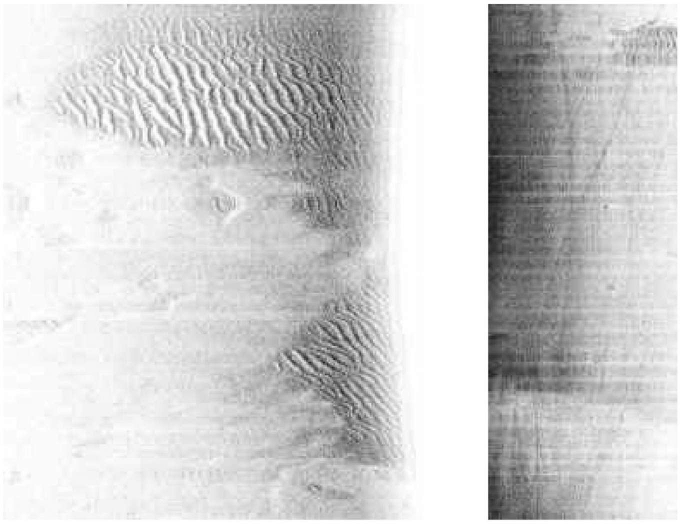


Figure II.B.4. Anthropogenic mechanical disturbance. Side-scan sonar records classify habitat as sand transitioning to softer sediment (left) and identify scours resulting from experimental trawls (right) in the Little Tow area off Scituate, MA. Image courtesy of NOAA/NMFS.

Other types of physical bed disruption with major ecological consequences include rapid deposition due to loading from above and/or from horizontal transport convergence, or the opposite, namely rapid erosion from vertical suspension and/or transport divergence (Aller and Stupakoff 1996). Similar rapid changes in the vertical position of the sediment - water interface can result from bedform formation and migration. Physical mixing and sorting of bed material, porewater convection, or bed liquefaction can cause ecological responses without notable net displacement of the sediment - water interface. Above the seabed, high sediment concentration and general water-mass advection can alter boundary layer hydrodynamics and composition.

In the water column, the above types of physical disturbance affect the benthos by causing advective changes in water-mass temperature and chemistry and by introducing and removing organisms (McKinnon et al. 2003). Closer to the seabed, suspended sediment can block light and overwhelm suspension feeders (Schaffner et al. 2001). At the sediment - water interface, highly energetic flow, often in concert with sediment transport, can mechanically stress or destroy benthos, change sediment texture (Fig. II.B.5) and bury immobile organisms (Fig. II.B.6; Posey et al. 1996). Physical overturning of the seabed rapidly releases chemical constituents from porewater and can inject oxygen and organic matter, greatly accelerating respiration within the seabed (Aller 1998; Abril et al. 2004). The physiological stress associated with intense physical disturbance can change benthic community structure, typically shifting the community toward smaller, more opportunistic and less diverse macrobenthic species, and increasing the percentage of respiration associated with microbes (Hall 1994). Changes in the benthic community can feed back to changes in the physical structure of the benthic community which then can feed back to the nature of future physical disturbances.

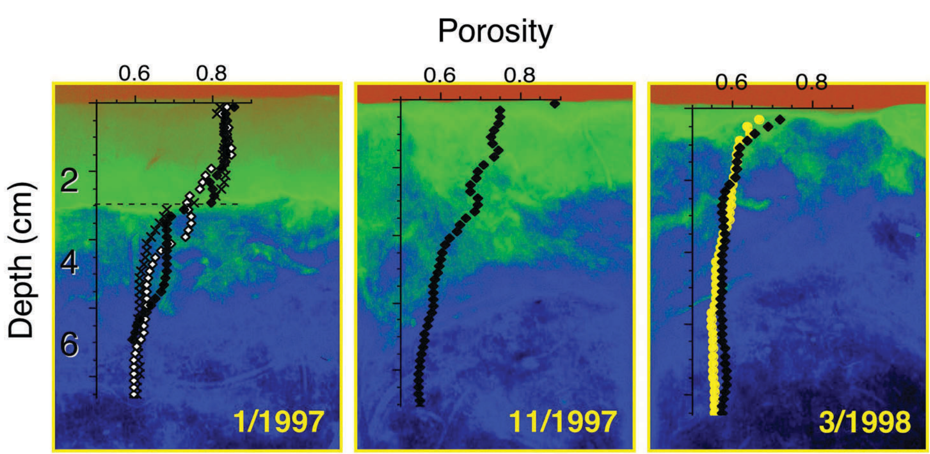


Figure II.B.5. Evolution of seabed structure and porosity on the mid-shelf off the Eel River, CA following an energetic flood event. A return to a normally consolidated bed requires months to a year. During this process bioturbation mixes away much of the distinct interface between the flood layer and underlying strata. Images courtesy of Rob Wheatcroft.

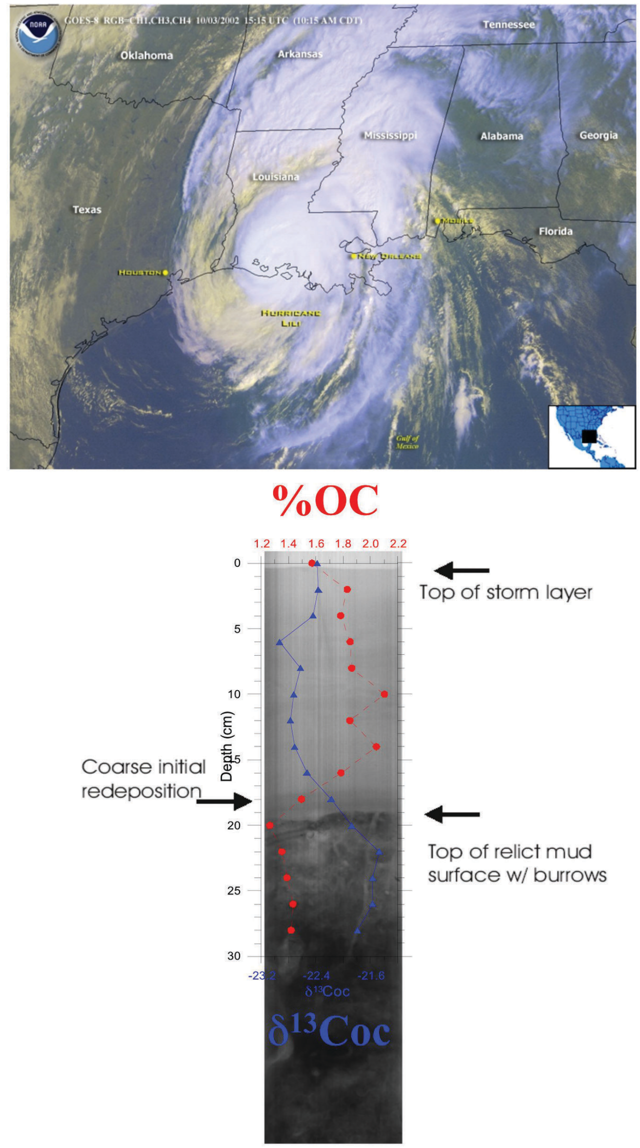


Figure II.B.6. Hurricane Lili (upper) and core collected off the Atchafalaya River, LA, in October 2002 (lower) during a rapid response cruise after landfall of Hurricane Lili. The thick storm layer, which trapped macrobenthos in their burrows, also delivered a significant pulse of organic carbon to the seabed with a distinct isotopic signature. Image courtesy of Miguel Goni.

Many questions remain concerning physical disturbance and its biological and biogeochemical impacts. For example, are large storms typically a major "disturbance" to the benthic ecology, or is the benthos in most energetic locales largely adapted to survive or even utilize major storms? Is the timing of physical disturbance relative to recruitment key to determining its ecological impact? To what extent does physical disturbance in various coastal environments significantly enhance net respiration by recharging the bed with oxygen? Is primary production soon after major bed disturbance typically enhanced by recycling of nutrients from within the bed to the water column?

Sediment transport issues

Ecological and biochemical consequences of physical disturbance of the seabed are largely forced by the more physically-oriented processes of sediment mobilization, horizontal flux and deposition (Fig. II.B.7). Although numerous aspects of sediment transport are central to benthic boundary layer interactions, several poorly constrained aspects were specifically highlighted by contributors to the CBED workshop as essential to the near-term advancement of understanding of benthic exchange, namely suspension and deposition of cohesive sediment and the dynamics of nepheloid layers and fluid mud.

The resistance of fine-grained material to erosion is a complex function of a number of factors including grain size, composition, depositional history, and the degree of biological reworking (Mehta and McAnally 2004). However, bottom sediment is usually characterized in transport models only by particle size. Entrainment of cohesive sediment in coastal waters has been traditionally treated as an engineering problem. Much of the effort has been directed at predicting entrainment rates rather than describing the processes that lead to them. For example, studies of entrainment have continued to use power-law formulations with a range of forms for the general equation (Nairn and Willis 2002). Too often, these different formulae have been used to describe specific sets of data rather than elucidate the relationship between entrainment and sediment properties.

Dewatering is a time-dependent process that, in the absence of other processes, will cause clays to compact and become aggregated, leading to a resistance to further resuspension (Toorman 1999). Engineering parameterizations of

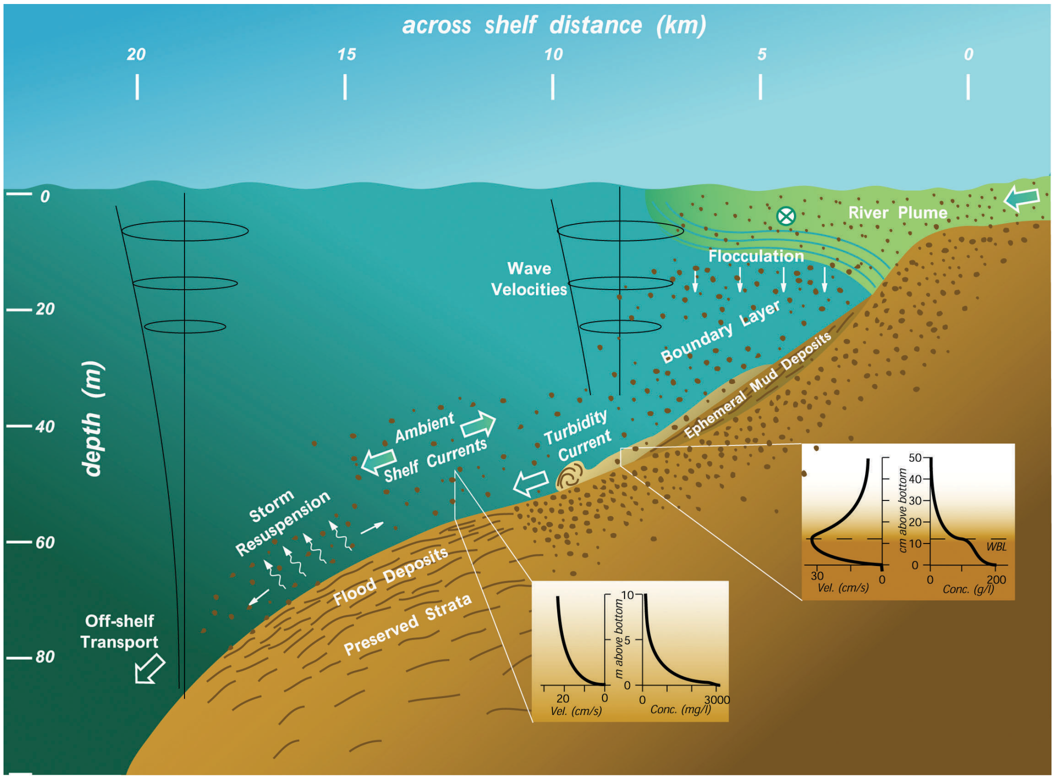


Figure II.B.7. Schematic of the sediment-transport processes on the Eel River shelf. Sediment enters the shelf domain in the river plume, and it rains into the bottom boundary layer on the inner shelf at a rate determined by particle aggregation within the plume. Sediment accumulates within the boundary layer or deposits as ephemeral mud deposits on top of inner-shelf sands, depending on the energy for wave resuspension. If concentrations are high enough, then turbidity currents within the wave boundary layer transport the sediment to the mid-shelf deposits. Beyond mid-shelf depths the wave energy at the seafloor is too low to resuspend sufficient concentrations to maintain the turbidity currents. Ambient currents in the bottom boundary layer also disperse the sediment, ultimately causing off-shelf transport due to preferential resuspension in the higher-energy, inner-shelf region. Storm resuspension remobilizes some of the sediment, and may result in sediment export off the shelf. Some fraction of the deposit is ultimately preserved as part of the geological record. From Geyer and Traykovski (2001).

sediment transport do not generally incorporate these types of factors. Another important process is bioturbation, which is loosely defined as physical, geological or chemical disruption by the activity of burrowing organisms. Such burrowing activity tends to decrease the resistance of sediment to entrainment but in nonuniform ways (Murray et al. 2002). Burrowing parallel to bedding has been seen to increase both the rate and mode of entrainment.

To date it has not been possible to relate sediment shear strength to any easily measured property, so at present direct in situ measurements of the sediment shear strength are required (Houwing and van Rijn 1998). Since these measurements are quite difficult and expensive, very few are made in any given program. This usually means that a few measurements at a few sites are extrapolated to cover large areas, and that temporal variations are not considered. Time-series observations show, however, that lateral and temporal variations in bottom resistance are common in many different environments.

Deposition of cohesive sediment is just as problematical as entrainment (Sanford and Halka 1993). Most approaches depend on the pioneering work of Krone (1962; 1993) and Partheniades (1965). These semi-empirical models use calibration factors that are oversimplifications of complex collision dynamics. They are also based on a limited number of laboratory studies by only a few researchers. Additional work on flocculation dynamics gives some additional insight into the physics of cohesive sediment adhesion. This subject has in general been ignored in most studies because of the difficulties of describing these processes.

Cohesive floc properties that are important for deposition, such as density, floc size, and settling speed, are also very difficult to describe with present knowledge. It is not possible to understand cohesive sediment dynamics without addressing the problem of flocculation. Both field and laboratory studies have shown a general dependence of floc properties on shear within the water column (Milligan and Hill 1998), but it is not clear to what degree laboratory measurements of these properties can be extrapolated to the marine environment. Furthermore, there is a suspected but not well-known dependence of clay flocculation on organic content. What other marine suspended and dissolved material is important in understanding these processes?

Nepheloid layers also exert a critical influence on the benthic ecosystem. These layers are hypothesized to be due to local sediment resuspension and may be an important pathway for the offshore transport of both nutrients and pollutants, but processes responsible for their maintenance are not well documented. In the Great Lakes, for example, these layers are quite common during the stratified period (roughly June to October, Fig. II.B.8), but are much less common when the water is isothermal (Hawley 2004).

Recently, several investigators have documented bottom resuspension by internal waves on the continental shelf. An important example on shelves seems to be internal bores that propagate along a near-bottom density interface (Fig. II.B.9). These are highly nonlinear waves of elevation, characterized by high turbulence, high particle speeds (0.6 m s^{-1}) one meter above the bed and high bed stresses, and they are capable of moving fluid in their direction of propagation (Klymak and Moum 2003). Direct measurements show intense sediment resuspension associated with these events. A

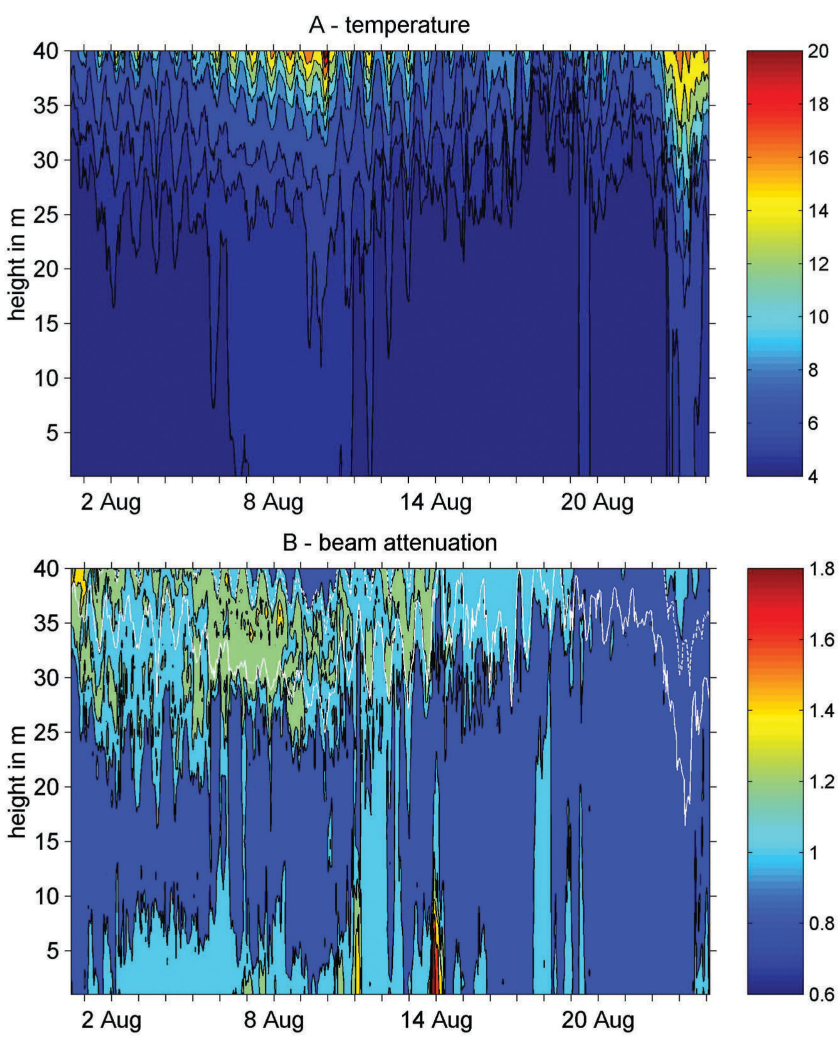


Fig. II.B.8. Hourly measurements from a vertical profiler located at a station in 55 m of water in southern Lake Michigan during August 2001. The data show a benthic nepheloid layer near the bottom and an intermediate nepheloid layer just below the thermocline. The nepheloid layers change in response to the inertial oscillation of the lake (period is 17.6 h). A. Water temperature. Contours are at 4.5, 5, 6, 8, 10, 12, 14, 16, 18, and 20°C. B. Beam attenuation coefficient. Contours are at 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 1/m. The white lines are the 6°C (solid) and 12°C (dashed) isotherms. Figures from Hawley and Muzzi (2003).

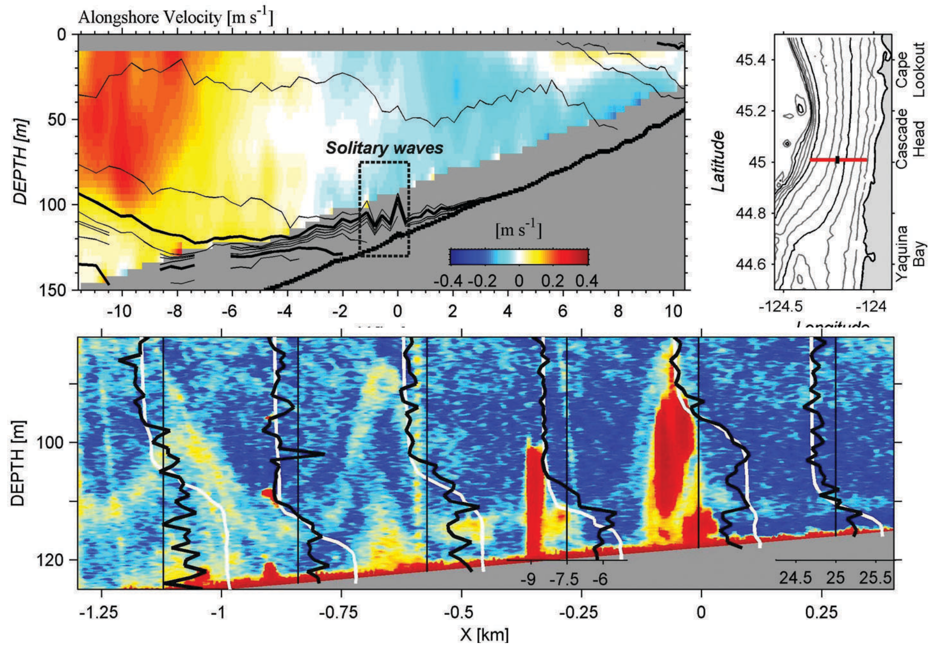


Figure II.B.9. Upper: Near-bottom solitary waves from January 2003; shown is a section of potential density and N-S velocity off the Oregon coast. Isopycnals are in intervals of 0.2 kg m^{-3}; the surfaces of 25 and 26 kg m^{-3} are bold; 120 kHz echo-sounder image shows the outline of 30-m tall waves.

Lower: Profiles with the Ocean Mixing Group's turbulence profiler Chameleon indicate that the waves are along a sharp density interface near the bottom and that the region below the interface is very turbulent. Proximity to the bottom means that significant near bottom stresses will enhance sediment suspension. Other data indicate that these waves are propagating onshore at approx. 0.5 m s^{-1}. A numerical fit indicates that the lead wave may have a recirculating core transporting fluid from offshore, and possibly trapping organisms consistent with the cloud of scatterers in the echo-sounder image. From Klymak and Moum (2003).

program directed at determining the role of internal waves in maintaining the benthic nepheloid layer could also provide information on the importance of internal waves in exchange of material between the water column and underlying sediments.

An even more vexing problem is the generation of fluid mud, namely mobile suspensions with concentrations so high (10s to 100s of grams per liter) that sediment settling is physically hindered. Fluid mud is important because of its tendency to overwhelm macrobenthos, greatly accelerate microbial processing, and transport and deposit massive amounts of sediment (Aller 1998). Unlike other marine sediments, which have comparatively fixed properties and known distributions, fluid mud has widely variable characteristics and often goes undetected by classical sampling techniques because of its presence in very thin, highly mobile, near-bed layers (Traykovski et al. 2001; Fig. II.B.10).

There is a debate today whether fluid muds are generally produced by deposition from high concentrations, generated by resuspension processes, or formed by horizontal transport convergence.

The behavior of fluid mud has important consequences for exchange of sediment-bound material between the water column and seafloor. Thus it is important to understand the three-dimensional structure of exchange processes within these suspensions. For example, what is the dependence of fluid mud generation on local turbulence? How important is clay mineralogy and adsorbed material like organic matter to the formation of these layers?

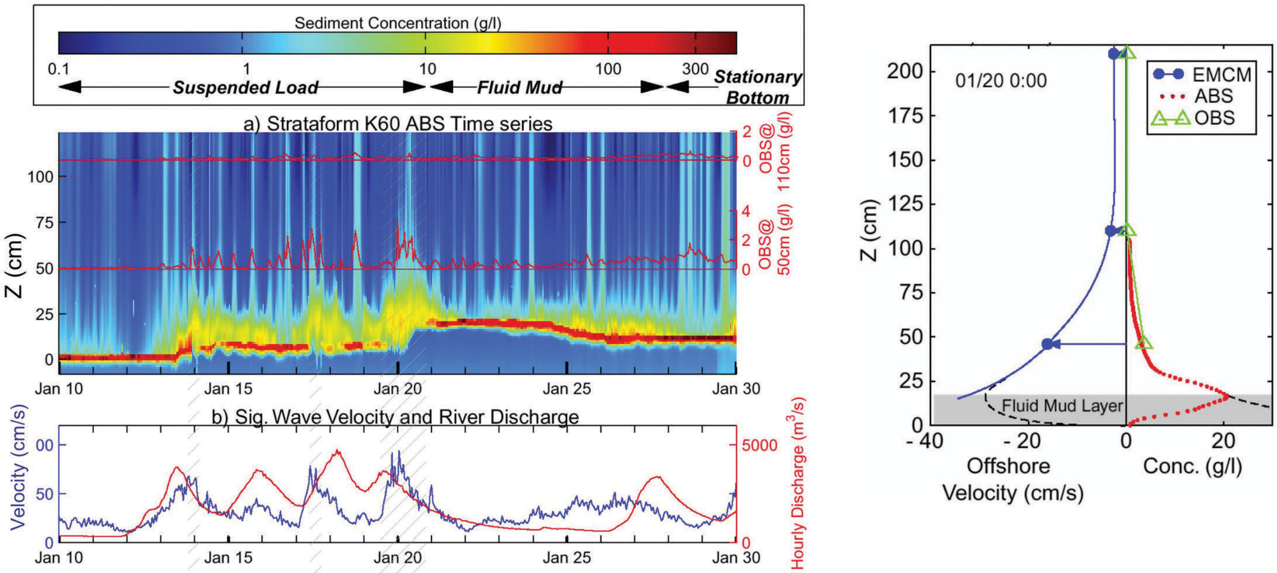


Figure II.B.10. (left, a) Time series of acoustic backscattering (ABS) depth profiles. The concentration is indicated by the color scale. During the period from January 14 to 20 there exists a thin (10-20 cm thickness) layer of high-concentration fluid mud (yellow layer, with yellow corresponding to 30-50 g/l). The bottom return from the acoustics (bright red starting at 0 cm on January 10) shows two depositional events on January 14 and January 20 associated with fluid mud layers and one erosional event on January 24-26. Peaks in suspended sediment above the fluid layer are visible in both the optical backscatter (OBS) records (red lines, right y-axes) and the ABS data. (left, b). The fluid mud layer visible in the ABS data occurs only during periods of high wave velocities that are also associated with high river discharge events. (right) Electromagnetic current meter velocity and burst-averaged OBS and ABS sediment concentration profiles taken during a downslope density flow event on January 20th. The velocity profile is interpolated between data points (colored dots) and extrapolated to the top of the fluid mud layer using a piece-wise cubic spline fit. This extrapolation indicates downslope velocities of approximately 30 cm/s at the top of the fluid mud layer. Modified from Traykovski et al. (2000).

II.C. Benthic-Water Column Exchange

Processes of material exchange couple biogeochemical pathways and transformations in sediments to the overlying water column in coastal environments. Most notably, in coastal upwelling regions, seabed respiration and nutrient regeneration are important factors controlling rates of surface primary production. However, in environments where water clarity permits the penetration of light to the seafloor, benthic primary production may rival water-column production. Quantifying the fluxes of nutrients and organic matter that determine the relative roles of the benthic and pelagic sub-systems is fundamental to advancing understanding of contrasting coastal ecosystems.

In addition to impacting integrated rates of biological processes, benthic exchange may influence compositions and life histories of biological communities both at the seafloor and above. High rates of benthic oxygen consumption during periods of water-column stratification may lower bottom-water oxygen concentrations triggering die-offs of sessile organisms and fish migrations. Sedimentary denitrification is important in many shallow-water sediments and may alter the ratio of silica to fixed-nitrogen that is returned to the water column by remineralization of biogenic materials in the sediments. This feedback may influence the composition of the phytoplankton community. Phosphorus may also be removed by sedimentary processes. Although phosphorus is efficiently recycled by heterotrophic respiration in sediments, it is readily removed from pore waters by freshly precipitated iron oxides that commonly occur in the surface oxic layer of coastal sediments. Shelf sediments may also supply iron to coastal ecosystems, but changes in the chemical speciation of iron as it is exchanged between zones of the benthic boundary layer have never been described. In short, there is much to learn about how benthic boundary-layer processes affect biological communities by regulating bio-availability and supply of important macro- and micro-nutrients in coastal waters.

One reason that the many effects of benthic exchange on coastal nutrient and carbon cycles are poorly constrained is because of the complexity of coastal systems and the difficulty of sampling permeable sands, rocky outcrops, fluid muds and other heterogenous bottom types typical of the coastal benthos. Modes of pore-water exchange in coastal

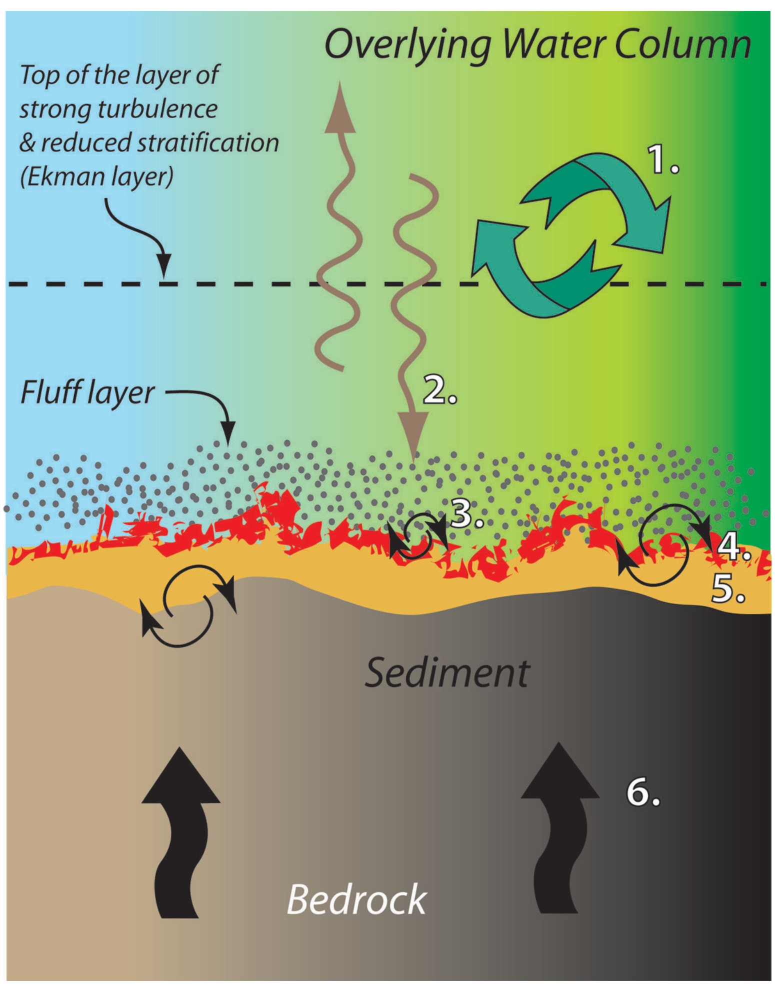


Figure II.C.1. Schematic diagram of sub-regions within the benthic boundary layer, and six primary flux mechanisms, each of which is described in more detail in the text. 1. Exchange of BBL-interior water by turbulent eddies and advection. 2. Particle sinking and resuspension. 3. Exchange across the diffusive boundary layer. 4. Exchange across the interfacial layer. 5. Sediment mixing zone. 6. Deeper fluxes, including groundwater. Figure courtesy of Parker MacCready.

sediments are rarely limited to molecular diffusion. Mechanisms controlling particulate transfers are equally complex as described in the preceding section. Important flux mechanisms, imbedding within the sub-layers of the benthic boundary layer, are illustrated in Fig. II.C.1. To understand how external factors influence net material exchange, these processes and their interdependencies need to be studied individually and in concert. Perspectives on key issues related to these mechanisms are broken out below.

1. Exchange between the BBL and the overlying water column

The BBL is embedded within the Ekman layer, a region of distinct hydrodynamics. Operationally, the BBL can be defined as the bottom zone in which turbulence levels are enhanced by bottom stress-generated turbulence, or where the stratification is reduced by this turbulence. It may be on the order of 5-50 m thick. If there are currents or waves creating bottom stress, then properties are generally mixed by turbulent eddies across this region over relatively short periods. However, this rapid mixing only extends to the top of the Ekman layer, and often Ekman-layer properties can be markedly different from those in the overlying water column, as for example in the "Dead Zone" anoxic/hypoxic region underlying the Mississippi River plume (Rabalais and Turner 2001).

While boundary layer turbulence and the thickness of the Ekman layer are relatively well-parameterized in current physical circulation models, exchange across the top of the Ekman layer is not. This exchange can occur vertically, as when occasional storms mix the water column from surface to bottom. Horizontal exchange is generally caused by flow-topography interactions, as when wind-driven upwelling brings thermocline water across the shelf. But it can also be forced by flow past more complex topography, such as banks, headlands, canyons, and coral reefs (Garrett et al. 1993; McPhee-Shaw and Kunze 2002; Edwards et al. 2004). Quantifying this type of exchange is much more difficult, because it requires mapping of currents at horizontal scales of 10-1000 m, and cannot be addressed by a vertical array alone.

