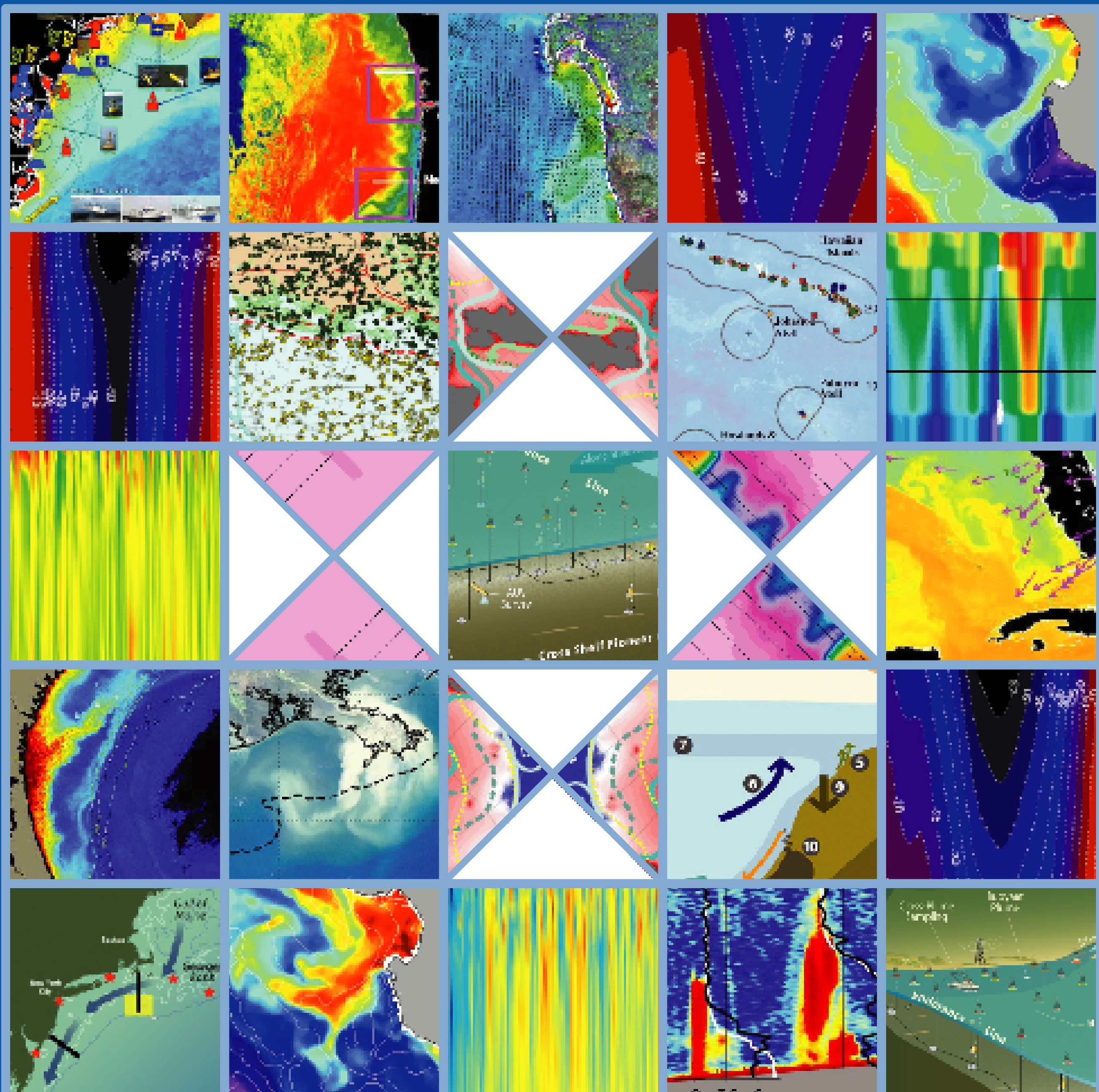
Coastal Observatory Research Arrays:
A Framework for Implementation Planning



CoOP Report Number 9

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SkIO TR-03-01

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Report on the CoOP CORA Workshop
12-13 November 2003
Chicago, Illinois

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Coastal Ocean Processes (CoOP) Program Report Number 9

December 2003

Technical Report

Funding provided by the National Science Foundation under Grant No. OCE-0301872 and by the Office of Naval Research under Grant No. N00014010129.

This report should be cited as:
Skidaway Institute of Oceanography Technical Report TR-03-01.

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Executive Summary

The design of coastal observatories presents a significant challenge - how to incorporate the vast range of relevant scales required to advance our understanding of important coastal processes. Cross-margin exchanges and transport may often be focused or aligned by local topography and yet interactions of processes may change regionally in response to differences in larger-scale environmental factors.

In the previous 18 months, numerous workshops and reports have concluded that the development of coastal ocean observatories would significantly advance ocean research. These reports include: the CoOP Coastal Observatory Science (COS) report, the Scientific Cables for Oceanographic Time-Series (SCOTS) report, the Cabled Regional Observatory Workshop (CROW) and the National Research Council report entitled "Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories".

These reports identified or acknowledged compelling science issues that will require advanced observational techniques and agreed that emerging observatory infrastructure will permit the exploration of ocean processes at time and space scales previously not possible. Because there was generally only a small overlap in the participants at the various workshops, these activities demonstrated significant community-wide support for establishing coastal observatories.

The COS report suggested a nested, three-tiered approach in which observatories with multiple observation nodes are installed in widely-distributed regions. In addition, relocatable mooring arrays (Pioneer Arrays) were recommended for development to provide detailed information about targeted processes. The COS report did not specify numbers of the different components, nor did it recommend an implementation schedule. The subsequent NRC report noted that the scientific justification was well established for coastal observatories, but that there was no clear implementation path and in particular, that there was no community consensus concerning the proportion of fixed and relocatable observatory elements.

The Coastal Observatory Research Array (CORA) Workshop (Chicago IL, 12 - 13 November 2003) was convened specifically to develop consensus regarding the design of coastal observatories. The goal of the workshop was to provide an overall vision of the mix of required coastal Ocean Observatories Initiative (OOI) elements, thereby providing a framework upon which future implementation plans could be built.

CORA attendees agreed that the scientific justification for developing comprehensive coastal observatories for research is well established in the preceding documents and that there is a need to develop a broad portfolio of observational capabilities based on fixed, moored and cabled technologies; mobile platforms, such as gliders, autonomous underwater vehicles, and ships; and land, air and space-based remote sensing systems. The OOI will need to work with other agencies and initiatives to ensure that the full spectrum of observational tools are available to meet future research needs.

To achieve the range of observing scales identified in the science issues, the three-tiered, nested organization of coastal observatories was again adopted. It is recommended that permanent and relocatable observing arrays be installed in the US coastal ocean. The fixed array, termed the Endurance Array, would be comprised of a set of observing locations arranged as cross-shelf lines and individual moorings that would be installed throughout the major coastal regions of the US.

For implementation purposes, the US coastal area was subdivided into geographic provinces consisting of: Middle Atlantic Bight/Gulf of Maine, South Atlantic Bight, Gulf of Mexico, Southern California Bight, Central California, Pacific Northwest, Gulf of Alaska/Arctic, Hawaiian Region and Great Lakes. Because these regions encompass a range of margin geometries and process interactions, distributed observatories are required to provide the diversity of observations necessary to advance our understanding of coastal physical and biogeochemical dynamics.

To achieve the widely distributed array that is envisioned, it is recommended that Endurance Array elements be installed in each region during the first five-year phase of the OOI. A subset of Endurance Array locations must be equipped with high power and communications bandwidth capabilities to support diverse interdisciplinary sensors, observatory operations and engineering development activities.

It is further recommended that four arrays of relocatable sensor moorings capable of real-time data telemetry (Pioneer Arrays) be developed. The design of these arrays should be optimized for environmental conditions such as those characterizing the East coast, Gulf of Mexico coast, Great Lakes, West coast, and Gulf of Alaska coast, which will provide a significant logistical benefit. As the Pioneer Arrays are a relocatable technology, they are available for use in all coastal regions and all areas will benefit from their development.

It must be stressed that these permanent and relocatable components synergistically support each other. The Pioneer Arrays provide detailed information of the interactions among processes and spatial variability not achievable from limited, fixed locations while the Endurance Array provides the temporal context in which to interpret the process study observations. As such, these two arrays form the complete vision of the OOI coastal effort.

We recommend that the funding profile for the Endurance and Pioneer Arrays be concentrated in the beginning of the OOI support period. This frontloading reflects the state of readiness of coastal observatory technologies and the immediate need for test sites for engineering design and development of the components for the regional cabled and global buoy-based observatories. To support this early implementation, there is an immediate need for detailed design studies to more firmly establish cost estimates and focus the discussion on specific deployment sites and configurations.

Finally, it is envisioned that once the observatories are installed and operating, research funding to use this infrastructure will continue to be based on the NSF peer-review system to ensure that the highest quality of research is supported.

I. Introduction and Background

Coastal observatories will contribute to the success of the Ocean Observatories Initiative in three fundamental ways. First, many of today's compelling science issues and emerging research programs require a significantly improved understanding of the physical dynamics, biogeochemistry and ecology of ocean margins. The range of space and time scales involved and the diversity of necessary measurements require the establishment of coastal observatories. Second, regional cabled and global moored observatories require significant engineering development before they can be implemented. Coastal observatories provide the opportunity to efficiently develop and test new technologies prior to installation in remote locations. Third, ***coastal regions are the interface between the human-populated terrestrial and oceanic realms. As such, coastal observatories will advance our understanding and appreciation of human-marine interactions and thereby provide a major conduit for public outreach upon which future interest and support depend.***

To advance the planning for coastal observatories, the 2002 CoOP Coastal Observatory Science (COS) workshop convened to determine what critical research questions could be best answered using coastal observing systems and to identify the current and emerging technologies that would be most useful and would jump-start the development of a coastal observing system (Jahnke et al. 2002). The participants at the 2002 workshop concluded that ***coastal observatories should be comprised of three basic components: widely-spaced, distributed moorings; additional observatories positioned to examine specific coastal features; and relocatable arrays of moored instruments (Pioneer Arrays)***. These observatories would be supplemented by land, aircraft and satellite-based remote sensing (e.g., high frequency (HF) radar and hyperspectral sensors) and measurements from mobile platforms such as ships, gliders and autonomous underwater vehicles (AUVs).

Because the COS workshop preceded the SCOTS workshop which was specifically charged to address the issue of cable-based observatories and because the definition of a national "backbone" to be implemented as part of the Integrated Ocean Observing System (IOOS) was in its infancy, much of the COS discussion focused on the design of the Pioneer Array. This array was envisioned as a relocatable, flexible, adaptable matrix providing instrumentation support which could be modified to each deployment environment and research question.

In the approximately 18 months since the COS workshop, several important reports have been released. The SCOTS report (Glenn and Dickey, 2003) specifically identifies the added benefits of high bandwidth, high-power cabled observatories to coastal research. The National Research Council (NRC) report entitled "Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories" (2003) concluded that the scientific motivations and benefits of research-based ocean observatories are well-defined in existing workshop reports and related documents for all three major OOI components. However, scientific planning to define locations, experiments and instrumentation was considered to vary significantly among the groups, and in particular, the NRC report found no community consensus on the appropriate balance among relocatable observatories (Pioneer Arrays), cabled observatories, and long-term time series measurements needed for coastal ocean and Great Lakes research (NRC OOI report, pp. 4-5). Since the Pioneer Arrays were proposed in anticipation of the advent of the IOOS backbone, permanent coastal cabled arrays were not discussed in detail at the COS workshop or in the report.

To further the planning for the design and implementation of coastal observatories, a workshop was held in Chicago IL on 12-13 November 2003, with the goal of developing a generalized vision of the coastal OOI elements. This framework would provide the basis for future, more detailed implementation plans. At this workshop, the nested, three component design proposed in the COS report was retained but modified slightly. The design developed at this workshop is comprised of two major array elements. The Endurance Array is composed of a widely distributed set of cross-shelf transects, or lines, each consisting of 3 - 6 instrumented sites and strategically located individual buoys. All or a selected subset of the sites may be cabled. Pioneer Arrays are envisioned as high-density clusters of moorings that can be deployed for specific experiment durations to examine defined processes and provide the spatial and temporal context for the Endurance Array observations.

Given the regional differences and heterogeneity of US coastal environments, meeting participants divided the coastline into regional areas with sufficient geographical and process relatedness to be viewed as a subsystem. For purposes of observatory and process description, the following broad regions were named: Middle Atlantic Bight/Gulf of Maine, South Atlantic Bight, Gulf of Mexico, Southern California Bight, Central California, Pacific Northwest, Gulf of Alaska/Arctic, the Great Lakes, and Hawaii (Fig. I.1). While the OOI Project Office will direct the detailed implementation, we provide likely Endurance Line locations to focus the discussion. Potential initial lines are indicated in solid orange. Other candidate sites recommended to be considered initially or in the future are also shown. Sites at regional boundaries are shown in solid blue; sites within regions are dashed blue. Dashed orange lines denote the prospect of international collaboration. To achieve the initial distributed array, it is anticipated that Endurance Array Lines and/or Buoys will be installed in each region in the first five-year phase of OOI funding.

Figure I.1. Potential Endurance Array line locations.

II. Design Elements of Coastal Observatory Research Arrays

Several environmental and technological factors differentiate the design requirements and implementation of coastal observatories from their regional and global counterparts. First, correlation length scales are generally shorter than in open ocean regions. This provides a significant challenge to resolve the relevant processes. Additionally, many important transport mechanisms along margins, such as river plumes, offshore jets, or density flows, are focused or aligned by local topography and coastal features. This also provides a design challenge - how to incorporate specific, localized effects and yet assess regional, margin-scale phenomena and transports. Secondly, the mixture and character of controlling processes vary as a consequence of regional differences in environmental factors and processes, examples of which are listed in Table 1. As an initial step for incorporating these different scales of variability ***the three-tiered, nested approach for the design of coastal observatories*** has been adopted.

Table 1. Continental margin characteristics that control transport processes

Shelf width
Shelf bathymetry and basement composition
Coastal geomorphology and topography
Wind-driven transports
Local storm characteristics (duration and frequency)
Buoyancy and sediment sources (magnitude and distribution)
Tidal range
Wave climate
Ocean boundary currents
Anthropogenic pressures

A. Endurance Array

The Endurance Array is comprised of permanent cross-margin transects or lines of intense observation locations distributed around the US coastline (Fig. I.1). This configuration recognizes the need to determine cross-shelf variability with greater resolution than along-shelf variability for issues related to seasonal, interannual and climatic time-scales. Depending on shelf width and dominant processes, Endurance Lines will generally consist of 3-6 stations, one or all of which may be cabled. These locations

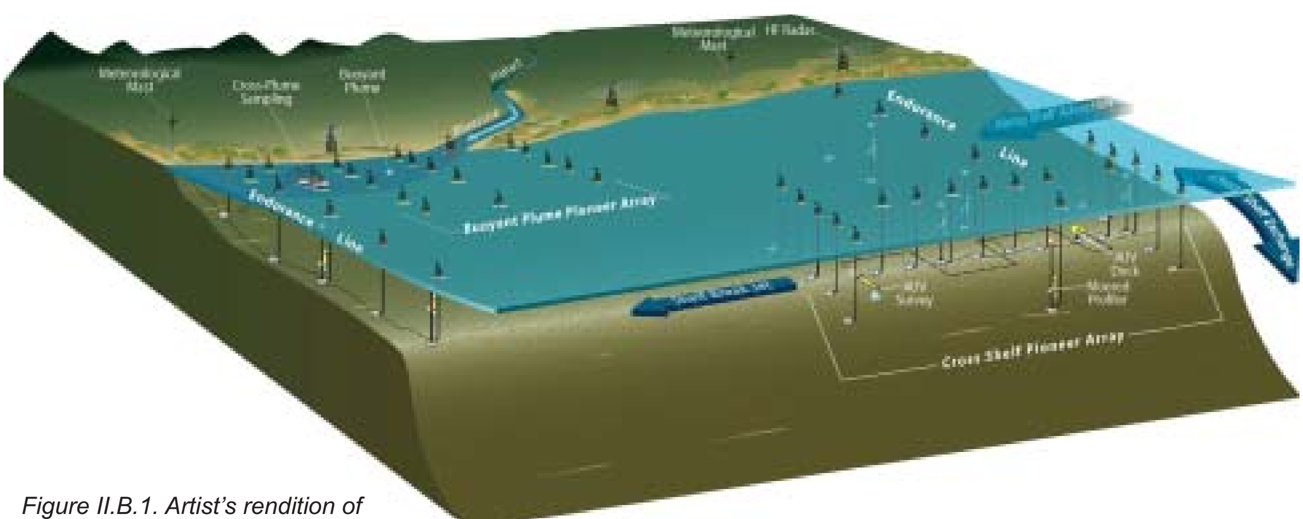


Figure II.B.1. Artist's rendition of Pioneer Array and Endurance Line deployment.

are intended to provide sustained observations and high observational frequency. The infrastructure, bandwidth and power at these locations should be sufficient to support a wide range of interdisciplinary sensors and to support future sensor development and measurements. Where beach and nearshore processes are of critical importance, the shoreward nodes or moorings of Endurance Lines should extend into the nearshore.

Integrated with these Endurance Lines but intended to provide information about enhanced local exchange processes, solitary, densely-instrumented Endurance Buoys will be placed at selected locations in order to resolve local variability. Potential sites include the mouths of rivers and estuaries and offshore features such as submarine valleys, where enhanced exchange may affect shelf-wide variability in physical and biogeochemical processes and characteristics.

Endurance Buoys will also be deployed in strategic regions that may not immediately be associated with the initial Endurance Line observatories, such as in the Great Lakes, the Arctic, or Hawaii. An Endurance Buoy would be a permanent mooring, possibly cabled depending on location. Endurance Buoys will provide good inshore termination platforms in areas where Endurance Lines are anticipated in subsequent implementations. Endurance Buoys can also provide insight into the optimization of subsequent Endurance Line locations.

B. Pioneer Arrays

To resolve small spatial variability of coastal processes and to provide an appropriate spatial resolution to interpret the observations from the Endurance Lines and Buoys, Pioneer Arrays (Fig. II.B.1) of moorings will be developed. These will be comprised of relocatable, scalable moored sensor arrays capable of real-time telemetered data around and near the Endurance Arrays for specific experiment lengths (several months to several years). The Pioneer Arrays primarily provide a spatial and short-term temporal aperture while the permanent Endurance Lines and Buoys focus on resolving temporal variability. Pioneer Arrays will define important locations for future Endurance Line and Buoy deployments.

Pioneer Array sampling strategies need to consider the scales that are not resolved by other means, and over-resolve spatial correlation scales to provide sufficient spatial resolution so that advective scales can be distinguished from true temporal changes. Resolving turbulent closure of interacting surface and bottom boundary layers and the effect of internal waves on mixing are good examples. A lucid discussion of a prototype biophysical array designed to resolve microscale turbulence is provided in the SCOTS report (Glenn and Dickey, 2003, pp 35-36).

C. Supporting Remote Sensing and Measurements from Mobile Platforms

It is anticipated that the in-water observatory infrastructure will be supported by measurements obtained remotely and by mobile platforms. These measurements will play an important role in advancing the research conducted at the observatories and the design anticipates their contributions.

Remote sensing from satellites will continue to provide synoptic coverage of a variety of parameters, such as temperature, chlorophyll, turbidity, bathymetry and basement composition. The optical complexity in coastal environments makes algorithm development for these parameters more difficult, necessitating more extensive ground-truth measurements. In addition, the spatial, temporal and spectral resolution of satellite remote sensing platforms, while improving, is still not fully utilized to resolve many coastal features. Development of hyperspectral, geostationary satellites capable of even higher resolution and more extensive use of both land-based and aircraft-borne sensors will be important for resolving nearshore dynamics.

Land-based remote sensing of the nearshore (e.g., video) can provide needed spatial and temporal resolution of waves, currents, plumes, shorelines and morphology over three to five km of beach simultaneously. Aircraft can provide a

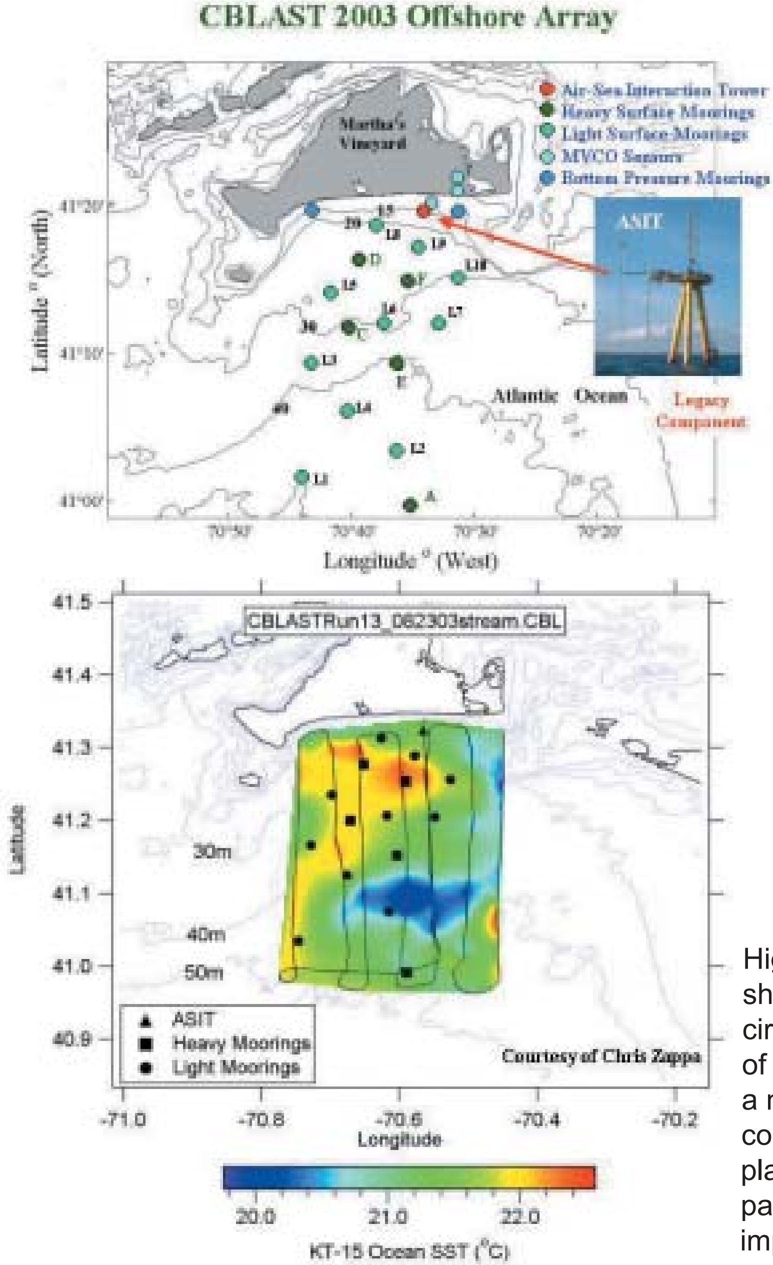


Figure III.1. Upper: The offshore array deployed during the CBLAST experiment. The array was designed to investigate the role of mesoscale horizontal variability on air-sea exchange and coupled boundary layer response. The array included heavily instrumented moorings with meteorological and water column measurements of temperature, salinity and velocity at 2 m resolution (Heavy surface moorings), 10 moorings with water column measurements of temperature at 2 m resolution (Light surface moorings), and the Air-Sea Interaction Tower (ASIT) connected via cable to the Martha's Vineyard Coastal Observatory (MVCO). The ASIT remains in place as part of the MVCO.

Lower: An example of the mesoscale variability in the SST field within the offshore array. These high resolution images were generated using aircraft mounted IR radiometers by Chris Zappa (WHOI) and Andy Jessup (UW/APL). These measurements are being combined with the offshore array and numerical modeling efforts to improve the predictability of these features and our understanding of their role in coupled boundary layer response.

means of periodically providing high-resolution measurements between coastal observatory arrays. This may be especially important for providing regional initial conditions for model simulations. In addition, both land-based and aircraft-borne sensors provide high-resolution measurements of specific events such as patterns of regional beach erosion associated with major storms. Incorporation of aircraft into routine measurements will be facilitated by the newly-created UNOLS Scientific Committee on Oceanographic Aircraft Research (SCOAR; http://unols.org/scoar/).

High frequency radar installations along the shoreline will be critical to understanding circulation and transport processes. Many of these installations are already in use and a national coastal network to provide complete coastal coverage is being planned through the Ocean.US office as part of the IOOS. Nevertheless, their importance to the coastal OOI effort is recognized and the coastal research community must work together to ensure that a seamless capability is implemented.