2. Particle exchange

Generally, it is the reactions with particulate compounds that create and sustain pore-water concentration gradients that drive solute fluxes. Understanding the exchange of particles between the water column and sediment surface is critical to the advancement of benthic studies in general. The complexity of these processes was also emphasized in Section II.B. To summarize, we need to be able to model and measure particle flux with high spatial and temporal resolution. We must also be able to distinguish particle sources, e.g. whether they are autochthonous or allochthonous. Resuspension flux is poorly understood, particularly with respect to cohesive sediments and wave - current interaction. Resuspension can have very different effects on water column processes depending upon when it occurs in the diagenetic progression. There are also

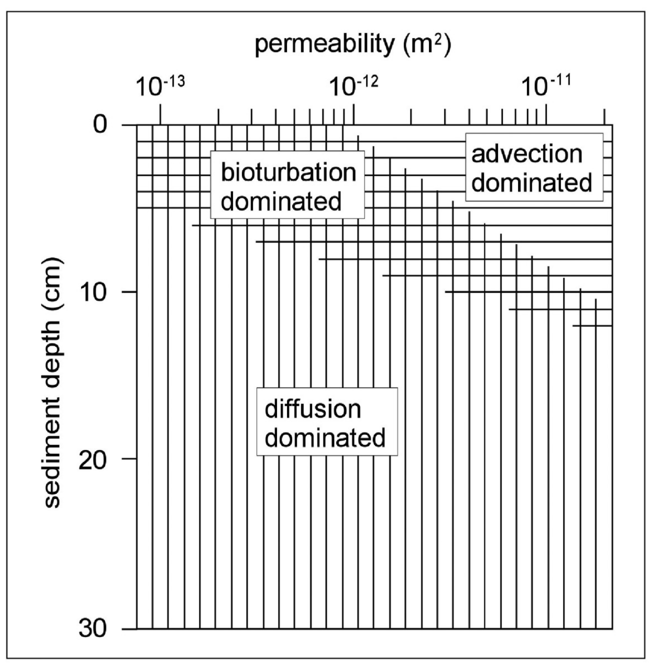
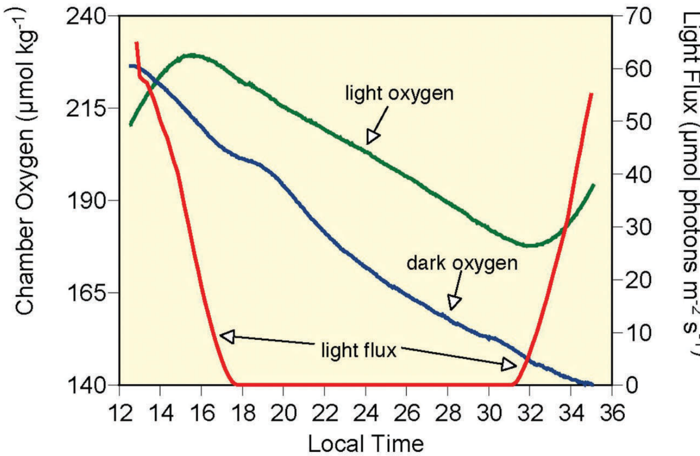


Figure II.C.2. The vertical distribution of the dominant porewater transport processes as a function of sediment permeability. Molecular diffusion dominates at depths greater than approximately 10 cm. The importance of advective transport increases with permeability above values of 10^{-12} m^2. Modified after Huettel and Gust (1992).



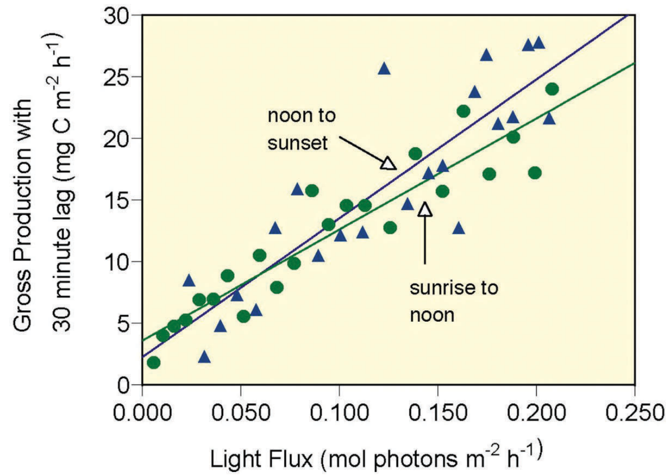


Figure II.C.3. Upper panel: Time-series measurements of the light flux to the sea floor and chamber water oxygen concentrations in paired light and dark benthic flux chambers. The difference between the rate of change of oxygen in the different chambers in the presence versus absence of light provides a minimum estimate of the gross benthic primary production. Note that the oxygen flux in the lighted chamber significantly differs from the dark chamber even at very low light flux. Lower panel: Estimated gross primary production rate relative to the instantaneous light flux binned into 10-minute intervals for the daylight periods. Because there is a time delay in the measurement of the oxygen response, a 30-minute lag period has been applied to the results. Nelson et al., in prep.

important anthropogenic resuspension effects, e.g., trawling. We particularly lack understanding of particle aggregation and disaggregation and the temporal dynamics of these processes. The latter can dramatically alter settling velocities.

3 and 4. Exchange across the sediment - water interface

Just above the interface in low permeability sediments, fluid velocities are slowed by viscosity and chemical fluxes are limited by molecular diffusion (Gunderson and Jørgensen 1990). Spatial and temporal variabilities of this diffusive boundary layer are poorly understood. The layer is topologically very complex, as the fluid - water boundary may extend up over porous or rough biogenic structures, and down some distance into porous sediments. Some biological structures will extend well above the usual viscous boundary layer, and so levels of turbulence or currents due to waves may strongly enhance instantaneous fluxes (Jackson 1997; Nepf 1999; Kaandorp et al. 2003). Steep concentration gradients in the nepheloid layer also may be important in affecting these fluxes. Such effects have not been investigated to date. Sufficiently large organisms may bypass diffusive limitations, for example by pumping water from above the laminar sublayer down into and through the sediment.

When surface sediments exhibit higher permeabilities (Fig. II.C.2; approximately 10^{-12} m^2), pressure fluctuations due to the passage of gravity waves and shear due to bottom currents can significantly enhance interfacial exchange. However, means to calculate such fluxes accurately remain controversial. Surface roughness features such as sand ripples, coral and rubble, all can interact with both bottom currents and wave-induced pore-water motions. These effects have been studied extensively in flumes (Huettel and Rusch 2000; Precht and Huettel 2003) but field measurements are scarce. Assessment of the magnitude and vertical distribution of transport requires not only fine-scale measurements of interfacial pressure and hydrodynamics but also the three-dimensional structure of sediment permeability.

In all sediments, characteristics of the sediment-water interface layer can influence reactions and fluxes. This “layer” is defined as the zone where particle concentration increases from nephloid layer concentration to sediment concentration. The layer can be very thin (e.g., fine sand sediment without fluff layer) or it can be a continuum that gradually changes from

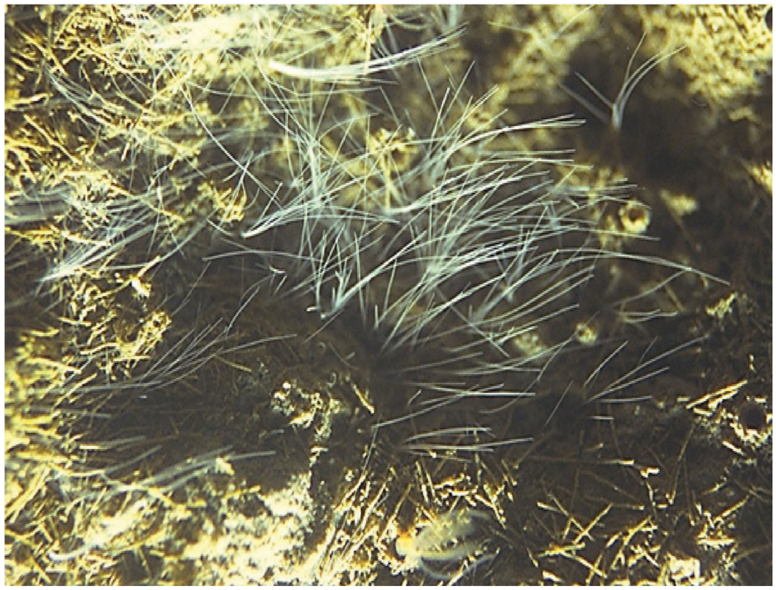


Figure II.C.4. 150 trichomes of the sulfide-oxidizing bacterium Thioploca with a total length of 1 m extend from one square cm of sediment, doubling the surface area for exchange. Figure courtesy of Markus Huettel.

fluid to solid over tens of centimeters. The interface layer can include the fluff layer (Stolzenbach et al. 1992), microbial mats and, if the sediment surface is in the photic zone, a microalgal layer (Fig. II.C.3; Jahnke et al. 2000; Marinelli et al. 1998; Nelson et al. 1999). It can also be shaped by meiofauna or bacteria (Fig. II.C.4), macrophytes, and calcifying organisms, and they will exert a strong influence on fluxes through, and transformations within, this layer. It sets the hydrodynamic roughness of the bottom, and thus it can influence drag on the overlying flow, intensity of turbulence within the Ekman layer, and rate of mixing through its own structures (especially in cases such as coral and kelp). Morphology and ecology of the interfacial layer are strongly affected by episodic sediment deposition, and by human disruption (such as trawling and dredging). Despite their pivotal role for sediment - water exchange, many open questions remain regarding the functioning of interfacial layers in the shelf environment, due to the high degree of complexity and variable temporal dynamics.

5. Sediment mixing zone processes

Porewater and particle transport in the sediments directly below the surface can be important to such processes as diagenesis and carbon burial (Aller 1994; Reimers et al. 1996) and to the establishment of porewater gradients. Exchange of porewater and particles in the sediment can be caused by a variety of processes, such as bioturbation, physical mixing, groundwater seepage, and diffusion (Huettel et al. 1998; Webster et al. 1996). Particle transformation processes can include precipitation and dissolution reactions, aggregation - disaggregation, organic matter degradation with associated redox reactions and secondary biological production. Sediment can also be host to microbial layers, and may be the matrix for systems of macrophyte roots. Although there is a wealth of information available on biological transport in this zone, there are still many open questions regarding the physical mixing process caused by waves and currents and their effects on solute and particle exchange in the seabed.

6. Deeper fluxes

Groundwater - tidal interactions: In addition to wave- and current-driven porewater transport that is generally confined to the upper 10 cm of the sediments, groundwater and other exchanges may occur much deeper in the sediment column. Recent observations on the South Atlantic Bight shelf have revealed advective exchanges occurring several meters below the sediment surface. Measurements in 4-m deep monitoring wells on the inner shelf at the 15-m isobath (Fig. II.C.5, Moore et al. 2002) revealed temperature variations in phase with the tide during the summer (warmer water in the well during high tide) and out of phase during the winter (colder water in the well during high tide) during 4 years of record. These observations require deep fluid exchange between the ocean and the monitoring wells.

Little is known about the mechanisms that control transport magnitude and areal extent of this deep exchange. It has been estimated that it would require only 4% of the inner shelf area to exhibit this exchange to explain the entire

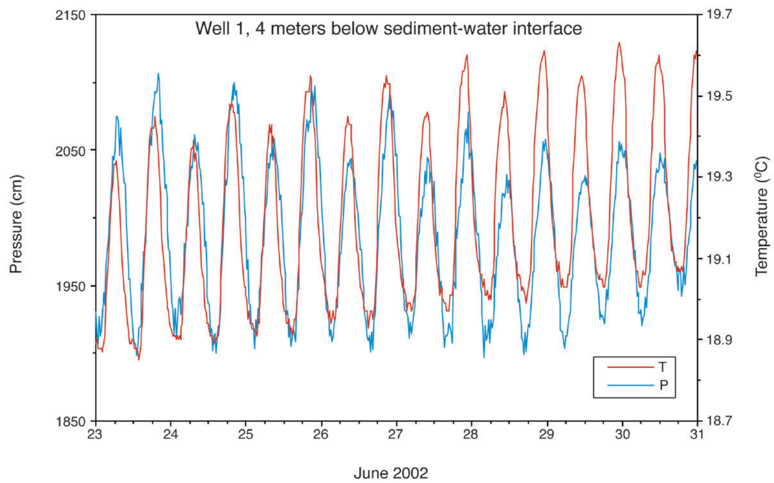


Figure II.C.5. Synchronous variations in pressure and temperature in subsurface well waters on the South Atlantic Bight continental shelf. Temperature fluctuations are temporally well correlated with the tidal cycle, indicating rapid exchange of well water and shelf waters even at a well depth of 4 m below the sediment - water interface. Figure courtesy of Billy Moore.

inventory of measured excess ^{226}Ra in the water column. Because groundwater can also be a significant source of nutrients, it is important to improve understanding of the dynamics of this exchange. In addition to tides, recent observations suggest that the passage of storms and seasonal heating and cooling of shelf waters also impact this process.

Deep porewater exchange provides a direct link between the water column and important biogeochemical processes occurring in the sediments below the mixing zone. They include denitrification, sulfate reduction, and methanogenesis. There may be metal mobilization, authigenic mineral formation, and reverse weathering. In addition there is a growing awareness that microbial communities and viruses inhabit sediments to great depth. This research is drawing more attention recently. The effect of groundwater seepage and reactions in deeper sediment layers are relatively poorly known despite their potentially large impact on sediment - water flux, and indeed on global chemical cycles of numerous elements.

II.D. Benthic Habitat, Community and Activity

Seafloor habitats are the net result of interactions between processes controlling material inputs and exports, internal processes, and an underlying geological framework. Understanding how habitat characteristics are maintained and how they may vary temporally or spatially presents a significant intellectual challenge. In this context, processes cannot be examined individually. Rather the physical, geological, biological and chemical characteristics must be interpreted holistically.

Physical characteristics of the seafloor

While hard-bottom outcrops and corals capture the focus of photographers and sport fishermen, benthic habitats are overwhelmingly dominated by sedimented areas. At these locations, particle grain size is probably the most basic habitat descriptor, for it signals conditions favorable for specific biological communities and material transformation processes. Commonly, grain size depends on the balance between the rate at which fine and coarse-grained sediment is transported into a habitat and the strength of bottom currents and wave shear that control resuspension and export. A small supply of fine-grained materials can produce a muddy habitat in deep water because there is usually little energy to resuspend and transport the fine materials away. However, muddy deposits can also be maintained in energetic, shallow-water areas where the supply of fine-grained sediments exceeds their erosion rate such as near the mouth of a sediment-laden river.

Where sediment input to the coastal ocean is low, sands generally dominate continental shelf environments. On passive margins (such as the eastern seaboard of the US), rise in sea level during the most recent glacial - interglacial transition has trapped river-borne fine materials within coastal estuaries (Emery 1968). This global trend has resulted in sediment-starved shelves where the gradual winnowing of fine-grained sediments has left sandy, relict deposits. Sandy deposits are also often located near the shelf break where breaking internal waves and strong currents winnow away finer grains. However, it must also be emphasized that even in non-accumulating, relict environments, events such as floods and offshore plumes and seasonal pulses in local productivity can provide fresh organic and lithogenic particles that may temporarily accumulate in the surfacial sediments. Advancing understanding of the dynamics of the episodic processes that control the across-shelf transport of sediment was one of the initial goals of CoOP (Brink et al. 1990, 1992).

Sediment permeability, generally correlated with grain-size, exerts a critical control on habitat. In muddy sediments, solute transport is limited to molecular diffusion through the pore spaces and, where present, accelerated transport through organism activities. Where permeabilities are sufficiently large, flow over bedforms (e.g., ripples) and surface gravity waves create horizontal pressure gradients that can drive advective pore water flow through the sediments (e.g., Huettel and Webster 2000; see Fig. II.D.1; Falter and Sansone 2000; Fig. II.D.2.). This advective circulation greatly enhances solute and particulate transport (Precht and Huettel 2003). Although there have

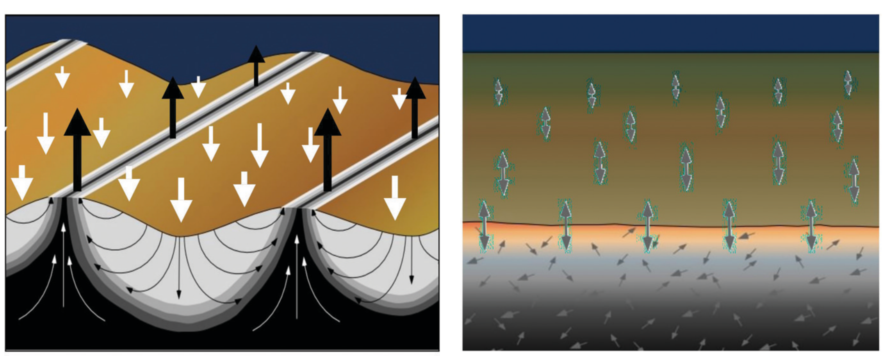
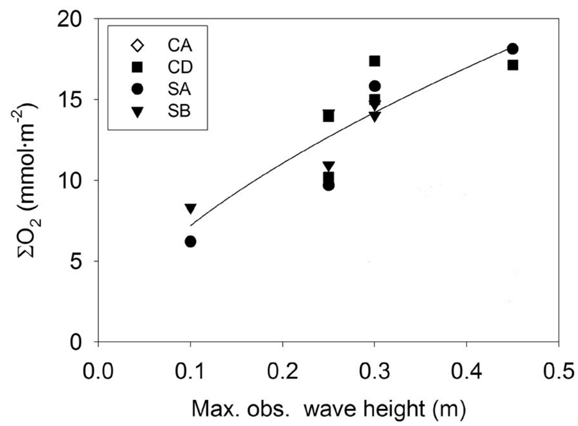


Figure II.D.2. Schematic of interfacial flux in filtering (left) and cohesive (right) beds. Figure courtesy of Markus Huettel.

Figure II.D.2. Depth-integrated concentration of dissolved O_2 (ΣO_2) in sandy sediments on Checker Reef, Oahu, Hawaii versus maximum observed wave heights over a five-month period. Adapted from Falter and Sansone (2000).



been a number of sophisticated laboratory studies of transport and biogeochemical processes in permeable sediments (e.g., Huettel and Rusch 2000; Precht and Huettel 2003), field studies remain few (Reimers et al. 2004). Recent studies in intertidal (Rusch et al. 2000, D'Andrea et al. 2002) and shallow (< 40 m) shelf sands (Jahnke et al. 2000) have begun to quantify carbon cycling under field conditions. There is, however, pressing need to expand field measurements to a range of shelf environments to effectively incorporate dynamic carbon processes in permeable sands into global carbon models.

The role of the biological community in influencing the physical character of the benthic habitat needs also to be studied more widely. Biological structures protruding into the water column can alter near-bottom hydrodynamics; pelletization of sediment particles can influence erodibility; and burrow construction can cement grains together. Unfortunately, little is known about the feedbacks and thresholds that control these interactions.

Benthic biogeochemistry and ecology

Biogeochemical characteristics of benthic habitats depend on input of food energy that can be utilized metabolically and chemically, and on the rate at which metabolic products and reactants are exchanged with the overlying waters. In a broad sense, organic matter that reaches the seabed may be resuspended, remineralized, incorporated into biomass or permanently buried. Remineralization of organic matter results in the regeneration of macro- and micro- nutrients that may further fuel benthic and pelagic primary production. The balance between the metabolic consumption and local and water-column supply of oxidants determines the vertical (and sometimes horizontal) redox zonation of the sediments. The net result exerts a primary structuring influence on benthic ecosystems.

Deposition of organic matter is generally episodic, and much of what we know about the benthic response to phytodetrital pulses (Fig. II.D.3) comes from studies of either shallow, semi-enclosed coastal areas (e.g., Baltic Sea, Graf 1992 and references therein) or the deep sea (e.g., NE Atlantic, Station M in the East Pacific, Beaulieu 2002; Gooday 2002 and references cited therein). These studies have found that sediment community oxygen consumption increases in some cases (e.g., Smith and Baldwin 1984) but not in others (e.g., Smith and Kaufmann 1999). In addition, while bacteria (e.g., Lochte and Turley 1988) and foraminifera (e.g., Moodley et al. 2002) have

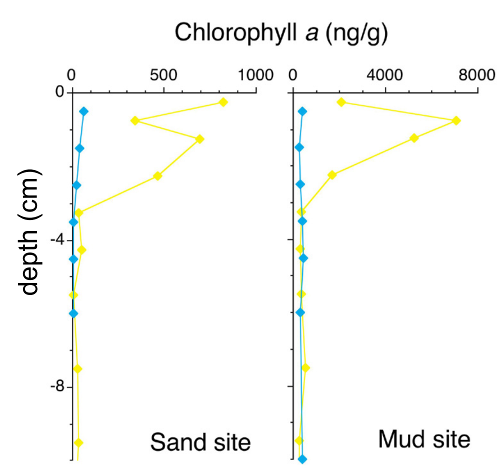


Figure II.D.3. Sedimentary distribution of chlorophyll a at sandy and muddy coring locations on the Oregon continental shelf. The significant difference in near-surface values measured between July (blue symbols) and August (yellow symbols) cores demonstrates substantial episodic inputs and a rapid turnover of phytodetritus in these surfacial sediments. T. D'Andrea, unpublished.

Figure II.D.4. Biological structures at the sea bed. (top) A field of the polychaete Paraprionospio; (middle) worm tubes in reduced sediments showing oxidized walls, and Callianassa, and (bottom) Limulus and a small unidentified crab. Images courtesy of Markus Huettel.

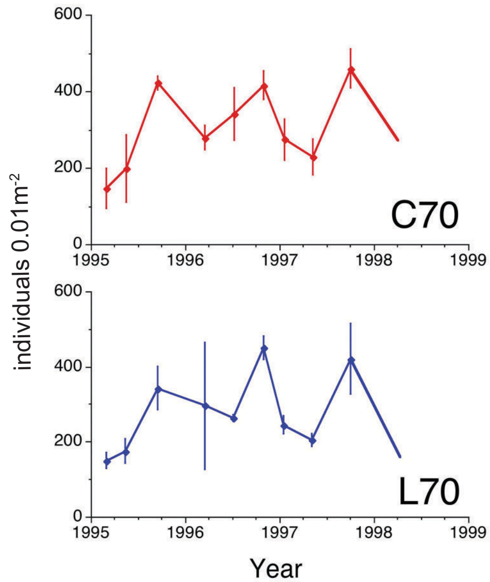
been shown to respond rapidly to episodic phytodetrital inputs, response time of the macrobenthos (i.e., biomass) has been more variable. Recently, experiments using ^{13}C-labeled phytodetritus (e.g., Middelburg et al. 2000) have documented rapid responses in behavior and consumption by the macrobenthos. While these studies are important, it is uncertain to what extent the Baltic and deep-sea results apply to open continental shelves.

Recent studies (Jahnke et al. 2000; Wenzhöfer and Glud 2004) have also demonstrated that in many shelf environments, benthic photosynthesis may be an important process structuring the benthic ecosystem. Seafloor primary production provides a benthic source of oxygen and organic matter and a sink for dissolved nutrients. These fluxes may trigger small-scale spatial and temporal changes in other geochemical signals and benthic faunal activity (Wenzhöfer and Glud 2004). Recent reports of expansive macroalgal meadows in sandy sediments at 100 m water depth in coastal Hawaiian waters may extend our interpretation of ‘photic zone’ (F Sansone, pers. comm.).

Clearly some habitats fluctuate from being shaped by BBL physics versus biological activities. For example, sedimentary burrows and long, sheathed bacterial chains may facilitate transport of oxidants to depth in the sediments, thereby altering metabolic pathways available to the subsurface benthic community. Filter feeders or biological structures that extend above the sediment-water interface may capture particles or alter bottom-water hydrodynamics, facilitating deposition or reducing resuspension, while sedimentary tracks and burrowing may erase seafloor ripples, altering benthic roughness and pore-water advective transfer (Fig. II.D.4). Quantifying feedbacks between physical processes, energy fluxes and biological community composition and function requires mechanistic understanding of individual processes that result in the observed habitat.

Yet our knowledge of shelf macrofauna, in general, is rudimentary. Recent studies on the northern California shelf (Fig II.D.5, Wheatcroft and Fritz in prep.) and in an exposed shelf off Northumberland, England (Buchanan and Moore 1986; Buchanan 1993), have documented a clear seasonal pattern (maximal numbers and biomass in early fall, minimal in

Figure II.D.5. Seasonal variations in macrobenthic population densities on the northern California shelf. Wheatcroft and Fritz in prep.



late winter). However, explicit links to the input of algal carbon on appropriate time and spaces scales have not been made. While there is growing appreciation of the role of macrobenthic activities in solute transport and hence remineralization in shelf sediments (e.g., Jahnke 2001 and references therein; Heip et al. 2001; Berelson et al. 2003), detailed understanding of bio-irrigation is lacking. This knowledge gap is due, in part, to traditional separation among taxonomists, animal behaviorists, and students of processes such as respiration or nutrient recycling (Levin and Snelgrove 2004).

One research topic that may link macrofaunal behavior to chemical cycling is the effects of phagostimulants and waterborne attractants on foraging by benthic macrofauna. For example, large, burrowing gastropods (up to 20-cm long) follow plumes of dissolved chemicals and plow through porous sediments in search of prey. The sensory apparatus of these animals is largely immersed in surficial sediments, and bed-generated turbulence has been shown to enhance olfactory foraging by gastropod predators and scavengers. Transfer of attractive solutes (e.g., prey chemicals) across the sediment - water interface should be of primary importance for the foraging decisions and movements of burrowing gastropods (Ferner and Weissburg, in review). Understanding how benthic exchange rates vary in relation to local hydrodynamic regime and sediment characteristics would improve the ability to predict ecological and sedimentary impacts of these important bioturbators.

Benthic microbial populations and their impact on coastal biogeochemistry are only beginning to be examined, and the development of novel genetic tools is critical to further progress. Numerous fundamental questions must be addressed before the role of the microbial community can be determined in the context of the entire benthic ecosystem. For example, we presently know little of how the structure and function of microbial communities influence carbon and nitrogen cycling in permeable sand sediments of the continental shelf, or whether these structure/function relationships differ from their counterparts in fine-grained sediments.

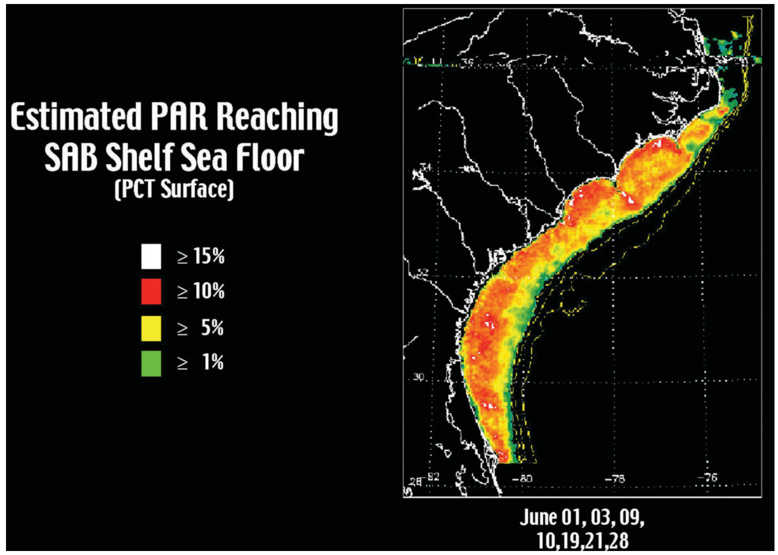
Past studies have hypothesized that bacterial communities are less abundant and their community composition fundamentally different in coarse-grained sediments compared to fine due to a lower specific surface area, lower organic content, or higher predation pressure. Limited previous studies in coarse-grained shelf sands have identified a mixture of aerobic and anaerobic groups including members of the Cytophaga-Flavobacterium, Planctomycete, and delta Proteobacterial sulfate-reducer groups (Rusch et al. 2003; Llobet Brossa et al. 1998). The majority of results on community composition in shelf sands were collected using fluorescence in situ hybridization (FISH) with oligonucleotide probes targeted to the 16S rRNA genes. FISH approaches have not detected significant changes in community composition along environmental gradients in permeable sediments, perhaps due to the broad specificity of the probes used. In addition, the organisms present have not been specifically identified to the genus or species. In order to elucidate mechanisms controlling organic matter processing in permeable sediments, the structure and function of microbial communities catalyzing organic matter decomposition must be better understood, ideally across gradients in sediment characteristics (to address the potential catalytic effect of porewater advection), organic matter loading, temperature, and other important environmental parameters.

Lastly, denitrification and anaerobic ammonia oxidation in shelf sediments are primary mechanisms for marine fixed-N removal, but we know little of their absolute and relative importance. As sinks for N, these processes should directly influence responses of global biogeochemical cycles to critical external forcings such as anthropogenic nutrient enrichments and global climate change. Recent work has suggested that rates of denitrification are significantly greater in permeable continental-shelf sediments than was previously estimated (Rao and Jahnke 2004). Previous studies of rates, pathways, and mechanisms controlling fixed-N removal in continental shelf sediments have focused mainly on fine-grained sediments. The majority of shelf areas worldwide are composed of sandy sediments, where relatively little research has been conducted on nitrogen transformation.

While new methods for assessing denitrification activities have become available (Scala and Kerkhof 1999, 2001), previous work has not often coupled the complete partitioning of organic matter decomposition pathways to an assessment of denitrification under near-in situ conditions. Also, few studies have related directly-measured denitrification rates to activities of benthic organisms in situ. Further research is required to constrain N removal by competing means of N_2 production on continental shelves. These efforts should include less-studied permeable sediments and should incorporate spatial and temporal variability in order to improve ecosystem budgets of N cycling.

II.E. Modeling of the CBED-Defined BBL

Figure II.E.1. Proportion of surface irradiance reaching the South Atlantic Bight sea floor estimated from satellite remotely-sensed reflectance and shelf bathymetry (Nelson et al. in prep.).



Currently available numerical models are insufficient to address the complex interplay of chemical, physical and biological processes and patchiness in the coastal environment. Mechanistic models that span the sediment-water interface and describe the important processes within the CBED-defined bottom boundary layer (CBED BBL) must be developed, refined, tested against observations, and incorporated into more comprehensive model systems that represent the larger-scale processes in the water column and the seabed. Sophisticated models that represent various processes within the CBED BBL exist (e.g., Shum 1992, 1993; Boudreau 1997, 2000; van der Loeff and Boudreau 1997; Hill and McCave 2001; Lee et al. 2002; Wiberg and Harris 2002; Middelburg and Soetaert in press), but none is truly comprehensive, all rely on parameterizations of poorly understood processes, all remain relatively untested by quantitative measurements, and few have been incorporated into more comprehensive model systems. In particular, model systems that couple realistic representations of physics, biogeochemistry, and biology in both the sediments and the water column have yet to be developed.