Autonomous vehicles, such as gliders and AUVs, will contribute important measurements to the research effort (Rudnick and Perry, 2003). Subsurface features that are not detectable by remote sensing technologies can be identified and mapped in three dimensions. This will provide valuable insights into the structure of the water column and provide subsurface informa-tion for initializing models. The power and bandwidth potential of the Endurance Array components will likely accelerate the develop-

Table 2. Framework Implementation Schedule

	new Endurance Line	*upgrade existing observatory to Endurance Line*	*Pioneer Array*	*Endurance Buoy*	*cost, USD*
individual component costs	*$6,000,000*	*$4,000,000*	*$6,000,000*	*$500,000*	
year					
1	*1*	*2*	*1*	*4*	*$22,000,000*
2	*1*	*1*	*1*	*3*	*17,500,000*
3	*1*		*1*	*3*	*13,500,000*
4	*1*		*1*	*2*	*13,000,000*
5	*1*			*2*	*7,000,000*
total #	*5*	*3*	*4*	*14*	
subtotal	*$30,000,000*	*$12,000,000*	*$24,000,000*	*$7,000,000*	
total cost					*$73,000,000*

note: shiptime costs are not included in Pioneer and Endurance Array costs with the exception of cable installation

ment of docking stations for autonomous platforms and extend the deployment duration of these platforms to provide continuous spatial context for the time series measurements in coastal regions.

III. Implementation

It is important to recognize that unlike the regional and global observatories planned for the OOI, pilot coastal cabled and uncabled observatories have already been installed at numerous locations. Cabled observatories are in place or being installed at LEO, Martha's Vineyard (MVCO), Duck, NC, and in Monterey Bay (MARS). Recent results from MVCO demonstrate the effectiveness of a Pioneer Array (Fig. III.1). Observatory buoys and platforms have been deployed at many coastal locations. A few examples include: the Gulf of Maine (GoMOOS), Southeastern US and Gulf of Mexico (SEA-COOS), Monterey Bay (MOOS), Gulf of Alaska (SALMON), Great Lakes, Santa Barbara Channel/Santa Maria Basin and San Diego. Websites for these locations and a link to a comprehensive listing are provided at the end of Section III. Generally, these installations do not have the complete suite of capabilities envisioned for the OOI observatories. They do, however, provide valuable lessons concerning the technology and resources required for implementing the components of the Endurance and Pioneer Arrays.

A. Implementation Plans and Timing

As noted in the NRC OOI report, ***the technology already exists for coastal moored observatories and simple cabled observatories, and deployment of these systems can begin as soon as funding is available.*** With the lessons learned from the pilot observatories already installed and operating, the implementation of coastal ocean observatories can proceed through a combination of upgrades to existing systems and the installation of new infrastructure. Furthermore, it is important to the OOI that coastal observatories be developed early in the program to provide the test sites for the engineering development programs that are required for the regional and global components.

The strawman implementation schedule is provided in Table 2 and reflects the readiness of coastal observatory technology and the immediate need for test sites. The development and deployment of Endurance Buoys is in concert with that of the Endurance Lines. In fact, in most cases the Buoys are an integral part of the Endurance Line concept, providing the local context for interpreting variability in the Endurance Line observations. Locations for all Buoys are not explicitly identified, however, but will be established later in the implementation planning process.

The process for community input and coastal OOI implementation should be based on the usual NSF review criteria, namely scientific merit and broader impact. Secondary but important criteria could be partnering with other agencies and with other elements in the OOI (e.g., regional and deep sea). Availability of other observational strategies including offshore platforms, land-based remote sensing, or AUV/glider technology, for examples, may also help guide implementation of OOI assets. Leveraging of existing resources and knowledge should be a consideration in implementation.

Pioneer Array implementation is recommended as one array per year for the first four years of the initial OOI effort. Individual array designs should be optimized for environmental conditions such as those characterizing the East coast, the Gulf of Mexico coast, the West coast, the Great Lakes and Alaskan coast. As the Pioneer Array is anticipated to be a relocatable technology, all coastal regions will benefit from their development. The Pioneer Arrays will migrate as scientific justification warrants. The infrastructure and capabilities of the individual arrays will likely differ between narrow, deep and broad, shallow shelf regions. Biofouling strategies will likely also differ between warm, cold and freshwater regions. Having Pioneer Arrays that are optimized for the different environments will provide significant logistical benefit.

It is recognized that our cost analysis is simplistic, and that in fact, a mooring deployed in the Middle Atlantic Bight will not look like one deployed in the Monterey Canyon or the Great Lakes; nor will they cost the same. This recommendation is presented as a strawman to provide a basis for further discussion and development. We have also omitted any discussion of the very real probability of cost sharing with other federal agencies and state and local entities interested in deployment in particular regions.

B. Summary of Required Array Elements

Examples of required technical components and capabilities for the Endurance Lines are listed in Table 3. In general, instruments and sensors listed in categories 1 and 2 are envisioned to be core and community sensors as defined in the NRC report, while those in categories 3 and 4 are generally defined as PI-owned sensors. It is important that at least a subset of Endurance Array locations be equipped with the power and bandwidth to support all of the activities in Table 3 and have sufficient excess capacity to support the development of new sensors and in-water instrument packages. Samplers in category 3 should be positioned at surface and bottom at the minimum; the number of samples to be taken will depend on technological limitations (sampling preferably event-triggered).

Table 3. Endurance Instrumentation and Capabilities

1. vertical profiling unit - full water column
- *temperature*
- *salinity*
- *pressure*
- *acoustic Doppler velocimeter*
- *chlorophyll fluorescence*
- *light transmission*
- *photosynthetically active radiation (PAR)*
- *optical backscatter*
- *dissolved oxygen*
- *other optical parameters*
- *nutrient sensors*
- *pH*
- *pCO_2*
- *bioacoustical instrumentation*
- *water velocity*
- *other low-power, low-bandwidth*

2. fixed, standard sensors
- *acoustic Doppler current profiler (ADCP)*
- *directional wave measurements*
- *turbulence-resolving velocimeters at near-bottom and near-surface*
- *ambient noise/passive acoustics*
- *bioacoustic profilers*
- *meteorological instrumentation*
  - *wind speed and direction*
  - *air temperature and pressure*
  - *relative humidity*
  - *solar and infrared (IR) radiation*
- *to calibrate and back up profiling unit, surface and bottom sensors for:*
  - *temperature*
  - *salinity*
  - *dissolved oxygen*
  - *other optics*

3. time-series water and sediment samplers

4. 'fancy' sensors for specific research efforts and other capabilities
- *gene probes*
- *flow cytometer*
- *laser optical plankton counter*
- *docking and charging stations for AUVs*
- *margin geophysical instrumentation*
- *digital particle image velocimetry*
- *direct covariance flux systems*
  - *3-axis sonic anemometers/thermometers*
  - *infrared hygrometers*
  - *IR gas analysers*
- *marine aerosol counters*
- *others in development*

C. Relationship to Other Programs and OOI Elements

Through the OOI Project Office, it is anticipated that the implementation of the Endurance and Pioneer Arrays will be coordinated with other OOI activities. For example, the Pacific Northwest NEPTUNE Workshop report (2003) states that it is imperative to have coverage on the continental margin (i.e., shelf and slope) at multiple cross-margin lines. The implementation of these lines should be conducted in concert with the installation of the PNW Endurance Lines and Buoys.

The implementation of the Endurance and Pioneer Arrays will also be conducted in the context of numerous national observing and research programs. It is anticipated that strong collaborative linkages will be formed with the Integrated Ocean Observing System (IOOS) Program being coordinated through the Ocean.US Office. Collaborations will follow three general strategies. First, operational observations from IOOS stations will provide background oceanographic information to supplement Endurance and Pioneer Array measurements. Examples of anticipated measurements that will be most useful include: HF radar measurements of surface currents and land and buoy-based basic meteorological measurements. Second, it is anticipated that the data management systems and protocols developed for both the OOI and IOOS will be fully interoperable, facilitating the visualization, interpretation and archiving of observatory data. Finally, the improved understanding of coastal processes developed through research projects employing the Endurance and Pioneer Arrays will advance the development of IOOS products and predictions.

The proposed Endurance and Pioneer Arrays will support a variety of emerging and planned research programs. For example, the International Geosphere - Biosphere Program is developing a new international ocean research program, Integration of Marine Biogeochemical and Ecological Research (IMBER), which is envisioned as the successor of JGOFS and eventually GLOBEC. The Science Plan and

Implementation Strategy for this project calls for the development of instrumented time-series research sites in continental margin systems. The IMBER implementation strategy also calls for detailed process studies to be conducted at the time-series locations so that the observations can be placed in a temporal context. The combination of Endurance Lines and Pioneer Arrays can directly support this research plan.

The Implementation Strategy for the Ocean Carbon and Climate Change (OCCC) Project also recommends the establishment of additional time-series study sites. Similar to IMBER, this project further recommends that some of these sites be located at continental margins and serve as the focus for detailed process studies. The nested Endurance Line and Pioneer Array design proposed here fits well into these plans.

Research projects focused exclusively on the margin systems will benefit from the implementation of the Endurance and Pioneer Arrays. For example, the RiOMar project is designed to examine shelf processes and transports on continental margins dominated by riverine inputs. The CoOP Program currently focuses on shelf systems dominated by wind-driven transports (COAST and WEST Projects) and those dominated by freshwater inputs (RISE and LATTE Projects) and is planning its next projects which are anticipated to focus on Coastal Benthic Exchange Dynamics (CBED). Because of the expanded range of scales over which observations can be made, the proposed Endurance and Pioneer Arrays will provide the infrastructure to significantly advance these research efforts.

Websites for US Coastal Observatories in Planning or Operation

Websites for coastal observatories are developing so rapidly that any list published here will be quickly outdated. For a comprehensive summary of US coastal observatory websites and links, please visit the NOAA Coastal Services Center website:

http://www.csc.noaa.gov/coos

A few websites to regions referred to in this report include:

Gulf of Maine - GoMOOS: *http://www.gomoos.org*

Martha's Vineyard - MVCO : *http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi*

LEO: *http://marine.rutgers.edu/mrs/leo/leo15*

Duck, NC: *http://www.frf.usace.army.mil*

Southeastern US and Gulf of Mexico (SEA-COOS: *http://seacoos.org*

San Diego Coastal Ocean Observing System - SDCOOS: *http://www.sdcoos.ucsd.edu*

Santa Barbara Channel - Santa Maria Basin Circulation Study: *http://www.ccs.ucsd.edu/research/sbcsmb/sbc_home.html*

MARS: *http://www.mbari.org/mars/*

MOOS: *http://www.mbari.org/muse/*

Pacific Northwest: *http://www.damp.oce.orst.edu/coast/*

Gulf of Alaska: SALMON - *http://www.SALMONproject.org*

Great Lakes: *http://waterbase.glwi.uwm.edu; http://www.glerl.noaa.gov/res/Task_rpts/cmbrandt13-3.html)*

D. Summary of Candidate Locations for Implementation

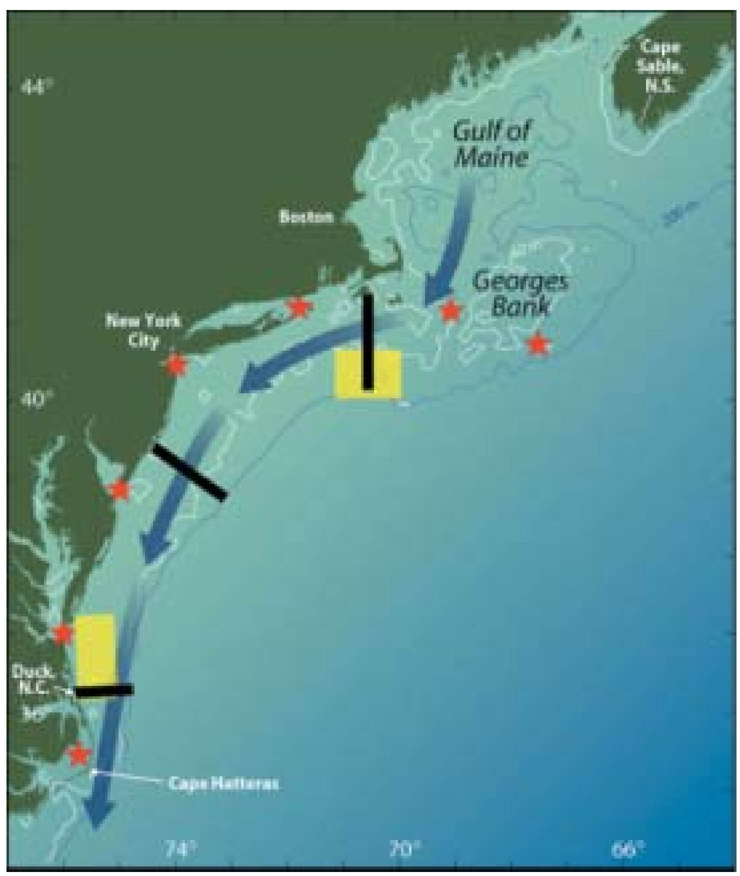
It should be recognized that due to the small size and timing of the CORA workshop upon which this report is based, not all of the identified regions were equally represented. Furthermore, because of the speed at which this report was assembled in advance of the ORION Workshop, an equal level of detail could not be supplied for all regions. The following short descriptions and the expanded ones later in the report are intended to provide examples of the diversity of environments and array designs that can be installed to support coastal research.

Eight Endurance Lines are recommended in the first round of implementation (Fig. I.1), although it is noted that this represents minimum coastal coverage and more Endurance Lines would be beneficial in several of the regions. A short description of each is provided below, with additional information provided in Section V. Three of the locations already have or will soon have working cabled or hybrid arrays in place and offer the logical locations for development of emerging technologies. The experience gained and modes of deployment and maintenance which have proven functional at existing arrays will be highly informative for subsequent efforts. The five additional Endurance Line locations are recommended, one per region, because they present opportunities to advance our knowledge of coastal processes with the most likelihood of early success. While example locations are indicated on Figure I.1, it is assumed that the OOI Planning Office will conduct more detailed implementation planning and specific site selection.

Four Pioneer Arrays are recommended for establishment in the first round of implementation. Fourteen Endurance Buoys are also recommended to be distributed throughout all regions. The Endurance Buoys are integral to the success of the Endurance Array, providing local information on dominant sources of variability in locations which may not be instrumented with Endurance Lines, for example, in the mouths of estuaries or submarine canyons which are not directly associated with a Line location.

Middle Atlantic Bight/Gulf of Maine *(MAB/GoM):* The MAB/GoM is a broad continental shelf region extending from Nova Scotia, across Georges Banks and Nantucket Shoals, and along the eastern seaboard to Cape Hatteras (Fig. III.D.1). The system is characterized by mean southwestward flow and a prominent offshore front that separates fresher shelf water from more saline slope water. Shelf water from the western GoM and southern flank of Georges Bank enters the MAB from the east past Nantucket Shoals (Beardsley et al. 1997). As the shelf water flows first westward and then southward along the coast, inputs of freshwater, nutrients, and contaminants enter via the Con-

Figure III.D.1. Endurance Array Lines (thick black lines) and moorings (red stars) proposed for the Middle Atlantic Bight. The yellow boxes indicate potential areas for higher resolution studies involving Pioneer Arrays (see Section V.A).



necticut and Hudson Rivers and Chesapeake and Delaware Bays. Along the offshore boundary, various processes at the shelfbreak front contribute to exchange between shelf and slope waters (Loder et al. 1998) and enhanced biological production (e.g., Marra et al. 1990, Ryan et al. 1999). The shelf narrows approaching Cape Hatteras, southward transport decreases in compensation for net off-shelf transport to the east, and very little flow extends southward around Cape Hatteras (Savidge and Bane 2001).

Thirty percent of the US population lives along the MAB/GoM, resulting in heavily urbanized coastal zones that are increasingly impacting this productive shelf ecosystem in ways that remain poorly documented and understood due to under-sampling. The MAB experiences extreme seasonal variations in physical, chemical, and biological properties and is subject to high impact episodic events such as severe storms. Recent evidence also documents important region-wide interannual-to-decadal scale variability in water masses (Mountain 2003), which may be associated with basin-scale climatic variability (Drinkwater et al. 1999). Improved understanding of physical and ecological regulation in the MAB/GoM will require modeling efforts integrated with temporally resolved long-term observations that include scales from hours to years.

The regional plan calls for three cross-shelf Endurance Array Lines, one at the upstream boundary (MVCO), one near the along-shelf center of the region, and one off Duck, NC, near the southern end of the MAB (Fig. III.D.1). The upstream boundary Endurance Array Line anchored at MVCO is recommended for the initial implementation in the MAB region. Since some aspects of water mass distribution in the MAB are driven by freshwater buoyancy forcing from farther north, additional Endurance Array components in the Gulf of Maine are recommended in subsequent implementations. Also, note that collaboration with Canada would be advantageous to establish an Endurance Array on the Scotian Shelf to further characterize MAB/GoM forcing and inputs.

South Atlantic Bight *(SAB)*: The SAB shelf extends from south of Cape Hatteras to approximately 27° N where the shelf narrows dramatically south of Cape Canaveral (Fig III.D.2). In the central SAB, adjacent to Georgia and South Carolina, the shelf achieves a maximum width of approximately 120 km. With a water depth at the shelf break of only 50 - 60 m and an area-weighted mean depth of 27 m, the SAB provides a unique opportunity to study processes favored by broad, shallow shelf environments. The seaward extent of the SAB is bounded by the Gulf Stream. Upwelling associated with meanders in the shoreward edge of the current is the dominant source of nutrients to the SAB. In the nearshore zone, freshwater discharge from numerous rivers maintains a low salinity coastal zone that remains separated from the shelf waters at a coastal frontal zone.

In this shallow environment with a large surface area, atmospheric forcing exerts dramatic control of shelf water flow. Summertime upwelling-favorable winds can cause outbreaks of low salinity waters across the shelf. Similarly, in the wintertime, relaxation of downwelling-favorable winds can cause the formation of

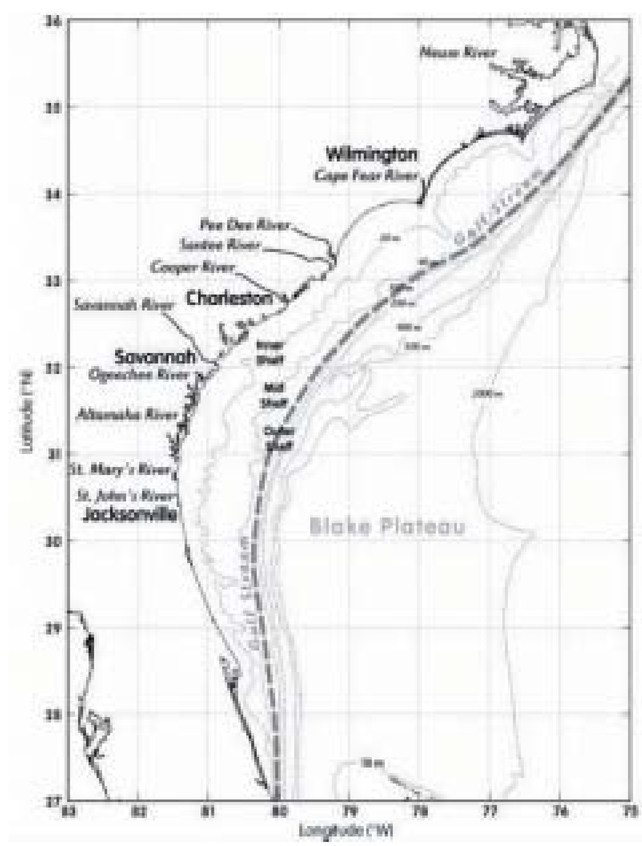


Figure III.D.2. Bathymetry of the South Atlantic Bight

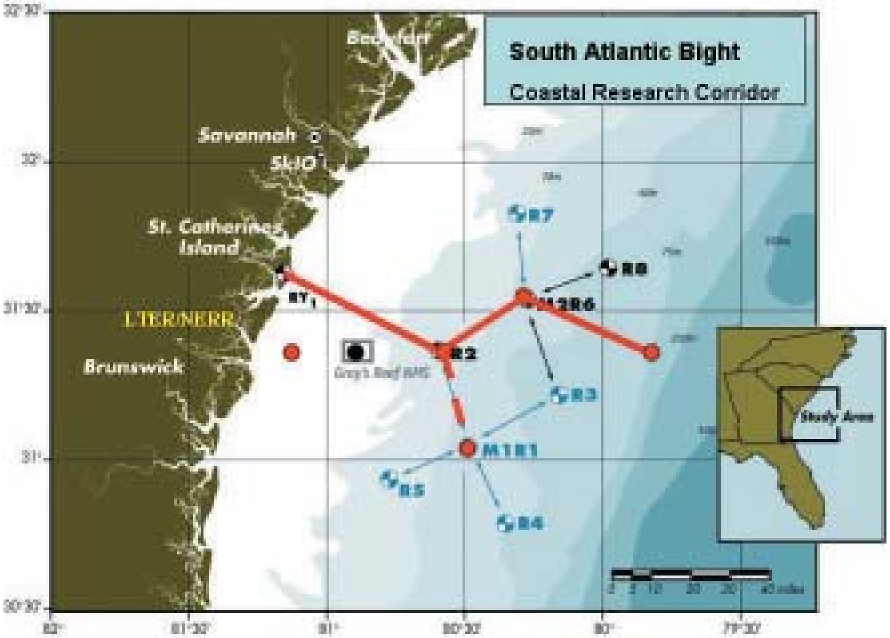


Figure III.D.3. Proposed location for South Atlantic Bight Endurance Line

extensive cross-shelf plumes. Interactions of the winds and buoyancy may also control the distance Gulf Stream waters intrude onto the shelf. Because of the shallow shelf, the sea floor also plays a more important role than in most other shelf regions. Most of the shelf seafloor is within the euphotic zone and benthic microalgal primary production on the mid and outer shelf often rivals water column productivity. Furthermore, the seabed is composed of well-sorted sands and exhibits high permeabilities. Advective porewater transport is an important exchange mechanism for solutes and particles between the sediments and the overlying water column.

The plan would be to establish an Endurance Line across the SAB shelf at the center and widest portion. This line would build on the South Atlantic Bight Synoptic Offshore Observing Network towers, the NOAA buoy and observations associated with Gray's Reef National Sanctuary and with coastal instrumented moorings associated with the Sapelo National Estuarine Research Reserve (NERR) and the Georgia coastal Long-Term Ecological Research (LTER) efforts (Fig. III.D.3). The goal would be to provide the infrastructure to have an interdisciplinary research corridor that would extend continuously from the head of tide in the estuary to the shelf break. Pioneer Array deployments to examine the dynamics of offshore plumes are also recommended.

A second Endurance Line off the east Florida shelf would permit direct observations of the dynamics of interactions of the Florida Current at a location where the shelf width is minimized. The northern boundary would be covered by the Endurance Array proposed off Hatteras/Duck in the MAB region (preceding section).

Gulf of Mexico: The Mississippi River is the 7th largest river in the world in terms of water and sediment discharge and second largest in drainage basin size, covering 40% of the conti-

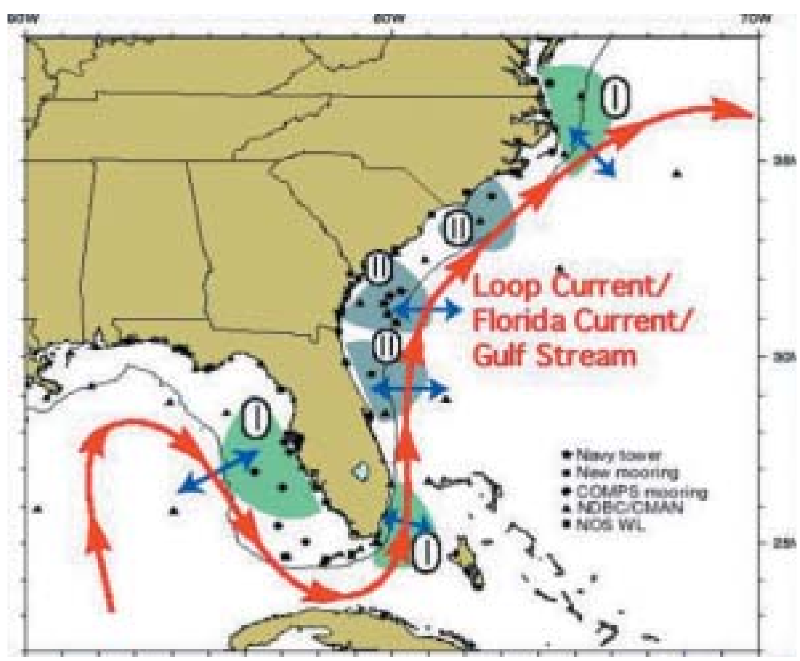


Figure III.D.4. Generalized path of the Loop, Florida and Gulf Stream current system schematically depicting areas of intensified shelf - boundary current exchange. Also shown are locations of observatory sites and present (I) and planned (II) HF radar coverage areas.

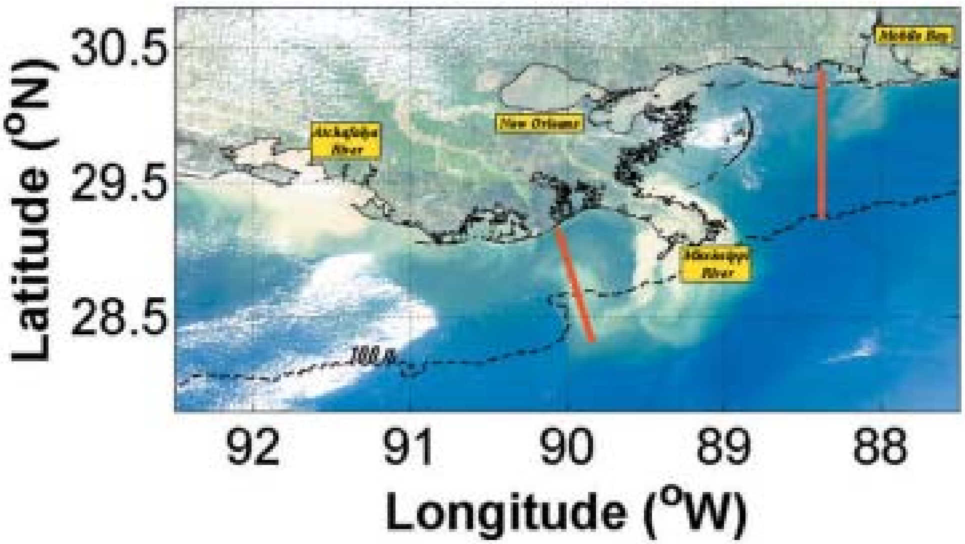


Figure III.D.5. Enhanced satellite image of the northern Gulf of Mexico showing approximate locations for Endurance Lines as described in the text.

nental US (McKee, 2003). Prevailing westerly currents move most of the fresh water, suspended sediments and dissolved and particulate nutrients onto the Louisiana and Texas continental shelf (Rabalais et al. 2002). A combination of water column stratification and enhanced respiration results in a large region of seasonal hypoxia on the inner shelf. The Mississippi Bight, immediately east of the delta, receives a significant fraction of the Mississippi River flow particularly in summer when wind conditions favor eastward flow of the plume. Interactions of Loop-Current-induced eddies along the shelf edge may be more common east of the delta, and can entrain river water and transport it eastward (e.g., Müller-Karger et al. 2000).

The west Florida shelf is wide with a relatively deep shelf break. Interactions with the Loop Current dominate offshore exchange (Fig. III.D.4). Harmful algal blooms form annually on the West Florida shelf although the sources of triggering nutrients and seed populations and mechanisms of nutrient delivery have not been identified. Eddies, originating from the Loop Current, also penetrate to the western Gulf of Mexico and Texas shelf where they are of concern to the extensive offshore oil and gas industry.

The Gulf of Mexico offers at least three logical locations for Endurance Lines and Pioneer Arrays. These are the Mississippi River plume/ Mississippi Bight region, the West Florida shelf, and the Texas shelf. Each environment presents unique scientific issues to justify implementation.

The Mississippi River plume/Mississippi Bight region is recommended for an initial implementation site (Fig. III.D.5). The Mississippi River provides the largest single buoyancy input to the North American coastal ocean. There is strong winter wind-forcing and dynamical coupling to the Gulf of Mexico Loop Current. An Endurance Line could begin in the nearshore of Terrebone Bay, bisect the ‘dead zone’ and cross the Mississippi far-field plume under normal conditions, or, alternatively, the Line could initiate further to the east in the nearshore of the Mississippi Bight. Endurance Buoys should be positioned to provide measurements of localized inputs from the Mississippi - Atchafalaya and other river discharges. Possible use of oil production platforms for some observatory infrastructure is recommended.

Southern California Bight *(SCB)*: Southern California is a densely populated (~ 20 million inhabitants), highly urbanized coastal region, representing approximately 25% of the nation's coastal population. The SCB is characterized by narrow, segmented shelves with submarine canyons, banks, large islands and the complex bathymetry of the Borderland Basins (Fig.III.D.6). Offshore it is marked by the presence of the California Current and by high speed winds that detach from the coast at Point Conception. These features lead to complex flow patterns. Within the Bight, local wind, wave and

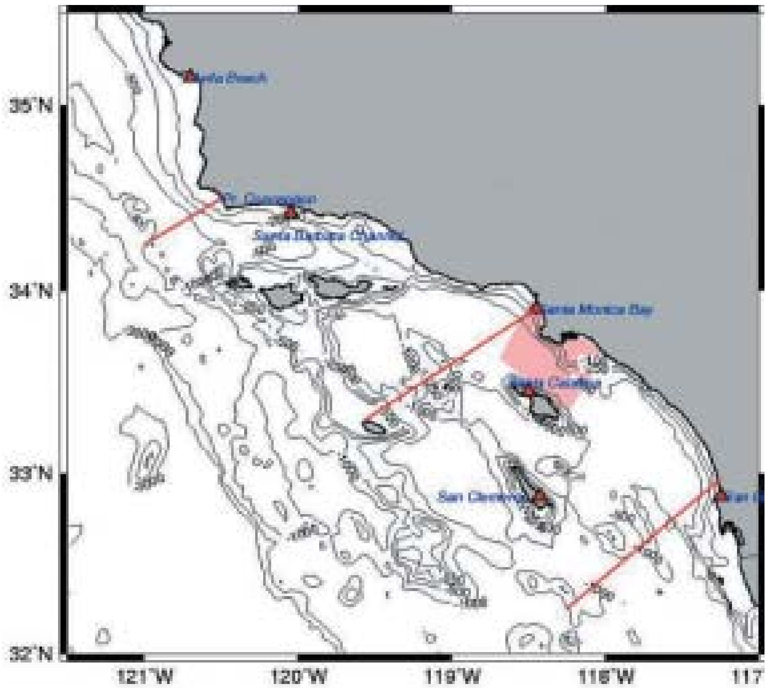


Figure III.D.6. Map showing Southern California Bight geography, bathymetry and proposed observing systems. Proposed cabled observatories are indicated by red triangles, proposed Endurance Array Lines are indicated by red lines, and the proposed Pioneer Array location is indicated by the pink shading.

riverine forcing are weak and episodic. Along the coast, evidence suggests remote forcing is important, with poleward propagation of coastally trapped waves and equatorward exchange driven by upwelling in the Santa Maria Basin (Hickey et al. 2003). Offshore forcing by recirculation of the California Current is also important (Hickey, 1993). The system responds to interannual variability including the Pacific Decadal Oscillation and El Niño events (e.g., Dever and Winant, 2002).

The northern boundary of the SCB, Point Conception, is a well-known biogeographic boundary, particularly for southern, warm water species (Dailey et al. 1993). Within the SCB, there is strong spatial and temporal variation in ecological communities caused, in part, by changes in water temperature, wave climate, current trajectories, nutrient levels, and available substrates. The SCB is the site of several long time series and the heart of the CalCOFI program. These time series have documented interannual variability (McGowan et al. 1998) including fisheries stocks changes and interannual changes (declines) in phytoplankton and zooplankton productivity (Roemmich and McGowan, 1995). On the other end of spatial and temporal scales, processes such as internal waves and submesoscale vortices have recently been identified as being particularly prominent in the SCB (DiGiacomo and Holt, 2001). These features may have an important impact in determining physical and biological connectivity between islands and between shelf regions defined by headlands and coastal canyons.

Single node cabled Endurance sites with offshore coverage provided by buoys may work well for the Bight (red triangles on Fig. III.D.6). High bandwidth will be needed for biological/physical coupling instrumentation in the nearshore, and buoys will be more practical offshore, given the spatial area and extreme bathymetric variations of the SCB. Two longer Endurance Lines are desirable at the upper and lower boundaries of the Bight out to the California Current. Given the importance of poleward propagating features, the southern boundary Line would have priority. The southern Endurance Line should extend shoreward across the shelf to the beach, providing observations of coupling between nearshore and shelf flows, and of changes in nearshore sand levels. The second northern Endurance line would allow study of the biogeographic boundary at Point Conception. A potential third location is off Los Angeles. This location would respond to societal concerns by making possible the long term study of urban effects on the coastal ocean.

A Pioneer Array deployment in the central Bight is recommended. This array will make possible the study of episodic and/or (sub) mesoscale processes and phenomena and their impacts (physical, biogeochemical etc.) on the local coastal marine (and human) ecosystem. The availability of spatial Pioneer data and temporal Endurance Lines will allow reinterpretation of the extensive historical CalCOFI data sets from the region.

Central California: Within the Central California region, Monterey Bay offers a compelling location for observatory development for a number of reasons (Fig. III.D.7). These include a north-south ecosystem gradient; a continental shelf of varying width to the north and south of the bay and a deep bisecting canyon; upwelling and ENSO periodicity; HAB development; and negatively buoyant flows from the Salinas River. The steep topography creates fluid flow through the sediments leading to the development of chemoautotropic communities and the highly irregular topography provides for a strongly variable nearshore climate of waves, currents and material transport.

Monterey Bay provides a unique natural laboratory for the study of nearshore currents and morphodynamics with a sandy shoreline backed by extensive dunes. Two existing littoral cells with differing processes are bisected by the Monterey Bay canyon (the largest in the western hemisphere). The northern bay processes are dominated by strong littoral drift intercepted down the canyon at mid-bay. The southern bay shoreline has a large erosion signal (l-3 m y^{-1}) and quasi-periodic rip current systems. Large variations in morphodynamic scale occur (0.1-1 km) associated with large alongshore gradients in wave energy owing to wave refraction over the canyon.

A 15-year time series of biogeochemical observations in the Bay is the longest on the West coast. A mooring array is already in use in the Bay out to 50 km offshore, and the MARS cabled observatory, with a node at approx.1200 m water depth, will be installed in 2005 as a testbed for the Juan de Fuca regional cabled observatory. Sensor development and testing is active, including an advanced, automatically-configuring mooring. All moorings currently in place telemeter in real time. AUVs make regular transects through the Bay.

An Endurance Array Line is recommended to skirt the canyon and extend to where the chlorophyll signal fades if practical (see Fig. IV.4). Both a Pioneer Array deployment and a nearshore MARS node are recommended for the central Bay. The MARS nearshore node would

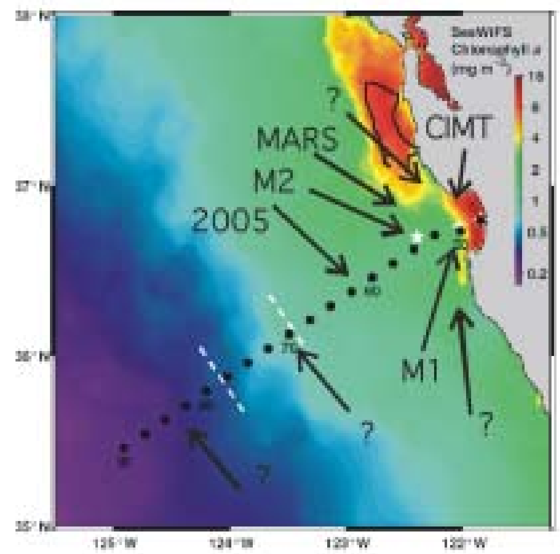


Figure III.D.7. Existing (M1, M2), planned (CIMT-2004, MOOS-2005) and possible (?) mooring locations offshore Monterey Bay. Black dots are stations along CalCOFI Line 67, which are regularly sampled. Dashed white lines are 1 and 0.3 $\mu g\ l^{-1}$ chlorophyll.

be installed in 18 m depth in a high-energy wave regime when the MARS shore terminus at the Duke Energy power plant is installed (est. 2005). An Endurance Array Line at the northern boundary of the region will provide a southern boundary for the Pacific Northwest region. The northern boundary Endurance Array Line described for the SCB would establish a southern boundary for this region.

Pacific Northwest *(PNW)*: Circulation and water mass properties over the Pacific Northwest (PNW) continental margin are influenced by a variety of processes which include the large-scale North Pacific gyre circulation, strong wind and buoyancy forcing, propagation from the south in the coastal wave guide, flow-topography interaction, bottom boundary layer processes, long-period high-energy waves, and large tidal excursions. The North Pacific Current splits into the poleward Alaskan Current and the equatorward California Current just offshore of the PNW continental margin (Hickey, 1979). The Columbia River is a major source of fresh water, micronutrients and, in winter, sediment.

Strong, time-varying wind events in the PNW drive "classic" upwelling and downwelling and

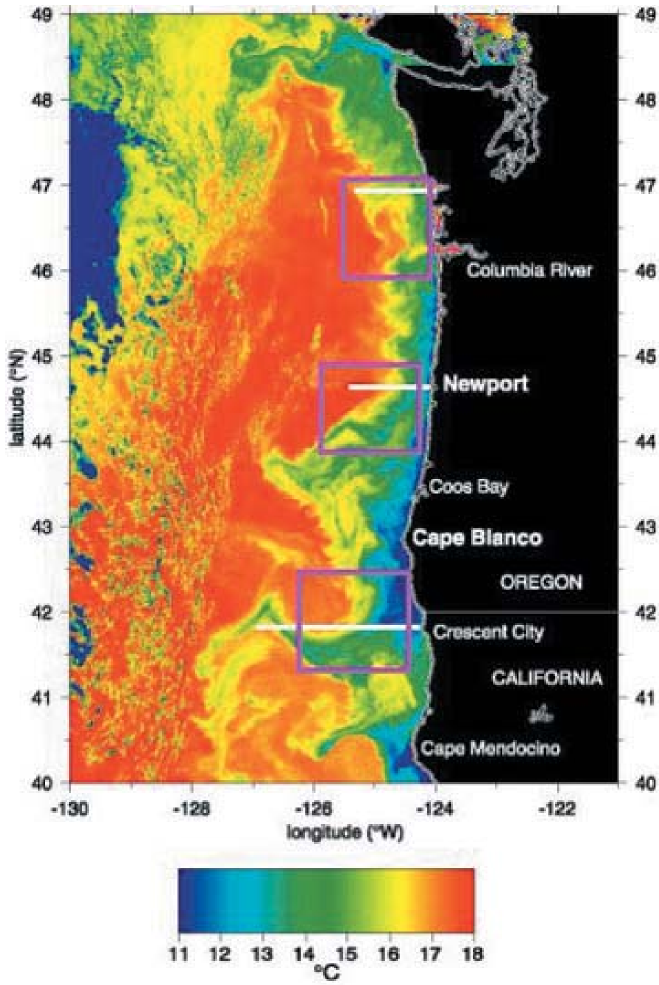


Figure III.D.8. Locations of Pacific Northwest Endurance Array Lines (east-west white lines) and Pioneer Arrays (magenta boxes) plotted on top of a satellite SST image from 2 September 1999.

create swift alongshore flows (Huyer, 1983). Spring and summer upwelling of nutrient-rich subsurface water into the euphotic zone over the continental shelf leads to strong phytoplankton growth and production of organic carbon. Upwelling favorable wind forcing is more intermittent compared with farther south in the California Current System, likely an important contributor to the region's high biological productivity. Harmful algal blooms affect shellfish along PNW beaches and in estuaries, and sometimes phytoplankton production levels are so high that respiration of this material at depth can drive shelf bottom waters anoxic (Grantham et al. 2003).

The hydrographic, velocity, nutrient, phytoplankton and zooplankton fields in the PNW all vary interannually in response to the El Niño/La Niña cycle. On interdecadal time scales, these fields as well as commercially important fish, e.g. salmon, are strongly influenced by the Pacific Decadal Oscillation (Mantua et al. 1997). Extensive short-range and long-range land-based coastal radar arrays exist off the Oregon coast. Ocean circulation models including those that assimilate surface currents from land-based coastal radar have been successfully applied to PNW waters (Oke et al. 2002). Significant estuarine environments with nearby major populations in the PNW include the Strait of Juan de Fuca/Puget Sound region and the Columbia River.

Three Endurance Array Lines are recommended (Fig. III.D.8). The Newport Line (44.65º N) is given priority in the first implementation not only because of its long historical record enabling research on low-frequency variability but also because it passes over gas hydrate fields of considerable interest. The Newport Endurance Line should preferably span the slope and shelf through the nearshore and right up onto the beach. A second Endurance Line north of the mouth of the Columbia River (46º N), again from beach to continental slope, will allow investigation of wintertime sedimentation events, sediment resuspension and flow interaction with submarine canyons. A third cross-margin Endurance Array Line is recommended for south of Cape Blanco near Crescent City (41.9º N) to investigate ecosystem dynamics and flow-topography interaction in a region of especially strong wind forcing. The Crescent City Endurance Line is also of interest to the Central California region as it will measure the southward flux of water and the biogeochemically important material it contains. Finally, it is hoped that Canadian colleagues will maintain and augment their historic cross-margin line off Vancouver Island.

Suggested locations for Pioneer Arrays include off central Oregon to study wind-driven processes near a submarine bank, off the Columbia River to investigate buoyancy-driven flows and sediment input to the shelf, and off northern California/southern Oregon to study ecosystem dynamics in a region of strong wind driving.

Gulf of Alaska(GOA)/ Arctic *:* The coastal waters surrounding Alaska offer several logical choices for coastal observatory development. These are the Gulf of Alaska, Bering Sea, and the Chukchi and Beaufort seas of the Arctic Ocean. The physical characteristics of each differ substantially from one another in bathymetry and geomorphology and in the annual cycles of wind stress, freshwater discharge, heating and cooling. Moreover, the role of tides, flow-topography interactions, and shelf/slope exchanges vary in importance from one region to another. These physical differences result in very different ecosystems; pelagic systems dominate much of the Gulf of Alaska, pelagic and benthic systems are important in the Bering, benthic communities dominate in the Chukchi, and pelagic in the Beaufort.

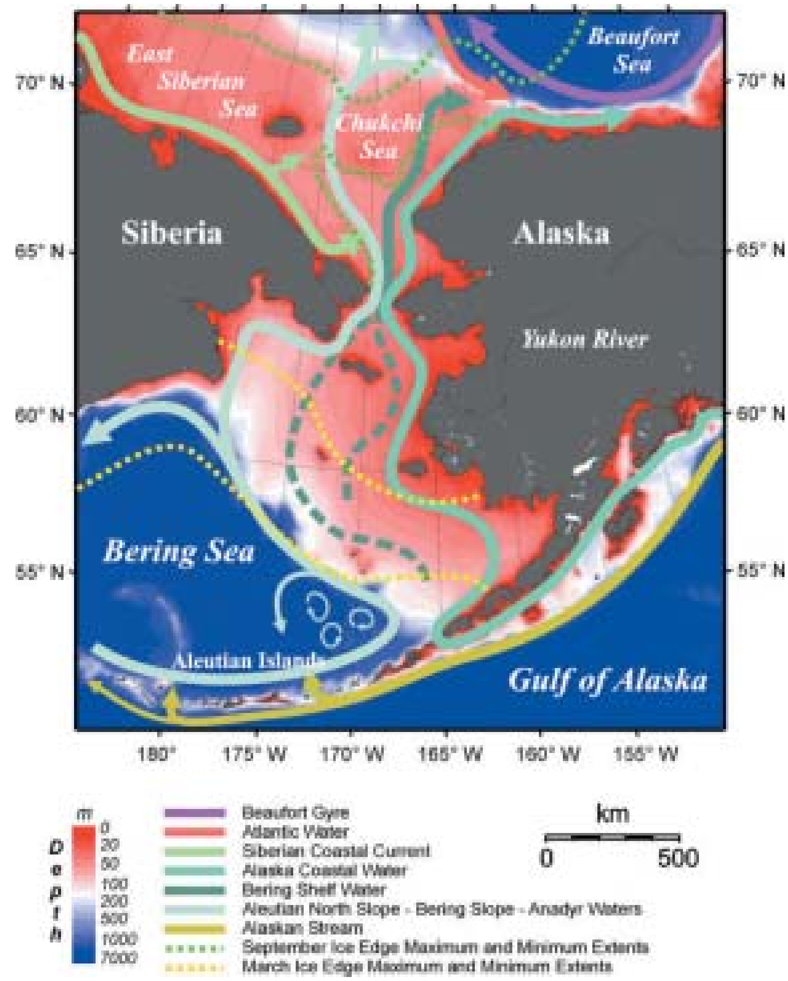


Figure III.D.9. Schematic of water masses and predominant currents surrounding Alaska

Global climate models consistently predict that high latitudes are very sensitive to climate change and will probably respond to these changes prior to mid- and low- latitudes. Already there is compelling evidence that the Arctic and Bering marine ecosystems are undergoing dramatic change. Hence detecting, quantifying, and identifying the symptoms and sources of this change is fundamentally important. Nevertheless, each of these ecosystems shares a common feature because waters from the Gulf of Alaska flow northward across the Bering-Chukchi shelves and into the Beaufort Sea (Fig. III.D.9). This pathway provides climate signals transmitted from south to north by the prevailing circulation. For this reason, along with abundant historical data and relatively easy access, the GOA is recommended to be the location for the intitial Endurance Line in the region.

The GOA extends approximately 2500 km from the British Columbia coast to the tip of the Alaska Peninsula. Along that path there are extreme variations in coastline topology, bottom topography and shelf width. The Alaska Coastal Current threads along the coast of Gulf of Alaska and may have its origins, at least seasonally, in the Columbia River discharge. It provides continuity to all regions in the coastal GOA.

The dynamics of the GOA basin and the shelf are tightly linked to the position and strength of the Aleutian Low pressure system. Storms propagating into the gulf are blocked by coastal mountains resulting in very high precipitation and persistent, cyclonic winds. The high precipitation, primarily in the fall, feeds an enormous freshwater flux (~20% larger than the Mississippi River discharge) that enters the shelf as a "coastal line source" around the gulf's perimeter (Royer, 1982). The winds and discharge jointly force a mean cyclonic alongshelf flow over the GOA shelf and slope (Reed and Schumacher, 1986). The flow interacts with a complex bathymetry and coastal geometry to generate mesoscale variability that enhances cross-shelf exchanges.

The GOA shelf supports a rich and diverse ecosystem and one of the world's largest fisheries. The causes of this high productivity are poorly understood and enigmatic because this deep shelf is subject to persistent coastal "downwelling". This situation contrasts with eastern boundaries of the Pacific Ocean where rich fisheries are sustained by wind-forced coastal upwelling that regularly replenishes the euphotic zone with nutrients.

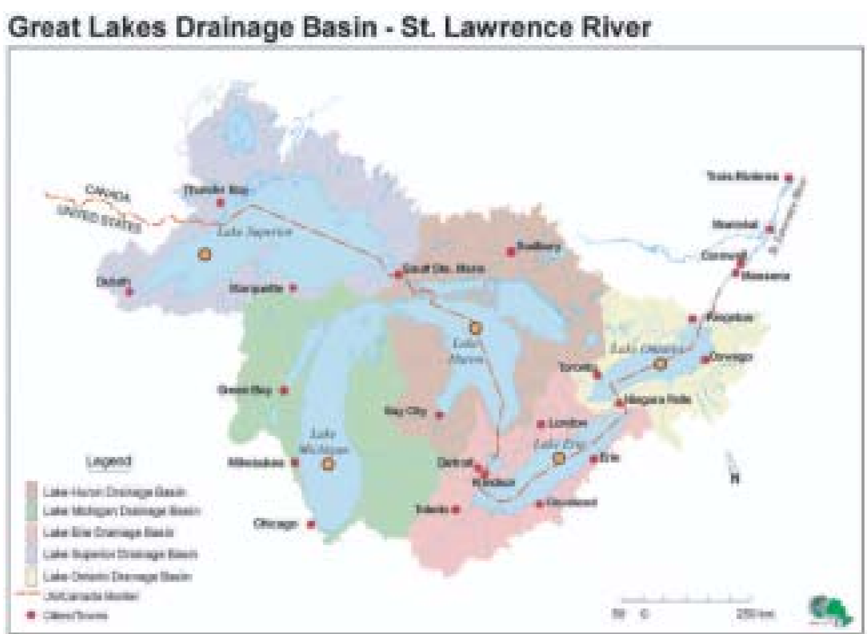
The GOA marine ecosystem has undergone remarkable changes in recent years. For example, the relative dominance of the commercially important fish species changed in the mid-1970s; crab and shrimp declined while salmon and groundfish populations increased. Subsequent ecosystem changes followed in the 1980s with declines in marine mammal and seabird populations. North Pacific fish stocks vary on decadal and longer time scales in conjunction with sea temperatures and other environmental variables. While such correlations suggest that the GOA ecosystem is sensitive to interannual and interdecadal climate variations, the mechanistic links between climate variability and ecosystem change are unknown.