Three compelling scientific problems illustrate the diversity, complexity, and range of scales that could be involved with modeling the CBED BBL. The first problem is quantifying high rates of primary productivity in the sandy shelf of the South Atlantic Bight (SAB). The second is the seasonal variability of carbon cycling in the coastal upwelling systems of the muddy, Pacific Northwest (PNW) shelf. The third problem is characterization of carbonate dissolution in permeable sediments of the West Florida Shelf (WFS). In all three systems, important chemical and biological transformations, in addition to physical and biological transport processes, occur within the seabed. In the SAB and PNW, quantification of the water-column processes that control exchange of carbon and nutrients with the seafloor is essential in order to understand seabed processes. The penetration of sunlight is critical to benthic productivity in the SAB (Fig. II.E.1), and resuspension and transport of muddy sediments are believed to have a

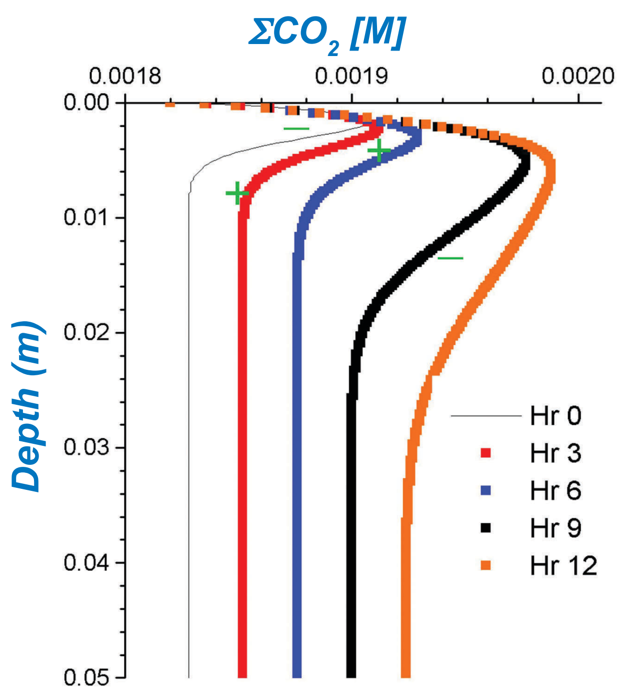


Figure II.E.2. $\Sigma CO2$ profiles from a coupled cohesive, sediment entrainment and bioturbation model. Nonequilibrium profiles result from rapid changes in deposition and erosion. Initial $CO_2 = C_0$. The profile is moving toward equilibrium. Note that (+) denotes deposition and (-) denotes erosion; coordinate system is moving with seabed elevation. Figure courtesy of T Keen and Y Furukawa

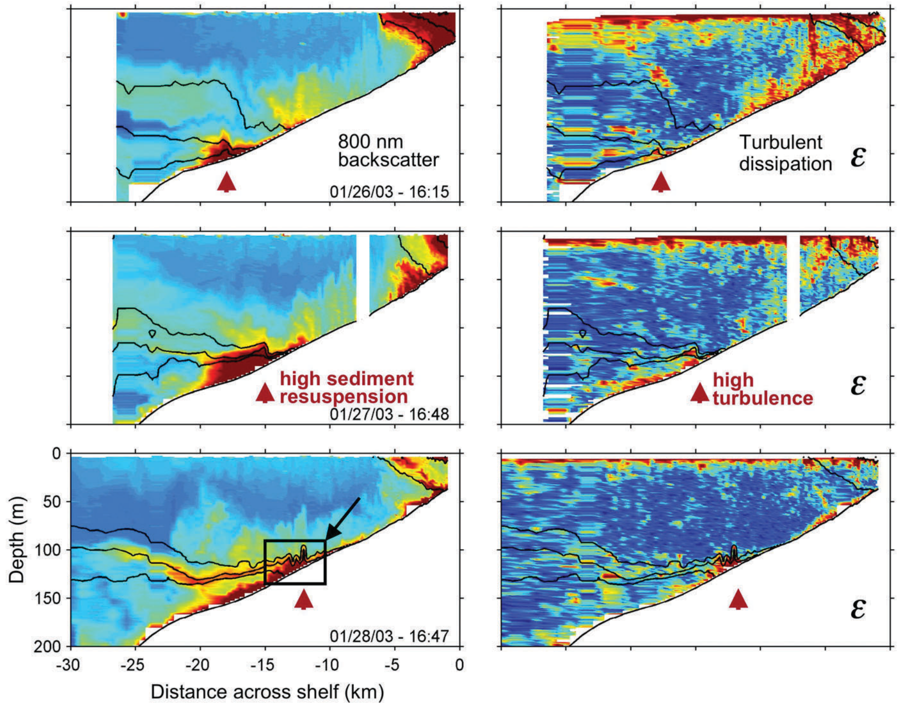


Figure II.E.3. Observations across the Oregon continental shelf (at 45°00' N) from inner shelf (30 m water depth) to shelf break (200 m water depth) in winter 2003 during a period of sustained downwelling circulation. They are derived from Chameleon profiler measurements of density (isopycnals are solid lines), optical backscatter (left panels) and turbulent kinetic energy dissipation (right panels). Observations were made over three consecutive days beginning at the inner shelf at 24-h time intervals. A well-organized southward flow (not shown) dominated the circulation. Light (fresh) fluid was pinned to the inner shelf by the downwelling circulation. The water column was nearly unstratified between 5 and 15 km offshore, resulting in strong mixing from top to bottom, especially during the first transect when winds were strongest. Near the bottom, an internal bore propagated up the shelf (countering the downwelling circulation of near-bottom fluid). It is denoted by the sharp density front and strong, near-bottom mixing. High backscatter within the bores is presumably due to resuspension of bottom sediments by the strong cross-shore flows (> 0.5 m s^{-1}) and turbulence. From our broader range of observations, it is apparent that the bores evolved from highly turbulent flows near the shelf break, through an undular form to clearly-developed internal solitary waves that propagated up the shelf (clearly seen at the leading edge of the bore in the final transect). The latter form has been investigated in more detail by Klymak and Moum (2003).

dominant effect on benthic processes in the PNW. In the WFS, groundwater transport in karsts and submarine channels that characterize the seafloor is a dominant process. In all three systems, vertical scales of seabed processes range from millimeters to meters (Fig. II.E.2), and horizontal scales that characterize regional transport processes are tens of kilometers (Fig. II.E.3). Temporal scales range from seconds (characterizing porewater pumping and resuspension by surface gravity waves, for example) to seasons (characterizing consolidation of seabed sediments and temporal variability in the upwelling circulation, for example).

The number of potentially important processes and phenomena that affect exchanges across the CBED BBL is daunting (Fig. II.C.1). Many of these processes are as yet poorly understood and/or poorly represented in existing models, although some are relatively well known, with mature model representations. A partial list includes the generation, migration, and destruction of bedforms in sandy sediments; advection by fluid motion in permeable sediment porewaters; transport, irrigation and mixing by biological processes; physical and biological resuspension, aggregation, disaggregation, and deposition of particles; formation, transformation, and destruction of interfacial fluff or floc layers and biofilms; degradation and production of organic matter with variable lability; grazing and predation; light penetration and interfacial photosynthesis; microbially-mediated processes (e.g. denitrification); dynamics of macroalgae and seagrasses; and influences of both microzones and mesoscale patchiness. Additional phenomena specific to muddy sites include generation of fluid muds, density-driven sediment flows, consolidation, and effects of spatially and temporally varying porosity. Processes specific to sandy and carbonate sites include carbonate dissolution, interactions between evolving bedforms and particle - solute exchange, and groundwater exchange.

Current coupled reactive transport models must be improved on several levels. They must reproduce the patchiness in time and space

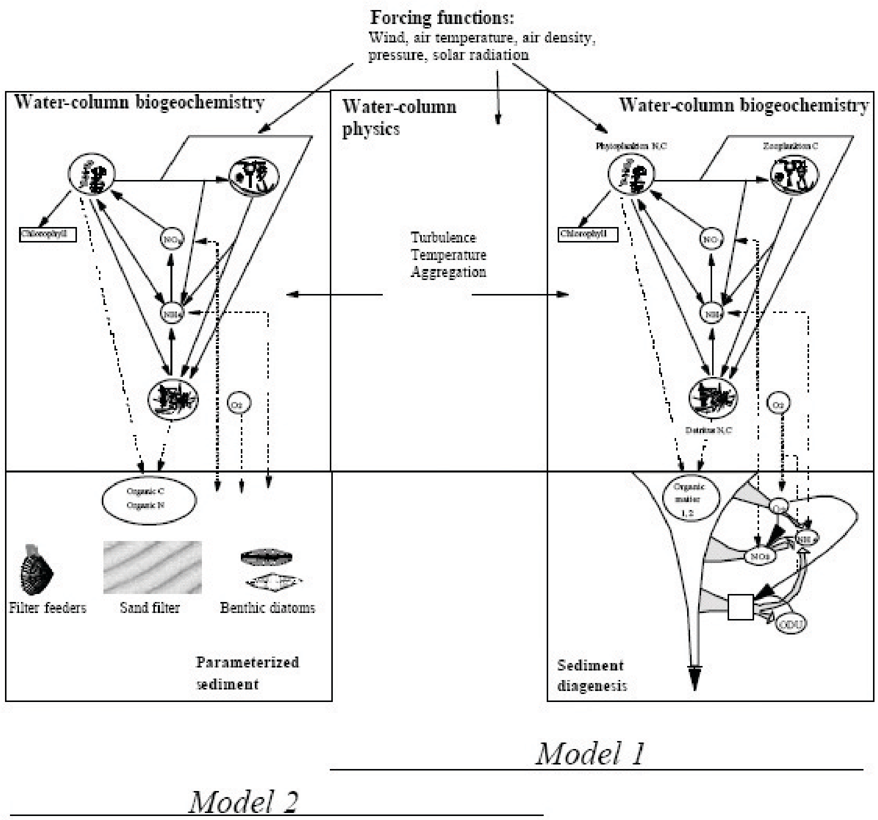


Figure II.E.4. The structure of two models, both encompassing the same physical and pelagic biogeochemical submodels, but differing in their benthic models. Model 1 includes a vertically resolved diagenetic model in the sediments, whereas model 2 employs more simple, integrated parameterizations for benthic filtering activities and benthic primary production. Model 1 is more realistic but more demanding of computer resources and data. Model 2 is less detailed but more useful for numerical experimentation. From Middelburg and Soetaert (2004).

typical of coastal benthic environments and integrate the complex relationships among chemical, physical, meteorological and biological shelf processes. Areas for advancement include:

Data integration and parameterization: Model parameterization suffers from the problem of non-uniqueness. A good fit to observation can typically be achieved with several parameter sets. Similarly, the data used (e.g., concentrations) are often not sensitive enough to a process parameter but integrate a multitude of effects (Berg et al. 1998; Brun et al. 2001; Meile et al. 2001). Rarely are sufficient data available covering extreme events (e.g., blooms, storms). While models may be able to fill in the response to varied forcing, they are typically tuned to average conditions (Nie et al. 2001).

Scaling up: As a comprehensive simulation of an entire region using mechanistic models of sedimentary processes is unfeasible, we need to develop methods for scaling up (Wood et al. 2003 and references therein). In a rather simplistic approach, one can tune models to characteristic "end-member" sites, and scaling up could occur via GIS (e.g., sandy vs. muddy sediments; possibly incorporating probability distributions for their abundance - one challenge is the identification of good end-members; see Schlüter et al. 2000; Quinn 2003). As an alternative, to expand from the small scale where reactive transport model foundation is supposedly valid, we may be able to develop expressions for the scale dependence of model parameters. Such correction terms arising from homogenization substitute for the characteristics that are not resolved explicitly at the larger scale (Kechagia et al. 2002; Meile and Tuncay, in review).

It is unlikely that a single "super-model" of the CBED BBL, including all possible interactions under all possible circumstances, is either feasible or desirable at the present time. Meaningful CBED BBL model studies, in combination with models of larger-scale dynamics, require judicious combinations of simulations at varied scales (Figure II.E.4), in addition to careful consideration of model results in light of inevitable uncertainties in model parameterizations, forcing, and boundary conditions. Interdisciplinary combinations of previously separate modeling approaches may be particularly fruitful. Among many such possibilities are models of advective porewater flow, particle filtering, and biodegradation coupled to models of sediment transport and dynamically varying seabed

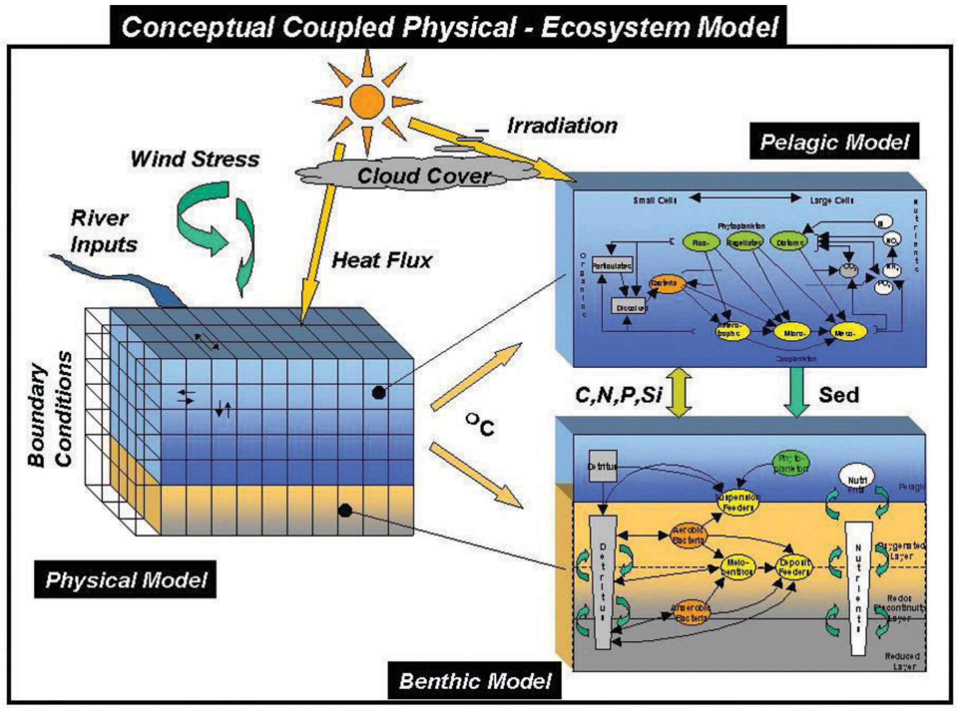


Figure II.E.5. Schematic of the coupling of pelagic, benthic and physical numerical models.

topography in sandy sediments, or models of early diagenesis coupled to models of biofilm formation or models of dynamically varying mud transport and consolidation in muddy sediments.

Ideally, these model frameworks would couple mechanistic models that represent processes at disparate scales (see, for example, Fig. II.E.5), in a manner that is standardized (i.e., with a uniform set of exchange variables and interpolators), distributed (i.e., consisting of independent modules communicating through a central server), and coupled (i.e., including multi-model feedback with standard interpolators).

Regardless of the specific modeling approaches adopted, they will need to be closely allied to related field and laboratory studies. In some cases, new measurement technologies are required to constrain and test models of the CBED BBL. Among the most important requirements are better analytical techniques for chemical species; in-situ measurements of particle size, density, and composition; and high-resolution, time-series measurements of seabed properties, biogeochemical constituents, and photosynthetic rates. In other cases, existing models can be used to generate testable questions and/or hypotheses, or to help design measurement programs, in the hope that data collected will enable improvements to the original models and their integration into more complete modeling systems.

II.F. Technologies - Opportunities and Challenges

Recent, rapid developments in remote and in situ sensing instruments, data communications, modeling, visualization, and archiving technologies provide exciting new possibilities for coastal research in general. Through these technologies, processes and system dynamics can be observed over a broader range of temporal and spatial scales than could be achieved previously. Many of these new tools are specifically directed toward observing the sea surface, such as the suite of sensors now routinely deployed on orbiting satellites. As this technology evolves, we can expect improvements in horizontal resolution. In addition, possible deployment on geostationary satellites and expanded use of aircraft may provide another major improvement in horizontal resolution. Shore-based HF radar stations provide means for measuring coastal surface currents at relatively high resolutions and efforts are underway to expand the coverage of these radars to all US coastal waters. Emergence of these technologies indicates a major opportunity to advance understanding of coastal systems.

As important and useful as the above technologies are, coastal systems present additional challenges. As described in the previous sections, interactions with the seafloor play a critical role in determining coastal dynamics. For example, friction with the bottom controls internal wave and current-generated turbulence; solute exchange across the sediment - water interface impacts geochemical cycles, nutrient inputs and biological production; and sediment resuspension and bed load transport are important pathways for oceanic - shelf and estuarine - shelf material exchange. Because the latter is controlled by well-defined thresholds where rare, energetic events often dominate over frequent, less-energetic events, continuous observation is necessary for significant advancement. As noted above, however, most of the emerging remote sensing technologies focus on the sea surface. To better advance understanding of coastal dynamics, therefore, development of benthic sensing systems is required.

Observing the dynamics of seafloor processes presents challenges beyond deployment and maintenance of in situ sensor, power and communications systems. Seafloor habitats are particularly sensitive to the presence of

Figure II.F.1. USGS autonomous "Poking Eyeball" seabed camera system. To periodically sample the bottom, a winch automatically lowers a digital camera to the sea bed until sediment grains are pushed right up to the window on the camera housing. (upper left) Just before deployment, (upper right) after 101 days on the seafloor, (lower) example image (7 mm across) from a 9-m site in the Adriatic Sea. The extreme biofouling emphasizes the potential environmental disturbance associated with any seabed instrumentation. From Chezar and Rubin (2003) and Sherwood (2003).

structures that may enhance scouring of the seafloor or particle deposition. Fish and, in particular, crabs may congregate at observatory installations where they may be joined by other "fouling species" that are attracted by the modified flows and substrata (Fig. II.F.1). Altered flows and habitat may, in turn, alter solute exchanges. This "island effect" cannot be eliminated by design. Therefore, seafloor observatories will require the use of mobile sensor platforms and sensors that can extend their measurement range away from the physical installation.

To answer the questions posed in the preceding sections, a broad array of measurements and measurement platforms will be required. It is not possible to review the state-of-the-art of all the required sensor measurements and provide an assessment of future developments and advances for each. Most of the identified research topics share the need to observe physical (water and sediments) dynamics, biological activities and seafloor solute exchange of the benthic boundary layer system. In the following we highlight present and emerging observing capabilities for these topics.

Physical dynamics of the water and particles in the benthic boundary zone

Relatively mature sensors are presently available to characterize physical conditions in the benthic boundary layer (Fig. II.F.2). In addition to temperature and conductivity, well-established acoustical techniques can measure velocity, stress, turbulence, suspended particle concentration, bed sediment type, and bedform morphology and migration (Ellingsen et al. 2002; Betteridge et al. 2003). Multi-frequency approaches can potentially be used to measure suspended particle size and distinguish among organisms of different sizes within the water column.

Laser diffraction, digital photography, video and particle imaging velocimetry can be used to document turbulence (including spatial structure), particle concentration and size, organism type and activity, bed evolution and, within chambers, particle settling velocity (Lunven et al. 2003; Mikkelson et al. 2004). Optical remote sensing is limited by turbidity under high-energy conditions, but near-field observations can continue to be collected within the water column and at the seabed (Fig. II.F.1).

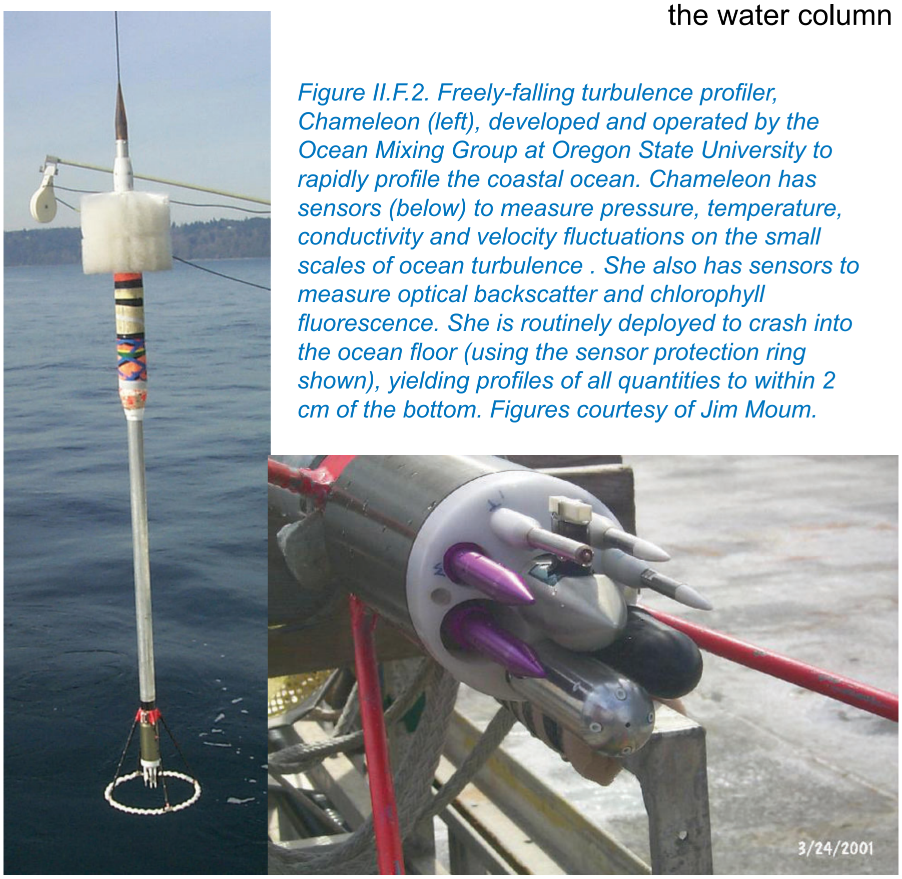


Figure II.F.2. Freely-falling turbulence profiler, Chameleon (left), developed and operated by the Ocean Mixing Group at Oregon State University to rapidly profile the coastal ocean. Chameleon has sensors (below) to measure pressure, temperature, conductivity and velocity fluctuations on the small scales of ocean turbulence . She also has sensors to measure optical backscatter and chlorophyll fluorescence. She is routinely deployed to crash into the ocean floor (using the sensor protection ring shown), yielding profiles of all quantities to within 2 cm of the bottom. Figures courtesy of Jim Moum.

Documenting the immediate impact of infrequent, highly energetic events on the benthos requires in situ time-series from long-term deployments. Acoustics, video and new sensor technologies for time-series observations are generally power- and data-intensive. Thus external power and high-bandwidth communications would significantly increase the duration, sophistication and extent of such deployments. It is clear that advances in the observation of physical disturbance in the benthic boundary layer would greatly benefit from the establishment of community-supported coastal observing systems. Because of the dominance of individual events in the physical transport of sediments, the ability to control these systems in real time will offer an unprecedented view of benthic processes.

At greater spatial scales many of the mobile platforms envisioned for coastal ocean observing systems will be extremely important. AUVs, ROVs, gliders and ship-based towed and station-deployed samplers and sensors will be essential for rapid mapping of horizontal patterns of tracers within the boundary layer.

Biological community composition and activities

Few strategies exist to examine biological community structure and dynamics. Sector-scanning acoustical techniques can provide time-series indicators of benthic activity both at the surface and within the upper few centimeters of the sea bed. It may also be possible to measure the relative intensity of bioturbation remotely via hydrophones, at least under quiescent conditions. Compared with other observational and sampling techniques, acoustics are relatively non-intrusive, and active sonar is able to operate in the benthic boundary layer under high-energy conditions. Radially scanning sonars are also ideally suited to monitoring fish abundances and behaviors. Fishes often show daily patterns of congregation at and dispersal from the seabed. Split-beam sonars add considerable capability for studies of nekton and plankton behaviors, including predator - prey interactions.

Subtle enhancement of monitoring and experimental capabilities can be achieved from continuously radially scanning sonars of moderately low frequency (40-200 kHz) set to scan at shallow grazing angles. These frequencies and geometries show some penetration of surficial sediments and backscatter both from surface microtopography and from largely biogenic volume heterogeneities (Jackson and Briggs 1992; Dworski and Jackson 1994). By correlating backscattered wave forms, one can assess the extent of change between two scans of the same seabed area. Absent any geophysical sediment transport events, the rate of decorrelation is largely biogenic (Jumars et al. 1996). Where episodic transport occurs and bedforms are produced, their biogenic degradation can be monitored (Richardson et al. 2001). Higher frequencies typically used in side scan (300-800 kHz) are useful for monitoring

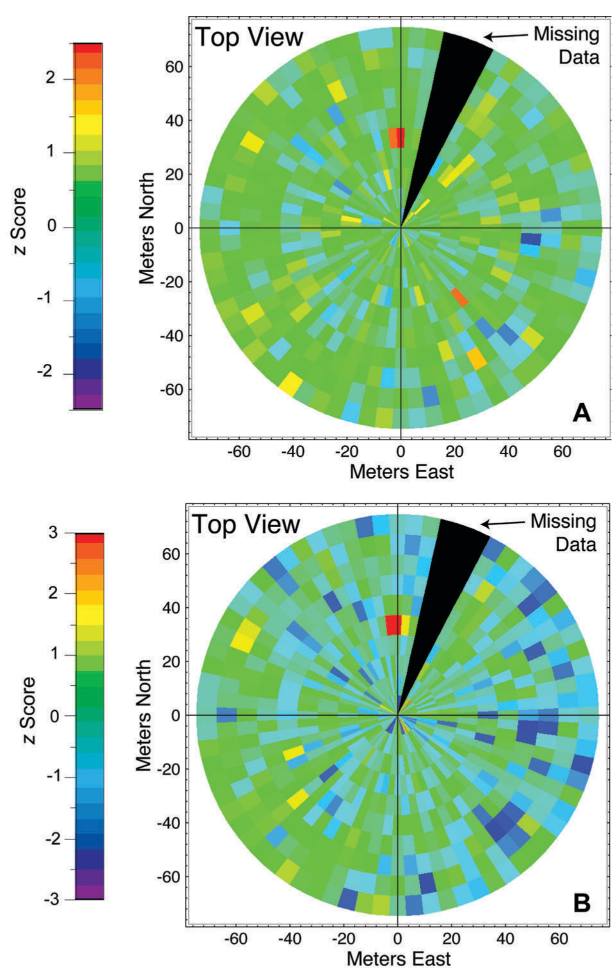


Figure II.F.3. Examples of processed data, plotted as z scores, from a circularly scanning, seabed sonar operating at 40 kHz as part of the STRESS (Sediment TRansport Events on Shelves and Slopes) Program (extracted from Jumars et al. 1996). (A) Change in the backscatter signal from the seabed in each pixel in 0.1 d, averaged over a 49-d record from 91 m water depth in winter 1988-1999. Pixels showed high consistency in activity levels during the entire study. In cabled mode, activity levels could provide one means of stratifying samples or selecting experimental sites. (B) Apparent activity levels of large nekton and megafauna showed a gradient toward increasing activity westward across the study site as well as considerable smaller-scale patchiness. Cabled time series could be used to detect artifacts such as increasing aggregation over time around a benthic observatory.

microtopography but under most conditions and geometries show limited bottom penetration.

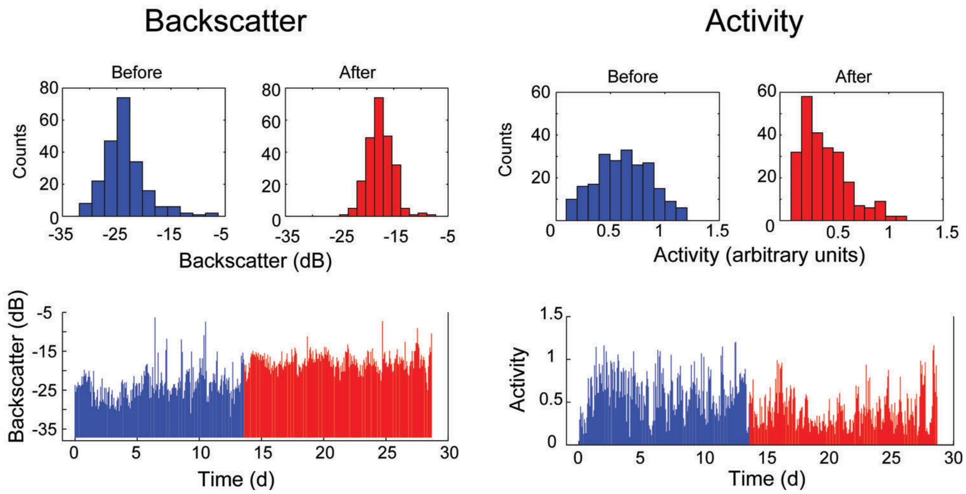


Figure II.F.4. Example of 40-kHz acoustic data collected from manipulations at the seabed as part of the SAX99 Program (Richardson et al. 2001) at a depth of approximately 20 m in 250-µm sands. In this experiment, the treatment comprised emplacement of sand dollars at a density of 100 m^{-2} *in a corral made with plastic fencing. The experiment was done in triplicate, with nearby cage controls. All three replicates showed similar effects of increased backscatter and decreased rate of decorrelation of the backscatter signal (or decreased "activity" as defined in Jumars et al. 1996). The mechanism of the effect remains unclear; this Gulf of Mexico species of sand dollar is never observed on the sediment surface but burrows at approximately 5 cm depth. Cabled observatories would allow much longer and repeated experimentation to elucidate the underlying mechanisms and ask related questions, such as the effect of the manipulation on microbial activities.*

Besides providing a valuable self-monitoring tool to see whether areas near an observatory change over time more than do more remote regions and to determine the spatial extent of such artifacts, periodic scans provide valuable context for basic biological, geological and chemical observations. Whenever such observations have been made, some areas have shown greater rates of change than others (e.g., Fig. II.F.3). Subsequent direct sampling and analysis can determine how these regions differ geochemically, microbially and faunally. The more correlations found, and processes identified that correspond with acoustically detected change, the more valuable becomes the acoustic experiment.

A focus on acoustics

Besides greatly enhancing observational capabilities, acoustics also provides context for other forms of experimentation. Local animal abundances can be manipulated, and biogenic effects can be mimicked, with acoustics used to monitor the persistence of the effects (Self et al. 2001). Intervention analysis is ideally suited to the kinds of time series that acoustics readily provide. Intervention analysis also provides a powerful statistical methodology to quantify experimental effects when the time and location of the experiment are clearly known, but the consequences are not (Box et al. 1994; Self et al. 2001). In this approach, one fits an explicit time-series model to the acoustic data prior to the manipulation, and then the experimental effect is quantified as a departure from the model's predictions after the event. These approaches should be just as powerful for quantifying consequences of natural events, such as storms or phytodetrital input events.

It is important to emphasize that acoustics have been used in this low-grazing-angle, scanning manner for seabed process studies in only a few instances, and there is yet no coherent mapping between specific animal activities and acoustic signatures (Fig. II.F.4). It is a young and tantalizing technology that has been severely limited in the past by onboard data storage capacity and power (e.g., Self et al. 2001). Cabled observatory applications will remove these serious constraints.

By contrast, acoustics have a longer history of application to plankton and nekton, but there is still considerable information to be gained from range-gated, multi-frequency acoustic time series looking upward from the seabed. Recent studies in West Sound, Orcas Island, Washington, and in the Damariscotta River (a coastal fjord in Maine, with little freshwater input), reveal striking nocturnal migrations from the seabed, dominated in both cases by mysid

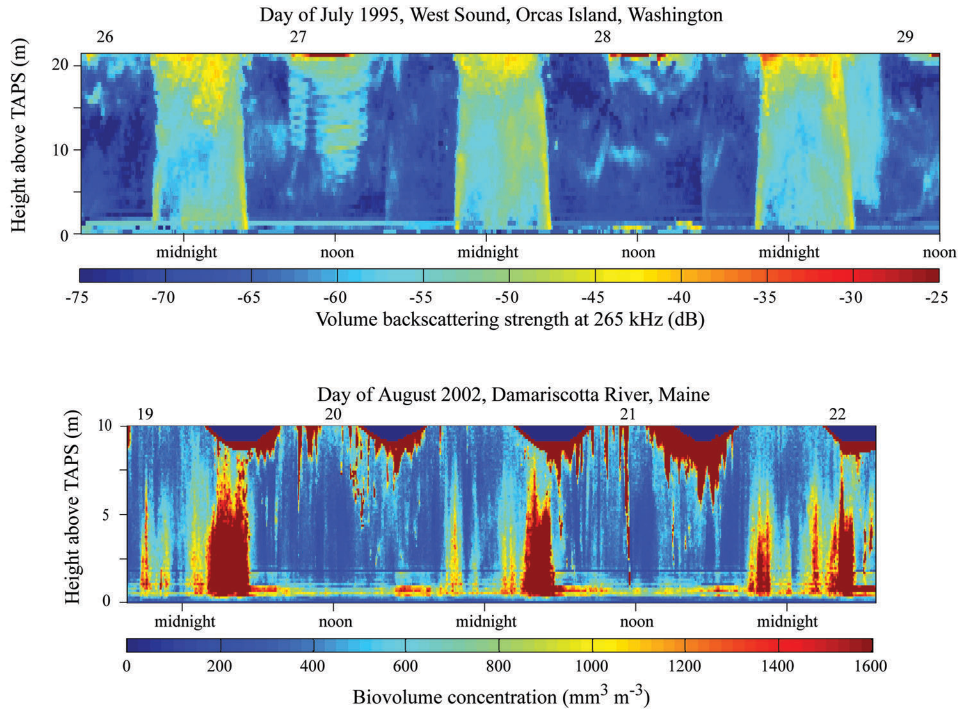


Figure II.F.5. Emergence events from the seabed. In both regions, emergence typically begins shortly after dusk. At the Damariscotta site, however, a second, larger event begins upon the first tidal deceleration after dark, irrespective of current direction. In both places, the mysids that constitute most of the emergence dominate planktonic (or micronektonic) biomass when they emerge. (Upper panel from Kringel et al. 2003, lower panel from data of Taylor et al. in review)

shrimp of order 1 cm long (Fig. II.F.5). Although such emergence patterns have been known for some time, the magnitude of such events appears to have been seriously under-appreciated. In both the Washington and Maine sites, integrated water-column biomass is an order of magnitude higher at night than during the day. Mysids are notoriously good at evading plankton nets, so perhaps their nighttime dominance of the plankton should not have been such a surprise.

Acoustics are also revealing previously unknown details, such as cueing of emergence by relative rate of change of light intensity, modulation of group vertical swimming speeds by ambient light, and substantial modulation of emergence by tidal phase (Abello et al., in review; Taylor et al., in review). In the Maine system, the migrations begin only when a benthic bloom terminates in late spring and last only until a fall benthic bloom begins. Contributions of such daily and seasonal migrations require serious attention in models and measurements of benthic-pelagic coupling. Animals in this size category moreover are major dietary components for juvenile fishes of commercial importance, and the migrations are surely key to encounter mechanisms used by predators. Acoustics through multi-frequency and split-beam approaches from cabled observatories hold great promise for vastly increasing understanding of planktonic and nektonic behaviors overall and interactions with the seabed in particular.