Located at the mouth of Resurrection Bay near Seward, Alaska, temperature and salinity versus depth profiles have been taken at oceanographic station GAK1 since December, 1970. This multi-decade time series is one of the longest running oceanographic time series in the North Pacific. Anchored by GAK1, the Seward Line of hydrographic stations extends approximately 230 km to the southeast. Opportunistic sampling from research vessels has occurred along this line intermittently since 1970. An Endurance Array Line installed along this line will build upon our understanding of biological production and its variability on this shelf. Pioneer Array experiments will be designed to explore the roles of mesoscale forcing in enhancing biological production.

***Great Lakes**:* The Laurentian Great Lakes extend 1200 km from west to east, and hold about 20% of the Earth's surface fresh water. Approximately one tenth of the population of the United States and one fourth of Canada's populace live in the Great Lakes basin, and utilize the lakes for shipping, recreation, fresh water supply, and more. Each of the five lakes has undergone major ecosystem change as a result of human activity, most notably from intense coastal development, the introduction of exotic species, and the input of both atmospheric and terrestrially-derived materials.

The Great Lakes provide unique opportunities for research based on a coastal observatory network. They have the unusual characteristic of being essentially closed systems with easily monitored outputs. The Great Lakes can be considered as regional integrators of environmental change on the continents, in which subtle trends in thermal budget, dissolved gas concentration, plankton community composition, suspended sediment load and other parameters

Figure III.D.10. Great Lakes drainage basin, with proposed locations for Endurance Buoys (yellow dots).



can be of substantial significance. In a sense, these lakes are continental equivalents of canaries in the coal mine: their response to environmental forcing, be it natural or anthropogenic, is a harbinger of future change.

For this reason, the major thrust of the Great Lakes component of the OOI initially should be to deploy Endurance Buoys at one location in each of the five lakes (Fig. III.D.10). The individual Endurance stations positioned at key points will allow biogeochemical mass balances to be constructed with a degree of precision virtually impossible on an open coast. Such observations would tie climatology to long term biogeochemical impacts over a range of response times determined by the unique hydrological structure of the system.

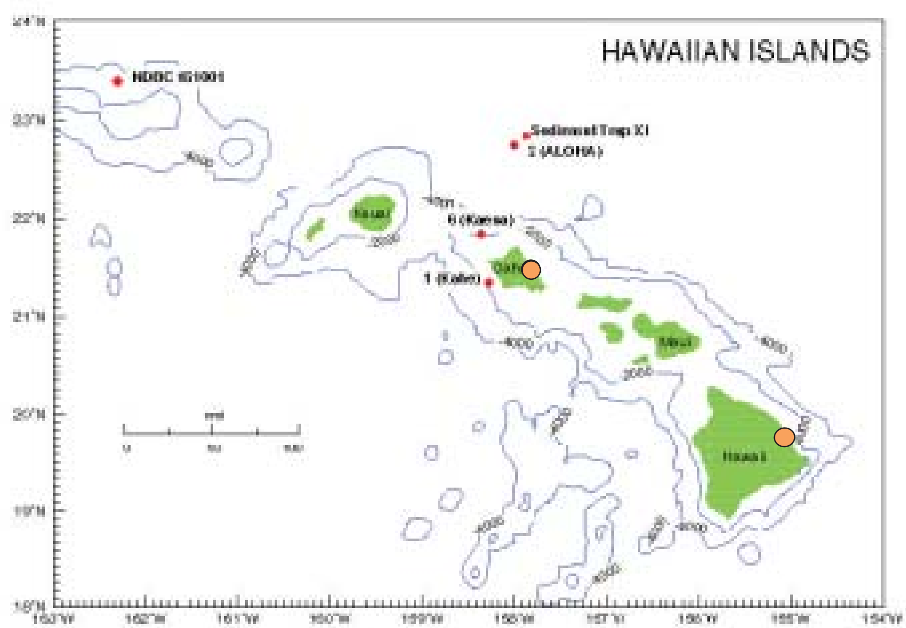
A number of observatories have been deployed or are planned for deployment in the near future in Lake Michigan. Incorporating these existing systems into a more complete Pioneer Array will result in a dataset with high temporal resolution and moderately high spatial resolution that would greatly increase our understanding of the linkages between physical, chemical and biological processes. The data collected by this array will facilitate the design of future longer-term, better equipped Endurance Lines in the Great Lakes.

While the Great Lakes exhibit many of the dynamic features described for the marine coastal environments, they also differ in substantial ways from the marine realm. Tides are negligible but seiches are commonplace. Thermal fronts arise from the temperature of maximum density of freshwater occurring at 4ºC, providing coastal dynamics that are unique to temperate and subpolar freshwater systems.

Thus, while the initial focus of OOI in the Great Lakes will be on temporal change measured by Endurance Buoys, and possibly a Pioneer Array, Endurance Lines are recommended in future endeavors. Southern Lake Michigan is a logical candidate for the deployment of an Endurance Line. Another potential site is along an axial transect in the western arm of Lake Superior, which encompasses a strong gradient in primary productivity and nutrient dynamics between riverine inflows and the oligotrophic open lake.

The Hawaiian Region: The physical environment around the Hawaiian Islands is complex, with surface and internal tides combined with wind-driven and general oceanic circulation patterns to create three-dimensional flows that render modeling efforts difficult. The Hawaiian island coasts are topographically distinct from their continental US counterparts. The islands are generally surrounded by relatively shallow fringing coral reefs with steep drops into the abyssal ocean. The main Hawaiian islands have nearly 1700 km of tidal coastline. Regions of the coastal zone are heavily burdened in terms of societal impact with point and non-point source pollution regularly affecting water quality.

Figure III.D.11. Hawaiian islands coastal bathymetry and location of Station ALOHA. Potential locations for Endurance Buoys in Kaneohe and Hilo Bays shown as yellow dots. Modified from HOTS website (http://hahana.soest.hawaii.edu/hot/)



The Hawaii Ocean Time-series (HOT) was developed in 1988 to obtain a long time-series of physical and biochemical observations in the oligotrophic North Pacific subtropical gyre in order to address long-term variability, oceanic carbon cycling and global change. Station ALOHA (Fig. III.D.11) is in deep water (4750 m), upwind of the islands and sufficiently distant to not be influenced by coastal ocean dynamics and inputs, but close enough to accomodate frequent, short cruises. A coastal analogue site was also established in 1500 m water off Kahe Point on the island of Oahu to allow convenient equipment testing and training of personnel.

Funding has been received by the University of Hawaii School of Ocean and Earth Science and Technology (SOEST) scientists to emplace a fiber optic linked bottom observatory at Station ALOHA and plans are to have a number of optics-linked extensions (up to 150 km each) up to the coast and perhaps inshore for continuous surveillance of onshore to offshore processes including but not limited to nutrient and freshwater inputs and sediment transport.

SOEST researchers have begun to develop and deploy a set of observational tools that will enable examination of the links between the physical and the biogeochemical environment in coastal areas with a focus on linking physical forcing (storms, waves, tides, currents) and coastal water quality and productivity as affected by land-ocean transfer of materials. The long-term goal is development of real-time observatories, which, coupled with numerical models will yield a predictive capacity for the nearshore environment.

Researchers have also started to investigate the direction and magnitude of the flux of CO_2 across the air-sea interface of Kaneohe Bay and Hilo Bay, two of the larger coastal marine ecosystems in the state of Hawaii. Aside from considerations related to their size, these two ecosystems were chosen because of their different ecosystem characteristics. Kaneohe Bay is dominated by coral reefs and associated carbonate sediments whereas the younger Hilo Bay lacks both features.

Thus one would expect that biogeochemical cycling of carbon in the waters and sediments of Kaneohe Bay and the flux of CO_2 at the seawater-atmosphere interface would be controlled by processes related to both production/respiration of organic carbon and calcification/deposition/solution of calcium carbonate. The Hilo Bay carbon cycle on the other hand should be dominated by organic metabolism alone, a conclusion which is supported by the preliminary data. Both bays during fall 2003 were sources of CO_2 to the atmosphere but in Hilo Bay total alkalinity behaves conservatively with salinity indicating that carbonate mineral formation through the process of calcification is not overly important in that ecosystem. However total alkalinity is not conservative with salinity in Kaneohe Bay showing that calcification by corals, coralline algae, etc. is important in controlling the behavior of the carbon cycle and the air-sea exchange of CO_2 in that ecosystem.

The studies in both bays are being extended to the shelf/slope break and out to the ALOHA station to tie in with the long-term ALOHA marine carbon system time series. Consequently, the logical first emplacement of Endurance instrumentation would likely occur in Kaneohe Bay on Oahu, an area with a well-documented history of urban development, anthropogenic nutrient and sediment input and reef degradation, followed by emplacement in the more pristine Hilo Bay.

Beach/Nearshore Locations: Long-term, biogeophysical observations are lacking in the very nearshore and beach areas, where episodic changes can be extremely large. Endurance Lines should therefore extend into the nearshore and beach areas in five of the regions described above. The observations will allow the comparison of seasonal and event-scale processes in high-, moderate- and low-wave wave energy beach environments with different geological frameworks (e.g., open, sandy beaches, muddy deltas). The observations, severely lacking at the present time, will provide the basis for improved modeling of surfzone fluid and material transport processes.

Fig. III.D.12. The US Army Corps of Engineers Field Research (USACE) Facility's Coastal Research Amphibious Buggy (CRAB). This deployment and retrieval platform is a tower on three wheels, hydraulically driven by a diesel engine located on the operations platform 11 m above the seabed. The CRAB can operate in 2 m high breaking waves in 10 m depth of water, with GPS-positioning accuracy to deploy fluid- and sediment-boundary layer sensors. The CRAB has also been used to measure monthly bathymetric changes at the Duck, NC site over the past 25 years.

The PNW Endurance Lines will provide long-term time series on high-energy, macro-tidal, low-slope sandy beaches that are presently unobtainable because of the logistical difficulty and costs. It is recognized that fluid and material transport process signals are extremely large on these beaches, thus providing excellent signal to noise ratios for process studies. The Central California observations of the Monterey Bay shoreline include heavily-barred reaches with powerful rip currents, coarse-grained steep beaches, and local wave exposures ranging from sheltered to extremely high-energy. The SCB southern boundary Endurance Line will monitor nearshore processes in a moderate-swell-energy, sandy, narrow-shelf environment with concomitant urban pollution concerns.

The MAB Endurance array at Duck NC is well located for observations of extreme episodic storms (hurricanes and nor'easters). Duck is the site of the most comprehensive nearshore process observations yet acquired, ranging from short-term process studies to the decadal geomorphic studies. The nearshore extension should include more physical and biogeochemical observations of the brackish plumes from Cheseapeake Bay that frequently propagate southward. The Gulf of Mexico Endurance Line shore termination will instrument a low-energy environment with muddy, cohesive sediments. Recent observations suggest that suspended muds effectively damp all gravity waves, not just those that reach the seafloor. Nearshore processes in muddy environments are of national importance, but are relatively unstudied.

Many of the sites listed above have ongoing observations, ranging from local bathymetric and high-resolution wave directional measurements (Duck, NC) to extensive coastal wave observation networks (CDIP and WAVCIS) in the vicinity of the SCB and GOM Endurance Lines. Repeated airborne (LIDAR) and ground-based surveys provide (in some cases decades) long time series of changing nearshore bathymetry at Monterey, Duck, and San Diego. Mobile nearshore platforms such as CRABs (Figure III.D.12) and jet skis, will continue to contribute access to important measurements in the nearshore research effort (Birkemeier and Mason, 1984; Dugen et al. 2001).

IV. Critical Research Questions/ Science Themes

Numerous previous workshops have identified and articulated important and compelling science issues for which coastal observatories will be required for significant advancement. For example, the Pacific Northwest Neptune Workshop Report states that ***"All of the working groups agreed that it is imperative to have coverage on the continental margin (i.e. shelf and slope) at multiple locations (usually in cross-margin lines) and at the same time have, at a minimum, sparse full plate coverage."*** Working groups at the SCOTS and Cabled Research Observatory (October 2003) workshops similarly identified shelf and slope sites as high priorities. Some of the science issues are focused directly on the coastal zone while others are related to global or regional issues which require an understanding of the coastal component of larger cycles and processes. In the following we bring together these ideas to more clearly identify those aspects of coastal research that are required to advance our understanding of these fundamental oceanographic research questions.

Observatory technology is anticipated to greatly expand the space and time scales over which observations can be made, leading to the discovery of previously unrecognized processes and the improved understanding of processes that had previously been under sampled or unresolved. This is especially important at ocean margins where many transport and exchange processes occur that are either unique or intensified (Fig. IV.1). Examples include: enhanced vertical exchange driven by turbulence generated by friction with the sea floor; chemical, freshwater, and sediment inputs from land focused at river mouths or areas of submarine discharge; increased nutrient inputs and cycling due to coastal upwelling; increased gradients at fronts and between stratified layers due to density differences generated from intensified thermal and salinity variations; increased benthic exchange and lateral transport within the benthic boundary layer; and interactions between currents, waves and a moveable ocean bed that can dramatically and rapidly alter nearshore bathymetry. Reflecting these processes, coastal margin systems are characterized by high rates of primary biological production, vertical and lateral material fluxes and are the location of most major fisheries.

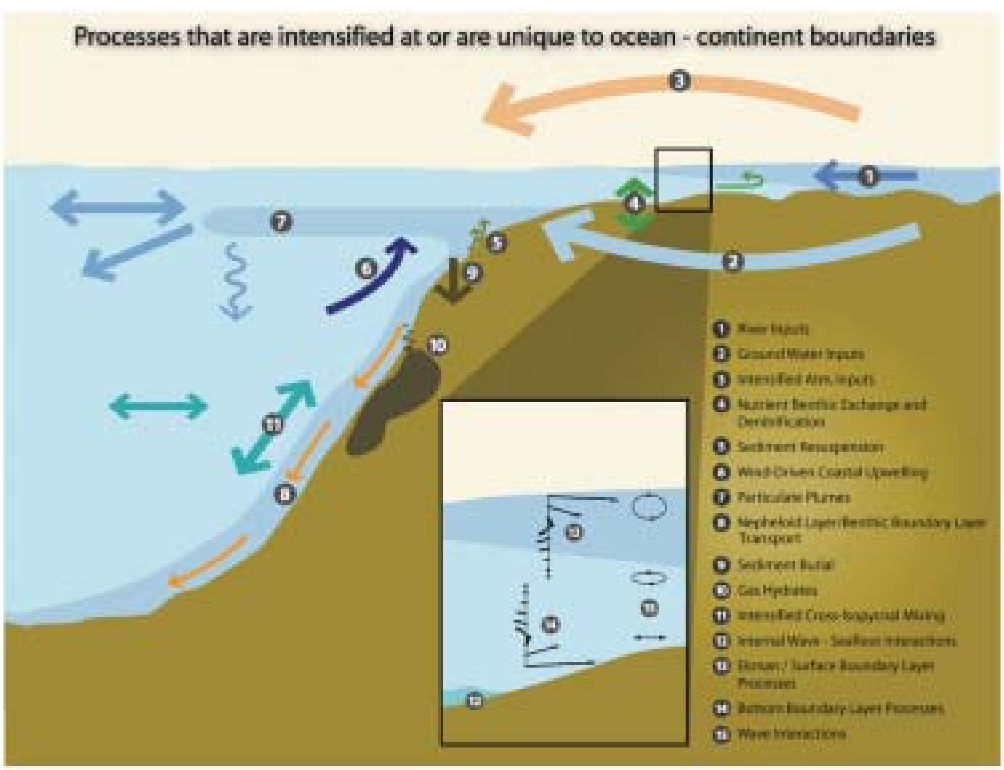


Figure IV.1. Schematic representation of transport processes that are either unique to or intensified at ocean margins.

As the interface between terrestrial and oceanic realms, improving our understanding of material exchanges across the coastal margin is key to understanding the pool size and response times of major biogeochemically active elements globally. As the intersection between the human-occupied terrestrial environment and the oceans, coastal systems dominate human-marine interactions in such areas as human health, resource management, recreation and national defense.

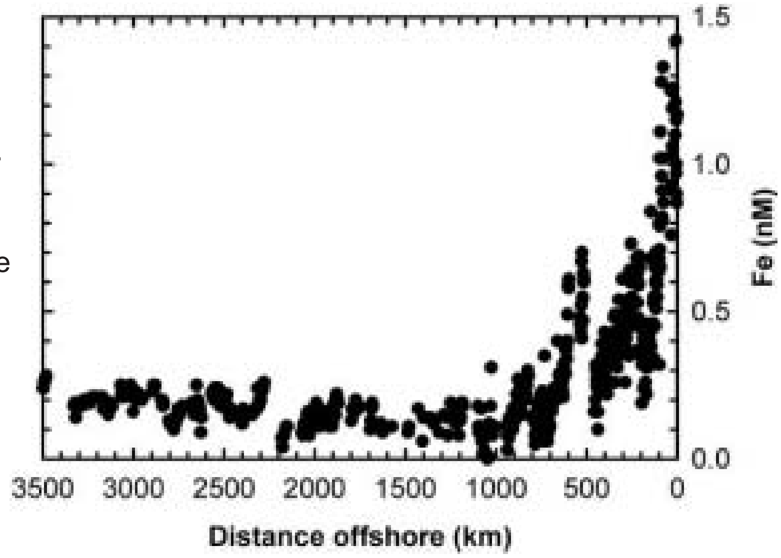


Figure IV.2. Distribution of dissolvable iron in North Pacific surface waters extending from the California coast to the central basin. Note that elevated iron levels extend to at least 600 km from the margin. Shelf pore waters and sediments appear to be the source of the iron. Modified from Elrod et al. submitted.

Separation of coastal margin regions from those targeted by regional and global observatory activities is an implementation decision. For many aspects of the marine system, margins are an integral part of the process and a holistic description can not be achieved without their inclusion. For example, biological productivity in margin environments is a major portion of total marine productivity; denitrification on margins dominates the removal of fixed nitrogen from the ocean and thereby exerts long-term control on ocean productivity; and cross isopycnal mixing of abyssal waters on margins may well dominate deep mixing in the ocean, thereby controlling deep thermal and nutrient distributions. As such, establishing a permanent observing system at the ocean-continental boundary is a critical and necessary step to fundamentally improve our understanding of the global ocean system.

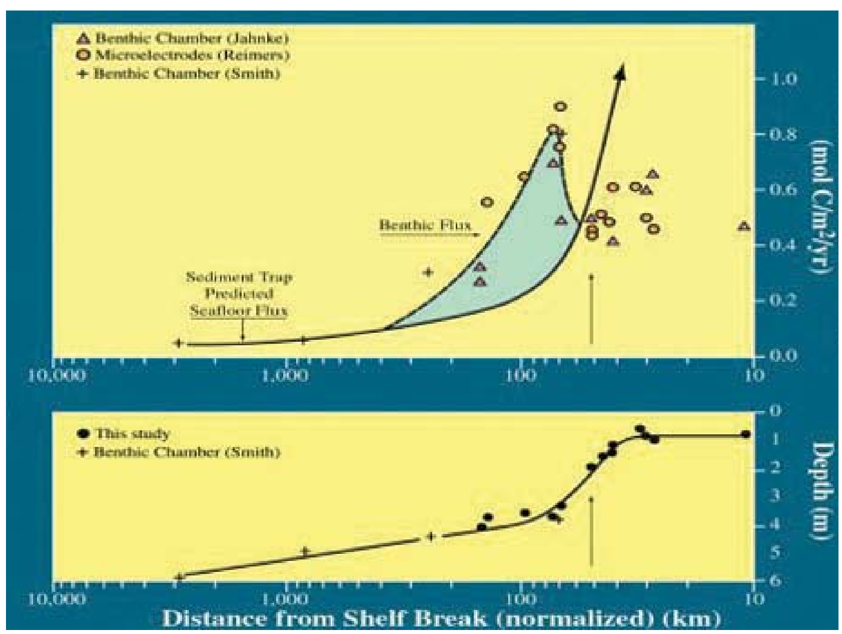


Figure IV.3. Benthic carbon fluxes extending from the central California margin to the central Pacific Basin. The heavy solid line is the flux estimated from surface productivity and water depth using the "Martin" curve. Note that sea floor fluxes exceed the estimated input flux for a distance of 200-300 km from the mid-slope. Modified from Jahnke et al. (1990).

A. Ocean Climate and Biogeochemical Cycling

The impact of the processes at ocean boundaries on the global carbon budget is not well known but likely provides major pathways for transferring carbon amongst the important, climatically relevant reservoirs. For example, wind-driven, coastal upwelling supports extremely high rates of primary biological produc-

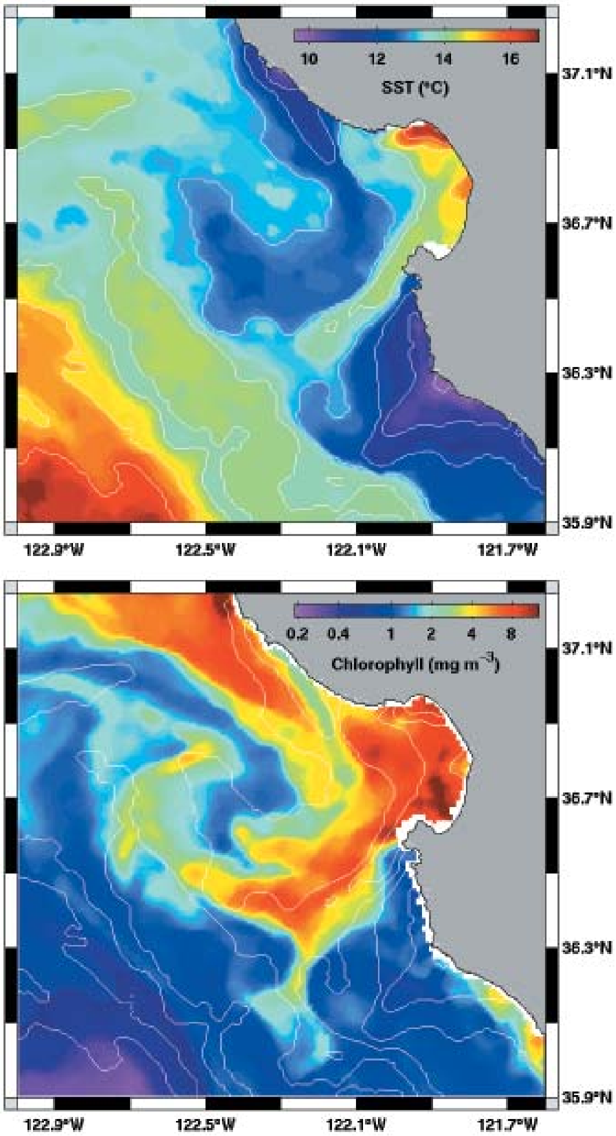


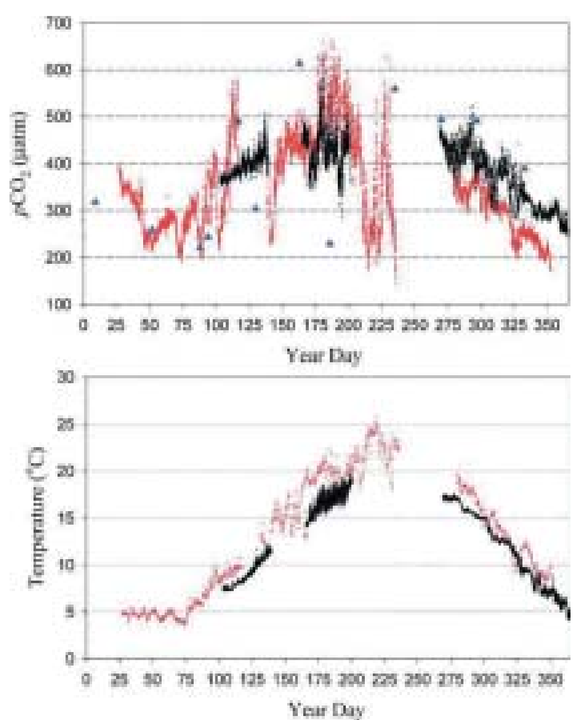
Figure IV.4. Surface temperature and chlorophyll distributions in Monterey Bay and the central California margin showing the complex distribution patterns and the offshore transport of associated organic matter. From Fitzwater et al. (2003).

tion and organic carbon sedimentation relative to the open ocean. Sea floor and water column-based estimates of the particulate organic carbon flux suggest that perhaps as much as half of the total biological pump transfer of organic carbon to deep waters occurs adjacent to the continents (Jahnke, 1996; Schlitzer, 2000).

Exchange of nutrients at ocean-continental boundaries may have global impacts. For example, denitrification at margins is the dominant removal mechanism of biologically available nitrogen from the ocean and thereby exerts control on global marine production (Codispoti et al. 2001). More recently, it has been suggested that shelf and slope sediments may be an important source of iron for surface waters. Increased iron concentrations associated with ocean-continental boundaries have been observed extending 600 km offshore (Fig. IV.2.). Nutrient inputs to surface waters along upwelling margins support high biomass and high seafloor particulate organic matter deposition rates extending hundreds of kilometers from the coastal zone (Figs. IV.3 and IV.4).

It has also been suggested that margins may provide a significant sink for anthropogenic CO_2 and perhaps contribute to the variability of atmospheric CO_2. Tsunogai et al. (1999) delineated several mechanisms that may act to pump CO_2 from continental shelf regions into intermediate and deep oceanic waters and estimated that this “continental shelf pump” could be responsible for as much as a 1 Pg C sink annually on a global basis. Follow-up and global circulation modeling studies support this possibility (Yool and Fasham, 2001). Observations of seasonally varying surface pCO_2 and large undersaturations of surface water pCO_2 (Figs.

Figure IV.5. Time-series of surface water temperature and pCO_2 in the Middle Atlantic Bight demonstrating large and rapid changes in pCO_2 concentrations. (DeGrandpre et al. 2002)



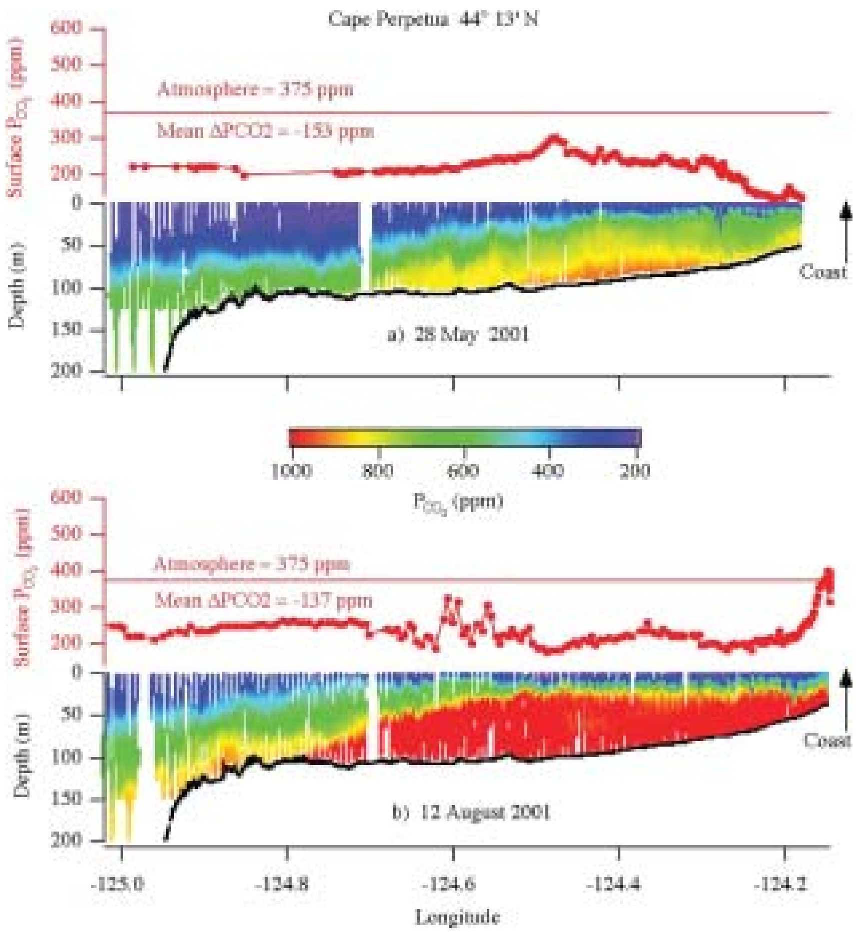


Figure IV.6. Cross-shelf, high-resolution measurements of pCO_2 on the Oregon continental shelf in May and August, 2001 (Burke Hales, unpublished results).

IV.5 and IV.6) demonstrate the need to better understand the processes controlling surface pCO_2 in coastal waters. Importantly, at some locations, direct inputs of terrestrially-derived atmospheric carbon via rivers, groundwaters and tidal exchange with coastal waters may supply much of the carbon transported off the shelf (McKee, 2003). This implies that assessment of air-sea exchange may not be sufficient to fully quantify the oceanic CO_2 sink and that terrestrial and oceanic carbon pools may be tightly linked through coastal transport processes. Additional carbon uptake by high rates of biological productivity that characterize river-ocean margins further suggests that these systems may be important focal points for the sequestration of anthropogenic carbon.

B. Ecosystem Dynamics, Turbulent Mixing and Biophysical Interactions

Understanding the processes and environmental factors that control the diversity and species composition of coastal biological communities is a fundamental goal of marine ecological and biogeochemical research (IMBER, 2004). Major regime shifts in coastal communities have, in a few selected cases, been well documented. Examples would include population shifts between anchovies and sardines (Chavez et al. 2003) and variations in total production correlated with ENSO cycles. Shorter-term variability in specific populations may be related to seasonal factors. Environmental control of population migrations and specific species blooms, such as the onset of harmful algal blooms, are not well understood. In many cases basic information such as migration characteristics, appearance or absence of specific predators, etc. is not available. In addition, coastal communities are subject to anthropogenic activities that may lead to harvesting and habitat changes that occur on a variety of time-scales.

Elucidating the dynamics of processes that control community composition is not only important to programs such as GLOBEC and, eventually, IMBER, but are also critical to the success of current attempts to identify marine species (Census of Marine Life, *http://www.coreocean.org/*). Obtaining this information requires a continued presence in the ocean to observe the processes that impact species composition and the ability to observe and identify individual species. While the identification of microbial species will require in situ application of molecular genetic techniques that are still in the development stage, high resolution video coupled to automated image analysis protocols is capable of directly observing and identifying larger organisms (Fig. IV.7). Thus, high bandwidth and high power (for lights and

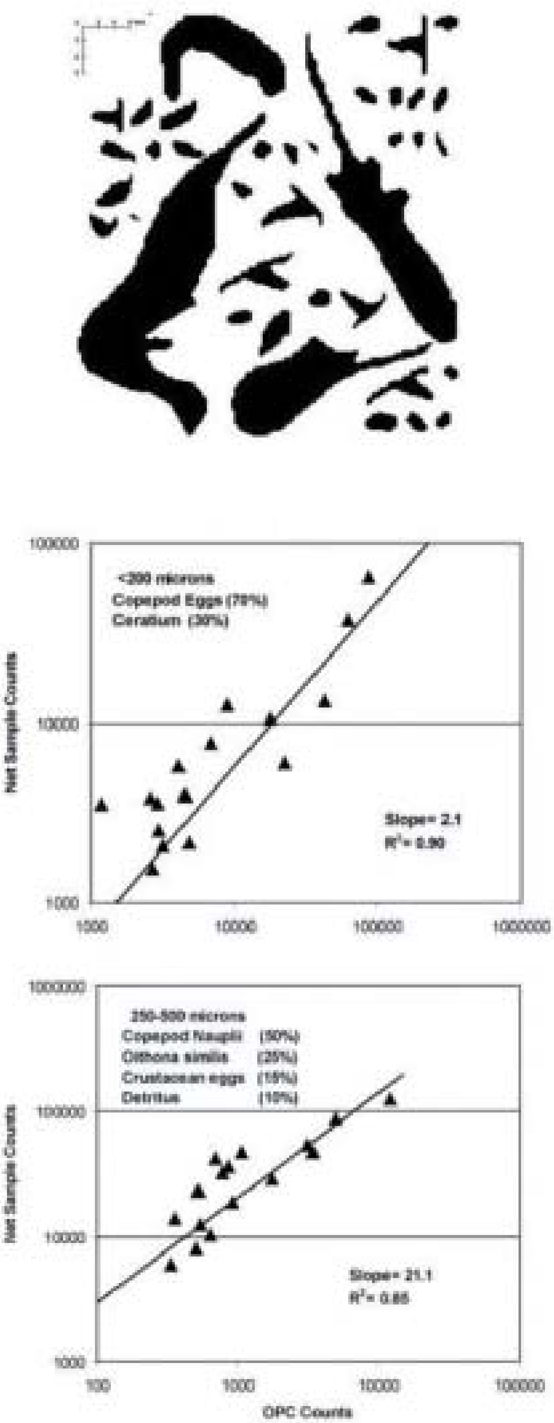


Figure IV.7. The Laser Optical Plankton Counter (LOPC) generates both size and shape of plankton and their abundance. Courtesy of Alex Herman, Bedford Institute of Oceanography.

antibiofouling applications) research nodes provide the technology to directly and continuously observe organism presence and behaviors. Examples of specific observations would include timing of migrations and spawning activities, community succession and life-stage completion. Coupled with the continuous measurement of environmental conditions as well as passive and active acoustical measurements, coastal observatories may provide a major leap forward in the study of coastal ecosystems and food webs.

Turbulence affects the biological community structure and metabolic processes in a variety of ways. At the ocean surface, large eddies determine the time-averaged vertical distribution of plankton, thereby controlling the peak and integrated light levels available to support photosynthesis. Vertical turbulent fluxes may also largely determine the input of “new” nutrients to the photic zone and the formation of exportable organic materials while turbulent shear may affect the integrity of marine snow particles. Turbulence has been suggested to impact phytoplankton community structure and the ability of zooplankton to sense and capture prey.

In shallower regions of coastal systems, turbulent interactions with the seafloor play an important role in sediment resuspension (Fig. IV.8). This, in turn, may supply trace elements to water column communities and may act to winnow fine-grained sediments from the sea floor, thereby controlling benthic habitats. Additionally, the generation and dissipation of turbulence is critical to the maintenance or dissipation of stratified water mass layers and fronts which provide special habitats for certain organisms.

C. Fluids and Life in Continental Margin Sediments

Gas hydrate deposits are common features in upper continental slope environments. Numerous examples are located at the subduction margins on the West coast (e.g. Hydrate Ridge on the Oregon slope), along passive margins on the East coast (e.g. Blake/Bahama Plateau) and in petroleum seepage areas (e.g. Gulf of Mexico northwestern slope). Catastrophic destabilization of hydrate deposits has been suggested as an important trigger for past climatic shifts. Complex sea floor observatories are currently being designed to examine the dynamics of these critical deposits.

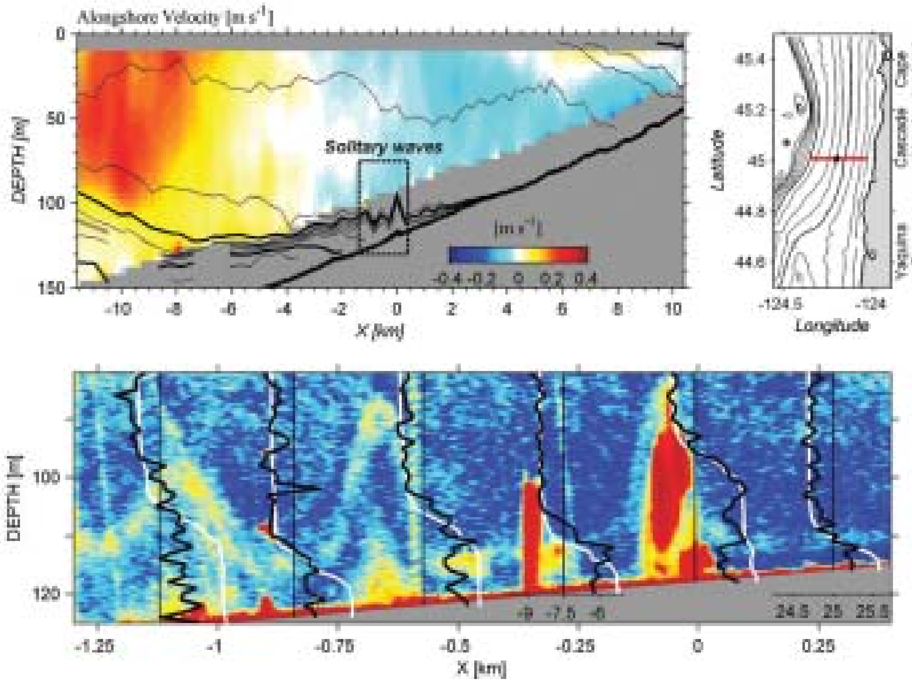


Figure IV.8. Upper: Near-bottom solitary waves from January 2003; shown is a section of potential density and N-S velocity off the Oregon coast. Isopycnal intervals are 0.2 kg m^{-3}; 26 and 25 kg m^{-3} are bold,120 kHz echo-sounder image shows the outline of 30 m tall waves.

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 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 biology consistent with the cloud of scatterers in the echo-sounder image (from Klymak and Moum, 2003).

Previous planning documents have identified key scientific questions that could be addressed with cabled sea floor observatories at strategically important hydrate locations. Examples include: How do rates of gas hydrate formation and dissociation respond to perturbations of pressure, temperature, fluid chemistry and flow rate? What are the influences of gas hydrate formation and dissolution on ocean and atmospheric chemistry, biology and climate? To what extent do biological processes control hydrate formation and dissociation? How are hydrate deposits and continental slope sediments associated and under what conditions does hydrate dissolution lead to slumping?

Sea floor chemical and physical sensors coupled with water column and sub-seafloor acoustic monitoring can be used to relate variations in bottom conditions to deposit stability and activity. Eventual development of remote-controlled, mobile samplers will permit direct characterization of chemical and biological characteristics and activities.

Continental shelf sediments may also exhibit strong linkages between bottom water dynamics and sedimentary biological and geochemical processes and characteristics. Seventy percent of continental shelf sediments are considered relict and many of these exhibit high permeabilities. Transport and reaction processes within permeable sediments are increasingly recognized as major factors controlling the biogeochemistry of coastal, estuarine and riverine systems. Because solute and particle transport through permeable sediments such as

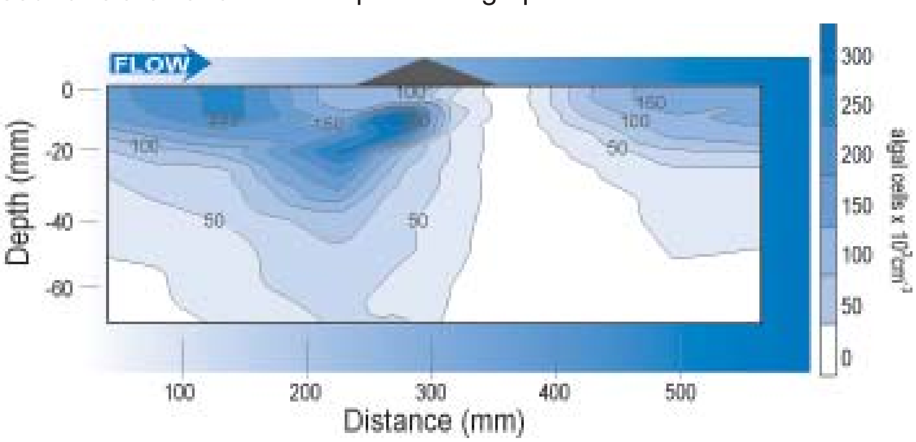


Figure IV.9. Results of a flume study demonstrating the potential role of pore water advection in transporting algae into permeable sediments (after Hüttel et al. 1996) sands can be very much greater than molecular diffusion, these systems are fundamentally different from those environments having fine-grained sediments upon which most present models of sediment - water column interactions are based (Fig. IV.9).

Where permeabilities are high, sedimentary pore water and particulate transport can be very rapid and tightly coupled to water column dynamics. As such, at these locations the degree of benthic - pelagic coupling is much greater than previously thought and sensitive to external forces. To capture the dynamics of the exchange, observatories must be equipped with seafloor and water column sensors which can capture specific events.

D. Cross-cutting Coastal Ocean Processes

Episodic events are likely to be major structuring influences along continental margins. Such events may be short-term such as the impact of high waves, storm surge (Fig. IV.10), internal waves or of an eddy interacting with the coastal waters and the sea floor. Other events, such as storm or river discharge events, may influence margin systems for longer periods. While individual interactions may have a short lifetime, they can exert considerable control on coastal ecosystems, biogeochemical cycling and mass transport rates. Response of coastal systems to variations in external forcing, such as climate change, may occur through variations in intensity, magnitude or frequency of these events. Assessment of coastal systems and long-term variability therefore requires resolution of processes and conditions on a wide range of time scales.

Interactions between waves, breaking waves, currents and the seabed are maximized in the nearshore zone and the associated transport and biogeochemical processes impact many of the science issues. Nearshore sediment transport exerts significant control on coastal morphology which, in turn, may determine groundwater flow, while breaking waves, bottom boundary layer dynamics and associated turbulence dominate the pore water exchange and benthic habitat characteristics. High resolution, sustained measurements are required to further our understanding of the dynamics and feedbacks of this system (Thornton et al. 2000).

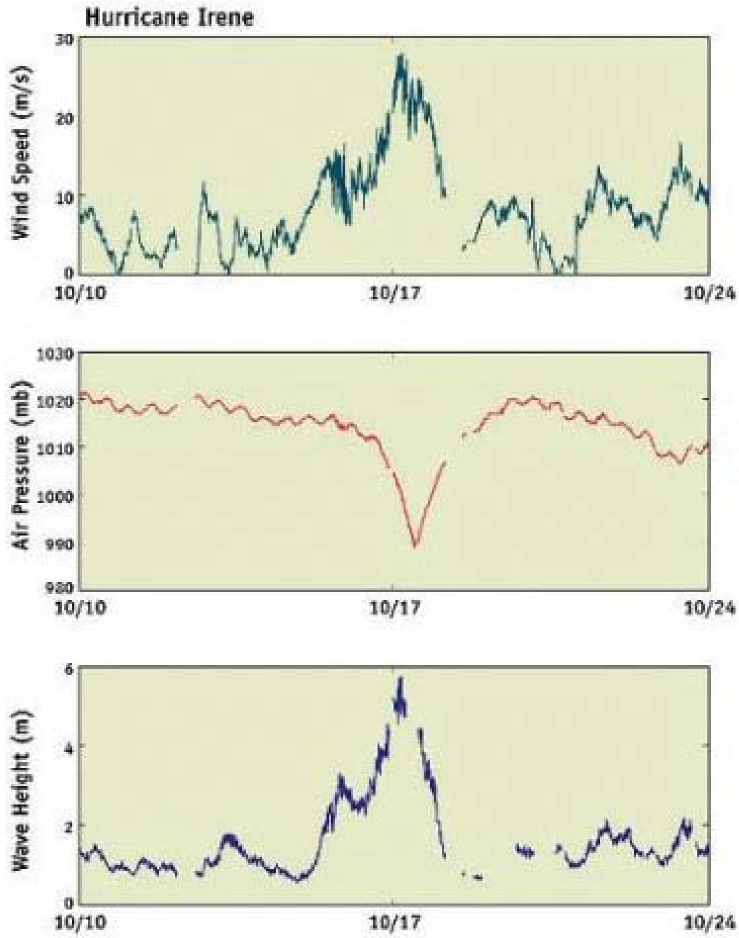


Figure IV.10. Observatory measurements of wind speed, barometric pressure and wave height on the South Atlantic Bight during the nearby passage of the eye of Hurricane Irene in 1999. Note how quickly the wave heights respond to variations in wind speed (H. Seim, unpublished results).

Furthering our understanding of ocean boundary current - shelf water interactions is also central to many of the identified science issues. Meanders in offshore boundary currents control upwelling and downwelling of slope waters impacting nutrient balances and cross-margin mass transport. Offshore currents also often contain populations of organisms that may "seed" a region if conditions are right for growth and reproduction. As such, the dynamics of exchange can significantly influence the chemical and biological character of an adjacent shelf environment.

V. Regional Settings and Justification of Candidate Locations

A. The Middle Atlantic Bight/Gulf of Maine

Endurance Array Lines

To plan locations of observing resources in the MAB/GoM, it is useful to conceptualize the system as dominated by along-shelf advective transport that is generally southwestward, while subject to variable inputs of freshwater and materials along the near-shore (coastal) boundary and to inputs and losses through shelf/slope exchange along the offshore boundary (Fig.V.A.1). This conceptual framework motivates the location of a cross-shelf Endurance Array Line along the upstream boundary of the region to constrain advective inputs. Two additional cross-shelf lines, one near the southern end and one near the along-shelf center of the region, plus a set of distributed moorings will be important for assessing effects of non-conservative processes acting within the region and for broadly constraining exchanges across the near- and offshore boundaries. The distributed moorings will be located near river mouths and other critical locations, such as at the northern inflow locations in the Gulf of Maine (Fig. V.A.2).

There are different physical regimes across the shelf and, particularly in the vicinity of the shelfbreak front, there are processes that have pronounced but poorly understood physical, chemical, and biological consequences. For this reason, the northern and central cross-shelf Endurance Array Lines should be cabled out to the shelfbreak (~200 m isobath) to permit vertical profilers and high-bandwidth, high-power physical, biological, and chemical sensors to be used across the shelf. Underwater nodes should be located at several isobaths (e.g., 10, 30, 60, 100, and 200 m) and each cabled line will have one or more offshore AUV docks.

Pioneer Arrays

Because of the high spatial and temporal variability and complexity of exchange processes across the near- and offshore boundaries of the MAB, it is not practical to observe them directly with the proposed Endurance Line. Instead, the cross-shelf exchanges must be constrained on the basis of a combination of available long-term observations and numerical models. While we have some understanding of the relevant exchange processes, current theories and modeling

Figure V.A.1. Existing and future observing assets covering the Middle Atlantic Bight and Gulf of Maine complement the proposed Coastal Observatory resources. The region has extensive remote sensing coverage, not only from satellite-based sensors, but also from long- and short-range CODAR systems. Buoys combined with fixed near-shore piers or cabled facilities provide leveraging and background information for placing new resources.

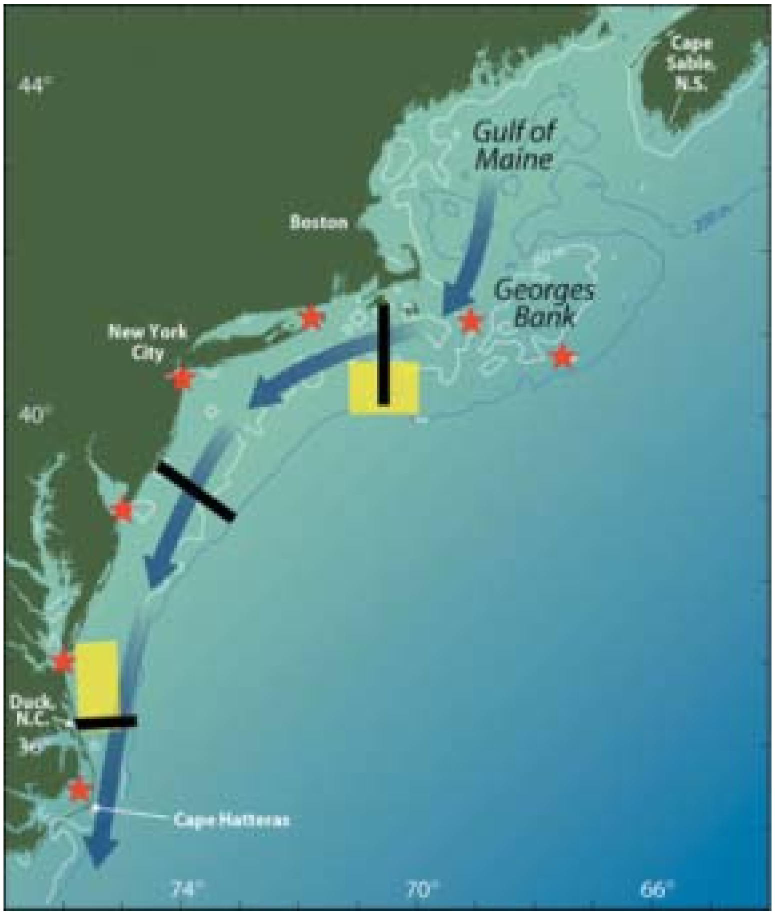


Figure V.A.2. Endurance Array lines (thick black lines) and moorings (red stars) proposed for the Middle Atlantic Bight. The yellow boxes indicate potential sites for higher resolution studies involving Pioneer Arrays (see Figure V.A.3)

capability are inadequate for this goal. Focused high-resolution but limited-duration process studies with Pioneer Arrays are necessary to develop this important aspect of the overall observing capability.

One candidate objective for a Pioneer Array study would be to improve characterization and modeling of shelf/slope exchange processes in the MAB. For this the Pioneer Array would be located near the offshore edge of the shelf along one of the Endurance Array Lines (Fig. V.A.3). The precise location of the shelfbreak front varies in space and time and the associated frontal jet is strong and narrow. In addition, shelf/slope exchange may be caused by processes as varied as warm core rings, frontal instabilities, intrusions, and wind forcing (Loder et al. 1998). For these reasons, a multi-platform 3-5 year observing effort would be required for this particular problem. The Pioneer Array would provide along-shelf observations spanning the outer portion of the MVCO Endurance Array line, with enhanced cross-shelf resolution in some areas. These moorings would be located up- and down-shelf from the Endurance Array Line in an array with ~10 km spacing along a section of the shelfbreak. Because of the large shifts in frontal positions due to both wind forcing and warm core ring interactions, repeat sections by autonomous vehicles will also be necessary to resolve cross-shelf fluxes. The AUV docks installed as part of the Endurance Array will facilitate this aspect of the focused Pioneer Array effort. Since the structure of both the bottom and surface boundary layers are critical for frontal dynamics, the moorings must carry sensors sampling throughout the water column plus surface sensors to determine the surface wind stress and heat flux.