Solute fluxes across the sediment-water interface

Solute flux across the sediment - water interface is a fundamental aspect of the benthic system. In general, this flux indicates the degree of coupling between pelagic and benthic systems, reveals the magnitude of benthic metabolism, responds on time scales relevant to assessing recovery from disturbance, and includes potentially important inputs from groundwater flow.

In muddy sediments, where permeabilities are generally less than approximately 10^{-12} m^2, sediments are capped by a diffusive sublayer. Under these conditions, solute transport is controlled by molecular diffusion except where enhanced by the activities of benthic organisms. In fine-grained sediments, diffusive fluxes can be estimated from near-surface porewater or diffusive boundary-layer concentration gradients, and appropriately corrected molecular diffusion coefficients (Fig. II.F.6). Microelectrodes have significantly increased the resolution with which near-surface gradients can

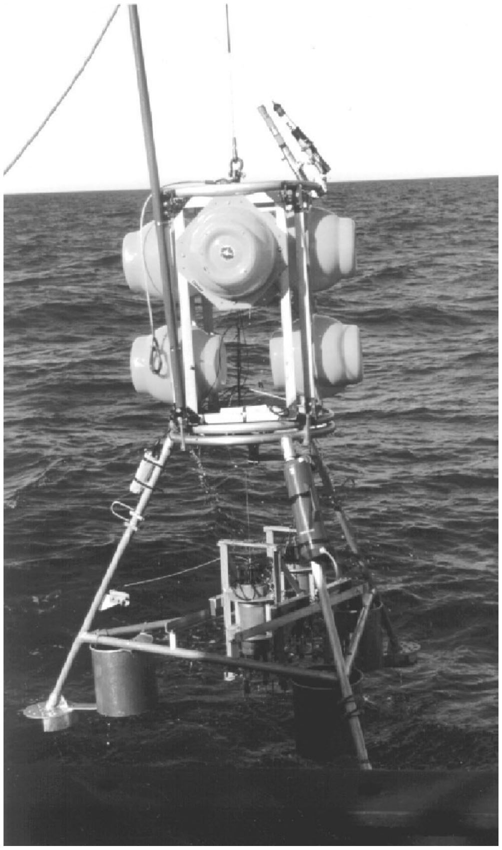
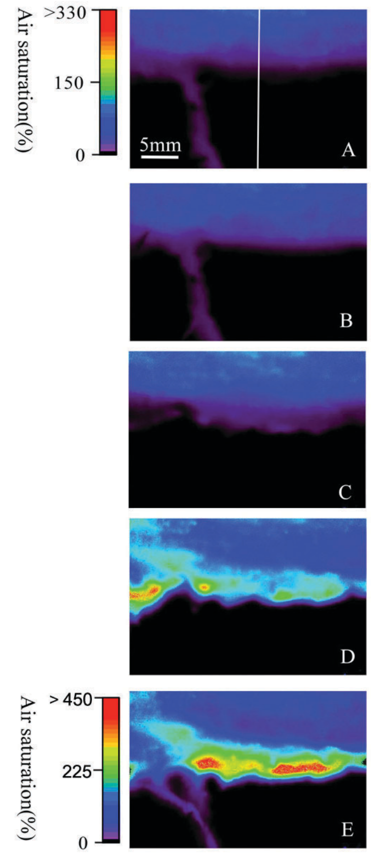
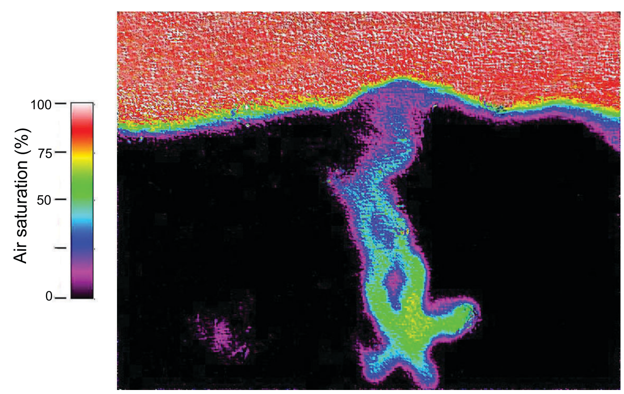


Figure II.F.6. In situ MicroProfiler, or IMP, free-vehicle instrumentation employed to measure sediment - water interfacial properties with microelectrodes. Image courtesy of C Reimers.

Figure II.F.7. (right) Oxygen distribution measured via planar optode in shallow photosynthetic sediment at 1 m depth in Öresund (SE Skagerrak, Denmark). The images were obtained at 7:33, 8:33, 9:33, 10:33 and 11:33 h, corresponding to a down-welling irradiance at the sea surface of 1, 8, 240, 633, and 1102 μmol photons m^{-2} s^{-1}. Upper scale is for panels A-D, lower scale is for panel E. From Glud et al. (2001).



(below) Oxygen distribution around a burrow of the brittle star Amphiura filiformis (H Staahl and RN Glud, unpubl. res.)



be measured, greatly improving these estimates. Recent advances have extended microelectrodes to voltammetric and optical microsensors (Fig. II.F.7), extending measurements to a larger suite of solutes (Viollier et al. 2003).

Direct sea floor sampling is inherently destructive of the local environment. Other porewater-sampling techniques that require coring or insertion of large sampling probes, such as peepers, are particularly disruptive. Because of their small sizes, microelectrodes measure near-surface sediment properties with little disturbance. This feature is important because microelectrodes have the potential to be installed on benthic instruments where they may be repeatedly deployed to examine the time-evolution of near-surface gradients after a perturbation. Spatially adjustable benthic profilers that are programmed to probe and/or core over grids through time are desirable (Fig. II.F.8). Another strategy that can be applied independently or in conjunction with spatial adjustment is adaptive "smart" sampling, which chooses the best time to perform destructive observations based on environmental triggers, such as hydrodynamic energy or changes in surface morphology. However, it must be remembered that the presence of any anthropogenic structure above or below the seabed produces its own form of physical disturbance (Parker et al. 2003).

In muddy areas where macrobenthic organisms may significantly increase exchange from molecular rates, benthic flux chambers have

Figure II.F.8. An autonomous resistivity profiler capable of relocating the position of the probes to facilitate repeated measurements in sediments without extensive disturbance.

proven an accurate tool for assessing fluxes. Although results are generally robust, chamber hydrodynamics can alter measured results when transport across the diffusive boundary layer limits the overall flux. With a few caveats about spatial scales of heterogeneities, these instruments provide accurate estimates of sea floor solute exchange even when exchange is enhanced by macrobenthos (Rao and Jahnke 2004; Fig. II.F.9). Furthermore, they have been installed on mobile, seafloor platforms to obtain time-series measurements (Smith et al. 1997).

Thus, for fine-grained, low-permeability environments, the above techniques are robust and provide accurate assessments of seafloor solute exchange and are ready to be adapted to observatory deployment platforms.

Eddy correlation above high-permeability sediments

Sediments of higher permeabilities (>10^{-12} m^2) present a greater challenge. For these types of sediments traditional corers work poorly, often not retaining intact porewaters; porewater diffusion gradient calculations do not reflect in situ fluxes; in situ chambers may interfere with bottom flows and alter benthic exchange; and whole core incubations cannot mimic in situ hydrodynamics and benthic light levels (Boudreau et al. 2001).

Recently the eddy correlation technique has emerged as a potentially powerful strategy for assessing benthic solute fluxes. This technique is applicable to all sediment types but its development is especially critical for sediments of high permeabilities where other techniques become inaccurate. In principle, this technique can be employed to measure the flux of any solute by simultaneously measuring the turbulent vertical motions and concentrations of the solute in near-bottom waters. Mean flux is then estimated as the sum over the sampling period of instantaneous upward and downward fluxes. Acoustic Doppler velocimeters provide an off-the-shelf technology for monitoring turbulent water motions. This technique is

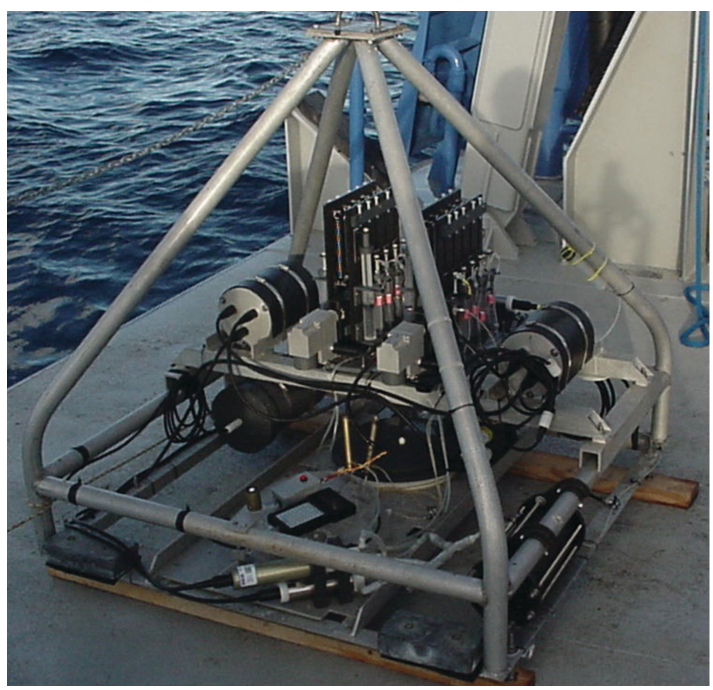


Figure II.F.9. Autonomous light/dark benthic flux chamber instrument. This device emplaces a clear and an opaque benthic chamber on the seafloor; circulates water to stir the overlying chambers; recovers time-series samples from within the chambers; monitors the oxygen concentration of the chamber waters continuously; and measures the ambient seafloor irradiance continuously.

presently limited by the availability of sensors that can detect chemical concentrations in the same water parcel and with the same or greater frequency as the turbulence measurements. To date, this technique has been successfully employed to estimate the fluxes of heat (Fukuchi et al. 1997; Shirasawa et al. 1997) and oxygen (Berg et al. 2003; Fig II.F.10). Also, promising estimates of particle fall velocities by eddy correlation were obtained by Fugate and Friedrichs (2002). Attempts are currently underway, utilizing the ISUS optical nitrate sensor, to also apply this technique to the flux of nitrate (K Johnson, pers. comm.). Because this technique is non-invasive, it is well suited for time-series studies.

Variations on this technique might be possible in which directly measured eddy fluxes and derived eddy diffusivities for one quantity are used in conjunction with careful vertical gradient measurements of a second quantity to estimate the vertical flux of the latter material. This modification will require additional development but holds the promise of extending this technique to solutes for which there is no rapid-response sensor available. The eddy correlation technique for measuring benthic fluxes can, in theory, be extended by using "disjunct eddy sampling" (Rinne et al. 2000). In disjunct sampling, short, separate samples are taken instead of continuously sampling the overlying water as in eddy correlation techniques. This method reduces the number of samples in a given time period but allows more time to process them. This additional analysis time would allow the fluxes of chemical species such as dissolved nutrients to be determined. However, this technique will require sampling over a longer period than is needed for eddy correlation techniques, and it is not presently known if this limitation will prevent the measurement of natural (e.g., tidal) temporal variability. Also, this technique, while validated for land-air exchange measurements, has not been tested with benthic systems.

Ground-truthing under field conditions and comparisons with in situ flux-chamber measurements (Berg et al. 2003) suggest that the eddy correlation technique may offer an improved approach for determining O_2 uptake by sediments. The technique is superior to conventional methods as measurements are done under true in situ conditions, i.e., without any disturbance of the sediment and under natural hydrodynamic conditions. Furthermore, this technique can be used for bio-irrigated or highly permeable sediments, such as sands, or for rocky substrates where traditional methods usually fail.

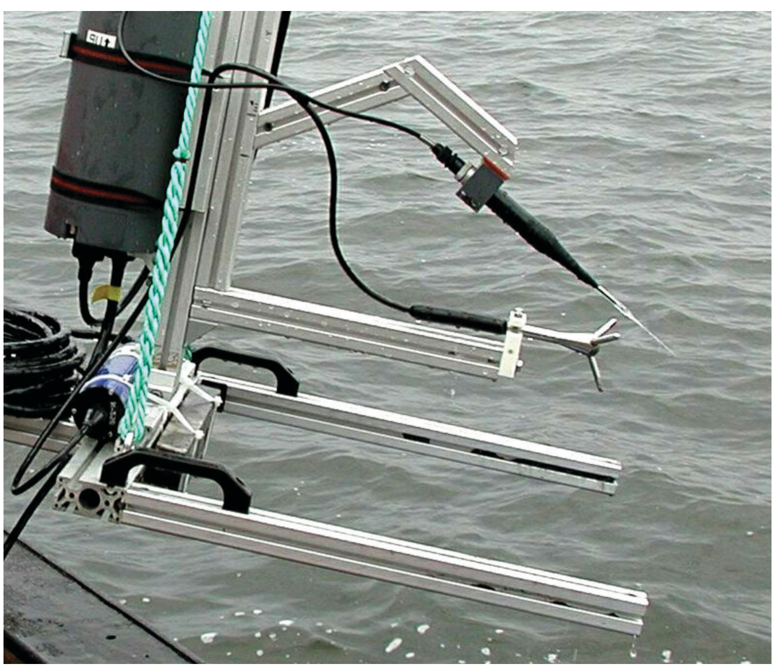


Figure II.D.10. Instrument package for measurement of vertical turbulent oxygen flux using the eddy correlation method. Turbulent velocities are measured acoustically in a small volume using an ADV (Acoustic Doppler Velocimeter), and oxygen is measured in nearly the same spot using a fast, in situ sensor, both at 25 Hz (Berg et al. 2003).

III. Plan for Action and Recommendations

Oceanography is at a critical crossroads. To significantly advance understanding of ocean processes and ecosystems, expeditionary research must be augmented by real-time remote observations that can supply measurements on a wider range of space and time scales than achieved previously and can direct shipboard and other sampling activities to specific targets and features. Processes below the sea surface that are dynamic and spatially variable should no longer be judged unfathomable. This change of perspective is particularly important for benthic studies where many processes, e.g., sediment transport, may have distinct thresholds and specific, episodic events may dominate mean transport. Studies of benthic boundary layer dynamics and the development of sea floor observing technologies must proceed in concert.

There was a strong consensus at the CBED workshop that the timing is ideal for an integrated, interdisciplinary research initiative focused on the linkages between external meteorological and hydrological forces and the processes of particle and solute transformation, transport, and exchange in the coastal ocean BBL. The seafloor was recognized as an integral component of coastal ecosystems, exerting considerable control over the biogeochemical and physical dynamics and biological communities that shape these environments. Furthermore, because seafloor interactions are important in all coastal settings, BBL studies conducted in a number of contrasting regions of the US continental shelf are needed as significant components of future syntheses of CoOP Program research.

Scientific goals and recommendations endorsed during the CBED Workshop appear throughout this report. In the following, we highlight the major recommendations.

Future interdisciplinary projects should quantify the dynamics of the BBL system and its response, in the widest sense, to various forms of both natural and anthropogenic disturbance. Because dynamics will vary with shelf characteristics such as bathymetry, sediment grain size and permeability, studies should be distributed among contrasting coastal regions. Specific research examples include the need to further examine relationships among flow fields, entrainment, deposition and sediment biogeochemical processes in cohesive sediments, and porewater advection, filtration and particle mixing in coarse-grained sediments. Across diverse seafloor habitats, factors causing porewater and particle transport, such as waves, macrofauna and meiofauna, groundwater flow, as well as mobile fishing gear, must be studied.

Because each measurement technique is associated with a limited range of spatial and temporal measurement scales, a multiplatform, holistic approach should be adopted in which ships, satellites, observatory moorings, autonomous vehicles, and other technologies are employed to optimize the range of space and time scales observed. Continued development of BBL sensors and deployment platforms is recommended, especially for those techniques that permit non-intrusive determinations of organism activities and abundances, and seafloor solute and particulate exchange. Particularly promising, non-intrusive sampling techniques include acoustic scanning and eddy correlation with high-frequency concentration measurements of suspended and dissolved constituents.

Fluxes of oxidants, nutrients, essential trace metals and organic matter that determine relative roles of the benthic and pelagic subsystems must be studied at key horizons in the BBL, and in concert, to advance understanding of contrasting coastal ecosystems. Given the potential importance of benthic productivity in many coastal regions, projects that promise to establish new means to make widespread benthic productivity measurements as well as means to determine other critical fluxes in time-series should be supported.

Structure and function of BBL microbial communities catalyzing organic-matter decomposition must be better understood, ideally across gradients in sediment characteristics, organic-matter loading, temperature, and other relevant environmental parameters. Continued development of molecular biological techniques for use in sediments is especially encouraged.

Experimental studies should be designed to improve our understanding of process dependence on measurable system variables such as temperature, light, flow, particle concentration, wave height and ripple spacing leading to reliable model parameterizations.

Comprehensive, interdisciplinary mechanistic BBL models bridging the sediment-water interface are needed for incorporation into full ecosystem models that include larger-scale dynamics and link coastal models to global carbon and nutrient models. These models should represent processes at disparate scales, in a manner that is standardized (i.e., with a uniform set of exchange variables and interpolators), distributed (i.e., consisting of independent modules communicating through a central server), and coupled (i.e., including multi-model feedback with standard interpolators).

IV. Acknowledgements

The CBED report benefited significantly from contributions made by several workshop participants, particularly as noted: Tim Keen, Jim Moum and Nathan Hawley in Section II.B; Bill Martin and Billy Moore in Section II.C; Paul Haberstroh and Tony D'Andrea in Section II.D; Tim Keen and Christophe Meile in Section II.E; and Pete Jumars, Jim Moum, Frank Sansone, Matt Ferner and Henrik Ståhl in Section II.F. CoOP SSC members Ola Persson and Roger Samelson provided additional information for Section II.B.

We thank invited speakers Rob Wheatcroft, Colin Jago and Peter Berg for setting the tone of the meeting and allowing use of their graphics throughout the report. Appreciation is also due other participants who generously offered the use of their graphics and data to illustrate the report. Pete Jumars provided a highly thorough, and very welcome, set of editorial corrections and comments.

Participants who contributed questions in advance of the workshop (see Section VI.C) provided a wealth of carefully-considered and thought-provoking text as well as an informal preview of what participants considered most important to the success of coastal benthic research. Contributors include Zanna Chase, Matt Ferner, Steve Fries, Paul Haberstroh, Nathan Hawley, Markus Huettel, John Jaeger, Colin Jago, Pete Jumars, Tim Keen, Joel Kostka, Bill Martin, Christophe Meile, Billy Moore, Jim Moum, Kathleen Ruttenberg Peter Swarzenski, George Voulgaris, Herb Windom and one anonymous contribution.

The United States Geological Survey's Center for Coastal and Watershed Studies Director Dr. Lisa Robbins and her staff generously welcomed the CBED group into their facility in St. Petersburg. Sandra Coffman should be singled out for her gracious assistance with all aspects of workshop arrangements. Discussions were fueled by 13 lbs of dark-roast Sumatran coffee beans and 2.5 gallons of half-and-half.

The workshop was elevated by a social event that involved gathering over fifty of the participants and a handful of USGS employees into opening night of the 2004 major league baseball season in St. Pete with the Tampa Bay Devil Rays besting the New York Yankees. Although sentiments were divided among workshop participants, a welcome diversion from the benthos was had by all who attended.

The CBED workshop and report were supported by a grant from the National Science Foundation (OCE-0301872) to the CoOP Office. The views expressed herein do not necessarily reflect the views of NSF.

V. References

Abello, HU, SM Shellito, LH Taylor and PA Jumars (2004) Light-cued emergence and re-entry events in a strongly tidal estuary. Estuaries, in review.

Abril, G, M Commarieu, D Maro, M Fontugne, F Guerin, and H Etcheber (2004) A massive dissolved inorganic carbon release at spring tide in a highly turbid estuary. Geophys. Res. Lett. 31: L09316, doi:10.1029/2004GL019714.

Allan, J and PD Komar (2000) Are ocean wave heights increasing in the eastern North Pacific? EOS 81:561-567.

Aller, JY, and I Stupakoff (1996) The distribution and seasonal characteristics of communities on the Amazon shelf as indicators of physical processes. Cont. Shelf Res. 16:717-751.

Aller, R (1994) Bioturbation and remineralization of sedimentary organic matter: effects of redox oscillation. Chem. Geol. 114:331-345.

Aller, RC (1998) Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors. Mar. Chem. 61:143-155.

Beaulieu, SE (2002) Accumulation and fate of phytodetritus on the sea floor. Oceanogr. Mar. Biol. Ann. Rev. 40:171-232.

Berelson, W, J McManus, K Coale, K Johnson, D Burdige, T Kilgore, D Colodner, F Chavez, R Kudela and J Boucher (2003) A time series of benthic flux measurements from Monterey Bay, CA. Cont. Shelf Res. 23:457-481.

Berg, P, N Risgaard-Petersen and S Rysgaard (1998) Interpretation of measured concentration profiles in sediment pore water. Limnol. Oceanogr. 43:1500-1510.

Berg, P, H Røy, F Janssen, V Meyer, BB Jørgensen, M Huettel, and D de Beer (2003) Oxygen uptake by aquatic sediments measured with a novel non-invasive eddy-correlation technique. Mar. Ecol. Prog. Ser. 261:75-83.

Betteridge, KRE, JJ Williams, PD Thorne and PS Bell (2003) Acoustic instrumentation for measuring near-bed sediment processes and hydrodynamics. J. Exp. Mar. Biol. Ecol. 285-286:105-118.

Boudreau, BP (1997) A one-dimensional model for bed boundary layer particle exchange. J. Mar. Syst. 11:279-303.

Boudreau, BP (2000) The mathematics of early diagenesis: From worms to waves. Rev. Geophys. 38:389-416.

Boudreau, BP, M Huettel, S Forster, RA Jahnke, McLachlan, JJ Middelburg, P Nielsen, F Sansone, G Taghon, W Van Raaphorst, I Webster, JM Weslawski, P Wiberg and B Sundby (2001). Permeable marine sediments: overturning an old paradigm. EOS 82:133-136.

Boudreau, BP and BB Jørgensen (2001) Introduction. In: BP Boudreau and BB Jørgensen (eds.), The Benthic Boundary Layer, Oxford University Press, Oxford, pp. 1-3.

Box, GEP, GM Jenkins and GC Reinsell (1994) Time Series Analysis: Forecasting and Control. Prentice-Hall, Englewood Cliffs, NJ, 598 pp.

Brink, KH, JM Bane, TM Church, CW Fairall, GL Geernaert, DS Gorsline, RT Guza, DE Hammond, GA Knauer, CS Martens, JD Milliman, CA Nittrouer, CH Peterson, DP Rogers, MR Roman and JA Yoder (1990) Coastal Ocean Processes (CoOP): Results of an interdisciplinary workshop. Contribution number 7584, Woods Hole Oceanographic Institution, Woods Hole MA, 51 pp.

Brink, KH, JM Bane, TM Church, CW Fairall, GL Geernaert, DE Hammond, SM Henrichs, CS Martens, CA Nittrouer, DP Rogers, MR Roman, JD Roughgarden, RL Smith, LD Wright and JA Yoder (1992) Coastal Ocean Processes: A Science Prospectus. Woods Hole Oceanographic Institution, Technical Report WHOI-92-18, 88 pp.

Brun R, P Reichert and HR Künsch (2001) Practical identificability analysis of large environmental simulation models. Water Resources Res. 37:1015-1030.

Buchanan, JB (1993) Evidence of benthic-pelagic coupling at a station off the Northumberland coast. J. Exp. Mar. Biol. Ecol. 172:1-10.

Buchanan, JB and JJ Moore (1986) Long-term studies at a benthic station off the coast of Northumberland. Hydrobiol. 142:121-127.

Chezar, H, and D Rubin (2003) The"“poking eyeball” - a prototype underwater camera system. USGS Sound Waves Monthly Newsletter 49:3-4, http://soundwaves.usgs.gov.

Collie, JS, SJ Hall, MJ Kaiser and IR Poiner (2000) A quantitative analysis of fishing impacts on shelf-sea benthos. J. Animal Ecol. 69:785-798.

D'Andrea, AF, RC Aller, and GR Lopez (2002) Organic matter flux and reactivity on a South Carolina sandflat: the impacts of porewater advection and macrobiological structures. Limnol. Oceanogr. 47:1056-1070.

Dernie, KM, MJ Kaiser, and RM Warwick (2003) Recovery rates of benthic communities following physical disturbance. J. Animal Ecol. 72:1043-1056.

Diaz, RJ, R Cutter and DM Dauer (2003) A comparison of two methods for estimating the status of benthic habitat quality in the Virginia Chesapeake Bay. J. Exper. Mar. Biol. Ecol. 285-286:371-381.

Dworski, JG and DR Jackson (1994) Spatial and temporal variation of acoustic backscatter in the STRESS experiment. Cont. Shelf Res. 14:1221-1237.

Edwards, KA, P MacCready, J.N Moum, G Pawlak, J Klymak, and A Perlin (2004) Form drag and mixing due to tidal flow past a sharp point. J. Phys. Oceanogr. 34:1297-1312.

Ellingsen, DE, JS Gray, and E Bjørnbom (2002) Acoustic classification of seabed habitats using the QTC VIEWTM system. ICES J. Mar. Sci. 59:825-835.

Emery, KO (1968) Relict sediments on continental shelves of the world. AAPG 52:445-464.

Falter, JL and FJ Sansone (2000) Hydraulic control of pore water geochemistry within the oxic-suboxic zone of a permeable sediment. Limnol. Oceanogr. 45: 550-557.

Ferner, MC and MJ Weissburg (2004) Slow-moving predatory gastropods track prey odors in fast and turbulent flow. J. Exp. Biol., in review.

Fugate, DC and CT Friedrichs (2002) Determining concentration and fall velocity of estuarine particle populations using ADV, OBS and LISST. Cont. Shelf Res. 22:1867-1886.

Fukuchi, M, L Legendre and T Hoshiai (1997) The Canada-Japan SARES project on the first-year ice of Saroma-ko lagoon (northern Hokkaido, Japan) and Resolute Passage (Canada High Arctic). J Mar. Sys. 11:1-8.

Garrett, C, P MacCready, and PB Rhines (1993) Boundary mixing and arrested Ekman layers: rotating, stratified flow near a sloping boundary. Ann. Rev. Fluid Mech. 25:291-323.

Geyer, R, and P Traykovski (2001) Wave- and density driven sediment transport. In: Ocean Sciences and the New Millennium. Ocean Sciences Decadal Committee, National Science Foundation, p. 91.

Glud, RN, A Tengberg, M Kuhl, POJ Hall and I Klimant (2001) An in situ instrument for planar O_2 optode measurements at benthic interfaces. Limnol. Oceanogr., 46:2073-2080.

Gooday, AJ (2002) Biological responses to seasonally varying fluxes of organic matter to the ocean floor: a review. J. Oceanogr. 58:305-332.

Gundersen, JK and BB Jørgensen (1990) Microstructure of diffusive boundary layers and the oxygen uptake of the sea floor. Nature 345:604-607.

Hall, SJ (1994) Physical disturbance and marine benthic communities: life in unconsolidated sediments. Oceanography and Marine Biology: an Annual Review 32:179-239.

Hawley, N (2004) Response of the benthic nepheloid layer to near-inertial internal waves in southern Lake Michigan. J. Geophys. Res. 109: doi:10.1029/2003JC002128.

Hawley, N and RW Muzzi (2003) Observations of nepheloid layers made with an autonomous vertical profiler. J. Great Lakes Res. 29:124-133.

Heip, CHR, G Duineveld, E Flach, G Graf, W Helder, PMJ Herman, M Lavaleye, JJ Middelburg, O Pfannkuche, K Soetaert, T Soltwedel, H de Stiger, L Thomsen, J Vanaverbeke and P de Wilde (2001) The role of the benthic biota in sedimentary metabolism and sediment-water exchange processes in the Goban Spur area (NE Atlantic). Deep-Sea Res. II 48:3223-3243.

Hérnandez-Arana, HA, AA Rowden, MJ Attrill, RM Warwick and G Gold-Bouchot (2003) Large-scale environmental influences on the benthic macroinfauna of southern Gulf of Mexico. Estuar. Coast. Shelf Sci. 58:825-841.

Hill, PSM and IN McCave (2001) Suspended particle transport in benthic boundary layers. In: BP Boudreau and BB Jørgensen (eds.), The Benthic Boundary Layer, Oxford University Press, Oxford, pp. 78-103.

Houwing, E and LC van Rijn (1998) In Situ Erosion Flume (ISEF): determination of bed-shear stress and erosion of a kaolinite bed. J. Sea Res. 39:243-253.

Huettel, M and G Gust (1992) Impact of bioroughness on interfacial solute exchange in permeable sediments. Mar. Ecol. Prog. Ser. 89:253-267.

Huettel, M, W Ziebis, S Forster and G Luther, III. (1998) Advective transport affecting metal and nutrient distribution and interfacial fluxes in permeable sediments. Geochim. Cosmochim. Acta 62:613-631.

Huettel, M and A Rusch (2000). Transport and degradation of phytoplankton in permeable sediment. Limnol. Oceanogr. 45:534-549.

Huettel, M and IT Webster (2000). Porewater flow in permeable sediment. In: BP Boudreau and BB Jørgensen (eds.). The Benthic Boundary Layer: Transport Processes and Biogeochemistry. Oxford University Press, pp. 144-179.

Jackson, DR and KB Briggs (1992) High-frequency bottom backscattering: roughness versus sediment volume scattering. J. Acoust. Soc. Am. 92:962-977.

Jackson, GA (1997) Currents in the high drag environment of a coastal kelp stand off California. Cont Shelf Res. 17:1913-1928.

Jahnke, RA (2001) Constraining organic matter cycling with benthic fluxes. In: BP Boudreau and BB Jørgensen (eds.), The Benthic Boundary Layer, Oxford University Press, Oxford, pp. 302-319

Jahnke, RA, JR Nelson, RL Marinelli, JE Eckman (2000) Benthic flux of biogenic elements on the Southeastern US continental shelf: influence of pore water advective transport and benthic microalgae. Cont. Shelf Res. 20:109-127.

Jahnke R, J Bane, A Barnard, J Barth, F Chavez, H Dam, E Dever, P DiGiacomo, J Edson, R Geyer, S Glenn, K Johnson, M Moline, J O'Donnell, J Oltman-Shay, O Persson, O Schofield, H Sosik and E Terrill (2003) Coastal Observatory Research Arrays: A Framework for Implementation Planning. Coastal Ocean Processes (CoOP) Report No. 9, December 2003. Skidaway Institute of Oceanography Technical Report, SkIO TR-03-01, 77 pp.

Jahnke, R, M Richards, J Nelson, C Robertson, A Rao and D Jahnke (2004) Organic matter remineralization and porewater exchange rates in permeable South Atlantic Bight sediments. Cont. Shelf Res. (submitted)

Jahnke, R, L Atkinson, J Barth, F Chavez, K Daly, J Edson, P Franks, J O'Donnell and O Schofield (2002) Coastal Ocean Processes and Observatories: Advancing Coastal Research. Coastal Ocean Processes (CoOP) Report No. 8, November 2002. Skidaway Institute of Oceanography Technical Report, SkIO TR-02-01, 51 pp.

Jumars, PA, DR Jackson, TF Gross and C Sherwood (1996) Acoustic remote sensing of benthic activity: a statistical approach. Limnol. Oceanogr. 41:1220-1241.

Kaandorp, JA et al. (2003) Simulation and analysis of flow patterns around the scleractinian coral Madracis mirabilis (Duchassing and Michelotti). Phil. T. Roy. Soc. B. 358:1551-1557.

Kechagia PE, IN Tsimpanogiannis, YC, Yortsos and PC Lichtner (2002) On the upscaling of reaction-transport processes in porous media with fast or finite kinetics. Chem. Engineer. Sci. 57:2565-2577.

Klymak, JM and JN Moum (2003) Internal solitary waves of elevation advancing on a sloping shelf, Geophys. Res. Lett. 30, OCE 3-1 - 3-4.

Kringel K, PA Jumars and DV Holliday (2003) A shallow scattering layer: High-resolution acoustic analysis of nocturnal vertical migration from the seabed. Limnol. Oceanogr. 48:1223-1234.

Krone, RB (1962) Flume studies of the transport of sediment in estuarial shoaling processes. Final Report, Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley, CA, 118 p.

Krone, RB (1993) Sedimentation Revisited. In: A.J. Mehta (ed.), Nearshore and Estuarine Cohesive Sediment Transport: Coastal and Estuarine Studies 42:108-125.

Lee, J-Y, P Tett, K Jones, S Jones, P Luyten, C Smith and K Wild-Allen (2002) The PROWQM physical-biological model with benthic-pelagic coupling applied to the northern North Sea. J. Sea Res. 48:287-331.

Levin, LA and PVR Snelgrove (2004) Biodiversity and function in marine sediments: a muddle or a solvable mystery? ASLO meeting, Honolulu HI, February 2004.