A second candidate Pioneer Array experiment in the MAB would focus on effects of buoyant plumes and other riverine input at the coast (Fig. V.A.3). This array would include multiple cross-shelf lines of moorings, each extending from the near-shore to the mid-shelf, starting to the north of a river outflow (e.g., Chesapeake Bay) and continuing 100 km or more to the south. The Pioneer Array would tie in with the Endurance Buoy at the mouth of Chesapeake Bay and the Endurance Array Line near Duck, NC. The Pioneer Array would provide a powerful means of addressing the complex spatial and temporal variability of the river plume and coastal current regime, which exhibit a tremendous range of spatial scales, from meters to hundreds of km, and likewise exhibit important temporal variability at virtually every measurable scale. Other

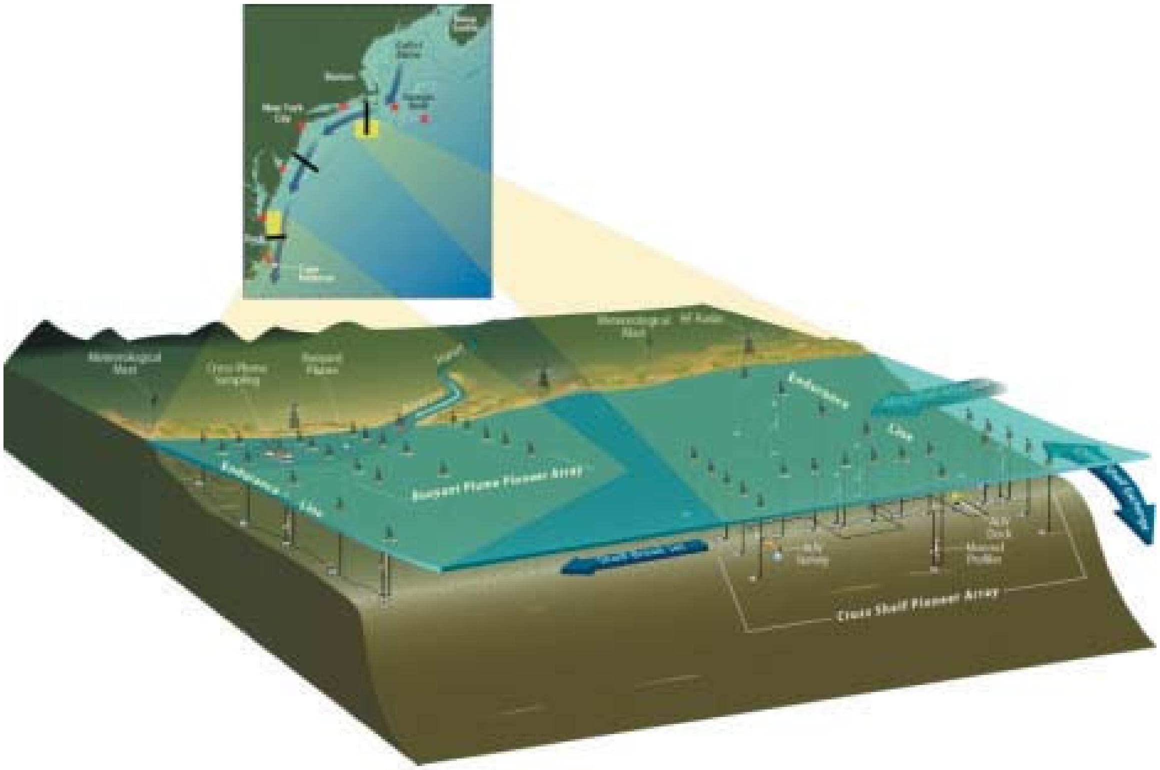


Figure V.A.3. Schematic view of two possible deployments of Pioneer Array components for observation and model development of critical processes in the MAB/GoM. The cross-shelf exchange Pioneer Array and buoyant plume Pioneer Array are composed of limited duration mooring deployments built around permanent Endurance Array components. These Pioneer Array examples are shown on the same diagram for illustration purposes only and are not expected to be contemporaneous.

measurement approaches such as AUVs, gliders and rapid-response shipboard surveys would complement the moored component of the Pioneer Array to provide the required spatial resolution and to perform more specialized measurements and sampling.

This approach could produce significant scientific impact across a broad range of disciplines (see McKee, 2003 for a recent synthesis). These include a rich variety of physical oceanographic issues spanning from small-scale stratified mixing processes to margin-scale transport mechanisms, with implications for climate change and the interpretation of the paleo-oceanographic record. Similarly, there are a suite of ecological questions at various scales, such as the impact of terrigenous nutrient delivery, larval dispersal, harmful algal blooms, and population dynamics. The zone of interaction between rivers and the coastal ocean is arguably the most important and complex environment for geochemical transformations in the ocean. The Pioneer Array would provide critical support for interdisciplinary investigations of this dynamic environment.

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B. South Atlantic Bight

The SAB extends from approximately 27ºN, where the shelf begins to widen to the north, to approximately 35º N where the shelf narrows near Cape Hatteras (Menzel, 1993). Between these boundaries, the continental shelf width broadens to a maximum of 120 km off of Georgia and South Carolina (Fig. V.B.1). With an area-weighted mean depth of only 27 m, the SAB provides a unique opportunity to study interactions between atmospheric forcing, shelf-water circulation, and sediments on a broad, shallow continental shelf. Furthermore, exchanges with ocean waters across the shelf break are dominated by interactions with the Gulf Stream while freshwater riverine inputs and tidal exchange with the extensive estuarine and saltmarsh system dominates coastal exchange. This region thereby provides a set of characteristics that are significantly different from other US shelf environments. As such, the comparison of the response of the SAB to external forcings to that of other shelf regions provides unique opportunities to examine the dynamics of the shelf system.

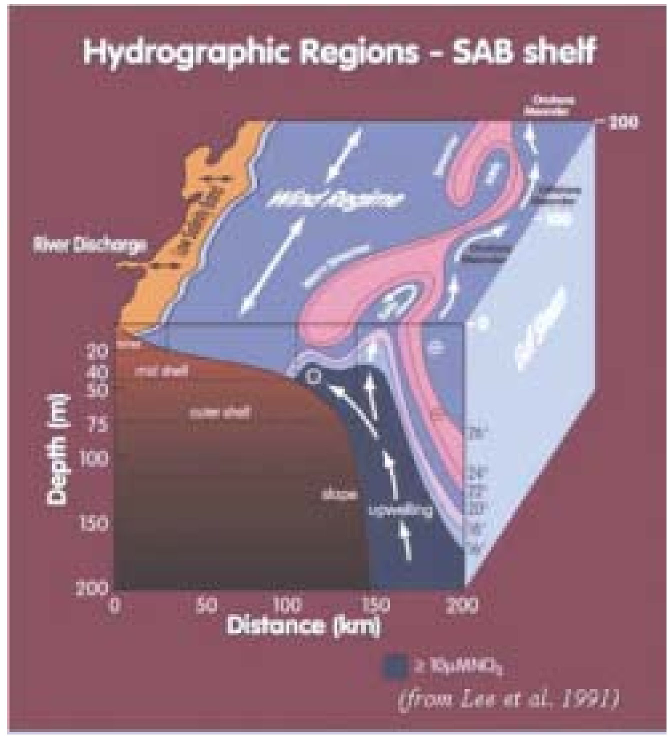
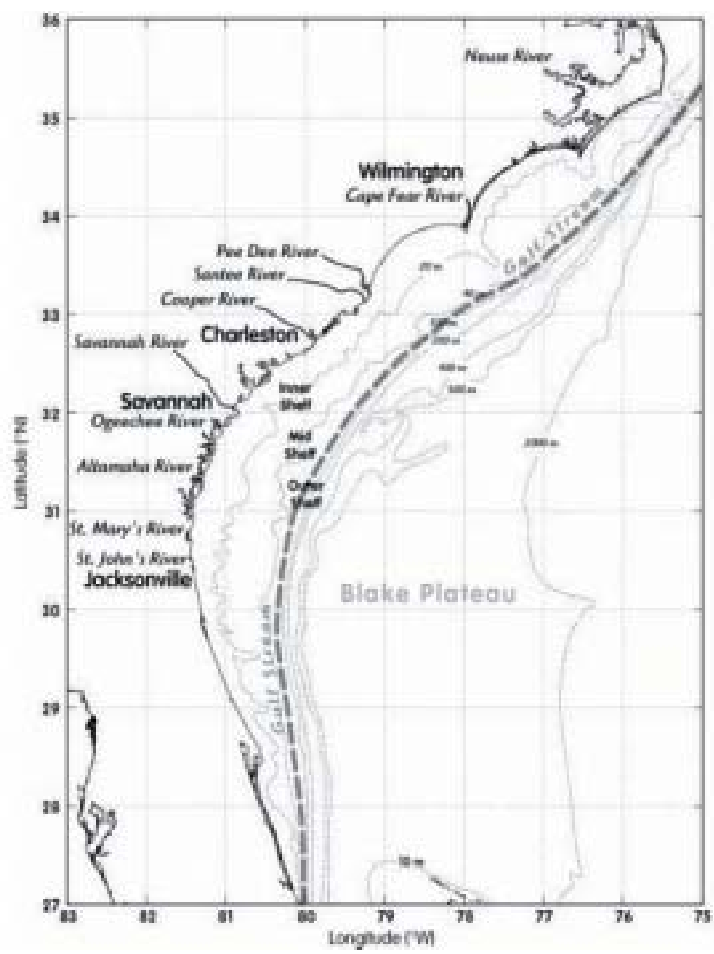


Figure V.B.2. Gulf Stream meanders schematic

Figure V.B.1. Bathymetry of the South Atlantic Bight



Major processes that impact nutrient cycling and biogeochemistry of the SAB

Gulf Stream Interactions: The main source of nutrients to the SAB shelf is the intrusion of nutrient-rich waters associated with meanders in the Gulf Stream (Lee et al. 1991). Nutrient-rich waters are upwelled and pushed onto the continental shelf as undulations in the Gulf Stream draw away from the continental shelf (Figure V.B.2). As these meanders progress northward, the intrusions recede back off the shelf, returning much of the upwelled nutrients (Atkinson et al. 1987; Lee and Pietrafesa, 1987). The proportion of the upwelled nutrients that are biologically taken up and enter the shelf biogeochemical system depends on a variety of factors such as: *1) How far onto the shelf does the upwelled water extend?*

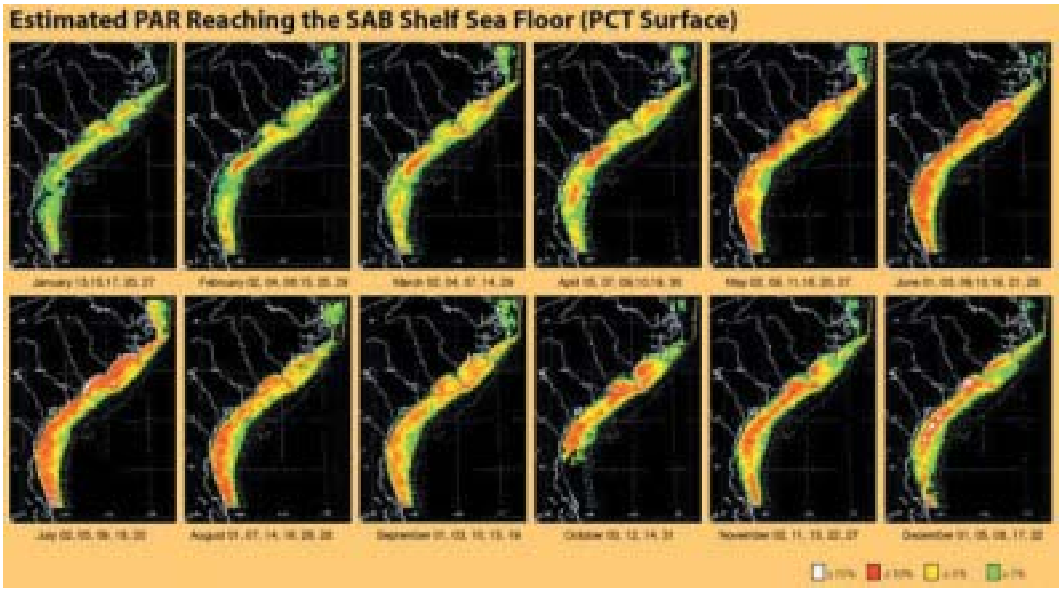


Figure V.B3. Monthly composite figures of benthic light fluxes (James Nelson, unpublished results).

2) What is the residence time of the waters on the shelf? 3) How stratified and turbid is the shelf water column? 4) What are the initial seed populations of autotrophs and grazers that would control the utilization and cycling of nutrients and resulting organic matter? Local atmospheric forces influence these factors and hence ultimately control nutrient cycling on the SAB shelf.

Atmospheric nutrient inputs: Previously measured inputs of nutrients to the SAB shelf indicate that the atmosphere is the second largest source of fixed N to the SAB shelf, exceeding riverine inputs by perhaps as much as a factor of five (Jahnke, unpublished results). These inputs are temporally and spatially highly variable, are associated with storms, and are particularly critical to the mid-shelf region which is distant from the Gulf Stream and riverine sources. Inputs of nutrients from the atmosphere will depend on: *1) the nutrient content of air masses from specific regions (i.e. terrestrial vs marine); and 2) the extent and duration of precipitation events.*

Benthic fluxes of nutrients: In coastal areas, the flux of nutrients from the continental shelf seafloor has been implicated in sustaining high rates of biological productivity, maintaining abundant fisheries production and the onset of harmful algal blooms. Additionally, approximately half of global denitrification is thought to occur in reducing continental shelf sediments. Seventy percent of global continental shelf areas have been classified as geologically relict, suggesting that most are comprised of non-accumulating sands and subject to rapid, physically-forced pore water and particulate exchange processes.

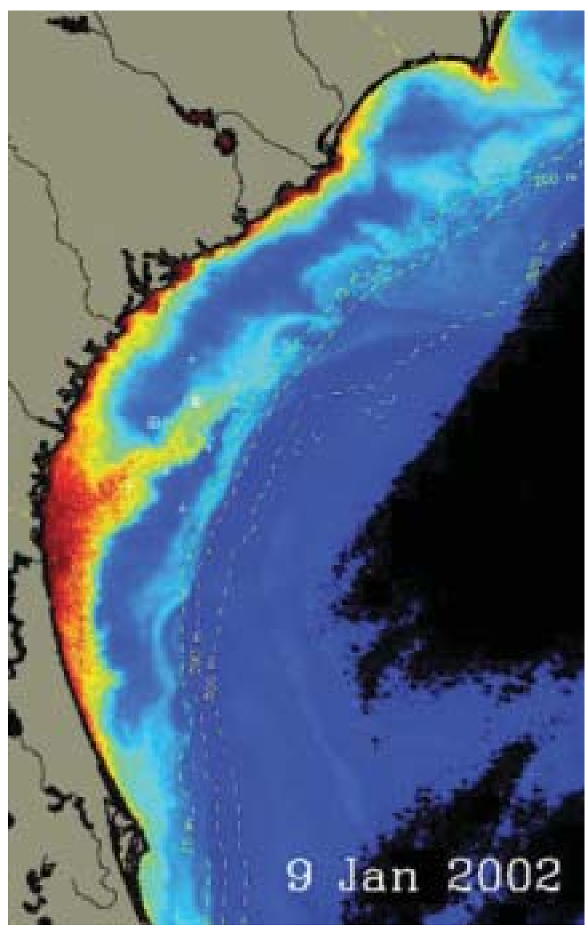


Figure V.B.4. Satellite image of off-shore flows (James Nelson and Jack Blanton, unpublished results).

Processes that drive benthic exchange include shear-driven flows associated with bottom currents including tidal currents; dispersive exchange due to pressure and current variations from the passage of gravity waves; and the interaction of these with bottom topography (Hüttel et al. 1996; Webster and Taylor, 1992). Variations in benthic exchange due to temporal variations in tidal currents (spring vs neap), wave heights and periods due to locally and remotely generated gravity waves provide a significant challenge for understanding benthic - pelagic coupling of nutrient cycles. Additionally, transport and filtration of small particulates within the sediments provide additional pathways for increasing the coupling of water column and benthic metabolisms.

Specific research questions include: *1) What is the magnitude of the mean rate of particulate and solute benthic exchange? 2) What is the magnitude of the variations in benthic solute and particulate exchange? 3) To which external forces is the rate of benthic exchange most sensitive? 4) How important is particle filtration in controlling benthic metabolic rates?*

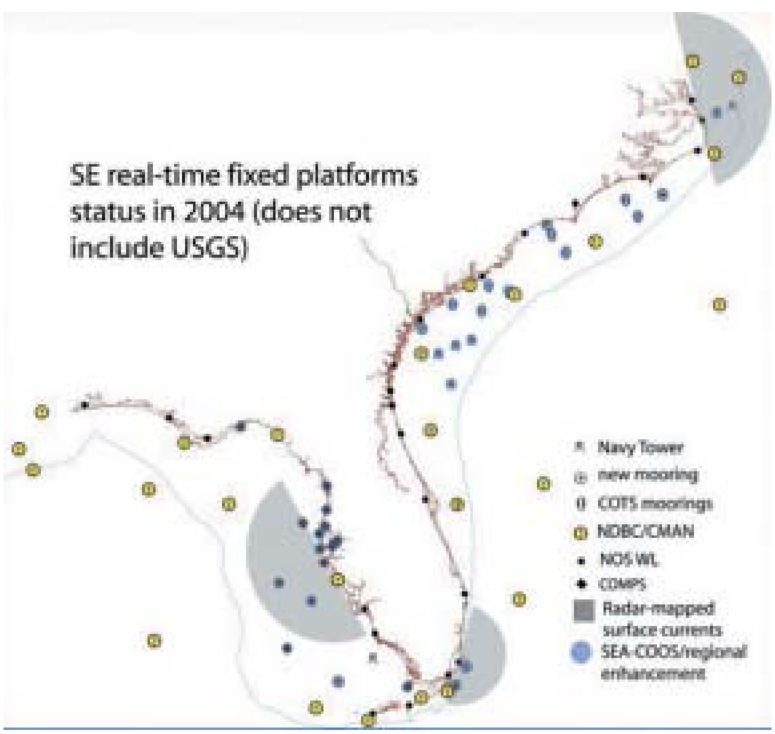


Fig. V.B.5. South Atlantic Bight and Florida shelf existing observatory elements.

Coupling and feedback between benthic and pelagic biological processes: Previous studies have demonstrated that a significant portion of the light at the sea surface reaches the sea floor (Fig. V.B.3). Rates of benthic primary production, especially within the mid-shelf region, often are comparable to rates of pelagic production (Jahnke et al. 2000). Benthic autotrophic production serves as a source of organic matter and oxygen and a sink for nutrients, opposite the traditional view of the role of the seabed in coastal ecosystems, and hence may exert considerable variability in the cycling of nutrients and organic matter on the continental shelf. Factors that influence the relative rates of pelagic and benthic photosynthesis are often inversely correlated because of their interactions with the light field. For example, increased water column nutrient concentrations will stimulate water column production, increasing chlorophyll levels and light attenuation. This, in turn, decreases benthic light levels, benthic production and the incorporation of nutrients into benthic biomass. Resuspension of particles due to storm waves or increased currents can similarly depress rates of benthic production. Conversely, during periods of water column oligotrophy or slow bottom currents with little sediment resuspension, benthic light levels and benthic production increase. Understanding the factors that control the temporal variations of production and metabolism in these systems is critical to furthering our understanding of shelf biogeochemistry.

Exchange with nearshore and estuarine waters with shelf waters

Typically, nearshore and estuarine waters are mixed tidally but remain trapped shoreward of a coastal frontal zone and generally flow southward, toward Cape Canaveral. Summertime transport of nearshore waters across the front and onto the shelf during periods of upwelling-favorable winds has been well studied (Blanton and Atkinson, 1983; Blanton et al. 1989). Less attention has been paid

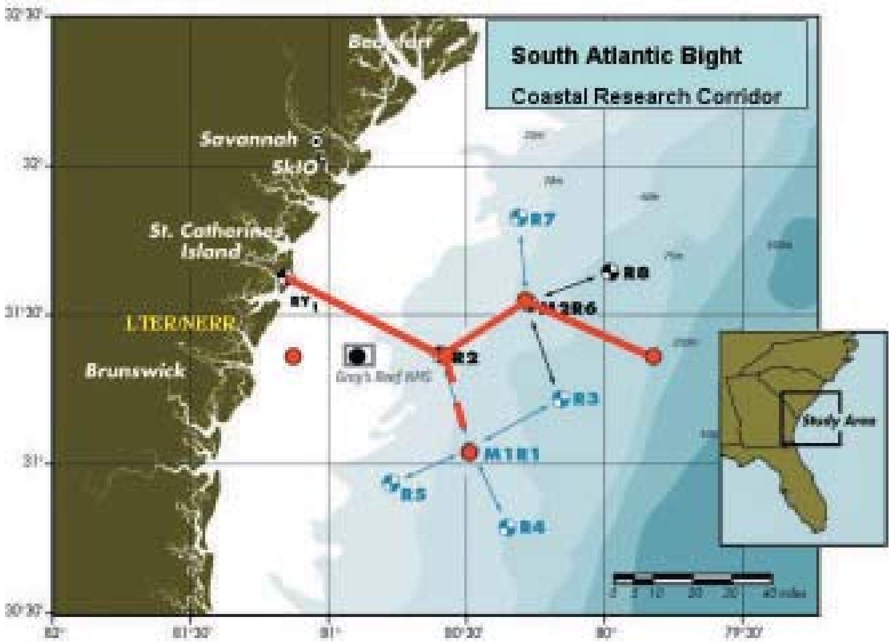


Figure V.B.6. Proposed Endurance Line using several of the array of Navy radar towers in the SAB, some of which have been instrumented by SABSOON.

critical to advancing our understanding of shelf biogeochemistry and perhaps the transport of important larvae.

Proposed SAB Endurance Line

A variety of observatory developments are already underway in the SAB (Fig. V.B.5). While providing an important context for the region, it is anticipated that these efforts will not provide the high power, high bandwidth, research and development focus that is the goal of the OOI. Therefore, in collaboration with these other activities, we propose to develop an Endurance Line in the central portion of the SAB (Fig. V.B.6). On the continental shelf, this line will build on the existing observational towers of the NOPP-funded SABSOON effort and the NOAA buoy and observations of Gray's Reef National Marine Sanctuary. At the nearshore end, this line will terminate directly at the Sapelo Island National Estuarine Research Reserve and Long-Term Ecosystem Research areas. These efforts maintain numerous buoys and other direct measurement programs that characterize river - estuarine - ocean interactions. At the offshore terminus, a research node will be

to exchanges in fall and winter (Fig. V.B.4). During these periods, persistent downwelling-favorable winds appear to push water toward the coastline, "mounding" the water surface near the Florida border due to the change in shoreline orientation relative to the wind (Werner et al. 1993). During periods of wind relaxation, offshore flows develop. aided by the buoyancy of the fresher coastal waters. Understanding this cross shelf exchange with nearshore waters is

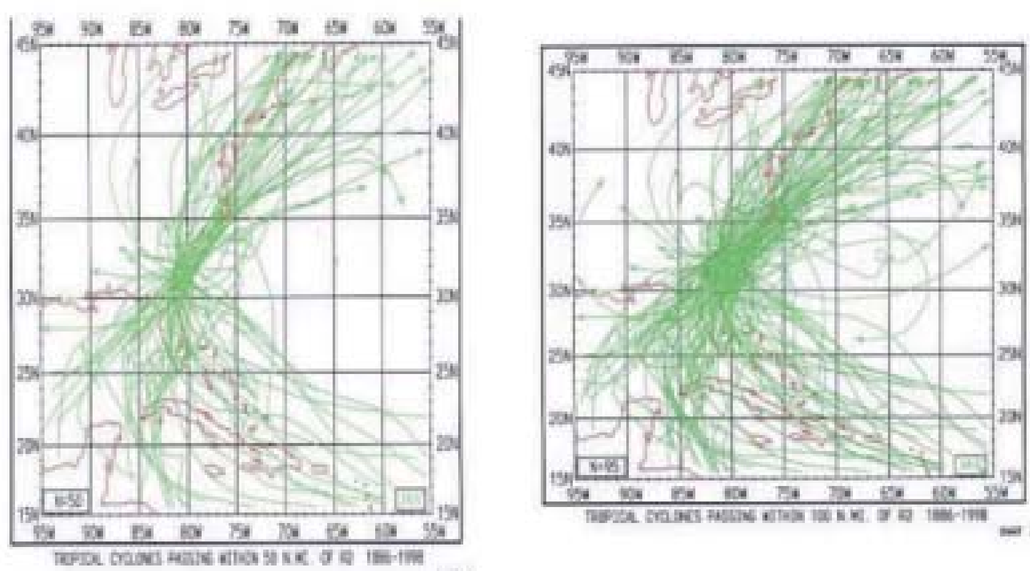


Figure V.B.7. Hurricane tracks from an R2- centric perspective (see Fig. V.B.6 for location of tower R2). Plots show hurricane tracks which passed within 50 (left) and 100 (right) nautical miles of R2.

established to better examine the dynamics of the shelf - Gulf Stream interactions. When installation is complete, this infrastructure should provide a powerful and flexible coastal research corridor, extending from the head-of-tide to the shelf break. In addition to the research issues highlighted above, such as array would be invaluable in examining the effects of hurricanes because of this location (Figure V.B.7).

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C. Gulf of Mexico

In addition to atmospheric forcing, major factors that control the dynamics and biogeochemistry of the Gulf of Mexico are the Loop Current and Mississippi River discharge. The Loop Current, seen as the warm tongue of water in Figure V.C.1, dominates the circulation in the eastern Gulf and feeds the Florida Current and ultimately Gulf Stream Current. Eddies from the Loop Current occasionally break away from the main flow and travel into the western Gulf. The Mississippi Bight, immediately east of the Mississippi delta, receives a significant fraction of the Mississippi River flow particularly in summer when wind conditions favor eastward flow of the plume. Interactions with Loop-Current-induced eddies along the shelf edge may be more common east of the delta, and can entrain river water and transport it eastward (Müller-Karger et al. 2000).

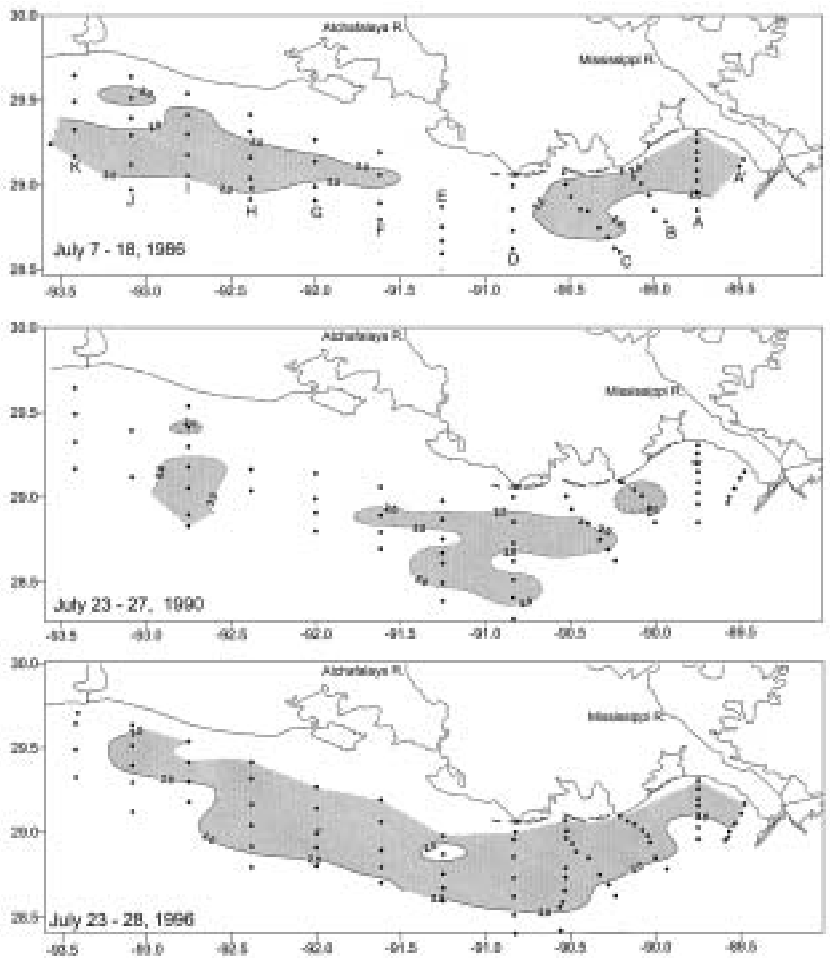
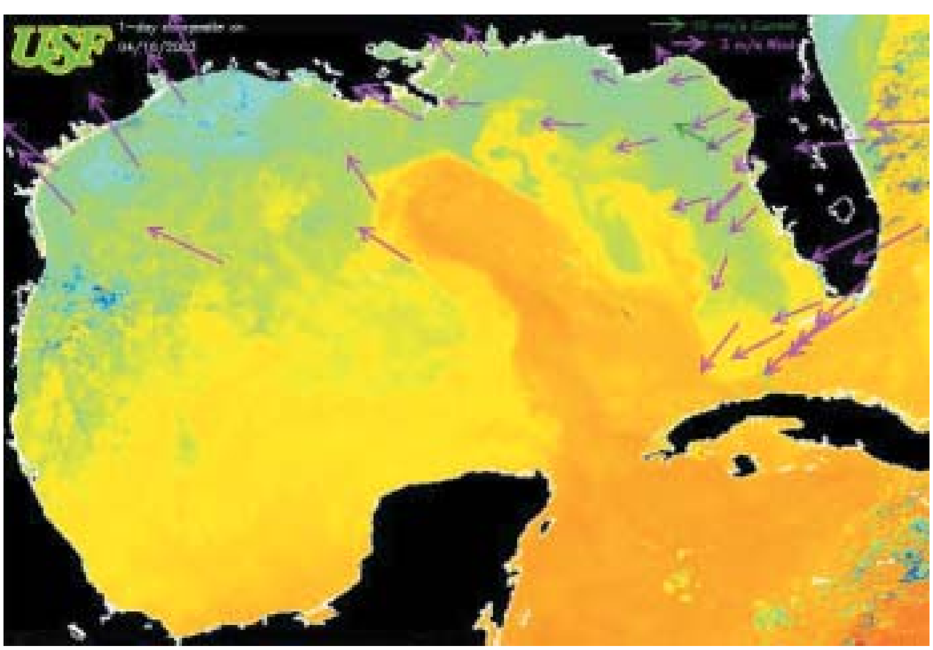


Figure V.C.2. Development of hypoxic zone in the Gulf of Mexico in July of 1986 (upper); 1990 (middle) and 1996 (lower). From Rabalais et al. (2002)

Figure V.C.1. Satellite image of Gulf of Mexico temperature, showing Loop Current and prevailing winds in April 2000.



The Mississippi River is the 7th largest river in the world in terms of water and sediment discharge and second largest in drainage basin size, covering 40% of the continental US (McKee, 2003). A third of the flow is diverted into the Atchafalaya River before delivery to the Gulf west of the main Mississippi birdfoot delta. In addition to freshwater, these discharges export the byproducts of intensive farming and urbanization throughout the watershed onto the shelf. The effects of increased nutrient loads have

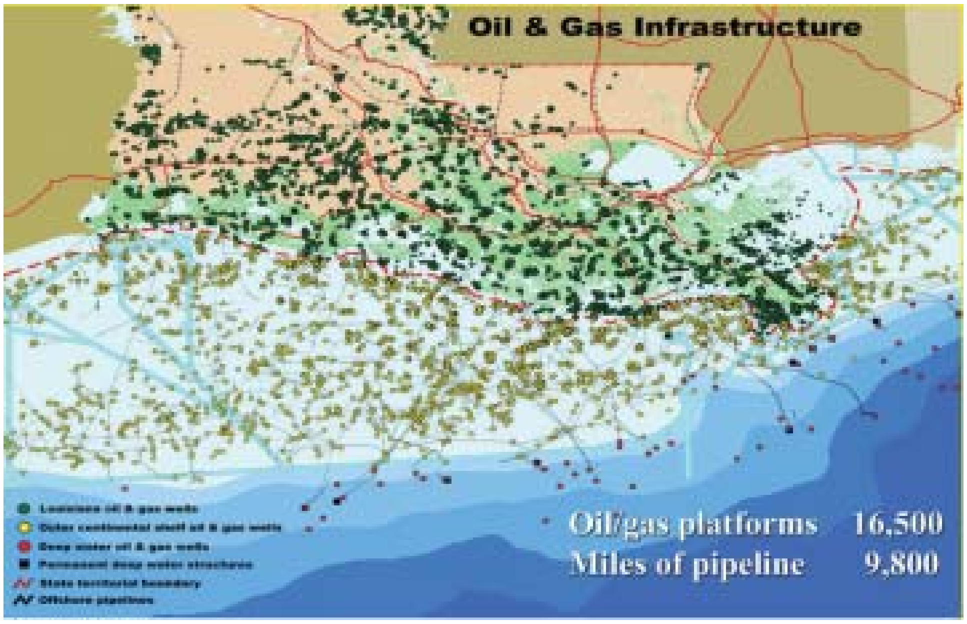


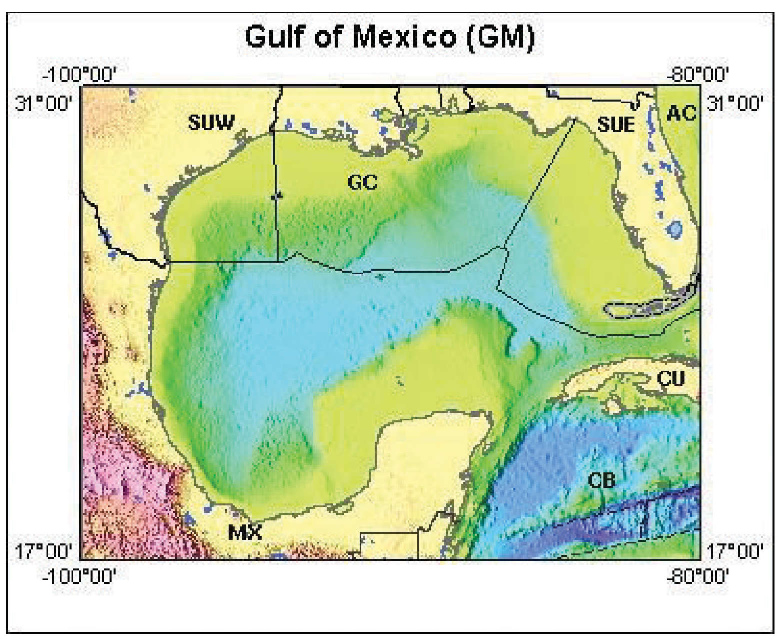
Figure V.C.3. Oil and gas infrastructure on the Mississippi delta and continental shelf.

contributed to the development of a large, recurring hypoxic zone west of the delta. Seasonal hypoxia or anoxia on the inner shelf accounts for the largest oxygen-depleted coastal zone in the western Atlantic (Fig. V.C.2).

Land loss is ongoing and pronounced, both natural and anthropogenic. Sea level rise coupled with subsidence is exacerbated by the development of levees, canals and navigation channels. Subsidence may also be further influenced by removal of oil and gas reservoirs underlying the region (Fig. V.C.3). Prevailing westerly currents move most of the fresh water, suspended sediments and dissolved and particulate nutrients onto the Louisiana and Texas continental shelf (Rabalais et al., 2002). Surface gravity wave energy in the Gulf of Mexico is often low, and changes in the nearshore bathymetry are slow. However, during winter the frequent passage of fronts from the north results in wind waves large enough to suspend and transport large quantities of mud. Recent observations (Sheremet and Stone, 2003) suggest that the increased turbidity of the water column damps short, locally generated chop, as well as the longer seas that interact directly with the seafloor. Onshore transport of mud during the waning stages of frontal events can cause several meters of shoreline accretion. Spatially variable wave damping, owing to patchiness of the seabed composition, could produce strong alongshore variability in accretion rates.

East of the Mississippi region, the Northeastern Gulf of Mexico shelf is bisected by the DeSoto Canyon (Fig. V.C.4). Surface sediments west of the canyon are fine silts and clays from the Mississippi River, and fine to medium quartz sands east of the canyon. This shelf is frequently affected by the western boundary Loop Current, and by warm and cold rings shed from it. Strong upwelling occurs in the region. The West Florida shelf is broad and relatively deep (shelf break is approximately 250m water depth), and is dominated by carbonate sediments interspersed with hardbottom (Schroeder et al. 1997). Hardbottom sites are common in water depths of 18-40 m on the inner shelf

Figure V.C.4. Shelf width variability in the Gulf of Mexico.



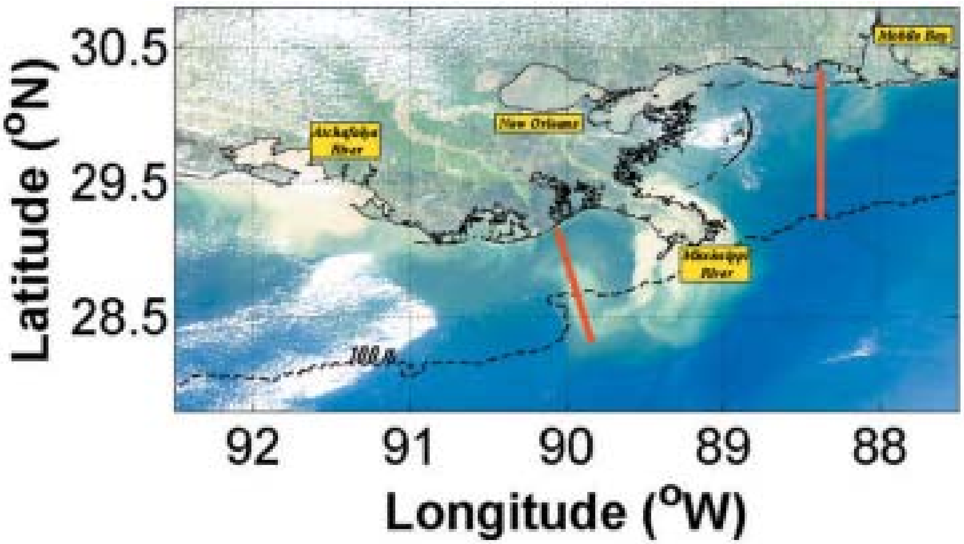


Figure VC.5. Enhanced satellite image of the northern Gulf of Mexico showing approximate locations for Endurance Lines as described in the text.

offshore of Alabama and Northwest Florida. Much of the inner shelf along West Florida is sufficiently shallow that light reaches the bottom, so that benthic microalgal productivity may be substantial.

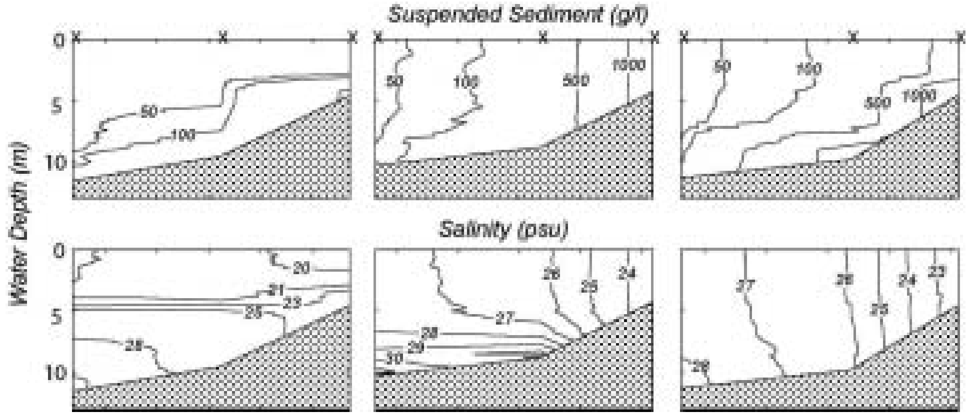
The Texas shelf is a low gradient, wave-dominated shelf. An inherent cyclicity in sedimentation on the shelf is due in part to the curvature of the coastline and the nature of longshore current transport. Predominant wind direction is from the southeast, setting up onshore directed winds and waves which strike the east and south Texas shelves at oblique angles. These asymmetric waves generate longshore currents which transport fine sands to the central Texas shelf.

The Mississippi River region is recommended as the priority for initial Endurance implementation. Two possible locations are suggested here (Fig. V.C.5). Each location has advantages in terms of proximity to research facilities, supporting infrastructure and access to research vessels for servicing.

An Endurance Array could begin in the near-shore or into the watershed at Terrebonne Bay, bisect the 'dead zone' and cross the Mississippi far-field plume under normal conditions. This location is close to LUMCON and access to the R/V Pelican and other service vessels. The Mississippi Bight immediately east of the delta is also a viable option, where the LSU Wave-Current-Surge Information System (WAVCIS) network is located, and coverage by NDBC buoys is better. USM will be deploying a long-term real-time kinematic (RTK) GPS buoy east of the delta later in 2004. This system will have data serving capability and there are plans to expand this network with other sensors and moorings. Coverage by NOAA buoys is also very good in this location, as is access to the ports of Pascagoula and Gulfport. Plans are also underway to establish a CODAR network in the area.

Possible use of oil production platform infrastructure for power and communications cables is recommended. Wave directional measurements are needed across the shelf. Infrastructure support is required to place instruments in depths less than 10m and to obtain high-spatial resolution bathymetry (i.e., CRAB, forklift, jet skis). In addition, a Pioneer short term array may be recommended for deployment over the winter and spring months to obtain data on waves, currents and turbidity characteristics under both quasi-stationary and actively evolving conditions. The passage of cold fronts through the area during this time would have an effect of enhanced turbidity on waves and currents; the measurements would capture this over a wide spatial domain. Additionally, both the Endurance and Pioneer arrays will be enhanced by the WAVCIS deployed by LSU (http://wavcis.csi.lsu.edu). This long-term installation could provide a stable infrastructure and institutional support for enhanced meteorological and oceanographic observations on the inner shelf of the region.

Figure V.C.6. Cross-sections of suspended sediments and salinity across the inner shelf adjacent to the mouth of the Atchafalaya River, showing the influence of winds in generating well-mixed conditions on the inner shelf. Left panels are increasing winds, middle panels are high winds and right panels are decreasing winds (from Allison et al. 2000).



Other factors which weigh into the recommendation for an Endurance Line in the northern Gulf of Mexico region include:

1) Input of sediment and terrigenous carbon (McKee, 2003): The Mississippi River delivers large quantities of sediment and terrigenous carbon into the coastal waters of the northern Gulf of Mexico. Current knowledge of factors controlling the transport and transformation of organic carbon in this and other river-dominated margins is limited, yet such information is key to quantifying the role of margins in sequestration of carbon in the world ocean.

2) Fisheries: The most valuable commercial fishery in the US is the shrimp fishery, the majority of which comes from Gulf States (Holliday and O'Bannon, 2001). Gulf states also accounted for the majority of the US menhaden harvest, which was the second largest US domestic fishery by quantity. The mode of delivery of Mississippi River outflow to the coastal waters and its enhancement of productivity appears to be a key factor in the productive fisheries in this region. However, the physical-biological linkages inherent in the extension of estuarine characteristics onto the shelf that may promote enhanced fisheries remains poorly understood. Such studies would benefit from continuous, long-term observations of physical and biogeochemical variables.

3) Entrainment and mixing of shelf and ocean water through mesoscale circulation processes: Seasonal patterns in wind forcing, coupled with variations in river discharge, result in dramatic changes in extent of the river plume and transport of river water and associated materials on the shelf. Flow is predominately westward along the shelf, except during summer when seasonal changes in wind patterns generate a reversal in flow (Li et al. 1997; Wiseman and Sturges, 1999). The dynamics of inertia-dominated surface plumes require further study, including considerations of effects of wind, discharge, and the remote effects of shelf-wide and mesoscale circulation. Loop Current-induced mesoscale circulation phenomena such as eddies have been shown to interact with shelf and plume waters (e.g., Walker et al. 1996; Müller-Karger, 2000). Such processes may have a profound impact on cross-shelf exchange of materials and ecosystem processes. Intense episodic circulation events can also pose problems for oil activities, bolstering the need for baseline information about such phenomena. Narrowing of the shelf near the Mississippi Canyon to the west of the delta may be a region of enhanced cross-shelf exchange, and may provide an ideal location for an Endurance Line.

An Endurance Line should terminate inshore in the region. The inner shelf and shoreline are dominated by muds, which would allow studies of nearshore sediment transport in a muddy coast environment including near-bottom flows (*Fig. V.C.6*). There is strong winter wind-forcing and dynamical coupling to the Gulf of Mexico Loop Current. The installation of an Endurance Line at this location would also permit detailed dynamical and biogeochemical studies on a river-dominated margin. Process studies might include: air - sea interactions, ocean - shelf water interactions, and the ecology of oxic, hypoxic and anoxic environments.

The West Florida shelf is recommended for an Endurance Array Line that would terminate in close proximity to Tampa Bay in subsequent implementations. The area is subject to strong winter wind-forcing related to cold air outbreaks, upwelling events and complex interactions with the offshore Loop Current. An Endurance Line in this region would be positioned to support detailed studies of the relationship between vertical mixing and atmospheric forcing, ocean - shelf interactions, coupled physical - biological interactions and the triggers of harmful algal blooms, and nearshore sediment transport studies.

The Texas shelf is also an important location for the possible future installation of an Endurance Line. This region is within the far-field of the Mississippi outflow, is impacted by inputs from large, muddy rivers and exchange with hypersaline lagoons. Additionally, harmful algal blooms, the so-called Texas ‘brown tide’, are common and persistent (Buskey et al. 2003). Periodic hypoxia has also been suggested (Osterman, 2003).

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D. Southern California Bight

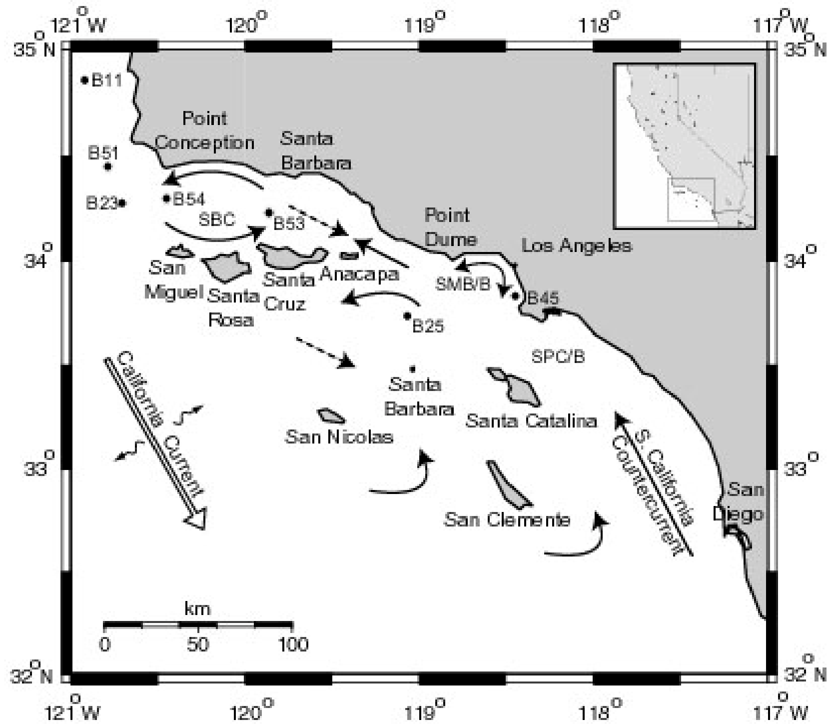


Figure V.D.2. Map showing California Bight major circulation features from DiGiacomo and Holt (2001)

The southern California Bight extends from Point Conception to the Baja California Peninsula (Fig. V.D.1). Offshore it is marked by a series of banks, the California Current, and high-speed winds that detach from the coast at Point Conception. The bathymetry is complex with narrow shelves, large islands, isolated deep basins, coastal canyons and offshore banks and seamounts, all leading to complex flow patterns (Fig. V.D.2). Within the Bight, local wind, wave, and riverine forcing are weak and episodic. The mean circulation consists of the southward California Current with some recirculation inshore, an inshore poleward countercurrent, and a strong cyclonic circulation in the Santa Barbara Channel. Along the coast, evidence suggests remote forcing is important with poleward propagation of coastally-trapped waves and equatorward exchange driven by upwelling in the Santa Maria Basin (Hickey et al., 2003). Offshore forcing by recirculation of the California Current is also thought to be important (Hickey, 1993). The system responds to interannual variability including the Pacific Decadal Oscillation and El Niño events.