Llobet-Brossa E, Rossello-Mora R, Amann R (1998) Microbial community composition of Wadden Sea sediments as revealed by fluorescence in situ hybridization. Appl. Environ. Microbiol. 64:2691-2696.

Lochte, K and CM Turley (1988) Bacteria and cyanobacteria associated with phytodetritus in the deep sea. Nature 333:67-69.

Lunven, M, P Gentien, K Kononen, E Le Gall, and MM Daniélou (2003) In situ video and diffraction analysis of marine particles. Estuarine Coastal and Shelf Sciences, 57:1127-1137.

Marinelli, RL, RA Jahnke, DB Craven, JR Nelson and JE Eckman (1998) Sediment nutrient dynamics on the South Atlantic Bight continental shelf. Limnol. Oceanogr. 43:1305-1320.

McKinnon, AD, MG Meekan, JH Carleton, MJ Furnas, S Duggan and W Skirving (2003) Rapid changes in shelf waters and pelagic communities on the southern Northwest Shelf, Australia, following a tropical cyclone. Contm Shelf Res. 23:93-111.

McPhee-Shaw, EE and E Kunze (2002) Horizontal intrusions generated by internal-wave turbulence along a sloping boundary: a laboratory investigation. J. Geophys. Res., 10.1029/2001JC000801.

Mehta, AJ and WH McAnally (2004) Fine-grained sediment transport, Ch. 4, In: M. Garcia (Ed.), Sedimentation Engineering (2nd ed.), American Society of Civil Engineering, Reston, VA (in press).

Meile, C, C Koretsky, and P Van Cappellen (2001) Quantifying bioirrigation in aquatic sediments: An inverse modeling approach. Limnol. Oceanogr. 46:164-177.

Meile, C and K Tuncay (2004) Scale dependence of reactions rates in porous media. Geochim. Cosmochim. Acta, in review.

Middelburg, JJ and K Soetaert (2004) The role of sediments in shelf ecosystem dynamics. In: The Global Coastal Ocean: Multiscale Interdisciplinary Processes. (eds) K Brink and AR Robinson. Cambridge, MA, Harvard University Press. Volume 12, in press.

Middelburg, JJ, C Barranguet, HTS Boschker, PMJ Herman, T Moens and CHR Heip (2000) The fate of intertidal microphytobenthos carbon: An in situ 13C-labeling study. Limnol. Oceanogr. 45:1224-1234.

Mikkelsen, OA, TG Milligan, PS Hill and D Moffat (2004) INSSECT - an instrumented platform for investigating floc properties close to the bottom boundary layer. Limnology and Oceanography: Methods, in press.

Milligan, TG and PS Hill (1998) A laboratory assessment of the relative importance of turbulence, particle composition, and concentration in limiting maximal floc size and settling behaviour. J. Sea Res. 39:227-241.

Moodley, L, JJ Middelburg, HTS Boschker, GCA Duineveld, R Pel, MJ Herman and CHR Heip (2002) Bacteria and foraminifera: key players in a short-term deep-sea benthic response to phytodetritus. Mar. Ecol. Prog. Ser. 236:23-29.

Moore, WS (1996) Large groundwater inputs to coastal waters revealed by Ra-226 enrichments. Nature 380:612-614.

Moore WS, J Krest, G Taylor, E Roggenstein, S Joye and R Lee (2002) Thermal evidence of water exchange through a coastal aquifer: Implications for nutrient fluxes. Geophys. Res. Lett. 29:Art. No. 1704.

Murray, JMH, A Meadows, and PS Meadows (2002) Biogeomorphological implications of microscale interactions between geotechnics and marine benthos: a review. Geomorphology 47:15-30.

Nairn, RB and DH Willis (2002) Erosion, transport, and deposition of cohesive sediments, Ch. 5. In: U.S. Army Corps Coastal and Hydraulics Laboratory, Coastal Engineering Manual, pp. III-5-1 - III-5-62.

Nelson, JR, JE Eckman, CY Robertson, RL Marinelli and RA Jahnke (1999) Variability in biomasses of benthic and planktonic microalgae on the continental shelf on the South Atlantic Bight. Cont. Shelf Res. 19:477-505.

Nelson, JR, CY Robertson, ME Richards and RA Jahnke (2004) Benthic primary production on the South Atlantic Bight seafloor. J. Geophy. Res., in prep.

Nepf, HM (1999) Drag, turbulence, and diffusion in flow through emergent vegetation. Water Resources Res. 35:479-489.

Nie, Y, IB Suayah, LK Benninger and MJ Alperin (2001) Modeling detailed sedimentary 210Pb and fallout 239,240Pu profiles to allow episodic events: an application in Chesapeake Bay. Limnol. Oceanogr. 46:1425-1437.

Ocean Studies Board (2002) Effects of Trawling and Dredging on Seafloor Habitat. National Academy Press, Washington, DC, 136 pp.

Okey, TA (1997) Sediment flushing observations, earthquake slumping, and benthic community changes in Monterey Canyon head. Cont. Shelf Res. 17:877-897.

Parker, WR, K Doyle, ER Parker, PJ Kershaw, SJ Malcolm, and P Lomas (2003) Benthic interface studies with landers. Consideration of lander/interface interactions and their design implications. J. Exp. Mar. Biol. Ecol. 285-286:179-190.

Partheniades, E (1965) Erosion and deposition of cohesive soils, J. Hydraul. Div. ASCE 91:105-139.

Posey, M, W Lindberg, T Alphin, and F Vose (1996) Influence of storm disturbance on an offshore benthic community. Bull. Mar. Sci. 59:523-529.

Precht E and M Huettel (2003) Advective pore-water exchange driven by surface gravity waves and its ecological implications. Limnol. Oceanogr. 48:1674-1684

Quinn P. (2003) Scale appropriate modelling: representing cause-and-effect relationships in nitrate pollution at the catchment scale for the purpose of catchment scale planning. J. Hydrology 291:197-217.

Rabalais, NN and RE Turner (2001) Hypoxia in the northern Gulf of Mexico: description, causes and change. In: NN Rabalais and RE Turner (eds.) Coastal Hypoxia, Consequences for Living Resources and Ecosystems, Coastal and Estuarine Studies, vol. 58, American Geophysical Union, Washington, D. C., 463 pp.

Ralph, FM, RM Rauber, BF Jewett, DE Kingsmill, P Pisano, P Pugner, RM Rasmussen, DW Reynolds, TW Schlatter, RE Stewart and JS Waldstricher (2004) Improving short-term (0-48 hour) cool-season quantitative precipitation forecasting: Recommendations from a USWRP workshop. Bull. Amer. Meteor. Soc., submitted.

Rao, AMF and RA Jahnke (2004a) Quantifying porewater exchange across the sediment-water interface in the deep sea with in situ tracer studies. Limnol. Oceanogr. Methods 2:75-90.

Rao, AMF and RA Jahnke (2004b) Denitrification in permeable continental shelf sediments on the South Atlantic Bight. ASLO program, p. 34.

Reimers, CE, SM Glenn, and EL Creed (1996) The dynamics of oxygen uptake by shelf sediments. EOS 76:202.

Reimers CE, HA Stecher, GL Taghon, CM Fuller, M Huettel, A Rusch, N Ryckelynck and C Wild (2004) In situ measurements of advective solute transport in permeable shelf sands. Cont. Shelf Res. 24:183-201.

Richardson, M, K Briggs, L Bibee, P Jumars, W Sawyer and others (2001) Overview of SAX99: environmental considerations. IEEE J. of Electrical Eng. 26:26-53.

Rinne, HJ, AC Delaney, JP Greenberg, and AB Guenther (2000) A true eddy accumulation system for trace gas fluxes using disjunct eddy sampling method. J. Geophys. Res. 105:24791-24798.

Roman, MR (1998) The Coastal Ocean Processes (CoOP) Program. Mar. Tech. Soc. J. 32:17-22.

Rusch, A and M Huettel (2000) Advective particle transport into permeable sediments - evidence from experiments in an intertidal sandflat. Limnol. Oceanogr. 45:525-533.

Rusch A, M Huettel, CE Reimers, GL Taghon G.L and CM Fuller (2003). Activity and distribution of bacterial populations in Middle Atlantic Bight shelf sands. FEMS Microbiol. Ecol. 44:89-100

Sanford, LP and JP Halka (1993) Assessing the paradigm of mutually exclusive erosion and deposition of mud, with examples from the upper Chesapeake Bay. Mar. Geol. 114: 37-57.

Scala, D and L Kerkhof (1999) Diversity of nitrous oxide reductase (nosZ) genes in continental shelf sediments. Appl. Environ. Microbiol. 65:1681-1687.

Scala, DJ and LJ Kerkhof (2001) Horizontal heterogeneity of denitrifying bacterial communities in marine sediments by terminal restriction fragment length polymorphism analysis. Appl. Environ. Microbiol. 66:1980-1986.

Scapini, F (2003) Beaches - what future? An integrated approach to the ecology of sand beaches. Est. Coastal Shelf Sci. 58S:1-3.

Schaffner, LC, TM Dellapenna, EK Hinchey, CT Friedrichs, M Thompson-Neubauer, M E Smith and SA Kuehl (2001) Physical energy regimes, sea-bed dynamics and organism-sediment interactions along an estuarine gradient. In: JY Aller, SA Woodin and RC Aller, (eds.) Organism-Sediment Interactions. University of South Carolina Press, Columbia, SC. pp. 161-182.

Schlüter, M, Sauter EJ, Schäfer A, and W Ritzrau (2000) Spatial budget of organic carbon flux to the seafloor of the northern North Atlantic (60°N - 80°N). Global Biogeochemical Cycles 14:329-340.

Self, RFL, P A'Hearn, PA Jumars, DR Jackson, MD Richardson, and KB Briggs (2001) Effects of macrofauna on acoustic backscatter from the seabed: Field manipulations in West Sound, Orcas Island, WA, USA. J. Mar. Res. 59:991–1020.

Sherwood, C (2003) The voyage to recover and redeploy instruments in the Adriatic Sea - the good, the bad and the ugly. USGS Sound Waves Monthly Newsletter, 49:1-3, http://soundwaves.usgs.gov.

Shirasawa, K, RG Ingram and EJJ Hudier (1997) Oceanic heat fluxes under thin sea ice in Saromako Lagoon, Hokkaido, Japan. J. Mar. Syst. 11:9-19.

Shum KT (1992) Wave-induced advective transport below a rippled water-sediment interface. J. Geophys. Res. 97:789-808.

Shum, KT (1993) The effects of wave-induced pore water circulation on the transport of reactive solutes below a rippled sediment bed. J. Geophys. Res. 98:10289-10301.

Smith, KL Jr. and RJ Baldwin (1984) Seasonal fluctuations in deep-sea sediment community oxygen consumption: Central and eastern North Pacific. Nature 307:624–626.

Smith, KL Jr., RC Glatts, RJ Baldwin, AH Uhlman, RC Horn, CE Reimers and SE Beaulieu (1997) An autonomous, bottom-transecting vehicle for making long time-series measurements of sediment community oxygen consumption to abyssal depths. Limnol. Oceanogr. 42:1601-1612.

Smith, KL Jr. and RS Kaufmann (1999) Long-term discrepancy between food supply and demand in the deep eastern North Pacific. Science 284:1174-1177.

Steele, J and the Committee on Ecosystem Effects of Fishing (2002) Effects of trawling and dredging on seafloor habitat. National Academy Press, Washington D.C.

Stolzenbach, KD, Newman, KA and CS Wong (1992) Aggregation of fine particles at the sediment-water interface. J. Geophys. Res. 97:17889-17898.

Taylor, LH, SM Shellito, HU Abello and PA Jumars (2004) Tidally cued emergence and re-entry events in a strongly tidal estuary. Estuaries, in review.

Toorman, EA (1999) Sedimentation and self-weight consolidation: constitutive equations and numerical modeling. Geotechnique 49:709-726.

Traykovski, P, WR Geyer, JD Irish, and JF Lynch (2000) The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. Cont. Shelf Res. 20:2113-2140.

US Ocean Commission (2004) An Ocean Blueprint for the 21st Century. Final Report of the US Ocean Commission on Ocean Policy. Washington, DC. 610 pp.

vanderLoeff, MMR and BP Boudreau (1997) The effect of resuspension on chemical exchanges at the sediment-water interface in the deep sea - a modelling and natural radiotracer approach. J. Marine Syst. 11:305-342.

Viollier, E, C Rabouille, SE Apitz, E Breuer, G Chaillou, K Dedieu, Y Furkawa, C Grenz, P Hall, F Janssen, JL Morford, JC Poggiale, S Robers, T Shimmield, M Taillefert, A Tengberg, F Wenzhöfer, and U Witte (2003) Benthic biogeochemistry: state of the art technologies and guidelines for the future of in situ survey. J. Exp. Mar. Biol. Ecol. 285-286:5-31.

Webster, IT, SJ Norquay, FC Ross and RA Wooding (1996) Solute exchange by convection within estuarine sediments. Estuar. Coastal Shelf Sci. 42:171-183.

Wenzhöfer F and RN Glud (2004) Small-scale spatial and temporal variability in coastal benthic O_2 dynamics: Effects of fauna activity. Limnol. Oceanogr. 49:1471-1481.

Wheatcroft, RA and C Fritz (2004) Post-depositional alteration and preservation of sedimentary event layers on continental margins, II. Infaunal assemblages and sediment mixing intensity. J. Mar. Res., in prep.

Wiberg, PL and CK Harris (2002) Desorption of p,p'-DDE from sediment during resuspension events on the Palos Verdes shelf, California: a modeling approach. Cont. Shelf Res. 22:1005-1023.

Wood BD, F Charblanc, M Quintard and S Whitaker (2003) Volume averaging for determining the effective dispersion tensor: closure using periodic unit cells and comparsion with ensemble averaging. Water Resources Res. 39:1210-1231.

VI. Appendices

VI.A. Working Group Reports (timescale consideration)

VI.A.1. Time Scale: up to hours (aka "short time scale")

Working Group 1 Participants
Barry, Jim
Ferner, Matt
Friedrichs, Carl
Fries, Steve
Fugate, David
Haberstroh, Paul
Huettel, Markus
Jumars, Pete
Kalnejais, Linda
Moum, Jim
Neely, Merrie Beth
Sansone, Frank - Discussion Leader
Souza, Alejandro
Thomas, Florence
Thosteson, Eric
Trowbridge, John - Rapporteur
Voulgaris, George

Charge: Formulate research questions of relevance to short time scale - up to hours duration. Identify four major categories of processes that must be studied to understand the role of the coastal benthos.

Category 1. How do episodic and short-period physical processes influence biogeochemical cycling in the benthic environment?

How do we characterize and quantify turbulent mass and momentum fluxes?

What are the effects of different kinds of bottom roughness and mixed sediments on turbulence and resuspension?

What are the effects of highly nonlinear internal waves?

What are the effects of surface waves (groups, natural surface wave spectra)?

How does wave action move porewater?

What are the impacts of short-term fluxes on sediment chemistry?

What is the importance of short-term changes in mechanical and material properties of the seabed?

What are the effects of density currents?

What are the effects of rapid burial?

Category 2. What is the influence of short-term biological variability on biogeochemical cycling in the benthic environment?

What are the effects of biopolymers on benthic fluxes of solutes and particles?

What is the importance of vertical migration of organisms to benthic fluxes?

What are the effects of variability in benthic and water column primary productivity?

How do short-term community interactions influence biogeochemical fluxes?

What are the effects of episodic anthropogenic activities (e.g., trawling, dredging)?

How do biogenic changes in mechanical and material properties of the seabed affect benthic fluxes?

How does bioturbation work on short time scales?

Category 3. How do episodic and short-term variations in physical and chemical processes influence benthic ecosystem structure and function?

What are the effects of changing bottom composition and roughness?

What are the effects of chemical cues on macrofauna?

What are the effects of fluxes on gene expression and the functional responses of biota?

How do microbial ecology and geochemistry change when sediments are resuspended?

What are the effects of rapid burial?

How does hydrodynamic variability affect biological patterns?

Category 4. How do biota and biogeochemistry affect physical processes?

What are the physical implications of biological variations in space and time?

How does biological activity affect the amount and composition of suspended sediments?

What are the effects of benthos on bed sediment characteristics?

What are the effects of biogenic structures on hydrodynamics?

What are the missing key technologies?

How can we measure the 3-D motion of porewater in the field?

What are the acoustical and optical scattering properties of natural particles?

How can we obtain long-term in-situ, high-frequency measurements of fluxes and other key processes?

How can we effectively exploit observatories?

How can we respond rapidly to events?

VI.A.2.Timescale: Hours to Weeks

Working Group 2 Participants
Adornato, Lori
Colman, Albert
Crusius, John
Darrow, Brian
Fauver, Laura
Halley, Bob
Howd, Peter
Jago, Colin
Keen, Tim
MacCready, Parker - Rapporteur
Meile, Christof
Nelson, Jim
Reimers, Clare
Sanford, Larry - Discussion Leader
Styles, Rich
Ståhl, Henrik
Thornton, Daniel

Charge: Formulate research questions of relevance to timescale (hours to weeks). Identify four major categories of processes that must be studied to understand the role of the coastal benthos.

Physical forcing:

Sunlight diurnal cycle, cloud cover

Tides – including internal tides (12, 24 hours and fortnightly)

Groundwater discharge & tidal pumping

Waves forced by storms (1-5 day "synoptic")

Wind-driven currents and upwelling (synoptic)

River input variability (floods, and regular river plumes)

Turbulence structure

Anthropogenic forcing:

Dredging and disposal

Trawling ("mobile fishing gear impacts")

Oil and sewage spills (after a few weeks, esp. heavy oils)

Offshore wind farms

Thermal discharge from power plants

Biological processes:

Phytoplankton blooms in the water column

Benthic biomass and productivity (primary and secondary) and respiration rates (diurnal)

Vertical and horizontal migration (esp. diurnal)

Bioturbation (mixing, micro-topography creation, bioresuspension)

Bio-irrigation (intensity varies diurnally)

Bio-cohesion (microbial films, mucus, fecal pellets)

Recruitment

Predator-Prey cycles; viruses

Chemical Processes:

Oxygen and other redox chemical dynamics

Metal and nutrient mobilization (kinetics)

Benthic fluff layer dynamics (organic matter degradation)

Adsorption/desorption

Benthic fluxes through the sediment water interface and through the top of the BBL

Nitrification and denitrification

Microenvironment development

Fate and transport of contaminants

Sedimentary Processes:

Flocculation, disaggregation

Bed form formation, migration, destruction, and biological degradation

Compaction (hours to days)

Resuspension and entrainment

Deposition

Sediment gravity flows

Laminae formation (tidal and storm timescales)

Stratification by suspended sediments

Fluid mud

Category 1. Physical Disturbance

How do physically-forced disturbances modulate biogeochemical fluxes across the sediment-water interface, and out of the BBL?

Magnitude and frequency of wave/current events

Event sedimentation

Sediment mobilization; cohesive/noncohesive

Trawling, dredging and disposal

Category 2. Effects of Benthic Light Variability

How does benthic primary productivity influence solute and particle exchange, benthic community structure, and benthic/pelagic coupling?

Bio-stabilization

Quantity and quality of organic matter

Interactions with suspended sediment (quantity and quality)

Diurnal variability of faunal activity (benthic)

Category 3. Integrative Modeling

How do we develop a suite of coupled benthic physical/biogeochemical models, that span the entire BBL, including into the sediment?

Adaptive sampling and data assimilation

Hypothesis testing

Category 4. Benthic-Pelagic Coupling

How do variability of topography, substrate properties and biological communities affect water column exchange with the BBL?

Temporal & spatial variation of vertical mixing

Groundwater flow effects

Temporal variation of hypoxia/anoxia

Phytoplankton bloom-crash cycle

Vertical and horizontal migration (demersal)

VI.A.3. Timescale: Month to year (e.g. seasonal cycles in physical forcing and fishing effort)

Working Group 3 Participants:
Bebout, Brad - Rapporteur
Chase, Zanna
D'Andrea, Tony
Hearn, Cliff
Jaeger, John
Klump, Val
Lisle, John
Martin, Bill
Pease, Tamara
Ruttenberg, Kathleen - Discussion Leader
Savidge, Bill
Waples, Jim
Wheatcroft, Rob
Windom, Herb

Charge: Formulate research questions of relevance to seasonal (month-to-year) time-scales. Identify four major categories of processes that must be studied to understand the role of the coastal benthos

Group 3 proceeded first by listing physical and biological forcing factors of importance on seasonal time scales, and benthic processes that can be perturbed by these forcing factors on seasonal time scales (see lists below). After compiling these lists, the group formulated research questions relevant to this time scale. A total of sixteen research questions were articulated. Although charged by the workshop chairs with prioritizing these research questions, the group voted not to prioritize, because many of the questions were considered of equal scientific significance and importance.

Many of the research questions contain within them broader questions relating to response time of the benthos to forcing factors, and the role of memory, or hysteresis, in response times. The group therefore decided to articulate two overarching themes (see below), which provide a cross-cutting context for the research questions listed. Finally, based upon the group's discussion of forcing factors and research questions, four categories of processes appropriate for study on seasonal time scales were proposed as organizing themes for the second day's break-out group discussions.

Overarching themes for research questions:

Response time of the benthic boundary layer and benthic sediments to forcing factors

The role of hysteresis in the magnitude and nature of response times and patterns of the benthos to extremes / anomalies in forcing factors (e.g. storms; delays in the timing of 'normal' events, such as phytoplankton blooms, larval recruitement and settling, etc.)

Physical and Biological Forcing Factors Important on Seasonal Time Scales:

wave energy; wave climatology

insolation

temperature

circulation patterns

upwelling/downwelling

physical roughness of seabed

sediment advection

phytoplankton blooms, primary production (pelagic and benthic)

storms

riverine input of particles, solutes, fresh water

water column stratification (salinity, temperature, wind-driven mixing)

redox conditions of seabed and bottom water

infaunal activity (bioturbation, irrigation, recruitment)

microbial respiration

fishing

storm-drain runoff/pollutive input

Benthic Processes That Can Be Perturbed on Seasonal Time Scales Due to the Forcing Factors Listed Above:

solute exchange

resuspension

organic matter mineralization

mineral dissolution

mineral precipitation

redox changes

creation/destruction of permeability, porosity

carbon retention and burial

nutrient (P, Fe, other) retention and burial

metal retention and burial (e.g. toxic metals, micronutrients)

development of interfacial microbial mats

primary production

bioturbation, irrigation

Research questions (not prioritized):

What is the nature and magnitude of benthic response to seasonal variations in key forcing functions (e.g. organic matter supply, insolation, wave climatology, temperature)? Some 'episodic' events of short duration (e.g., storms, floods) are nevertheless seasonal occurrences. For example:
storms, floods, and the occurrence of high-energy waves typically concentrate at certain times of year.

What is the time scale of benthic response to seasonal variations in key forcing functions (e.g. organic matter supply, insolation, wave climatology, temperature)?

To what extent are there benthic biological processes that are not externally (e.g., temperature, OM input) forced, on what time scale do they operate, and what are the consequences of these for benthic processes overall?

What is the effect of light that reaches the seafloor on benthic processes (e.g., primary production and resulting impact on redox state, production of reactive organic matter, consumption of nutrients, porosity, benthic flux, carbon (and other bioelement) burial; photochemistry)?

How do changes in magnitude or timing of perturbations of seasonal forcing factors impact benthic processes (e.g., benthic respiration, macrofaunal recruitment, nutrient fluxes, OM burial, redox conditions)?

Hysteresis: To what extent is there memory in the system? To what extent are present responses dictated by preceding conditions? Restated: To what extent do extremes in forcing factors precondition subsequent time scales and magnitudes of the benthic response? Over what time frame is the manifestation of a perturbation observable? How long does it take for the benthic environment to relax back to equilibrium after a perturbation?

Examples:

To what extent will a late spring wave event, that kills newly recruited macrofaunal larvae, impact subsequent development of the benthic system, and what is the time scale for recovery from such an event?

How will an erosional event that removes freshly deposited organic matter impact subsequent development of the benthic system, and what is the time scale for recovery from such an event?

How important is biodiversity in benthic biogeochemical processes?

Example:

If a given environment selects for irrigators vs. bioturbators, this will have important consequences for benthic processes such as redox zonation, oxidation of organic matter, etc.

What is the relative role of sandy versus muddy sediments in benthic-pelagic coupling? How realistic is it to assume that 'sandy' sediments and 'muddy' sediments are physically segregated in the natural environment, versus a continuum? Retention of fines by sandy sediments can alter the physical parameters of the sediment (e.g. porosity, cohesiveness, microbial and macrofaunal activity, etc.). What is the threshold amount of mud that must be retained by sandy sediments to cause a significant deviation in benthic response from that of pure sand?

Does the fraction of coarse vs. fine-grained sediment change seasonally? Shifts in grain-size, with consequent shifts in permeability, porosity, and reactivity, will have important seasonal effects on benthic biogeochemical processes.

How will a seasonally oscillating redox boundary affect benthic fluxes, and what impact will this have on benthic and pelagic processes (e.g. infaunal activity, resuspension)? What will be consequent impacts on benthic-pelagic coupling?

Sediments and the water column are linked by the benthic boundary layer (BBL), and processes affecting fluxes into and out of the seabed are mediated by the BBL. How does the BBL vary in response to seasonal forcing functions, and what is the impact of seasonal variation of the BBL on benthic-pelagic coupling?

What is the impact of groundwater input on the positioning, thickness, and biogeochemical characteristics of the BBL? How might groundwater input impact benthic-pelagic coupling?

To what extent and in what ways do seasonal forcing factors impact annual carbon (and associated bioelement) burial? (e.g. varve formation, flood deposits)

Seasonal temperature fluctuations will affect water column primary production with consequent impacts on POM flux to sediments. What is the time-scale and magnitude of response of the benthos to fluctations in POM flux to sediments?

For example:

how will such fluctions affect sediment and bottom water redox conditions, benthic faunal *assemblages and activity, and benthic fluxes?*

The seasonality of physical forcing is well documented in many regions (e.g. wave climatology (see Figure), temperature, insolation, etc.). However, in most cases there have not been parallel studies of BBL processes to explicitly link these processes, their timing and magnitude, to seasonal forcing factors.

To what extent, and in what ways, does seasonality in wave climatology affect the BBL and associated processes?

Examples:

seasonally energetic waves enhance pore water advection in sandy sediments

physical roughness in seabed forms during times of high wave energy but persist during lower energy periods, creating patchiness in deposition of phytodetritus, impacting benthic flux patterns, etc.

Category 1. Wave climatology ("the seasonal variability of wave amplitude and period, parameters that dictate wave energy input to benthic systems"):

Surface gravity wave intensity varies seasonally. How does seasonality in surface gravity wave intensity (i.e., height, period) influence coastal benthic exchange?

Examples of wave impacts:

sediment (including fluff) resuspension, with consequences for seabed and water column geochemistry, benthic fauna

formation of bedforms, with consequences for sediment focusing, erosion, localization of benthic fluxes

advective pore-water flows, including patterns of augmentation or suppression of benthic fluxes

micro-distribution of organic matter, with consequences for creation of microenvironments, juxtaposition of redox zones over small spatial scales

distribution of benthic fauna, with consequences for bioturbation and irrigation, redox zonation, benthic fluxes

Category 2. Accumulation and/or input of organic matter

Organic matter accumulation and/or input varies in quality, quantity and timing of delivery. Each of these factors interacts and/or controls benthic processes, including benthic flux, animal activity, sediment permeability, and evolution of redox conditions.

Examples of factors controlling organic matter accumulation and input include:

benthic primary productivity (controlled by irradiance, temperature, nutrient availability, physical energetics)

water column primary productivity (controlled by irradiance, temperature, nutrient availability, physical energetics)

presence and/or productivity of microbial mats

quality, quantity, timing of river input

Category 3. Kinetics

Temperature affects all biogeochemical reactions, including microbial activity, metazoan activity and abiotic reactions.

Category 4. Metazoan imprint on benthic processes

What is the relative importance of metazoan-facilitated geochemistry versus strictly physically forced (abiotic) and/or microbially-driven geochemistry?

Examples of forcing factors driven by metazoan activity, all of which have consequences for fluxes across the sediment/water interface, redox zonation, carbon (and associated bioelement) burial, benthic-pelagic coupling, include:

consumption of organic matter, including selective consumption

irrigation and bioturbation of sediment

interception of particles

inhibition of interfacial mat formation

VI.A.4. Timescale: Years to Decades (climate cycles, groundwater discharge, burial)

Working Group IV-1 Participants:
Charette, Matt
Flood, Roger
Cable, Jaye
Goni, Miguel
Jahnke, Richard
Kostka, Joel - Rapporteur
McManus, Jim - Discussion Leader
Moore, Billy
Niencheski, Felipe
Sikes, Liz
Slaby, Emilie
Snedden, Gregg
Swarzenski, Peter
Wakeham, Stuart

Charge: Formulate research questions of relevance to long time scales. Identify four major categories of processes that must be studied to understand the role of the coastal benthos.

Questions (implicit):

Question 1: Importance of short term physics, biology, and chemistry on longer term geologic processes and signatures.

Question 2: Big picture issues, i.e., an umbrella for our target questions/topics.

Question 3: Source and fate of materials (carbon) at sediment-water interface.

Question 4: Studying/ quantifying the product of events.

Category 1. Anthropogenic change (issues involving hydrologic cycle on coast)- deforestation, damming, land-use change, surface and ground water withdrawal)

How is human intervention influencing the quality, quantity, periodicity of materials delivered to continental shelves?

For example:
nutrient inputs, turbidity effects, surface and ground water inputs, allochthonous vs. autochthonous organic matter, exotic species

Category 2: Decadal climate change

What are the impacts of climate change on coastal ecosystem dynamics and hydrodynamics (surface and ground water)?

For example:
sea level, wave height, hydrograph, frequency and composition of algal blooms, temperature, pH, sediment delivery, structure of benthic communities

Cateogory 3: Interannual climate cycles

How are the effects of short-term climate cycles (El Nino, NAO/ PDO) superimposed on longer term climate signals?

For example:
precipitation, heightened erosion, evapotranspiration, upwelling, storm frequency

Category 4: Stochastic events

How do the effects of stochastic events (storms, floods, tidal waves, tsunamis) control the delivery and fate of materials on the continental shelf?

For example:
sedimentation, resuspension, lateral transport, pore water exchange, benthic community structure

Other questions that may or may not have anything to do with any particular timescale:

What is the role of shelf sediments in controlling global denitrification or bio-active trace element supply?

How important is shelf carbon to gas hydrate evolution—alternatively, how might changes in climate alter hydrate stability?

How do microbial community dynamics of permeable shelf sediments differ from their counterparts in fine-grained sediments?

VI.B. Participants

Lori Adornato
University of South Florida
Center for Ocean Technology
140 7th Avenue South, COT100
St. Petersburg FL 33701
727.553.1285
adornato@marine.usf.edu

Yogesh C. Agrawal
Sequioa Scientific, Inc.
2700 Richards Road, Suite 107
Bellevue WA 98005
425.641.0944 x 106
yogi.agrawal@sequoiasci.com

Jim Barry
Monterey Bay Area Research Institute
7700 Sandholt Road
Moss Landing CA 95039
831.775.1726
barry@mbari.com

Brad Bebout
NASA Ames Research Center
Exobiology Branch
Mail Stop 239-4
Moffett Field CA 94035-1000
650.604.3227
brad.m.bebout@nasa.gov

Peter Berg
University of Virginia
Department of Environmental Sciences
291 McCormick Road, PO Box 400123
Charlottesville VA 22904-4123
434.924.1318
pb8n@virginia.edu

Jaye Cable
Louisiana State University
Oceanography and Coastal Sciences
1229 Energy, Coast, and Environment Bldg.
Baton Rouge LA 70803
225.578.9402
jcable@lsu.edu

Matt Charette
Woods Hole Oceanographic Institution
Marine Chemistry and Geochemistry, MS 25
Woods Hole MA 02543
508.289.3205
mcharette@whoi.edu

Zanna Chase
SUNY Stony Brook
Marine Sciences Research Center
Stony Brook NY 11794-5000
631.632.3777
zanna.chase@sunysb.edu

Albert Colman
Carnegie institution of Washington
Geophysical Laboratory
5251 Broad Branch Road, NW
Washington DC 20015
202.478.8983
a.colman@gl.ciw.edu

John Crusius
United States Geological Survery - Woods Hole
384 Woods Hole Road
Woods Hole MA 02543
508.457.2353
jcrusius@usgs.gov

Tony D'Andrea
Oregon State University
Ocean and Atmospheric Sciences
104 COAS Administration Building
Corvallis OR 97331-5503
541.737.8079
dandrea@coas.oregonstate.edu

Brian Darrow
University of South Florida
College of Marine Science
140 7th Avenue South
St. Petersburg FL 33701
727.553.1112
bdarrow@seas.marine.usf.edu

Laura Fauver
University of South Florida
College of Marine Science
140 7th Avenue South
St. Petersburg FL 33705
727.553.1170
lfauver@seas.marine.usf.edu

Matt Ferner
Georgia Institute of Technology
School of Biology
10 Ocean Science Circle
Savannah GA 31411
912.598.2363
ferner@skio.peachnet.edu

Roger Flood
SUNY Stony Brook
Marine Sciences Research Center
Stony Brook NY 11794-5000
631.632.6971
roger.flood@sunysb.edu

Carl Friedrichs
Virginia Institute of Marine Science
Route 1208, Greate Road
Gloucester Point VA 23062-1346
404.684.7303
cfried@vims.edu

Steve Fries
University of North Carolina
Institute of Marine Sciences
3431 Arendell Street
Morehead City NC 28557
252.726.6841 x 166
jsfries@email.unc.edu

David Fugate
Rutgers University
IMCS
71 Dudley Road
New Brunswick NJ 08091
732.932.6555 x 233
fugate@marine.rutgers.edu

Miguel Goni
University of South Carolina
Geological Sciences, EWS 617
701 Sumter Street
Columbia SC 29208
803.777.3550
goni@geol.sc.edu

Paul Haberstroh
University of Texas at Austin
Marine Science Institute
750 Channel View Drive
Port Aransas TX 78373-5015
361.749.6844
paulh@utmsi.utexas.edu

Bob Halley
United States Geological Survey
600 4th Street S
St. Petersburg FL 33701
727.803.8747
rhalley@usgs.gov

Nathan Hawley
Great Lakes Environ. Research Laboratory
2205 Commonwealth Blvd.
Ann Arbor MI 48105
734.741.2273
nathan.hawley@noaa.gov

Clif Hearn
United States Geological Survey
600 4th Street S
St. Petersburg FL 33701
727.803.8747
cjhearn@usgs.gov

Peter Howd
University of South Florida
College of Marine Science
140 7th Avenue
St. Petersburg FL 33701
phowd@marine.usf.edu

Markus Hüttel
Florida State University
Department of Oceanography
900 West Call Street, OSB 517
Tallahassee FL 32306-4320
850.645.1394
mhuettel@ocean.fsu.edu

Alex Isern
Program Director, OTIC
National Science Foundation
4201 Wilson Blvd., 725N
Arlington VA 22230
703.292.8582
aisern@nsf.gov

John Jaeger
University of Florida
Geological Sciences
PO Box 112120
Gainesville FL 32611-2120
352.846.1381
jaeger@geology.ufl.edu

Colin Jago
University of Wales
Marine Science Laboratories
Menai Bridge
Anglesey LL59 5AB
United Kingdom
oss72@bangor.ac.uk

Rick Jahnke
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411
912.598.2491
rick@skio.peachnet.edu

Peter A. Jumars
University of Maine
Darling Marine Center
193 Clark's Cove Road
Walpole ME 04573
207.563.3146 x242
jumars@maine.edu

Linda Kalnejais
Woods Hole Oceanographic Institution
Marine Chemistry and Geochemistry MS#8
Woods Hole MA 02543
508.289.2785
lkalnejais@whoi.edu

Tim Keen
Naval Research Laboratory
Oceanography Division, Mail Code 7322
Stennis Space Center MS 35929
228.688.4950
keen@nrlssc.navy.mil

Val Klump
University of Wisconsin Milwaukee
Great Lakes Water Institute
600 E. Greenfield Avenue
Milwaukee WI 53204
414.382.1700
vklump@uwm.edu

Joel Kostka
Florida State University
Oceanography, 317 OSB
Tallahassee FL 32306-4320
850.645.3334
jkostka@ocean.fsu.edu

Jim Krest
University of South Florida
Environmental Science, Davis Hall 258
140 7th Avenue South
St. Petersburg FL 33701
727.553.4970
krest@stpt.usf.edu

Parker MacCready
University of Washington
School of Oceanography
Box 355351
Seattle WA 98195-5351
206.685.9588
parker@ocean.washington.edu

Bill Martin
Woods Hole Oceanographic Institution
Marine Chemistry and Geochemistry MS#8
Woods Hole MA 02543
508.289.2836
wmartin@whoi.edu

Jim McManus
Oregon State University
Ocean and Atmospheric Sciences
104 COAS Administration Building
Corvallis OR 97331-5503
541.737.8285
mcmanus@coas.oregonstate.edu

Christof Meile
University of Georgia
Marine Sciences
Athens GA 30602
706.542.6549
cmeile@uga.edu

Billy Moore
University of South Carolina
Geological Sciences, EWS 617
701 Sumter Street
Columbia SC 29208
803.777.2262
moore@geol.sc.edu

Jim Moum
Oregon State University
Ocean and Atmospheric Sciences
104 COAS Administration Building
Corvallis OR 97331-5503
541.737.2553
moum@coas.oregonstate.edu

Merrie Beth Neely
University of South Florida
Florida Marine Science Institute
140 7th Avenue South
St. Petersburg FL 33701
727.896.8626 x 1551
mneely@seas.marine.usf.edu

Jim Nelson
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411
912.598.2473
nelson@skio.peachnet.edu

Felipe Niencheski
Fundacao Universidade do Rio Grande
Laboratorio de Hidroquimica
Campus Carreiros, PP box 474
Rio Grande, Brazil 96201-900
55.53.233.6516
dqmhidro@furg.br

Tamara Pease
University of Texas at Austin
Marine Science Institute
750 Channel View Drive
Port Aransas TX 78373-5015
361.749.6746
tamara@utmsi.utexas.edu

Clare Reimers
Oregon State University
College of Ocean and Atmospheric Sciences
104 Ocean Administration Bldg
Corvallis OR 97331-5503
541.737.2426
creimers@coas.oregonstate.edu

Kathleen Ruttenberg
University of Hawaii
SOEST Oceanography at Manoa
1000 Pope Road
Honolulu HI 96822
808.956.9371
kcr@soest.hawaii.edu

Larry Sanford
UMCES - Horn Point Laboratory
PO Box 775
Cambridge MD 21613-0775
410.221.8429
lsanford@hpl.umces.edu

Frank Sansone
University of Hawaii at Manoa
SOEST Oceanography
1000 Pope Road
Honolulu HI 96822
808.956.8370
sansone@soest.hawaii.edu

Bill Savidge
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411
wsavidge@skio.peachnet.edu

Liz Sikes
Rutgers University
Institute of Marine and Coastal Science
71 Dudley Road
New Brunswick NJ 08901
732.932.6555 x518
sikes@marine.rutgers.edu

Emilie Slaby
Woods Hole Oceanographic Institution
Marine Chemistry and Geochemistry MS#8
Woods Hole MA 02543
508.289.5283
eslaby@whoi.edu

Donny Smoak
University of South Florida
Environmental Science, Davis Hall 258
140 7th Avenue South
St. Petersburg FL 33701
smoak@stpt.usf.edu

Gregg Snedden
Louisiana State University
Oceanography and Coastal Sciences
1225 Energy, Coast and Environment Bldg.
Baton Rouge LA 70803
225.268.7730
gsnedde@lsu.edu

Alex Souza
Proudman Oceanographic Laboratories
Bidston Observatory, Bidston Hill
Prenton CH43 7RA
United Kingdom
441516538633
ajso@pol.ac.uk

Henrik Ståhl
University of Copenhagen, Dept. of Biology
Marine Biological Laboratory Helsingör
Helsingör DK-3000
Denmark
45 49 21 33 44
hjstaahl@bi.ku.dk

Rich Styles
University of South Carolina
Geological Sciences
701 Sumter Street
Columbia SC 29208
803.777.4588
rstyles@geol.sc.edu

Peter Swarzenski
United States Geological Survey
600 4th Street S
St. Petersburg FL 33701
727.803.8747
pswarzen@usgs.gov

Florence Thomas
University of South Florida
Biology Department, SCA 110
4202 E. Fowler Avenue
Tampa FL 33620
813.974.9609
fthomas@cas.usf.edu

Dan Thornton
Texas A & M University
Department of Oceanography
3146 TAMU
College Station TX 77843-3146
979.845.4092
thornton@ocean.tamu.edu

Eric Thosteson
Florida Institute of Technology
Marine and Environmental Systems
150 West University Blvd.
Melbourne FL 32901
321.674.7411
thosteson@fit.edu

John Trowbridge
Woods Hole Oceanographic Institution
Mail Stop 12
Woods Hole MA 02543
508.289.2296
jtrowbridge@whoi.edu

George Voulgaris
University of South Carolina
Geological Sciences
701 Sumter Street
803.777.2549
gvoulgaris@geol.sc.edu

Stuart Wakeham
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411
912.598.2347
stuart@skio.peachnet.edu

Jim Waples
University of Wisconsin Milwaukee
Great Lakes Water Institute
600 E. Greenfield Avenue
Milwaukee WI 53204
414.382.1700
jwaples@uwm.edu

Rob Wheatcroft
Oregon State University
Ocean and Atmospheric Sciences
104 COAS Administration Building
Corvallis OR 97331-5503
541.737.3891
raw@coas.oregonstate.edu

Herb Windom
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411
912.598.2490
herb@skio.peachnet.edu

VI.C. Science Questions

CBED participants were asked by the organizing committee to consider the following in advance of the meeting:

Part 1: List three coastal benthic exchange processes/questions that would be best addressed with interdisciplinary CoOP-style research.

Part 2: Provide 2-3 paragraphs of background and rationale for each of the processes/questions in Part 1 (optional but appreciated).

Part 3: How amenable to deployed sensor arrays and other observatory approaches is new research on the processes/questions you have listed? Is new technology needed?

The individual participant responses (identified as A-T) were minimally formatted and compiled into a more-or-less anonymous list in the order submissions were received. The dominant focus of each question was organized for convenience into the categories shown in the figure below. Questions which cross several categories are listed in 'cross-cutting questions' at the end of the list. No editorial assumptions are implied by the categories or assignments.

process: response ID

1. river inputs: G2, O1

2. ground water inputs (nutrients, contaminants, biological populations, impacts): B1, B2, B3, C2, G1, L1, L2, O1,S1

3. intensified atmospheric inputs

4. benthic/pelagic exchange (redox, nutrients, carbon, metals, organisms, benthic primary production, permeable sediments): A1, A2, C1, D3, F1, F2, G3, J2, J3, K1, M1, N1, N3, P1, P2, P3, Q2, T1, R2, R3, S2

5. sediment resuspension/export/reworking: A3, D1, E2, F2, I1, K2, N2, Q1, T1

6. wind-driven coastal upwelling

7. particulate plumes/sinking (phytoplankton; microbial processes): M1, M2, N3

8. nepheloid layer/BBL transport: E1, F2, G2, I2, T1, T2, T3

9. sediment burial: T2

10. gas hydrates: D2

11. intensified cross-isopycnal mixing (turbulence): G1, M2

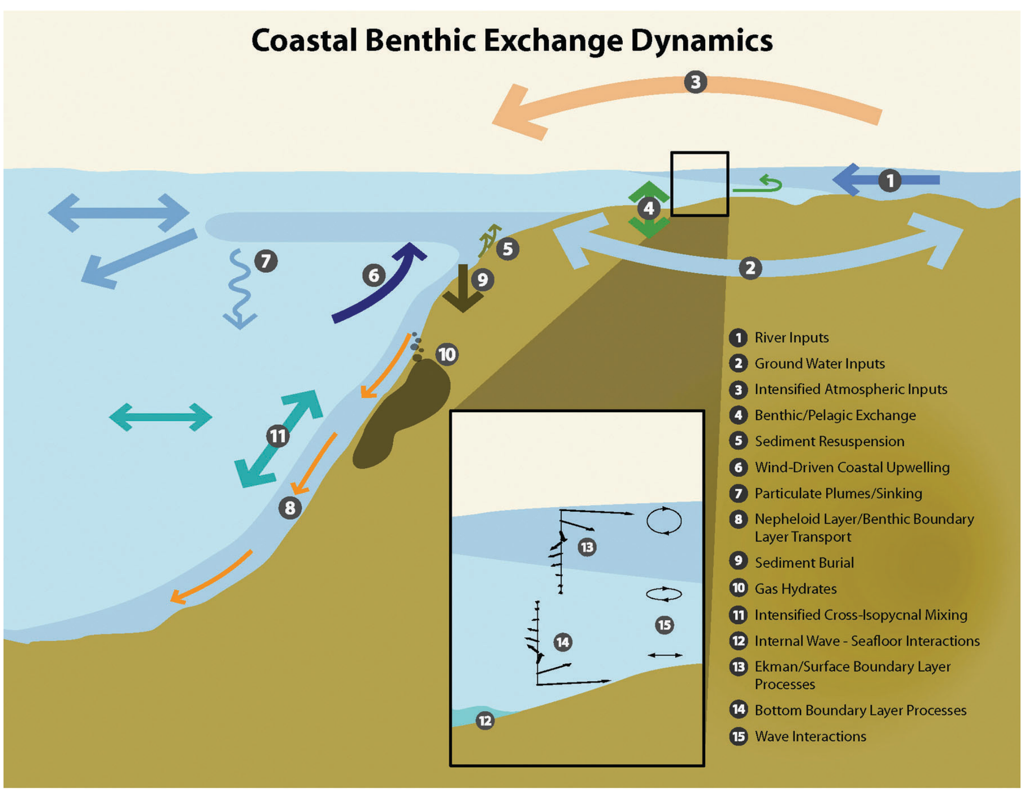
12. internal wave-seafloor interactions: E1

13. ekman/surface boundary layer processes

14. BBL processes: E2, F2, Q2, Q3

15. wave interactions: G1, I1, J1, J3, L1

16. cross-cutting questions (episodic events; time and space scale; bedform; climate change): A3, C3, D2, D4, E1, G1, G3, H1, H2, I3, L2, L3, M3, N1, N3, P1, Q3



A: Part 1 - questions
A1. Vertical solute fluxes

A2. Vertical fluxes of organisms, many of which migrate with daily and tidal periods (e.g., emergent fauna)

A3. Event-based vertical fluxes (e.g., solutes ejected by erosive events)

A: Part 2 - expansion
A1. I don't think you need my explanation for most of this one. I am thrilled to see eddy flux methods being attempted for estimation of vertical solute fluxes and to see these methods on the meeting agenda. There has been a poor match of electrode-based calculations with chamber-based measurements with one obvious explanation (i.e., short circuits through animal tubes and burrows). Our recent work on burrowing mechanics when coupled with Bernie Boudreau and Bruce Johnson's field measurements, however, suggests another unsteady input through mechanical "crack propagation" in cohesive sediments (including fairly coarse silts).

A2. In both Puget Sound and the Damariscotta River (a fjord with little freshwater inflow) my laboratory has documented nightly emergence, primarily of mysid shrimp, that increases vertically integrated biomass in the water column by an order of magnitude. These mysids are voracious omnivores and are themselves favored prey of fishes. Their migrations surely influence benthic-pelagic coupling, but their abilities to escape nets have led to lack of awareness of the magnitude of these nightly events. Fish predation on benthos is another source of vertical flux that is difficult to quantify by traditional means.

A3. Rare but potentially significant effects are the bane of ecological observation programs.

A: Part 3 - technology
A1. The eddy correlation method will take some interdisciplinary effort, and cabled observatories are ideally suited to measuring the parameters involved.

A2. Only high-frequency, nearly continuous acoustics has revealed the importance of this phenomenon. Its study requires high power and high bandwidth. It can't be done very effectively from anything but a cabled observatory. Ancillary measurements are needed, however, to assure that the identities of the organisms observed acoustically are known.

A3. The only practical solution is conditional sampling, preferably by autonomous instruments. Ships are often unable to operate when fluxes may be greatest.

B: Part 1 - questions
B1. Investigate the role of Submarine GW discharge as a water/submarine contaminant vector to coastal waters

B2. Examine bi-directional GW-SW exchange along Leaky Coastal Margins

B3. Is there a biological (benthic fauna/microorganism) component to SGD that warrants further investigation?

B: Part 3 - technology
There is much new technology that could be employed for SGD, GW-SW studies (remote acquisition/telemetry/new techniques)

C: Part 1 - questions
C1. What is the contribution of sediment filtration on the cycling of matter in the shelf/the ocean/on a global scale

C2. How important is groundwater seepage in the shelf for sediment-water nutrient exchange?

C3. what are potential consequences of climate change (currents, waves, temperature, water level) on the exchange processes in the shelf?

C: Part 2: expansion
C1. By carrying substrates and electron acceptors (e.g. oxygen, nitrate, sulfate) into the bed, advective pore water flows in marine sands boost sedimentary microbial decomposition as suggested by results from aquifer sciences and bioreactor research. Fluid flow of 4 cm h-1, as reached by the advective pore flows, is sufficient

to cause a several-fold increase in assimilation rates of solutes by bacteria attached to the particles. The filtration, thus, has the potential to convert permeable sands into biocatalytical filters with high organic matter mineralization rates, and first in-situ measurements that take advection into account support this hypothesis. The measurements by Marinelli, Jahnke, Reimers and others suggest benthic respiration rates in the Middle Atlantic Bight sands to range between 10 and 40 mmol O_2 $m^{-2}d^{-1}$ during summer. If such high rates are common in the filtering beds, a substantial contribution of these sediments for the cycling of matter can be expected. However, at present, we have only very few quantitative data.

C2. Previous work by Burnett, Moore and coworkers has shown that groundwater seepage from permeable shelf sediments can be significant and affect seawater composition in the shelf. Groundwater can carry large amounts of nutrients, and it is not clear, how the groundwater input affects primary production in the shelf. Quantitative data are needed to permit realistic budget calculations for the nutrient cycling in the shelf.

C3. Climate changes affect the currents and waves in the shelf, water level and water temperatures may change over time. All these changes will affect the filtration of water through the shelf sediments, which will affect the biogeochemical processes in these beds. Quantitative information is needed to get better insights in the potential consequences of climate change on shelf organic matter cycling and shelf fisheries.

C: Part 3: technology

The existing monitoring and measuring projects are needed to address these questions, however, it is necessary to add some key parameters to the variables that are presently recorded. We need more information on the filtration process (boundary flows, topography), the pore water flows, the groundwater seepage and benthic primary production. At least, we need to add permeability, bottom flow and topography measurements, isotope measurements, and benthic chlorophyll measurements to the standard monitoring procedures.

D: Part 1 - questions

D1. Coastal benthic regions as sinks for organic carbon

D2. Coastal benthic processes as sources of climatically active gases (e.g. N_2O, CH_4)

D3. Coastal benthic processes as sources of bioactive elements (micro and macro nutrients and toxins) to the overlying water column

D4. How are these (and other) processes affected by past and future climate change and other anthropogenic activities?

D: Part 2 - expansion

D1. Ocean sediments in general are an important long-term sink for organic carbon. It is not clear exactly how important the coastal regions are as sites of carbon burial. They receive large amounts of terrigenous carbon from runoff. Coastal regions also fix large amounts of carbon in-situ, as they tend to be far more productive than open ocean regions. However, remineralization rates are also high in shallow water, particularly where sediments are periodically re-oxygenated. Furthermore, upwelling and mixing can act to transport benthic CO_2 back to the surface, where it may be released to the atmosphere. Therefore the key to efficient sequestration of organic carbon entering and produced in the coastal zone may be export off the shelf into deep water.

D2. In addition to CO_2, other trace gases influence climate. The natural sources and sinks of gases such as methane and nitrous oxide need to be known accurately in order to model future climate change and to assess the impact of human activity. Coastal sediments are a source of both nitrous oxide, via denitrification reactions, and methane, released from seepage and during methanogenesis.

D3. One of the unique features of coastal systems is the proximity of the sediments to the euphotic zone. Sedimentary processes may therefore influence pelagic processes, rather than vice-versa, which typically occurs in the open ocean. Shelf sediments are known to be an important source of iron to coastal ecosystems. Many other elements are potentially mobilized by sediments, including other trace nutrients such as zinc and manganese, toxic metals such as copper and cadmium, and metal-chelating organic compounds. Land-borne pollutants may also be released from the sediments. The magnitude of the fluxes involved, as well as their chemical speciation and impact on pelagic ecosystems, is poorly known. In the case of metals, the relative concentration and speciation of different metals may be just as important as the absolute magnitude of individual fluxes.

D4. All of the processes just described are sensitive to climate change and may themselves potentially be agents of climate change. In order to understand such feedbacks we need to understand how these and other processes have responded to past climate change (e.g. glacial conditions) and how they might respond to future climate change and to future changes in human disturbance. Probably the most important impact of past climate change on benthic coastal processes is the dramatic reduction in shelf area at peak glaciation, when sea level was some 120 m lower than today. All shelf processes would have been affected. Determining these effects requires a paleoceanographic approach. Looking to the future, global warming, changes in land use and natural and anthropogenic changes in the hydrological cycle will all affect coastal benthic processes. Determining the exact impacts requires a modeling approach.

D: Part 3 - technology

Items 1-3 would all benefit to some extent from observatory approaches. A sensor array designed to track material transport off the shelf would be particularly useful to item 1. Item 2 would benefit greatly from sensor arrays if appropriate sensors exist for these gases. Item 3 is more process oriented, and, unless in-situ sensors are developed to measure metal speciation, sensor arrays will be of limited use. However, a high temporal resolution, yearlong record of total metal flux from coastal sediments, coupled with a similar record of surface productivity, would in itself be very valuable.

E: Part 1 - questions

E1. Do short-time scale, intermittently and perhaps infrequently-occurring events dominate transports of mass, momentum and chemicals across the sediment-water interface, including cross-shelf transports?

E2. By energetic resuspension of sediments and further mixing of these above the bed, are these the dominant processes by which bottom-trapped chemicals are redistributed throughout the water column?

E: Part 2 - expansion

An important example seems to be internal bores at the bottom that propagate along a near-bottom density interface. These are highly nonlinear waves of elevation, characterized by high turbulence and high particle speeds (0.6 m/s) 1 m above the bed, high bed stresses, and are capable of moving fluid in their direction of propagation. They apparently evolve from a turbulent to undular bore (Moum et al. 2004) and eventually into a train of solitary-like waves of elevation (Klymak and Moum, 2003) before either crashing in shallow water or evanescing as stratification weakens or disappears inshore. On the Oregon coast, they are roughly phase-locked to the M2 tide. Direct measurements show intense sediment resuspension associated with these events. Acoustic measurements indicate: a) systematic responses of scatterers that appear from the bottom as bores pass; b) trapped centimeter-scale scatterers in the cores of propagating waves – it is impossible to tell from our observations whether this is voluntary or not.

Another example of intense and intermittent high bottom drag is the intermittent internal hydraulic control over Stonewall Bank (Moum and Nash, 2000; Nash and Moum, 2001). Stonewall Bank is a rock bank likely because of intermittent scouring by these intense flows which reach in excess of 0.7 m/s at the bottom. It is also a prime fishing spot. We have yet to do the observational or modeling studies to link the biochemical processes that feed the fishery to these intense flows.

I was recently asked an interesting practical question by the Essential Fish Habitat coordinator for the Oregon Habitat Branch of NOAA Fisheries' Habitat Conservation Division who was tasked with "reviewing a proposal by the Corps of Engineers and EPA to designate a "deep water" dredged material disposal site off the Columbia River, and in pursuing some of the fish issues". She discovered that "we got (curiously enough) to some sediment and turbulence issues". She provided "A very brief background on the project: the "Deep Water Site", or DWS, is located approximately 4.5-6 miles southwest of the mouth of the river, and is in total 17,000 x 23,000 feet in size, with all material to be placed in an inner, core area of 11,000 x 17,000 feet (the rest is a "buffer" with no actual disposal but sediments may drift/slump/otherwise end up there). It is between 190 - 300 feet deep. The current sediment types are sand and sand/mud, and the proportions and invert assemblages vary seasonally according to some studies by a contractor for the Corps. The site is to be used primarily for sandy sediments dredged from the mouth of the Columbia and possibly from the navigation channel farther up; these sediments have/will be tested for contaminants and will meet established standards for ocean disposal, and they are coarser than the sediments currently found at the site. The Corps expects to use the site for 50 years, resulting in a 40' high trapezoidal sediment mound. They claim in their EIS that sediments deposited at the site will not move."

Specifically, I was asked "Is there any reason to expect that the formation of a sediment mound that at maximum size would be 40' high and up to 17,000 x 23,000 feet at the base would significantly affect the surrounding environment in terms of internal waves and mixing? Might that affect sediment transport?" I know that several of my colleagues were asked about other aspects of this problem.

The answer to such a question is not straightforward. Certainly, the sediment mount will be disturbed. There will be a dispersal of these sediments across and along the shelf. Perhaps more importantly, the existence of the mound will also change the local fluid dynamics. Will this change the hydraulic controls? (Interestingly, it is almost the same dimension as Stonewall Bank.) Will it eliminate the cross-shore transport of materials in the BBL by bores? Is it good/bad for the shelf ecosystem? The answers require better knowledge of the magnitude, importance and chemical signature of onshore transport of materials by bottom flows such as bores and hydraulically-controlled fluid dynamics.

An analogy that may be relevant is with the transports of gases, heat and momentum through the air-sea interface. We know that the bulk of the air-sea transfers occur at the infrequent times of intense forcing when wave-breaking enhances transports. It makes no sense to estimate mean air-sea transfers from observations made at low or moderate winds. Is it also true that the sediment-water transfers are dominated by these intense events? Does an observational program need to be geared toward resolving and understanding the rare intense events?

E. Part 3 - technology

We have been studying these features over the last few years with a combination of shipboard and bottom-moored devices.

a) A high-frequency echosounder mounted in the hull of a ship has proved to be a good tool in defining the structure of these features;

b) Using our turbulence profiler, we have intensively profiled through the BBL and into the bottom. This allows a clear view of the vertical structures of stratification, optical backscatter (880 nm) and turbulence as they evolve through these flows. From the turbulence measurements, estimates of bed stress are made (the bed stress increases more than tenfold with passages of these flows);

c) We have also developed a bottom lander upon which we have mounted ADCP, ADVs and T/C sensors. Sampled fast enough (> 1 Hz), this provides clear views of the vertical structure of the 3D velocity field, the turbulence 1 m above the bed as well as the large scale density gradients that drive the flows. It represents an important anchor point that, when combined with nearby shipboard measurements, tells us the propagation speeds of the fronts that lead these flows. It is a flexible platform upon which a range of sensors could be deployed for a process experiment. It is also inexpensive, so that many could be deployed.

Clearly, shipboard observations into the bottom are required. We have successfully worked with Burke Hales' pumping system in the past in a 2 wire operation into the bottom, so it is possible to simultaneously determine both the chemical signatures and physical properties of these flows.

References

Klymak, J.M. and J.N. Moum, 2003: Internal solitary waves of elevation advancing on a sloping shelf, Geophys. Res. Lett. 30 (20), OCE 3-1 – 3-4.
Moum, J.N., A.D. Barton, J.D. Nash. A. Perlin, J.M. Klymak and G.S. Avicola, 2004: Turbulent near-bottom bores and solitary waves of elevation over the continental shelf. 2004 Ocean Sciences Meeting, Portland, OR.
Moum, J.N. and J.D. Nash, 2000: Topographically-induced drag and mixing at a small bank on the continental shelf. J. Phys. Oceanogr. , 30, 2049-2054.
Nash, J.D. and J.N. Moum, 2001: Internal hydraulic flows on the continental shelf: high drag states over a small bank. J. Geophys. Res., 106(C3), 4593-4612.

F: Part 1 - questions

F1. This is the most basic question: what do benthic processes contribute to margin carbon and nutrient cycles?

F2.What is the relative importance of different modes of sediment / seawater exchange?

F: Part 2 - expansion

F1.Benthic respiration and photosynthesis appear to be quantitatively significant relative to shallow-water production and remineralization in the water column. Although important, results obtained to date that address this issue are limited. The challenges for future efforts are to (1) determine the set of water column and benthic measurements that will broaden the scope of currently existing data, and (2) address specific issues. Important among these is whether benthic processes affect the ratios of N and P that are available for local production. Denitrification, a means of removing fixed N, is important in many shallow-water sediments. P may also be removed by sedimentary processes. Although P is efficiently recycled by heterotrophic respiration in sediments, it is readily removed from pore waters by freshly precipitated iron oxides. Most shallow-water sediments lie beneath oxygenated water, hence have a thin, oxic surface that is enriched in Fe oxides – and P. How efficiently does this P removal sequester P, and does it affect the element's availability to local primary producers? Do the occurrence of sedimentary denitrification and P sequestration affect the ratio of supply of these elements to coastal waters?

F2. Distinctions should also be made between modes of solute transport: ionic / molecular diffusion across the sediment-water interface, transport via burrows through the activities of infauna, and advective transport in permeable sediments, driven by bottom currents and topography and by waves and tides. While it has been argued that a simple flux measurement, including all processes, is all that's needed, it's not enough: a flux measurement alone does not allow the generalization from a limited set of results that is needed for broad conclusions about coastal elemental cycles. Is it then important to use a variety of methods of benthic sampling / flux measurement that, together, can distinguish between different modes of transport?

F: Part 3 - technology

Observatory-based measurements can contribute important information to this effort. They provide essential information on cycling in the water column and may provide an effective base for benthic process studies. It will be important to consider whether the presence of the observatories affects the ecology of the benthos – for instance, will their presence attract organisms? If this consideration turns out to be important, will it be necessary to design benthic sampling / flux measurement instruments that can be deployed by AUVs or "crawlers" that can move on their own?

G: Part 1 - questions

G1.Turbulent Fluxes of bio-geochemical constituents over porous media with and without steady, groundwater discharges. How does bed morphology affect these fluxes (i.e., type of ripples)

G2.The role of the estuarine turbidity maximum in absorbing and/or releasing carbon, pollutants and other constituents. The bed water interface and its variability at the ETM controls the role of estuaries as a land-ocean interface from the geochemical point of view.

G3. Differentiation of organic versus inorganic matter and fluxes using remote techniques.

G: Part 2 - expansion

G1. The vertical component of the flow is controlled mainly by the turbulent eddies that are created in response to bottom friction. The community has made advances of measuring momentum fluxes near the bed and it has been shown that these fluxes can vary as a function of bed configuration (ripples) but also as a function of relative strength of wave vs steady current component. Consequently, we can hypothesize that turbulent fluxes of dissolved constituents (e.g. nutrients, etc) would depend on bed geometry but also on relative strength of waves and currents. The question that needs to be addressed is what is the role of bed configuration (i.e., ripple dimensions, particel size, porosity) in controling fluxes of dissolved contituents and how does this vary as a function of hydrodynamic conditions?

G2. Turbidity maximum is the area of sediment accumulation and temporarily storage of fine sediment. The sediment is discharged during periods of freshets. During the storage period there are diurnal and semidiurnal sediment resuspension events that can vary in magnitude and effect as a function of tidal strength and stratification intensity. However, during these cycles there are two processes that take place: introduction of material in the water column but also accumulation of new sediment. The question is what are the absorption / dissorption processes during the resuspension events? Is the ETM source or sink for constituents (organic matter for example). What is the control of the physical environment to these processes?

G3. Research has shown that organic matter is related to the amount of fine sediment in suspension. Some times this relationship, although empirical, seems to be holding and be accurate for a particular environment. These empirical relationships cannot be transferred for site to site as they are very site and sediment dependent. Acoustics have be proven to be adequate in measuring flows and also bulk sediment concentration. The use of different frequencies can be beneficial in providing predominant sizes of sediment in suspension. Exploratory research is required to see if acoustics can be used to provide a proxy of organic material and differentiate the organic from inorganic.

G: Part 3 - technology

The new technology required is in the area of fast responding chemical sensors so that we can measure turbulent fluxes ($\langle w'c' \rangle$). Also, although acoustics is standard for measuring flow and is becoming standard in measuring bulk suspended sediment concentration requires exploratory research to address the issue of response of acoustics to different density particles.

H: Part 1 - questions

H1. How can both spatial patchiness and discrete events in time be integrated into larger scale assessments?

H: Part 2 - expansion

A tool most appropriate for assessing such questions are numerical models, because they inherently can i) integrate different processes and ii) fill the gap in time and space that is not covered by measurements. However, in my opinion current coupled reactive transport models are not sufficiently able to assess and integrate the complex relationships between chemical, physical and biological shelf processes. I believe this is not the case on several levels:

H1. data integration & parameterization: Model parameterization suffers from the problem of non-uniqueness. A good fit to observation can typically be achieved with several parameter sets. Similarly, the data used (e.g. concentrations) is often not enough sensitive to a process parameter but integrates a multitude of effects. Rarely is there sufficient data available covering extreme events (e.g., blooms, storms). While models may be able to fill in the response to different forcing, they are typically tuned to average conditions.

H2. upscaling: As a comprehensive simulation of an entire region using mechanistic models of sedimentary processes is unfeasible, we need to develop methods for upscaling. In a rather simplistic approach, one can tune models to characteristic "endmember" sites, and upscaling could occur via GIS (e.g. sandy vs. muddy sediments; possibly incorporating probability distributions for their abundance - one challenge is the identification of good endmembers). As an alternative, to expand from the small scale where reactive transport model foundation is supposedly valid, we may be able to develop expressions for the scale dependence of model parameters.Such correction terms arising from homogenization substitute for the characteristics that are not resolved explicitly at the larger scale.

I: Part 1 - questions

These all have a common theme, which is the relative importance of physical and biological-geochemical processes at different time and length scales on the exchange of material between the bottom sediment and the overlying water column. These could be investigated in several different areas as characterized by biological (abundance and types of benthic organisms), and physical characteristics (water depth, frequency of storms, currents, sediment supply, water mass characteristics). All of these problems will require making detailed measurements in relatively small areas above and below sediment water interface. Measurements will need to be made over a wide range of spatial and temporal scales in order to sort out what is and isn't important.

Coastal arrays could be helpful to provide regional information on physical conditions, but much more extensive instrumentation would be necessary to document smaller-scale processes. Much additional instrumentation will be needed to monitor and measure what is going on in the sediments.

I1. The role and relative importance of physical and biological processes in determining the shear strength (resistance to erosion) of fine-grained bottom material as a function of physical parameters (wave energy, frequency of storms, bottom currents), and biological reworking (types and abundances of organisms).
I2. Determination of what physical processes are responsible for generating and maintaining benthic nepheloid layers.
I3. The importance of small-scale processes in space and time versus processes that act over larger time and length scales for sediment-water column exchange of material.

I: Part 2 - expansion

I1. Since many nutrients and anthropogenic pollutants are absorbed onto and transported by suspended sediments, knowledge of how this material is transported is required to accurately model the behavior of these materials. Bottom sediment is usually characterized in transport models by the particle size. For sand-sized and coarser materials this parameterization gives reasonable results, but the resistance of fine-grained material to erosion is a complex function of a number of factors including size, composition, depositional history, and the degree of biological reworking. To date it has not been possible to relate the shear strength of these materials to any easily measured property, so at present direct in-situ measurements of the sediment shear strength are required. Since these measurements are quite difficult and expensive to make, very few are made in any given program. This usually means that a few measurements at a few sites are extrapolated to cover large areas, and that temporal variations are not considered. Time series observations show, however, that lateral and temporal variations in bottom resistance are common in many different environments. It seems likely that the relative importance of physical and biological effects on sediment strength varies in different settings, but there has been no systematic of these effects in different sedimentary environments. A combination of field and laboratory studies (where the effects of different processes can be investigated individually) could help to improve the parameterization of fine-grained material in the large-scale numerical models of sediment transport presently being developed.

I2. Benthic nepheloid layers are regions of relatively high suspended sediment concentration extending upward from the sea bottom. These layers are hypothesized to be due to local sediment resuspension and may be an important pathway for the offshore transport of both nutrients and pollutants, but the actual processes responsible for their maintenance are not well documented. In the Great Lakes these layers are quite common during the stratified period (roughly June to August), but are much less common when the water is isothermal. During the stratified period, they are frequently observed at depths well below wave base and in areas where bottom currents are small, so it is unlikely that their presence is due to either surface wave action or to resuspension by bottom currents. Recently several investigators have documented bottom resuspension due to internal waves on the continental shelf, so these waves may be the process responsible for their formation and maintenance during the stratified period. However, details on the type of internal waves responsible (inertial, solitary, tidal), and the frequency of occurrence of the resuspension events generated by them are still unknown. A program directed at determining the role of internal waves in maintaining the benthic nepheloid layer could also provide information on the importance of internal waves in the exchange of material between the water column and the underlying sediments.

J: Part 1 - questions

J1. wave-driven porewater pumping mechanisms-are they analogous to dispersion?
J2. consumption and turnover of wave-driven porewater and overlying-seawater constituents
J3. relation of chemical fluxes at the sediment-seawater interface by mass-transfer versus that by wave-driven pumping.

J: Part 2 - expansion

There is a tremendous body of research that supports the driving mechanism of porewater-seawater exchange in relatively shallow water coastal systems to be wave-driven “pumping”. However, accurate means to calculate such fluxes remain controversial. By simplistically assuming that the trajectories of wave-induced porewater movement to be circular, one is then left with a non-sequitor, that net exchange is zero. However in virtually all natural wave-impacted systems the influence of waves on and through such heterogeneous matrices would likely result in far more complicated trajectories. Surface roughness features such as sand ripples, coral and rubble, all can interfere with both lateral currents and wave-induced porewater motion. Water motion above the sediment-seawater interface are accurately measured using pressure sensors. Can pressure sensors accurately record wave-induced porewater movement, and, if so, can the net vertical porewater movement then be expressed as a dispersion “step-length”?
If so, can such “step-lengths” be applied in conjunction with knowledge of chemical gradients to calculate chemical flux? In permeable systems such as carbonate sands the transmission of pressure by passing waves should induce significantly higher chemical flux than by molecular diffusion.

J: Part 3 - technology

A deployed sensor array combined with wave-sensitive benthic flux chambers would be -an ideal way to corroborate wave-induced benthic fluxes. Periods of high wave-action are in many cases physically impossible to conduct with endangering the observer, though it is during these periods that the most significant exchange takes place. Another concern is for the security of such expensive wave-sensors and benthic chambers. An established program of a sensor-array would help provide the security for these devices. New technology may not be as necessary, as compared to employing a combination of extant technologies on site to concomitantly-measure wave-action, currents, and benthic fluxes.

K: Part 1 - questions

K1. benthic flux (diffusional as well as enhanced by advective and/or tidal influence on overlying water movement)

K2. bottom sediment resuspension

K: Part 2 - expansion

Sediments underlying productive coastal regions are sites of active organic carbon deposition (Berner 1982; Hedges and Keil 1997) and serve as important sources of regenerated nutrients to the water column because of the proximity of sediments the photic zone. It has been estimated that nutrient flux from the seabed can support up to 70% of the annual N and P demands of primary producers (Rowe et al. 1975; Nixon et al. 1980; Nixon 1981; Twilley et al. 1999). Thus, benthic flux of nutrients can exert an overwhelming influence on the amount of primary productivity that can be supported by overlying waters. Further, because nutrient elements have distinctive chemical properties, interaction of dissolved nutrients with bottom sediments and resuspended sediments may fractionate dissolved nutrients from one another by differential retention from or release by sediments. The occurrence of such fractionation may influence the identity of the limiting nutrient in coastal systems by altering the ratio of available nutrients from the ideal uptake (e.g. Redfield) ratio.

The 70% figure cited above is derived either from sediment-based measurements of nutrient flux, or from modeling of pore water gradients. Implicit in these estimates is the assumption that the nutrients emanating from the seabed will quantitatively and directly impact primary productivity in overlying waters. There are a number of reasons to suspect that the actual scenario is more complicated. The dynamic nature of the strength and direction of bottom currents, and the possible influence of tidal processes on water flow in coastal regions, make it unclear what the path of sea-bed supplied nutrients will be. It seems overly simplistic to assume that seabed-derived nutrients will necessarily be transported to proximal overlying waters. Further, the benthic flux of nutrients will vary seasonally due to changes in geochemistry of bottom sediments forced by the seasonality of organic matter input to sediments.

Because control on benthic production of nutrients and subsequent transport involves a broad range of biological, geochemical, geological and physical processes, a quantitative evaluation of the controls on and magnitude of this phenomenon requires the multidisciplinary approach typical of CoOP studies. Further, because an important consequence of benthic nutrient production and delivery to overlying waters is the potential to support and influence the nature of overlying water biological productivity, a multidisciplinary study that includes a coupled benthic and water column component is essential. These coupled benthic-water column processes, in turn, can be directly related to carbon cycling and burial. For example, such a study would require coupling measurements of benthic nutrient flux with quantitative information on the water transport regime of the system to determine the path of bottom waters that have been imprinted with seabed-derived nutrients. Modification of the stoichiometry (e.g. N:P:Si:Fe) of seabed nutrient release by interaction with resuspended sediments should be determined. Within the context of a fully characterized nutrient transport regime, the limiting nutrient should be evaluated by quantifying nutrient deficiency indicators and conducting nutrient addition bioassays. Such a study would require a field program designed to capture temporal variability on a seasonal or shorter time-scale; thus making it highly appropriate for coastal observing system infrastructure. A comparative study between different coastal systems would be desirable because differences in water flow regimes, presence/absence of riverine input, physiography of the shelf, etc. will exert important influence on the critical processes to be monitored (e.g. benthic flux, prevailing currents/tides, nutrient transport). Finally, it would be extremely valuable to follow phytoplankton species composition during a seasonal process study of this type to attempt to link any observed species succession to changes in the nutrient regime forced by dynamics of benthic nutrient flux and transport to overlying waters.

Justification: Nutrient limitation is one of the fundamental controls on oceanic primary production and carbon burial with sediments. Although the dominant view is that Nitrogen (N) limits biological productivity in the coastal ocean, a number of more recent studies present strong evidence for phosphorus (P) and iron (Fe) limitation in coastal systems (Ammerman 1992; Smith and Hitchcock 1994; Justic et al. 1995; Monaghan and Ruttenberg 1998; Hutchins and Bruland 1998; Hutchins et al. 1999). These findings indicate that nutrient limitation in the coastal ocean is not well understood. For example, the occurrence of P and Fe limitation in coastal systems appears to be spatially heterogeneous and temporally dynamic, and the role of bottom sediments as sources of nutrients can be a determinant of which nutrient(s) limit biological productivity. The presence of suspended sediments, either derived from riverine input or bottom sediments, may play an important role in determining the limiting nutrient (e.g. Hutchins and Bruland 1998; Hutchins et al. 1999). As most carbon burial in the oceans (>80%: Berner 1982; Hedges and Keil 1995) occurs on the continental margins, it is of fundamental importance to understand the mechanisms driving nutrient supply and nutrient limitation of primary production in the coastal ocean. The role of the seabed in influencing nutrient supply and nutrient limitation is likely an important, perhaps key, factor, which is not well integrated into our understanding of coastal productivity. The CoOP Program is an ideal venue to tackle the kind of multi-disciplinary study required to address this question.

K: Part 3 - technology

Extremely amenable: influence of tidal & current driven water movement on magnitude of benthic flux and ultimate venue of out-cropping water carrying benthic-derived nutrients require measurement of physical, chemical, and biological parameters that change on timescales ranging from hours to weeks.

References:

Ammerman, J. W. 1992. Seasonal variation in phosphate turnover in the Mississippi River plume and the inner Gulf Shelf: rapid summer turnover. NECOP Workshop Proceedings, pp. 69-75. TAMU SeaGrant Publication TAMU-SG-92-109.

Berner, R.A. 1982. Burial of organic carbon and pyrite sulfur in the modern ocean: Its geochemical and environmental significance. Am. Jour. Sci. 282: 451-473.

Hedges, J.I. and R.G. Keil. 1995. Sedimentary organic-matter preservation - an assessment and speculative synthesis. Marine Chemistry. 49: 81-115.

Hutchins, D. A., and K. W. Bruland. 1998. Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime. Nature. 393: 561-564.

Hutchins, D.A., Franck, V.M. Brzezinski, M.A., and Bruland, K.W. (1999). Inducing phytoplankton iron limitation in iron-replete coastal waters with a strong chelating ligand. Limnol. Oceanogr. 44(4): 1009-1018.

Justic, D., N. N. Rabalais, R. E. Turner and Q. Dortch. 1995. Changes in nutrient structure of river-dominated coastal waters: Stoichiometric nutrient balance and its consequences. Estuar. Coast. Shelf Sci. 40: 339-356.

Nixon, S. W. 1981. Remineralization and nutrient cycling in coastal marine ecosystems, pp. 111-138. In: Neilsen, B. J. and L. E. Cronin (Eds.) Estuaries and Nutrients, Humana Press.

Nixon, S. W., J. R. Kelly, B. N. Furnas, C. A. Oviatt and S. S. Hale. 1980. Phosphorus regeneration and the metabolism of coastal marine bottom communities, pp. 219-242. In: Tenore, K. R. and B. C. Coull (Eds.) Marine Benthic Dynamics. Univ. South Carolina.

Rowe, G. T., C. H. Clifford, K.L. Smith, Jr., and P.L. Hamilton. 1975. Benthic nutrient and its coupling to primary production in coastal waters. Nature. 255: 215-217.

Smith, S.M. and G.L. Hitchcock. 1994. Nutrient enrichments and phytoplankton grown in the surface waters of the Louisiana Bight. Estuaries: 17(4): 740-753.

Twilley, R. R., J. Cowan, T. Miller-Way, P. A. Montagna and B. Mortazavi. 1999. Benthic nutrient fluxes in selected estuaries in the Gulf of Mexico. In: Bianchi, T. S., J. R. Pennock and R. R. Twilley (Eds.) Biogechemistry of Gulf Coast Estuaries, John Wiley & Sons, New York, pp. 163-209.

L: Part 1 - questions

We know that waves and currents drive frequent pore water exchange to depths of 0-10 cm in sandy sediments. Recent data require much deeper exchange-on the order of meters. These data lead to several questions regarding the frequent exchange of deep pore waters with the overlying ocean.

L1. Do tides cause significant fluid exchange in the upper several meters of the sea bed?

L2. Do large storms cause fluid exchange in the upper several meters of the sea bed?

L3. Do temperature inversions between the sea bed and the overlying ocean cause fluid exchange in the upper several m of the sea bed?

L: Part 2 - expansion

L1. We have data of diurnal temperature variations measured in 4 m deep monitoring wells (15 m water depth) on the inner shelf (Moore et al., 2002). These variations have been in phase with the tide during the summer (warmer water in the well during high tide) and out of phase during the winter (colder water in the well during high tide) during 4 years of record (see poster, this meeting). These observations require deep fluid exchange between the ocean and the monitoring wells. We have estimated that if only 4% of the inner shelf off South Carolina exhibited such exchange, we could explain the observed excess 226Ra present in the surface water (Moore et al., 2002). How common is this phenomena? Can we identify characteristics of the sea bed that lead to such exchange? What volume of fluid is involved? What are the consequences?

L2. We have data showing significant temperature variations in 2-4 m deep monitoring wells in the sea bed during storm passage (see poster, this meeting). These variations were measured in some wells that showed diurnal temperature variations and in others that showed no diurnal temperature variations. These observations require deep fluid exchange during storm passage. How common is this phenomena? What is the threshold for initiating exchange? What volume of fluid is involved? Can we identify characteristics of the sea bed that lead to such exchange? What are the consequences?

L3. We have limited data (1 case) suggesting that rapid cooling of the coastal ocean caused rapid cooling in a 1.6 m deep monitoring well in the sea bed (see poster, this meeting). This cooling was measured in a well that showed no diurnal temperature variations. This observation requires deep fluid exchange. How common is this phenomena? What volume of fluid is involved? Can we identify characteristics of the sea bed that lead to such exchange? What are the consequences?

L: Part 3 - technology

L1-3. These questions are best answered using geophysical surveys (high resolution seismic and electromagnetic), geochemical measurements (tracers and fluid characterization), and deployed sensor arrays (T, P, salinity, flow rate, nutrients). For question L2, deployed sensor arrays are essential to obtaining data during large storms. For question L3, deployed sensor arrays are essential for correlating changes in the seabed and overlying ocean. New technology is required to adequately estimate exchange rates. Measurements made by these techniques should answer the questions if used at enough locations.

Reference

Moore, W.S., J. Krest, G. Taylor, E. Roggenstein, S. Joye, & R. Lee, Thermal evidence of water exchange through a coastal aquifer: Implications for nutrient fluxes, Geophys. Res. Letters, 29, 10.1029/2002GL 014923, 2002.

M: Part 1 - questions

M1. How are the properties of suspended matter mediated by phytoplankton especially during blooms?

M2. How does turbulence determine the properties of suspended matter especially in relation to the settling flux of biologically-mediated suspended matter?

M3. What are the spatial and temporal variabilities of the plankton-turbulence-suspended matter interactions which govern the flux of organic matter to the seabed?

M: Part 2 - expansion

M1. Carbon drawdown and biogeochemical exchanges across the sediment/water interface are dependent on the settling of particle-associated organic matter which accumulates on the seabed as benthic fluff. The fluff layer is an important transitional stage for organic matter and it determines whether benthic remineralisation takes place under aerobic or anaerobic conditions. The settling flux of phytodetritus – which determines both spatial and temporal distributions of the fluff layer – depends on the size and density of the aggregated suspended matter in which it is incorporated. There is qualitative evidence, though little quantitative evidence, that algae themselves influence the properties of suspended matter by mediating in particle aggregation. It is suspected that such biologically-mediated particle aggregation at the end of algal blooms gives rise to rapid fall-out of phytodetritus and a rapid increase in water clarity as settling aggregates scavenge other suspended matter in the water column.

The probable mechanism for algal aggregation is production of sticky carbonates (polysaccharides) due to nutrient limitation. How algae become attached to suspended matter, whether actively or passively, must be dependent on their morphology and activity. This is likely to be different between different functional groups (e.g. diatoms, flagellates) and between different stages of their life cycle (e.g. bloom onset, bloom crash). The activities of algae in these respects are dependent on nutrient supply which has large spatial and temporal variabilities in the coastal zone, and these are significantly linked to climate change and anthropomorphic activity

M2. Recent technological advances have enabled us to measure turbulence and suspended sediment properties with the resolution needed to determine the role of turbulence in particle aggregation and disaggregation. New field results confirm that aggregation takes place in low turbulent shear regimes and disaggregation in high turbulent shear regimes – this has previously been shown only in the laboratory. Thus, for example, aggregation and increased settling flux occur in the low turbulence region of the thermocline in stratified waters. Furthermore, aggregation may occur during times of low turbulent shear and disaggregation during times of high turbulent shear. In tidal environments, aggregation and disaggregation may occur on tidal time scales. Since aggregation/disaggregation controls the size and density of flocs, it determines settling velocity and settling flux.

However, the ease with which turbulence breaks up flocs depends on floc strength. Floc strength depends on the mechanism of aggregation which in turn depends on the level of turbulence, the volume concentration of the suspended matter, and the properties of the primary particles. Thus, for example, laboratory evidence shows that weak flocs are formed under low turbulence, low concentration conditions. Weak flocs are then readily broken once the ambient turbulent shear stress exceeds floc strength. Little, or nothing, is known about the floc strength of flocs bonded by biological secretions: does the floc strength of biologically-mediated aggregates vary with time (e.g. between the onset and crash of a plankton bloom) and between algal functional groups? Nothing is known about the time history of floc strength in response to progressive aggregation and disaggregation.

M3. These interactions are strongly interrelated with the vertical structure of the water column. So the vertical flux of organic matter differs in mixed, frontal and stratified conditions. Exchanges may vary on tidal, lunar and seasonal time scales. The settling and resuspension fluxes of aggregates are critical since they determine how much time suspended matter spends in the water column which, in turn, controls pelagic and benthic remineralisations. In seasonally stratified waters, such phenomena are likely to be related to the relative timings of the onsets of stratification and blooms. They are likely to be sensitive to climate changes which control, for example, freshwater input and storminess both of which influence vertical structure and exchanges (of both water and nutrients).

M: Part 3 - technology

Observational strategies: opportunities and limitations.

Recent advances in technologies and techniques provide the potential for new observations of the critical features of the turbulence and suspended sediment regimes. Thus, for example, ADCPs linked to optical devices such as the LISST laser sizer, can produce the data needed to answer some of the outstanding questions relating to the flux of suspended matter in the coastal zone. High resolution datasets are needed which encompass the critical spatial and temporal scales of variability. Linked coastal observatories provide the potential for generating such datasets.

An important parameter which we cannot measure with any great confidence or with the required resolution is particle settling velocity. In many respects, this is a more important property than particle size.

Where we are currently constrained is in the provision of comparable high resolution data on nutrients and phytoplankton. A greater constraint is a lack of data on zooplankton: grazing of algae by zooplankton is a first order process in the biogeochemical cycle but the present lack of automated procedures for quantifiying zooplankton is a major handicap.

N: Part 1 - questions

N1. Improved observation of temporary habitats generated by short time scale exchanges

N2. Sediment transport influences on geochemical transformations of organic matter.

N3. Microbial ecology of transported material with a focus on organic matter fate

N: Part 2 - expansion

N1. The observation and prediction of benthic habitat dynamics would build on the growing recognition of the importance of ephemeral environments in the water column for fisheries and algal blooms. This research direction would add fishing activities to the list of forces (storms, eddies, internal waves) resulting in acute and potentially temporary habitat change. The best first method for investigating this research area would be the deployment of observatory-style instruments and samplers. The tools currently available should do an adequate job of making the required measurements. Instrument response and adaptability to changes in the environment would improve observation frequency during events of interest. The optimal set of measurements would include the response and recovery of bed roughness, permeability, and geochemical environment in the sediment.

N2. When sediment is in motion, it represents a physical disturbance that changes the depth distribution of chemical and particles, as well as exposing grains and pore fluid to the benthic boundary layer. All of these fluxes could radically alter the chemical and biological transformations of particulate organic matter. Given the short durations of sediment transport events, portable observational techniques must be employed that are capable of monitoring the flow environment as well as sample the organic matter and bacterial characteristics of the fluid and suspension. Current instruments can get the job done, however, water samples are necessary for characterizing organic matter and bacterial dynamics at present. New instrumentation might allow these measurements to be taken in situ, greatly expanding the range of acceptable conditions and lengths of deployment (limited by alteration of samples in the bottles).

N3. Fine particle suspensions could provide a setting for increased microbial activity or a means of transport organisms from site to site. Both of these implications are important in determining the rates and location of organic matter degradation. Exploring these possibilities would require investigators to employ sampling schemes resembling an observatory under-way, tracking a suspension and the changes in microbial activity and populations. Recent work on tracking river plumes provides a framework for attacking this sort of question, but a heavy reliance on water sampling and (relatively) slow processing of bacterial measures may hinder the work using existing technologies. There would be many other uses for new methods that rapidly process samples (maybe in situ) to estimate bacterial and geochemical dynamics fast enough to follow transporting material or resolve high frequency events.

O: Part 1 - questions

What portion of the land runoff to the coastal ocean arrives there through a subterranean pathway and how is this input chemically modified (i.e. different from surface runoff?)

O: Part 2 - expansion

A lot of attention has been directed at estimating groundwater inputs from surficial aquifers and assessing the difference in the composition of this source as compared to surface runoff. But in many areas much of the surface runoff in rivers is diverted to a pathway through permeable sediments upon reaching the coast. This often occurs below the downstream-most river gauging station.

In some coastal areas, such as those characterized by coastal lagoons, the fraction of the gauged river discharge may be quite large and the composition of the input from this diverted pathway can be significantly different, making input estimates of materials from rivers to the coastal ocean relatively meaningless.

O: Part 3 - technology

Very amenable to emerging technology

P: Part 1 - questions

P1. How does the structure/ function of microbial communities limit key C and N cycling reactions in permeable sand sediments of the continental shelf? Do these structure/ function relationships differ from their counterparts in fine-grained sediments?

P2. Is coupled nitrification/ denitrification a significant pathway for nitrogen removal in permeable shelf sediments?

P3. What are the predominant rates and pathways for the terminal decomposition of organic matter in permeable shelf sediments?

P: Part 2 - expansion

P1. Little is known about the community composition of microorganisms inhabiting permeable, sand sediments. Past studies have hypothesized that bacterial communities are less abundant and their community composition fundamentally different in coarse-grained sediments due to a lower specific surface area, lower organic content, or higher predation pressure. The analysis of microbial communities which mediate C and N transformations in marine sediments have thus far concentrated on studies of diversity, and the “active” community members catalyzing important processes such as terminal organic matter decomposition or coupled nitrification-denitrification have not been extensively identified/ quantified.

Thus far a mixture of aerobic and anaerobic groups, members of the Cytophaga-Flavobacterium, Planctomycete, and delta Proteobacterial sulfate-reducer groups were detected in the greatest abundance in shelf sands (Llobet Brossa et al., 1998; Rusch et al., 2003). The majority of results on community composition of shelf sands were collected using fluorescence in situ hybridization (FISH) with oligonucleotide probes targeted to the 16S rRNA genes. FISH approaches have not detected significant changes to community composition along environmental gradients in permeable sediments, perhaps due to the broad specificity of the probes used. In addition, the organisms present have not been specifically identified to the genus or species level. In order to elucidate the mechanisms controlling organic matter processing in permeable sediments, the structure/ function of microbial communities catalyzing organic matter decomposition must be better understood.

P2. Denitrification represents a primary sink for N removal in the world ocean, and thus it should directly influence the response of global biogeochemical cycles to critical external forcings such as anthropogenic nutrient enrichment and global climate change. Recent work has suggested that rates of denitrification are significantly greater in continental shelf sediments than was previously estimated. Previous studies of the rates, pathways, and mechanisms controlling denitrification in continental shelf sediments have focused mainly on fine-grained sediments. The majority of shelf areas worldwide are composed of sandy sediments, where relatively little research has been conducted on N transformation processes.

New methods for the direct in situ measurement of denitrification rates have become available, and previous work has not often coupled the complete partitioning of organic matter decomposition pathways to an assessment of denitrification under near in situ conditions. Also, few studies have related directly-measured denitrification rates to the activities of benthic organisms in situ. Further research is required to constrain N removal by N2 production on continental shelves. Future research should focus on less-studied permeable sediments and should incorporate spatial and temporal variability in order to improve ecosystem budgets of N cycling processes.
P3. Due to their low organic carbon content and in some cases a lack of accumulation of reactant/ products of diagenesis, permeable shelf sediments were thought to contribute little to organic matter remineralization. Thus in comparison to their fine-grained counterparts, carbon oxidation processes in sandy permeable sediments have not been well characterized. Recent studies have suggested that permeable shelf sediments may make a much larger contribution to organic matter processing than was originally perceived.

Future research should determine the predominant rates and pathways of organic matter degradation across gradients in sediment characteristics (to address the potential catalytic effect of pore water advection), organic matter loading, temperature, and other important environmental parameters. Spatial and temporal variability in the rates/ pathways must be addressed in order to better scale-up estimates across entire shelves. Wherever possible, the latest techniques which allow for proper reconstruction of in situ conditions should be employed. Studies should tightly couple geochemical along with microbiological approaches to determine the controls or mechanisms of carbon cycling in shelf sediments.

P: Part 3 - technology

P1. Deployed sensor arrays may not be very useful in addressing microbial community structure, however arrays would be key to identifying the environmental parameters limiting microbial metabolism. New nucleic-acid based technologies need to be developed and improved in order to better quantify the “active” members of microbial communities and these techniques need to be automated wherever possible to increase sample throughput.

P2. Deployed sensor arrays will be useful for studying denitrification on continental shelves. Sensors for nitrogen species and oxygen should aid in determining the controls or mechanisms of denitrification as well as for estimating the importance of denitrification to overall N flow.

P3. Monitoring of reactants and products of organic matter remineralization over the large scale using deployed sensor arJ: Part 1 - questions

Q: Part 1 - questions

Q1. What is the contribution of stochastic resuspension events (i.e., large storms) to the total benthic exchange of nutrients on shelves? How can these events be modeled along with steady-state processes?

Q2. Fate of nutrients released into the bottom boundary layer (BBL) during sediment resuspension events. What is the partitioning of these nutrients between rapid biological assimilation within the BBL, lateral advection in the BBL, and mixing into the photic zone? What is the fate of these nutrients if resuspension occurs during periods of low primary production (e.g., winter)?

Q3. Is there a benthic source of nutrients on autochthonous sandy shelves? If so, from what sub-seafloor depths? Does the now-buried antecedent Pleistocene subareal environment (e.g., lacustrine, marsh, fluvial) supply nutrients to the coastal ocean? If so, through what pathways does it reach the seafloor?

Q: Part 3 - technology

Important for Question #2. Having nutrient sensors currently deployed on moorings on tripods used to measure BBL processes (e.g., current velocity, suspended sediment concentration) would be important to correlate BBL resuspension events with changes in BBL nutrient concentration.

R: Part 1 - questions

R1. How do sediment porosity and small-scale topography interact with boundary layer turbulence to affect spatial and temporal patterns of solute exchange?

R2. How does boundary layer turbulence affect the transport and adsorption kinetics of dissolved compounds released by benthic macrofauna?

R3. How is solute flux through porous sediments affected by the morphology and sinuosity of tidal channels?

R: Part 2 - expansion

Phagostimulants and waterborne attractants are critical determinants of foraging by benthic macrofauna. Deposit feeders, filter feeders, grazers, scavengers, and predators have all been shown to detect and respond to dissolved chemicals, and animal responses to these foraging cues have consequences for processes affecting benthic exchange rates. For example, large burrowing gastropods (up to 20-cm in length) follow plumes of dissolved chemicals and plow through porous sediments in search of prey. The sensory apparatus of these animals is largely immersed in surficial sediments, and bed-generated turbulence has been shown to enhance olfactory foraging by gastropod predators and scavengers. Transfer of attractive solutes (e.g., prey chemicals) across the sediment-water interface should be of primary importance for the foraging decisions and movements of burrowing gastropods. Understanding how benthic exchange rates vary in relation to local hydrodynamic regime and sediment characteristics would improve our ability to predict the ecological and sedimentary impacts of these important bioturbators.

R: Part 3 - technology

Acoustic Doppler probes can be used to quantify hydrodynamic processes in benthic environments, and pulse-coherent technology is particularly well suited for collecting high resolution velocity measurements within boundary layer flows. Reductions in probe size and cost could provide a realistic incentive to incorporate more of these instruments into deployable sensor arrays.

S: Part 1 - questions

S1. How important is submarine groundwater discharge (SGD) in freshwater and nutrient budgets of continental shelves (any location).

S2. Can we accurately quantify rates of nutrient recycling and transformations in permeable sediments? (esp. near sed-water interface)

S: Part 3 - technology

Radon detectors could be placed at multiple surface-water locations to constrain temporal variability in groundwater input. Not a trivial engineering feat, but much harder things have been done. Would need cable and/or Reimers fuel cell to power.

Also, it would be great if someone could design some sort of "benthic chamber" that would give useful results from permeable sediments without interfering with fluxes due to advection, currents, tidal pumping, etc.

T: Part 1 - questions

T1. Entrainment of cohesive sediment

T2. Deposition of cohesive sediment

T3. How is fluid mud generated?

T: Part 2 - expansion

T1. The entrainment of cohesive sediment in coastal waters has been traditionally treated as an engineering problem. As such, there has been a dependence on parametric approaches that rely heavily on measurements. This is understandable given the necessity of accurate predictions in economic decision-making. The most common approach is a power-law equation of the type a = bsc, where b is a coefficient and s can be either a constant or an excess shear stress term. Sometimes, b is constant or can incorporate a time dependency. This approach has been convenient because of the uncertainty of the processes that determine clay flocculation and disaggregation. Several independent lines of research have focused on these effects. For example, clay particle physics is of great interest in chemical and environmental engineering and the relationship between electrochemical behavior and flocculation has been studied. The adsorption of chemical species like PCB's to clay particles has also sparked interest in the causes of flocculation. There is also interest in biogeochemical processes in the seafloor, which have direct effects on the microstructure of cohesive beds and their entrainment properties.

Each of these problems has been extensively studied over the years, resulting in a basic understanding of the physical processes. However, there has been no coherent multidisciplinary effort to understand the contribution of each process to the observable entrainment behavior of cohesive sediments. Furthermore, much of the effort has been directed at predicting the entrainment rather than describing the processes that lead to these observations. For example, studies of entrainment have continued to use power law formulations with a range of forms for the general equation. These different formulae have been used to describe specific sets of data rather than elucidate the relationship between entrainment and sediment properties. These processes have overlapping effects. Dewatering (consolidation) is a time-dependent process that, in the absence of other processes, will cause clays to compact and become aggregated, leading to a resistance to entrainment. Another important process is bioturbation, which is loosely defined as physical disruption by the activity of burrowing organisms. Bioturbation has structural and chemical impacts that vary tremendously. Some infauna burrow vertically and others form u-shaped burrows. Some follow random-walk paths. The depth of burrowing is also highly variable and is a function of chemical and physical environments. Such burrowing activity tends to decrease the resistance of sediment to entrainment but in nonuniform ways. Burrowing parallel to bedding has been seen to increase both the rate and mode of entrainment in cores. Associated chemical processes tend to cement sediments within burrows and also produce heterogeneous geochemical zones within sediments. Extruded sediments and fecal material significantly alter the character and thus properties of surface sediments. Infilling of burrows is also heterogeneous. Very little is known of the dependence of clay flocculation processes with respect to the geochemical changes accompanying these biological processes.

Ultimately, the entrainment of cohesive sediments depends on sediment properties and the structure of turbulence in the bottom boundary layer. Thus it is important to understand the feedback between the evolving bottom properties and the turbulence field within the water column. A theoretical approach similar to that taken for sands is required. It is also necessary to measure the turbulence structure over mud bottoms. This is important in order to understand the dependence of "gross" entrainment on local entrainment, which is a direct function of the turbulence pattern.

T2. The deposition of cohesive sediment is more problematical than entrainment. Most approaches depend on the pioneering work of Partheniades and Kronin. These semi-empirical models use calibration factors that are oversimplifications of complex collision dynamics. They are also based on a limited number of laboratory studies by only a few researchers. Additional work on flocculation dynamics gives some additional insight into the physics of cohesive sediment adhesion (which is applicable to sticking to the bed). This subject has in general been ignored in most studies because of the difficulties of describing these processes.

The description of cohesive floc properties that are important for deposition, such as density, floc size, and settling speed, is also very difficult to describe from our present knowledge. Some laboratory studies have been supplemented by sparse field studies but there is a lack of a coherent rationale for these efforts. It is not possible to understand cohesive sediment dynamics without dealing with the problem of flocculation. Both field and laboratory studies have shown a general dependence of floc properties on shear within the water column. This needs to be examined in more detail. It is not clear to what degree laboratory measurements of these properties can be extrapolated to the marine environment. Furthermore, there is a suspected but not well-known dependence of clay flocculation on organic content. What other marine suspended and dissolved material is important in understanding these processes?

T3. An even more vexing problem is the generation of fluid mud. Observations of fluid mud indicate that it is not necessarily a permanent state but that it can be produced from otherwise normal clay sediments under the right circumstances. It is important because of its mobility and heterogeneous properties, which can totally obscure the bottom. Attempts to deal with the properties of clay bottoms and fluid mud have focused on isopycnal approaches with water/sediment layers of different properties. Models like this have shown a response similar to that seen in natural muds but they are limited in their applicability and they cannot generate a fluid mud. Unlike other marine sediments, which have relatively fixed properties and fairly well-known transport processes, fluid mud has widely variable properties and cannot be easily distinguished from high density mud concentrations. There is a debate today whether these sediments are produced by deposition from high concentrations or generated by resuspension processes.

The behavior of fluid mud has important consequences for the exchange of sediment-bound material between the water column and the seafloor. Thus it is important to understand the three-dimensional structure of exchange processes within these suspensions. What is the dependence of fluid mud generation on local turbulence? How important is clay mineralogy and adsorbed material like organic matter on the formation of these layers?

T: Part 3 - technology

Deployed sensor arrays could prove useful in characterizing the spatial structure of turbulence, chemistry, and physical properties of the bed. The use of arrays of probes to examine the heterogeneity of geochemical signatures would help understand the problem of bridging scales, from microscale to macroscale. This would help in developing statistical approaches to describing bed properties and entrainment. It would be necessary to develop mechanical systems to accurately locate high-resolution instruments like sediment microprobes. However, the sensors exist today and are used in both laboratory and field experiments.

VI.D. Agenda

Coastal Ocean Processes (CoOP) Program
Coastal Benthic Exchange Dynamics (CBED) Workshop
April 5 - 7, 2004
USGS Center for Coastal & Watershed Studies
St. Petersburg, Florida

Monday, April 5

0745 Registration and continental breakfast

0820 *Introduction to CoOP Program*, Rick Jahnke, Chair of CoOP Scientific Steering Committee

0830 *Introduction and charge to workshop*, Clare Reimers and Carl Friedrichs, Co-chairs of Organizing Committee

0840 *Sediment response to biophysical interactions in the water column and bottom boundary layer*, Colin Jago, University of Wales

0920 *Episodic sedimentation and post deposition alteration on muddy continental shelves*, Rob Wheatcroft, Oregon State University

1000 Coffee break

1030 *Dynamics of seabed biogeochemistry on the South Atlantic Bight continental shelf*, Rick Jahnke, Skidaway Institute of Oceanography

1110 *Biological and physical transport processes at the seafloor*, Markus Hüttel, Florida State University

1150 *Eddy correlation - a promising technique for benthic flux time-series measurement*, Peter Berg, University of Virginia

1230 Lunch

1330 *Breakout Session I: Major CBED questions organized by time-scale of forcing*

Group I: Up to hours (e.g., turbulence, waves, biological pumping, a trawling event)

Group II: Several hours to a few weeks (e.g., diurnal cycles of light, tides, storm and flood events, biological blooms)

Group III: Month to year (e.g., seasonal cycles in physical forcing and fishing effort)

Group IV: Years to decades (e.g., climate cycles, groundwater discharge, burial)

1515 Coffee break

1545 *Breakout Session I* (cont.)

1730 *Poster Social* sponsored by the Alliance for Coastal Technologies (ACT)

1830 Barbeque Dinner sponsored by ACT

Tuesday, April 6

0800 Continental breakfast

0830 *Reports from working groups*

1030 Coffee break

1100 *Plenary discussion*

1230 Lunch with *presentation by Herb Windom, Alliance for Coastal Technologies*

1330 *Breakout Session II: Major CBED questions organized by issue, such as: Fishing effects; Carbon cycling; Nutrient cycling; Sediment diagenesis; Sediment exchange; In-situ instrumentation*

1515 Coffee break

1545-1730 *Breakout Session II* (cont.)

1900 Evening Social: Devil Rays vs. Yankees Season Opener

Wednesday, April 7

0800 Continental Breakfast

0830 *Reports from working groups*

1030 Coffee Break

1100 *Plenary discussion and summary of workshop*

1230 Workshop adjourns; participants depart

1230 *Workshop organizing committee/working group chairs/rapporteurs meeting*

VI.E. Poster Abstracts

The role of margin sediments in mediating the weathering flux of phosphate to the oceans

AS Colman; Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC, USA, a.colman@gl.ciw.edu

Global biogeochemical cycle models routinely calculate chemical weathering fluxes from continents to the oceans based solely on dissolved concentrations in rivers. Phosphorus is delivered via rivers to the oceans in a variety of reactive phases both dissolved and particulate. A compilation of benthic phosphate fluxes from continental margin and deep sea sediments reveals that the global efflux of phosphate from marine sediments is on the order of 30 times higher than the global river dissolved flux of P.

The total benthic flux can be apportioned between two P sources: allochthonous (i.e., derived from riverine reactive particulate P phases) and autochthonous (i.e., derived from marine reactive particulate P phases). Calculations of the allochthonous flux show that 80-90% of the weathering flux of P into the oceans enters initially in reactive particulate form. This P is released as phosphate to the water column only subsequent to diagenesis, mainly in continental margin sediments. Inclusion of this input flux of P to the oceans results in a marine residence time on the order of 10,000-20,000 years.

Sources and distribution of organic matter in sediments from the Fly River clinoform, Gulf of Papua (Papua New Guinea)

MA Goni, N Monacci and R Gisewhite; Department of Geological Sciences, University of South Carolina, Columbia, SC 29208 USA; goni@geol.sc.edu

Surface sediments were collected from the clinoform of the Fly River (Papua New Guinea) as part of a multidisciplinary effort to understand the sources, transport and fate of sediments and organic matter. Sediments from the area northeast of the Fly River mouth, which appears to be a zone of temporary storage, were characterized by organic carbon contents (%OC) of 1.0 to 1.4 wt. %, atomic organic carbon:total nitrogen ratios ([C/N]a) of 14 to 24 and stable organic carbon isotopic compositions ($\delta 13C_{oc}$) of –26 to –27 per mil. The sediments from the delta front region adjacent to the Fly River Delta, on the other hand, displayed %OC values of 0.4 to 0.8 %, [C/N]a ratios of 12 to 24 and $\delta 13C_{oc}$ values of –24 to –25 per mil. These compositions indicate that a large fraction of the organic matter in the surface sediments originated from terrigenous C3 plant sources, including vascular plant fragments from the delta and soil organic matter from the Fly River drainage basin. The contrasts between the northeast and the delta front regions suggest differential deposition and transport conditions between the two areas. On-going analyses of organic biomarkers (e.g. lignin phenols) and sediment characteristics (e.g. mineral surface area) will be used to further refine these initial interpretations.

Can pressure sensors be used to measure wave-induced vertical porewater movement? Comparison of measurements of non-breaking wave-action on and in a hawaiian coral patch reef, to those in a laboratory-based vertical head oscillator.

PR Haberstroh, Marine Science Institute, The University of Texas at Austin, Port Aransas, USA, paulh@utmsi.utexas.edu and FJ Sansone, Department of Oceanography, University of Hawaii, Honolulu, USA, sansone@soest.hawaii.edu

In Checker Reef, Oahu, rather exhaustive measurements by Tribble (1990) using piezometers connected to well point samplers concluded that the dominant physical mechanism responsible for driving exchange between interstitial water and surface seawater is high-frequency vertical mixing, induced by non-breaking, wind-driven gravity waves (Tribble et al. 1992). In coral reef frameworks and other advectively-dominated permeable sedimentary systems such exchanges may promote microbial respiration and diagenesis within the framework by providing dissolved oxygen and both dissolved and particulate organic matter. This wave-induced exchange may in turn provide autotrophs on the reef surface with considerable amounts of inorganic nutrients, since reef interstitial water is typically enriched in inorganic nutrients compared to the overlying surface seawater (Andrews and Müller 1983; Buddemeier and Oberdorfer 1983, 1986; Sansone 1985; Sansone et al. 1988, 1989, 1990; Carter et al. 1989; Tribble 1990; Haberstroh and Sansone 1999a; Falter and Sansone 2000).

Horizontal currents impinging on surface-roughness features typical on reef flats further induce pressure differences above and below the sediment-seawater surface, also inducing vertical (and horizontal) exchange of porewater and seawater (Huettel and Gust 1992, Shum 1992, 1993; Precht and Huettel 2003). We have routinely employed electronic pressure sensors on the wave-impacted Checker Reef to more easily measure the net vertical motion induced by non-breaking wave-action occurring just above (20 cm) the sediment-seawater interface, to that occurring within the permeable reef framework.

Spectral analysis of the logged times series of wave-action above and within the reef displays progressively strong filtering of the shorter-period (2-6 s) components with reef- framework depth, as well as providing wave parameters (e.g. significant wave height, rms-amplitude, period, etc.) for models of nutrient flux. However, there were concerns that the internal surface area of the connecting tubing and well-point sampling tubing may differentially-filter shorter-period wave signals. Also, while our sensors show excellent sensitivity (< 1 mm head difference) and linearity of response to static head variation (typically $r2 \geq 0.99$) there was also concern that we had not thoroughly checked their ability to measure dynamic oscillations in head. We also cross-checked our spectral analyses with physical oceanographers at the Conrad Blucher Institute for Mapping and Surveying at Texas A&M-Corpus Christi, who typically measure wave action throughout the Gulf of Mexico, using NOAA-vetted spectral analysis techniques. We present a method to cross-check these possibilities. We constructed and filled a large tube ("Big Tube") with water to a depth of approximately 1 m, and induced mono-chromatic oscillations of the surface-head by means of a motor-driven cylinder. We compared the performance of the pressure sensors to measure the same fluctuations of the oscillating head with all three sensors attached at the same level beneath the Big Tube. We also compared the sensors when connected to the tube bottom with difference lengths of stiff tubing and also directly video-taped the surface-oscillations, and logged the pressure-time series.

The vertical head oscillator ("Big Tube") yielded monochromatic oscillations with periods ranging from 2- 6 s and root-mean-square (rms) amplitudes of 4-5 cm. When the sensors were all mounted at the same level they all agreed to within 1% of the rms-amplitude of the 3-sensor mean-oscillation, e.g. within 0.4-0.5 mm. The rms-amplitude detected at over 1.2 m below the tube base was only 1-2% lower than that detected directly below the Big Tube base ("0 m – Pressure Sensor"), and was not affected by the period of the oscillation. However, the rms-amplitude detected by the sensor 1.8 m below the Big Tube base was only 80% of the$»ms-amplitude detected directly below the Big Tube base, but curiously there was also no discrimination of signal loss with oscillation-period. The loss of pressure-signal in the natural carbonate framework of Checker Reef was far greater at 1 m framework depth (15-25%), and at 2 m framework depth (43-57), than that lost by the 1.8 m stiff tube in the Big Tube experiments. We conclude that there is significant vertical porewater motion in the reef framework and this may result in significant inorganic nutrient flux.

Quantifying sediment mixing in estuaries: Implications for benthic exchange rates

JM Jaeger[1], J Cable[2], J Martin[1], M Sun[3], and J White[4]; [1]Department of Geological Sciences, University of Florida; [2]Department of Oceanography and Coastal Sciences, Louisiana State University; [3]University of Georgia, Department of Marine Sciences; [4]Soil and Water Sciences, University of Florida

Sediment mixing by bioturbation and through physical resuspension by waves and currents influences sediment-water nutrient fluxes by rapid releasing nutrient-rich porewaters, changing the porosity and permeability of near-surface sediments and by ventilating sediments with oxygen-rich porewaters, thus changing sedimentary redox potential, which in turn controls organic matter regeneration rates. In order to properly employ diagenetic transport-reaction models to quantify the fate of nutrient, it is necessary to constrain the role that sediment mixing plays in controlling the relevant environmental parameters: biological and physical particle mixing rates, including physical resuspension; biodeposition, and bioadvection; bioirrigation; sediment porosity and permeability. Adequate quantification of these parameters requires measurements made over a range of temporal and spatial scales that are commensurate with the diagenetic process of interest. This poster illustrates examples of these measurements that have been made in two estuarine settings in eastern Florida.

The St. Johns River estuary is a tidally dominated blackwater estuary dominated by organic-rich, high porosity muddy sediments that undergo daily to weekly tidal resuspension and biological mixing is minimal. For the St. Johns River estuary, a simple Peclét number (PE) scaling can be used to determine the relative contribution of advection and diffusion in controlling transport across the sediment-water interface. PE ~1 for a dissolved substance (Ds=$2*10^{-5}$ cm^2 s^{-2}; 2 cm^2 d^{-1}) in a 1-2 cm-thick surface mixed layer undergoing 1 cm d^{-1} advection (i.e., resuspension). Consequently, diffusion and advection fluxes are roughly equal for the St. Johns River estuary. Desorption/ adsorption reactions are not considered.

The Indian River Lagoon is a shallow sandy lagoon where physical mixing is largely absent and transport across the sediment-water interface is likely entirely driven by bioirrigation. A time-series of porewater salinity to ~ 2 m depth below the seafloor was done in 2003 and revealed that salinity below ~100 cmbsf is determined by steady-state upward flow at rates of ~0.05 cm d^{-1} probably driven by the hydrostatic head of the Surficial aquifer. Temporal variations in porewater salinity above 100 cmbsf represent rapid advective mixing between the pore water and overlying water column. A time-series sediment tracer experiment revealed that rapid bioturbation occurred only over the upper 10 cm of the sediments and could not explain the rapid changes in porewater salinity over deeper sediment depths.

Modeling early diagenesis at the seafloor: Transport intensities and pore-scale analysis

C Meile, Department of Marine Sciences, The University of Georgia, Athens GA

Burrowing fauna can significantly affect elemental cycling in aquatic sediments. Here, three modeling approaches to quantify solute mixing intensities are presented. They differ in the amount of detail and type of data used and the level of linkage between transport and reaction processes. Burrows counteract vertical redox-zonation, and hence influence the distribution pattern of microbial populations. As the spatial scale relevant for microbes is smaller than the one resolved with current early diagenetic models, a novel analysis of reaction and concentration distribution at the pore-scale is introduced.

Assessing fluid exchange between the continental shelf and the ocean: Chemical and physical indicators

WS Moore, Department of Geological Sciences, University of South Carolina, Columbia, SC 29208, USA, moore@geol.sc.edu

Below some, perhaps many, continental shelves lie complex subsurface systems of shallow permeable sediments and deeper semi-confined aquifers. Groundwater in these systems exchanges frequently with overlying waters. This exchange may be driven by an inland hydraulic head in semi-confined aquifers as well as wave and tidal pumping and bottom currents. These processes deliver a considerable supply of nutrients, metals, and carbon to coastal waters. Elucidating the effects and driving forces of these processes challenges coastal oceanographers and hydrologists.

Many workers have discussed shallow (1-20 cm) exchange through sandy sediments driven by waves and currents. In this poster I present evidence of deeper (1-4 m) exchange based on physical and chemical tracers. In some cases deep exchange is so rapid that temperature is an effective tracer of fluid advection. For example temperature recorders in some offshore monitoring wells reveal a cyclic signal that is in phase with the tide. These observations suggest tidal pumping is daily circulating water between the ocean and a 4 m deep aquifer. In nearby wells rapid temperature changes only occur in response to storm events and sudden temperature changes in overlying waters.

To assess the supply of materials to the ocean by subsurface fluids, oceanographers use chemical tracers that have high concentrations in the fluids and low chemical reactivity in the ocean. The four isotopes of radium meet these criteria as natural tracers of fluid exchange. These isotopes, which have half lives ranging from 3.7 days to 1600 years, are each produced by decay of a thorium isotope. Because thorium is perpetually bound to surfaces and radium is free to migrate to salt water, solids continually release radium to the ocean. The effect of such releases may be evident in coastal waters where activities of Ra-226 may exceed open-ocean values by a factor of four. To translate the radium excess to a fluid flux, we must evaluate potential sources of radium, quantify excess radium, determine the coastal ocean residence time, and measure the radium concentration in the underlying fluids. Along the SE Atlantic coast, radium isotope studies have revealed substantial exchange between water in coastal aquifers and overlying waters. Such exchange brings water enriched not only in radium, but in nutrients, carbon, and metals to the coastal ocean. These studies indicate that dissolved nitrogen and phosphorus inputs from the groundwater exceed inputs from rivers and the atmosphere.

Spatial and temporal patterns of dissolved phosphorus distribution in coastal waters of central Oregon

KC Ruttenberg and SD Dyhrman; Dept. of Oceanography, University of Hawaii at Manoa, Honolulu, Hi 96822

As part of the CoOP-funded COAST project, we have analyzed 0.4 um- and 0.2 um-filtered water samples for Total Dissolved Phosphorus (TDP), Soluble Reactive Phosphorus (SRP, sometimes referred to as Dissolved Inorganic Phosphate (DIP), or simply phosphate). The difference between TDP and SRP provides an estimate of Dissolved Organic Phosphorus (DOP) concentration. Surface water samples from the Spring (May 2001) and Summer (August 2001) two cruises have also been analyzed for bulk water alkaline phosphatase (APase), a phosphohydrolytic enzyme that can render DOP compounds bioavailable, as well as for cell-specific APase using Enzyme Labeled Fluorescence (ELF).

Depth profiles of TDP, DOP and SRP from both spring and summer cruises show highest DOP concentrations occur in the upper water column, but that many of the deeper water samples also contain resolvable DOP. In spring, DOP ranges from 10-40% of TDP in the upper 40 m of the water column, with highest proportions (30-40%) in the upper 5 m. DOP concentrations range from undetectable to 0.5 uM. In summer, DOP in the upper 10 m of the water column ranges as high as 80% of TDP, averaging 40%. The average fraction of DOP in the upper 20 m in summer is 22-28%, for 0.4 and 0.2 um filtered water, respectively. DOP concentrations in summer range from undetectable to as high as 1.8 uM. Thus in summer, the segregation of the DOP concentration maxima to the upper water column is compressed into the upper 20 m, and DOP concentrations are significantly higher. In contrast, DOP maxima in spring are expanded to occupy the upper 40 m, and concentrations are lower.

Bulk-water (e.g., unfiltered) Alkaline phosphatase activity is present in surface waters during both spring and summer, but can only be clearly resolved in samples with low levels of SRP. More samples showed ELF activity than showed APase activity, illustrating the higher degree of sensitivity of the ELF technique over the standard fluorometric technique applied to bulk waters. The fluorometric technique is now being applied to particulate samples concentrated from bulk waters, and improved detection will permit us to resolve APase activities in samples for which activities in the bulk water are too low. The presence of APase activity in waters with low SRP yet high DOP concentrations suggests that DOP may play a role in meeting phytoplankton phosphorus demand in this system.

Permeable-sediment research at the University of Hawaii

FJ Sansone, Dept. of Oceanography, University of Hawaii at Manoa, Honolulu, HI 96822

This poster describes four active research projects at the University of Hawaii that are studying a variety of aspects of permeable sediments. The project titles/sponsors, investigators/affiliations, and objectives are listed below:

1) Wave-Driven Pore Water-Seawater Exchange in Sandy Coastal Sediments (NSF-Chemical Oceanography). Frank Sansone (PI, UH Oceanography), Mark Merrifield (co-PI, UH Oceanography), Geno Pawlak (co-PI, UH Ocean and Resources Engineering), Ian Webster (Senior Associate, CSIRO Land and Water).
This project aims to describe and quantify the transport of solutes and particulate matter in sandy sediments. This research will be conducted off the south shore of Oahu, Hawaii, a site that is subject to a wide and predictable range of wave conditions. This research will provide practical methodologies to quantify porewater and particle motion, including sediment-water fluxes, and develop a generic process understanding that will allow the estimation of interstitial transport rates in biogeochemical models used to represent diagenesis in sandy sediments.

2) Microcosm Investigation of Carbonate Reef Microbial Biogeochemistry (NSF-Biogeosciences). Eric Gaidos (PI, UH Geology and Geophysics), Frank Sansone (co-PI, UH Oceanography), Angelos Hannides (Graduate Research Asst., UH Oceanography).
This project is a one-year proof-of-concept project that is demonstrating the use of a laboratory microcosm to investigate the impact of elevated atmospheric CO2 levels and higher carbonate solubility on the microbial community and biogeochemistry of carbonate reefs. We are reconstructing the interior reef sediment and its heterotrophic microbial community; the system is being "fed" natural particulate organic matter from seawater and is subjected to simulated surface-wave-induced porewater-seawater mixing.

3) Nuisance Macroalgal Blooms in Coastal Maui: Physical Factors and Biological Processes (NOAA-ECOHAB). Celia Smith (PI, UH Botany), Frank Sansone (co-PI, UH Oceanography), Heather Spaulding (Graduate Research Asst., UH Botany), Iuri Herzfeld (Graduate Research Asst., UH Oceanography).
Sporadic macroalgal blooms in west Maui have long eluded explanation, prompting an interdisciplinary investigation to determine possible interactions between the geochemical (water-column and sediment) environment and macroalgal abundance. This inter-disciplinary approach, used across a wide depth range offshore, will enable a thorough characterization of the west Maui coastal environment and its algal dynamics. Evaluation of current and future algal blooms in west Maui will be possible with the baseline data provided by this investigation.

4) Exploration Of Deep-Water Macroalgal Meadows In The Main Hawaiian Islands (NOAA-Ocean Exploration). Celia Smith (PI, UH Botany), Frank Sansone (co-PI, UH Oceanography), Heather Spaulding (Graduate Research Asst., UH Botany).
Deep-water (~100 m) surveys have documented expansive, macroalgal meadows of native and introduced species spanning tens to hundreds of kilometers in the Main Hawaiian Islands (MHI). These undescribed assemblages provide structural complexity over otherwise featureless

expanses of sand, and may serve as a significant food source, habitat, or substrate for commercially important fishes and invertebrates. Submersible dives will be used to provide a quantitative description of deep-water macroalgal assemblages, associated macrofauna, and seawater and porewater nutrients; these will be used as a habitat description and a basis for monitoring any changes in the community structure over time.

Forcing functions governing subtidal water level variability in a Mississippi deltaic estuary

GA Snedden[1], W Wiseman[2], and JE Cable[1], [1]Department of Oceanography and Coastal Sciences,Louisiana State University, Baton Rouge, LA 70803; [2]Arctic Natural Sciences Office of Polar Programs, National Science Foundation, Arlington, VA 22230

Estuarine sea-level variations are forced by a variety of phenomena over a broad range of time scales. In addition to local wind forcing and non-local forcing from shelf sea level variability, river forcing can have substantial effects on subtidal water levels, particularly in estuaries of the Mississippi River deltaic plain. One such system, Breton Sound, is a distributary estuary that receives moderated river inputs through a gated control structure located at the head of the estuary.

We used empirical orthogonal function (EOF) analysis to examine a four-year dataset from six stations in an estuary of the Mississippi delta to characterize spatial and temporal variability of subtidal sea level. Cross-spectral analysis was then employed to relate modes of sea-level variability to various forcing functions acting on the system. EOF analysis identified two principal oscillation modes were that explained over 90% of sea level variability. The first mode represented the oscillations of the subtidal signal that were common to all six locations, and accounted for 83% of the total variance. The second mode accounted for approximately 11% of the variance, and described oscillations in sea-level difference between the seaward and landward ends of the estuary. Mode 1 amplitudes showed an annual cycle, with negative values occurring during late-winter to early-spring and positive values from late-summer until early-winter, and this mode was highly coherent with seaward wind stress and non-local sea level. Strong loadings on mode 2 were coherent with large fluvial inputs at the landward end of the estuary over longer periods (~30 d), or local wind forcing over shorter periods (3-20 d).

These data indicate that different forcing functions interact to elicit a dual-mode water level response in the estuary. Physically, the first mode represents long-period system-wide fluctuations primarily forced by non-local phenomena while the second mode depicts a tilting of water levels along the estuary axis resulting from either fluvial inputs or higher-frequency wind forcing.

Observations of turbulence and suspended sediment within the POL Coastal Observatory.

AJ Souza[1], J Howarth[1], SE Jones[2] and CFJago[2] [1]Proudman Oceanographic Laboratory, Bidston Hill, Prenton, CH43 7RA, UK; [2]School of Ocean Sciences, University of Wales Bangor, Menai Bridge, LL59 5AB, UK

Measurements of Reynolds stresses, turbulence production, water column temperature structure and suspended sediment concentrations were carried out over several spring-neap tidal cycles, between May and July 2003, in the Irish Sea northwest of Anglesey in the “SPM cloud”. The measurements were carried out using a moored fast sampling ADCP, LISST-100, LISST-ST, transmissometers, conductivity and temperature sensors. The moored observations were supplemented by four intense periods of observations, in which vertical profiles were carried out, for at least a tidal cycle, using a CTD, equipped with transmissometers and LISST-100 systems, as well as obtaining water samples.

The observations indicate a strong correlation between suspended sediment concentrations and levels of turbulent kinetic energy (TKE), mainly related to the tidal flow. The principal variations of SPM concentration are due to resuspension and settling of bed material. There are clear spring-neap and M4 variability in both suspended sediment and TKE, with a time lag increasing with height.

The observations suggest that the main resuspension in this part of the Irish Sea is tidally controlled, although there is strong indication of flocculation effects.

Planar O_2 optodes: a tool for 2D studies of O_2 dynamics in benthic communities

H Ståhl and RN Glud, Marine Biological Laboratory, University of Copenhagen, Strandpromenaden 5, DK-3000 Helsingör, DENMARK

The distribution and exchange of O_2 are key measures during investigations of benthic communities. Traditional methods for determining benthic O_2 dynamics includes measurements of concentration changes within sediment enclosures (i.e. benthic chambers) and O_2 microsensor profiles (i.e. microelectrodes). Benthic chambers measure the total exchange of O2, integrating effects of e.g. sediment heterogeneity and irrigation but give a limited insight in the O_2 distribution, the specific activity and small scale variability. Microprofiles on the other hand, allow detailed studies of oxygen dynamics but only on a few selected points. The introduction of planar optodes into aquatic biogeochemistry allows 2D-quantification of spatial and temporal variations in O_2 distribution at heterogeneous benthic interfaces with high spatial (<0.2 mm) and temporal (<1-5 sec) resolution over larger areas ca 35 cm2. This new technique bridges the gap between the “black box” approach of the benthic chamber and the single point measurements performed by microelectrodes. Planar optodes can be applied in a wide variety of studies of spatial and temporal variability in O_2 dynamics within the benthic community (e.g. microbial mats and benthic primary production; impact of fauna activity and burrow structures; “hot spots” and anoxic microniches).

Distribution and sources of organic matter to the Hauraki Gulf, New Zealand, using molecular characterization and carbon isotopic analysis of sedimentary lipids

ME Uhle[1], EL Sikes[2], S Nodder[3], ME Howard[1], and MM Hage[1], [1]Department of Earth and Planetary Sciences, University of Tennessee, [2]Institute of Marine and Coastal Sciences, Rutgers University, [3]National Institute for Water and Atmospheric Research, Wellington, New Zealand

The Hauraki Gulf, on the northeast coast of the North Island of New Zealand, is highly productive, supporting a large local fishing industry. River runoff to the Gulf is local and limited in volume, whereas the Gulf has prevailing currents and quasi-annual upwelling events that deliver open ocean waters and nutrients to the shelf and are believed to drive the high productivity in the area. Organic matter in a coastal and shelf sediments are derived from both allochthonous and autochthonous sources. Bulk chemical characterization of sedimentary organic matter alone cannot provide detailed source apportionment. Molecular level analysis however, can yield detailed information on source of organic matter input as chain length and carbon number of marine and terrestrial derived lipids is source specific. Bulk chemical characterization of sedimentary organic matter alone cannot conclusively differentiate marine and terrestrial organic matter. Molecular level analysis, however, can yield detailed information on source of organic matter input as chain length and carbon number of marine and terrestrial derived lipids is source specific. The presence of C25 to C32 n-alkanes with a predominance of odd-chain lengths are indicative of higher-plant waxes, whereas of C14 to C25 n-alkanes are dominant components of algal-derived lipids. Compound specific isotope analysis further pinpoints sources because carbon isotopic values of marine organic matter are typically enriched in $\delta^{13}C$ relative to values for C3 terrestrial plants.

We report here on sediment samples recovered from the Hauraki Gulf during the summer of 1999. Samples were collected using a multicorer from both near-shore and open environments to investigate the sources and distribution of organic matter in the gulf. Results show a mix of sources throughout the gulf and somewhat follow current flows. Nonetheless, the most upcurrent site showed significant terrestrial inputs. Other sites within the gulf, including those located on the shelf, show a mixture of sources. These results indicate that a significant amount of terrestrial organic matter is being transported out onto the narrow shelf of the gulf through small rivers. In contrast, the site most landlocked and furthest down current, showed a strong predominance of marine input. The organic matter at Firth of Thames where relatively high discharges of fresh water enter the gulf, is predominantly derived from algal input and not terrestrial sources as may be expected at the mouth of a river. The dominant n-alkanes are typically short chain (C15 to C24) and the carbon isotope values range between -25 and -30‰, typical of marine derived lipids. We interpret the predominance of marine input at this site as due to the influx of nutrients from the surrounding farmland enhancing phytoplankton growth.

The Alliance for Coastal Technologies

Herb Windom, Skidaway Institute of Oceanography, Savannah GA 31411

ACT has been established to aid technology developers and users from research institutions, management agencies, and private sector companies in demonstrating and verifying innovative coastal monitoring sensors, platforms, and software, and to provide information on the latest and most efficient technologies for monitoring and predicting the state of coastal waters. ACT is comprised of Partner institutions, a Stakeholder Council, and a larger developing body of Alliance Members.

Partners include the following organizations:

NOAA Coastal Services Center, Charleston, SC (founding ACT Partner)

University of Maryland Center for Environmental Science, Solomons, MD (founding ACT Partner)

Gulf of Maine Ocean Observing System, Portland, ME

Moss Landing Marine Laboratory and Monterey Bay Aquarium Research Institute, Moss Landing, CA

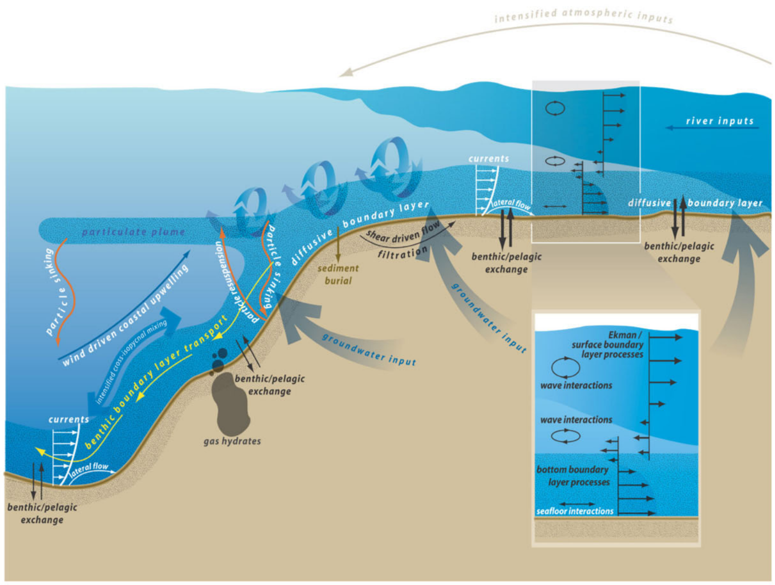
Skidaway Institute of Oceanography, Savannah, GA

University of South Florida, St. Petersburg, FL

University of Hawaii, School of Ocean Science and Technology, Honolulu, HI

University of Michigan, Cooperative Institute for Limnology & Ecosystems Research, Ann Arbor,MI

The Stakeholder Council fosters the interactive flow of ideas and information and ensure that ACT maintain visibility and viability through participation in various commercial, scientific, or governmental alliances, partnerships, or focus groups.



CoOP Office

Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah, GA 31411 USA
912.598.2493
www.skio.peachnet.edu/coop