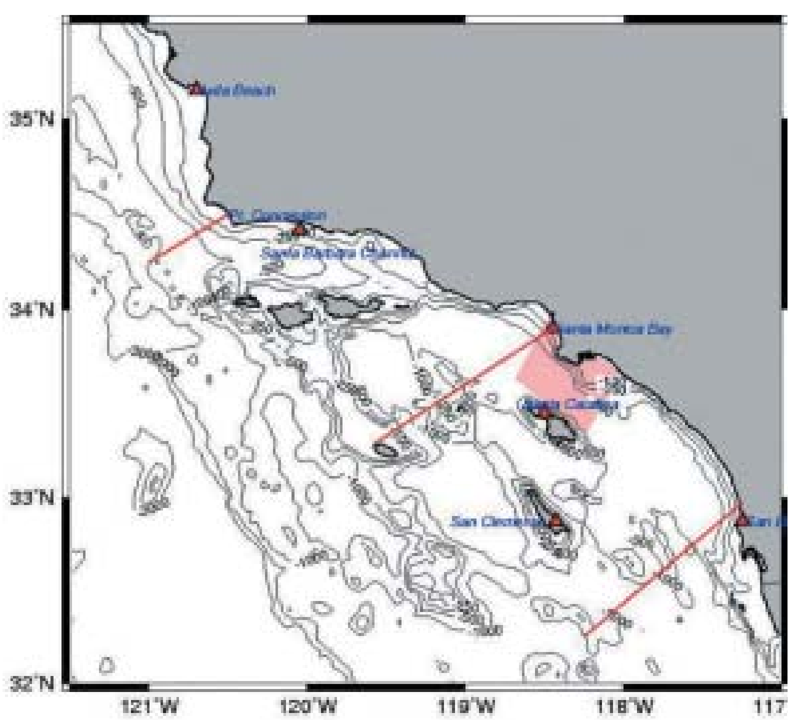


Figure V.D.1. Map showing Southern California Bight geography, bathymetry and proposed observing systems. Proposed cabled observatories are indicated by red triangles, proposed Endurance Array Lines are indicated by red lines, and the proposed Pioneer Array location is indicated by the pink shading.

The northern boundary of the southern California Bight, Point Conception, is a well-known biogeographic boundary, particularly for southern, warm water species (Dailey et al., 1993). Within the Southern California Bight, there is strong spatial and temporal variation in ecological communities caused, in part, by changes in water temperature, wave climate, current trajectories, nutrient levels, and available substrates. The southern California Bight is the site of several long shore-based time series as well as the heart of the CalCOFI program (Fig. V.D.3). More recently, the CDIP program has characterized the wave climate in the area. These long time series have

Figure V.D.3. Map showing present Southern California Bight long-term observations from a recent SCCOOS proposal

documented interannual variability (McGowan et al., 1998) including fisheries stocks changes, the Pacific decadal oscillation, El Niño events (Fig. V.D.4; Dever and Winant, 2002), and interannual changes (declines) in phytoplankton and zooplankton productivity (Roemmich and McGowan, 1995).

The forcing characteristics and complex coastline and shelf make the southern California Bight unique in many ways. One of the most striking characteristics is the role of relatively short-scale, episodic features. Short-scale features are evident in SAR imagery (Fig. V.D.5; DiGiacomo and Holt, 2001), HF radar velocities (Fig. V.D.6; HF radar images), and in the short space scales present in moored time series (Winant, 1983). The lack of strong spatially coherent forcing such as wind or river input, combined with the complex topography gives rise to several science questions that cannot be answered with existing observations:

What is the incidence for and interaction of submesoscale features with longer and larger scale variability?

How do local (presumably shorter and more isotropic) spatial covariance scales compare with those found further north and on other coasts?

What is the physical and biological connectivity between islands and between shelf regions defined by headlands and coastal canyons?

How do episodic inputs of momentum, waves, buoyancy and sediment affect the system?

How does the complex regional bathymetry, submesoscale features and episodic processes impact biological productivity, as well as carbon and nutrient flux? How does this differ from regions to the north?

To what degree is Point Conception a biogeographical boundary and what processes lead to exchange of water masses, nutrients and biological communities between the California Bight and the Central Coast of California?

How does intermittent, anthropogenic input from rain events within the highly urbanized Southern California watersheds impact the coastal environments?

What are the primary drivers for local harmful algal bloom (HAB) events?

Proposed Observing Systems

To better understand the Southern California Bight and specifically the impact of Bight scale processes on near shore dynamics, we propose several cabled observatories within the Bight and Endurance Arrays across the Bight at southern, central and northern transects. Given the spatial heterogeneity of the southern California Bight, several locations with limited nodes are preferred over a single location with many nodes.

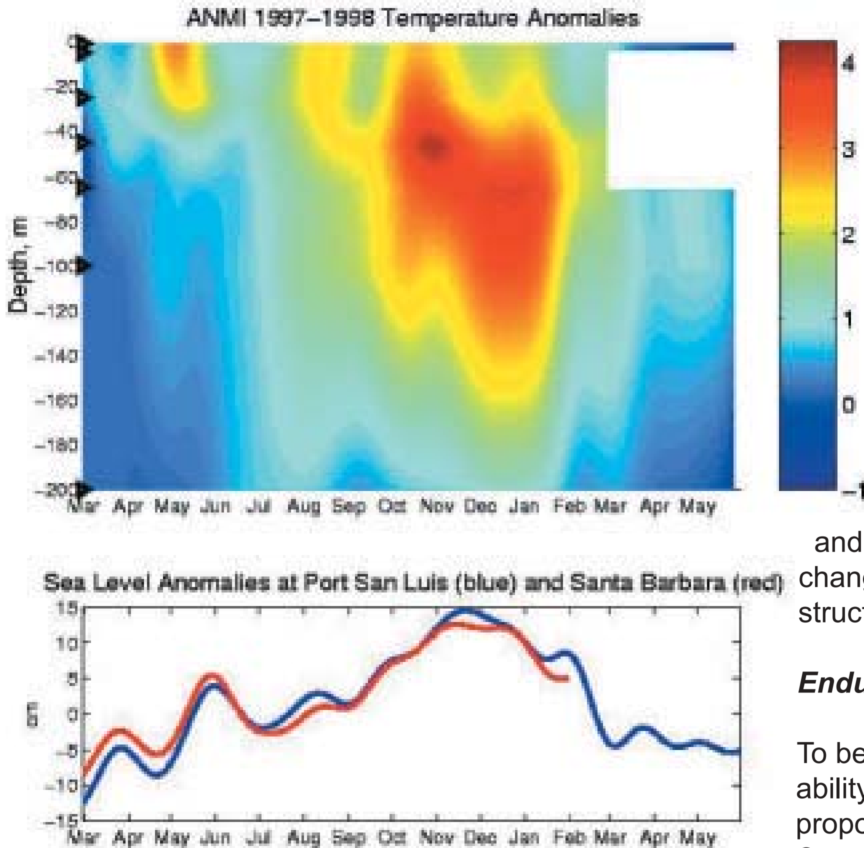


Figure V.D.4. El Niño temperature anomalies adapted from Dever and Winant (2002). The mooring location (ANMI) is at the eastern entrance to the Santa Barbara Channel in 200 m total water depth. The anomalies are based on the 1993-1999 seasonal cycle. The anomalies (indicated in degrees C) show the depth extent of the El Niño event. Its surface sea level expression is indicated in the bottom panel.

Basic instrumentation would be compatible with other Endurance observatories. One feature that would be developed for each node is infrastructure to support AUV docking capability. Other instruments that may be useful and require high bandwidth and power include sideways looking sonar for nearshore currents, and bio-acoustic measurements for detection of biological sounds, vertical profilers that would contain a broad suite of biophysical-chemical sensors, and video plankton recorders to track changes in near shore community structure.

Endurance Array Lines

To better define the Bight scale variability and boundary conditions, we propose 3 Endurance Arrays: off Point Conception, from Santa Monica Bay past Santa Catalina Island to San Nicolas Bank and from San Diego to Cortes Bank. These lines would be coincident with CalCOFI lines 80, 87, and 93 respectively. Each Endurance Array

Cabled Systems

Systems would be cabled from the coast to a node at a nominal depth of 60 m. In most cases, this depth is within 10 km of the coast. Sites would be chosen based on inherent oceanographic interest, regions of contrast within the Bight, and their proximity to logistical support on shore. Possible sites in order of priority include: La Jolla, Santa Monica Bay, Santa Barbara, Santa Catalina, San Clemente Island, and Avila Beach. Each of these sites (Fig. V.D.1; Table V.D.1) includes power and communications from shore and are ideal sites for providing shore-side cable infrastructure support. With the exception of San Clemente, each site is owned by an academic institution. The San Clemente site is owned by the US Navy.

Table V.D.1. Location and institutional ownership of proposed sites for cable terminations

location	***controlling institution***
San Diego, SIO pier	*UC, San Diego*
Santa Monica, Marina Del Ray	*UC, Los Angeles*
Santa Barbara	*UC, Santa Barbara*
Santa Catalina, Wrigley Center	*U Southern California*
Avila Beach, Cal Poly SLO pier	*Cal Poly SLO*
San Clemente	*US Navy*

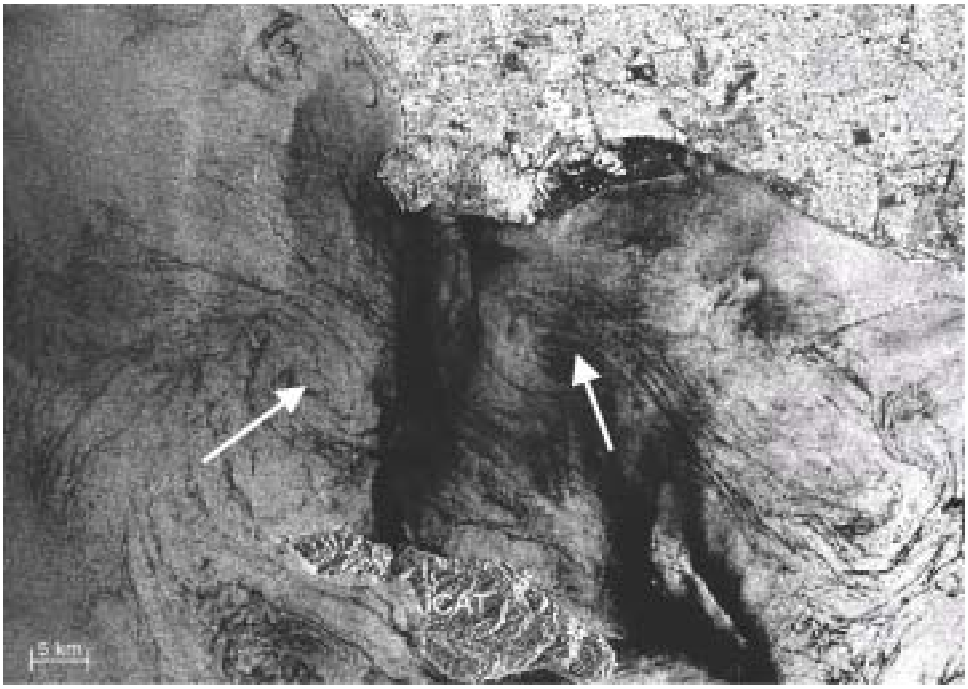
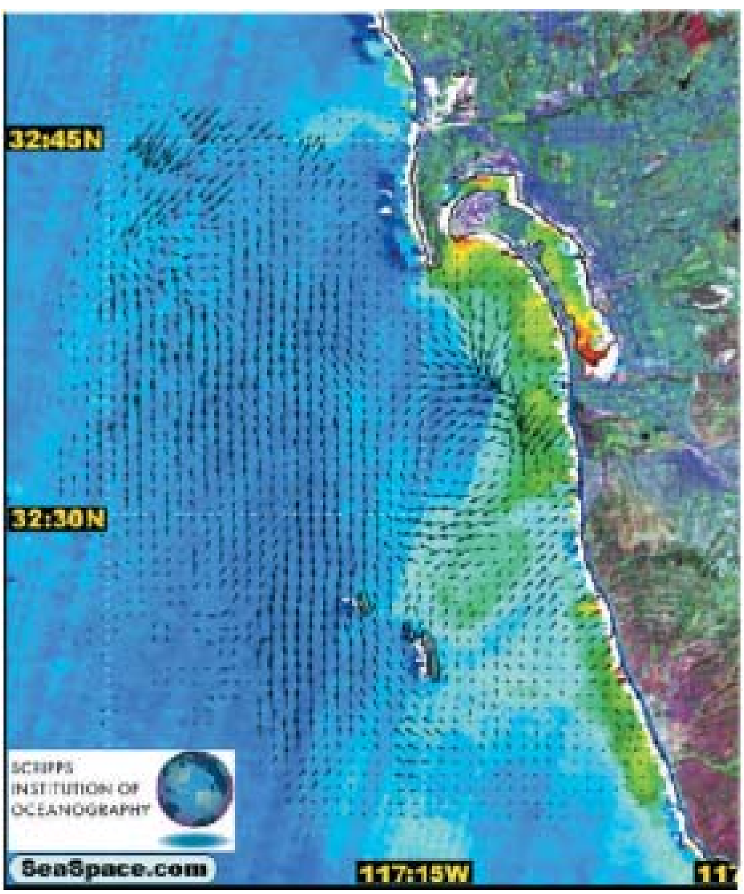


Figure V.D.5: ERS-1 SAR image of the San Pedro Channel from April 21, 1994, at 1833 UTC. Arrows indicate anticyclonic eddy (left) and cyclonic eddy (right). Copyright European Space Agency 1994. From DiGiacomo and Holt (2001).

Line could consist of 3-5 moorings with a surface expression and profiling instruments in at least the upper 500 m. The lines in order of priority are southern, northern, and central. The platforms and measurement capability would be similar to other Endurance Array Lines extending northwards to Alaska to allow examination of broad scale coastal features.

Figure V.D.6. Recent HF radar observations off Imperial Beach, California



Pioneer Array

To explore the relevant scales of variability over the shelf (e.g., Fig. V.D.5), we propose a high-resolution mooring array between Palos Verdes and Santa Catalina Island. Resolution of the system would be up to 5 km in along-shelf and cross-shelf directions. This should enable good resolution of mesoscale features and some submesoscale features including eddies, internal tides and features associated with coastal headlands. Up to 20 moorings would be deployed extending from 30 m to the full depth of the San Pedro Channel (900 m). Several moorings would include a full suite of multidisciplinary sensors while others would define spatial scales of physical properties with more basic multidisciplinary measurements. The pioneer array would be in place at least one year to capture seasonal variability. Preferably at least 3 years of data would be acquired to give some indication of interannual variability, which is prevalent in the region (McGowan et al., 1998).

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E. Central California

In the Central California region, there are a variety of compelling reasons to establish a long-term Endurance Array Line off Monterey Bay (Figure V.E.1). The area is well suited for fundamental studies of oceanographic processes such as:

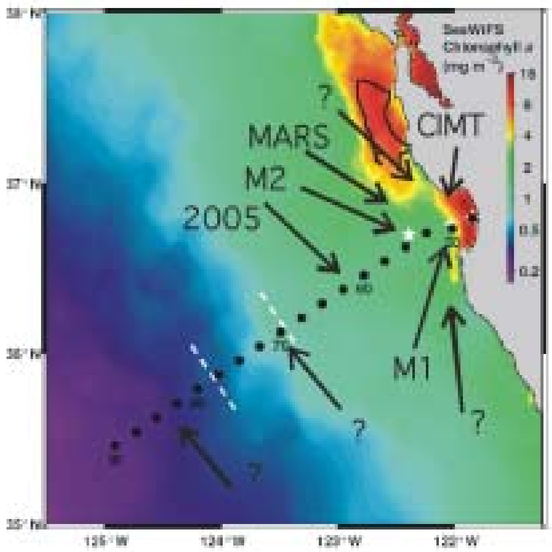


Figure V.E.1. Existing (M1, M2), planned (CIMT-2004, MOOS-2005), and possible (?) mooring locations offshore Monterey Bay. Black dots are stations along CalCOFI Line 67, which are regularly sampled. Dashed white lines are 1 and 0.3 $\mu g\ l^{-1}$ chlorophyll.

the role of the coastal ocean in the global carbon cycle,

coastal sediment transport (including canyon dynamics and negatively buoyant river plumes),

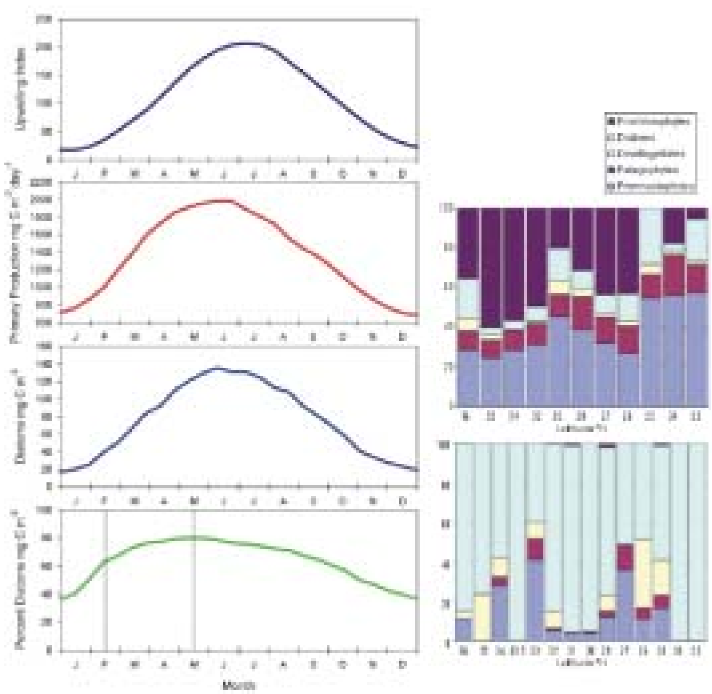
effects of environmental factors on ecosystem structure (including Harmful Algal Blooms),

response of the coastal ocean to ENSO, and

the impacts of fluid flow through sediment on chemoautotrophic communities and sediment stability.

Regular cycles of upwelling (Figure V.E.2) create a natural laboratory for studying the response of the ecosystem to changing conditions. Large differences in the width of the continental shelf to the north and south of Monterey Bay produce a large gradient in iron concentration and a natural iron fertilization experiment. The cycles of productivity are interupted on a periodic basis by ENSO events (Figure V.E.3). The Monterey Canyon, which bisects the Bay, is regularly the conduit for negatively buoyant flows of sediment from the Salinas River (Figure V.E.4). The steep topography in offshore waters creates fluid flow through sediment and large populations of chemoautotrophic communities that are fueled by sulfide produced during anerobic methane oxidation are present.

Figure V.E.2. Seasonal cycles of upwelling, primary production and diatoms off central California (left). On the right we show taxonomic changes between seasonal transects to and from the Gulf of California showing how the ecosystem changes seasonally to a diatom dominated system ALONG THE ENTIRE TRANSECT. Note the methods for taxonomic partitioning differ between epifluorescence microscopy (left) and HPLC pigments (right).



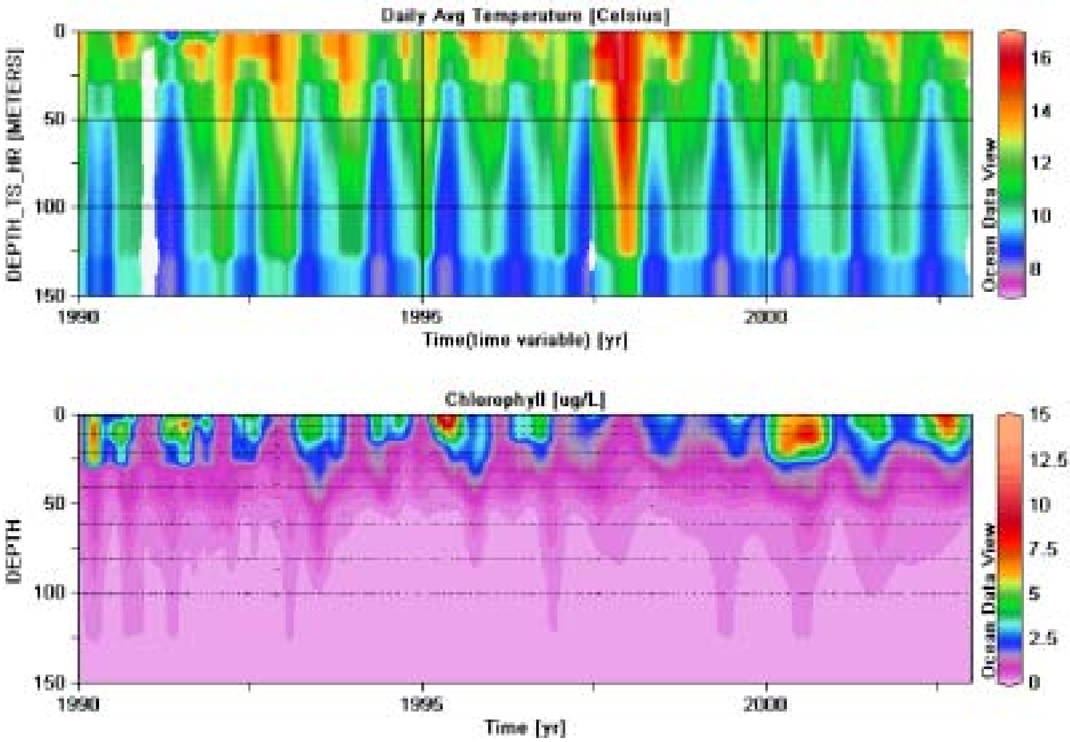


Figure V.E.3. A) Daily average temperature measured since 1990 on the M1 mooring in Monterey Bay. Note the large El Niño in 1997/98. B) Chlorophyll concentrations measured from hydrocasts made every 3 weeks at the M1 mooring since 1990.

Further, a large community of ocean scientists (at UCSC, NPS, MLML, MBARI) has already established a major ocean observing infrastructure in Monterey Bay. An array of oceanographic moorings operates in the Bay and out to 50 km offshore. It will soon be extended to 90 km offshore. Oceanographic vessels have been making regular, time series observations at a suite of stations in the Bay for more than 15 years, producing the longest biogeochemical time series on the West coast. Remotely Operated Vehicles deployed from two ships make routine observations in the Bay. Autonomous Underwater Vehicles are now making regular transects through the Bay (Figure V.E.5). The MARS cabled observatory, with a node at ~1200 m depth, will be installed in 2005. A variety of sensor development efforts are taking place in the region and being tested on all of these assets (Figure V.E.6).

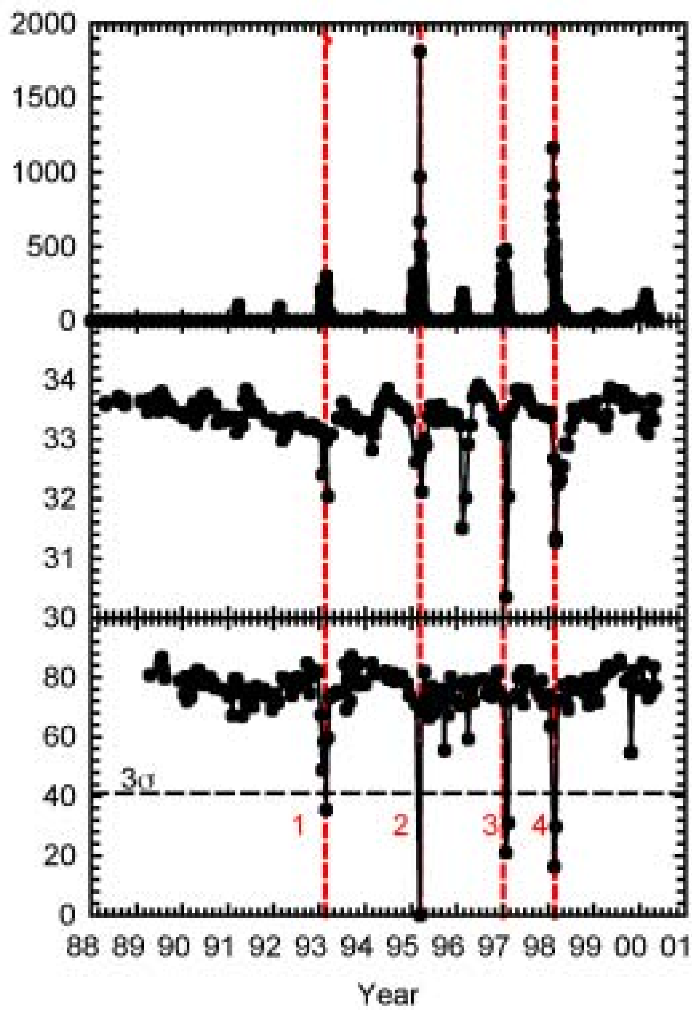


Figure V.E.4. Salinas River flow, salinity at the M1 mooring, and light transmission at 200 m depth in the Monterey Canyon. Light transmission anomalies, which occur only during periods of high river flow, indicate negatively buoyant plumes of river water that are driven by the high sediment load (Johnson et al. 2001).

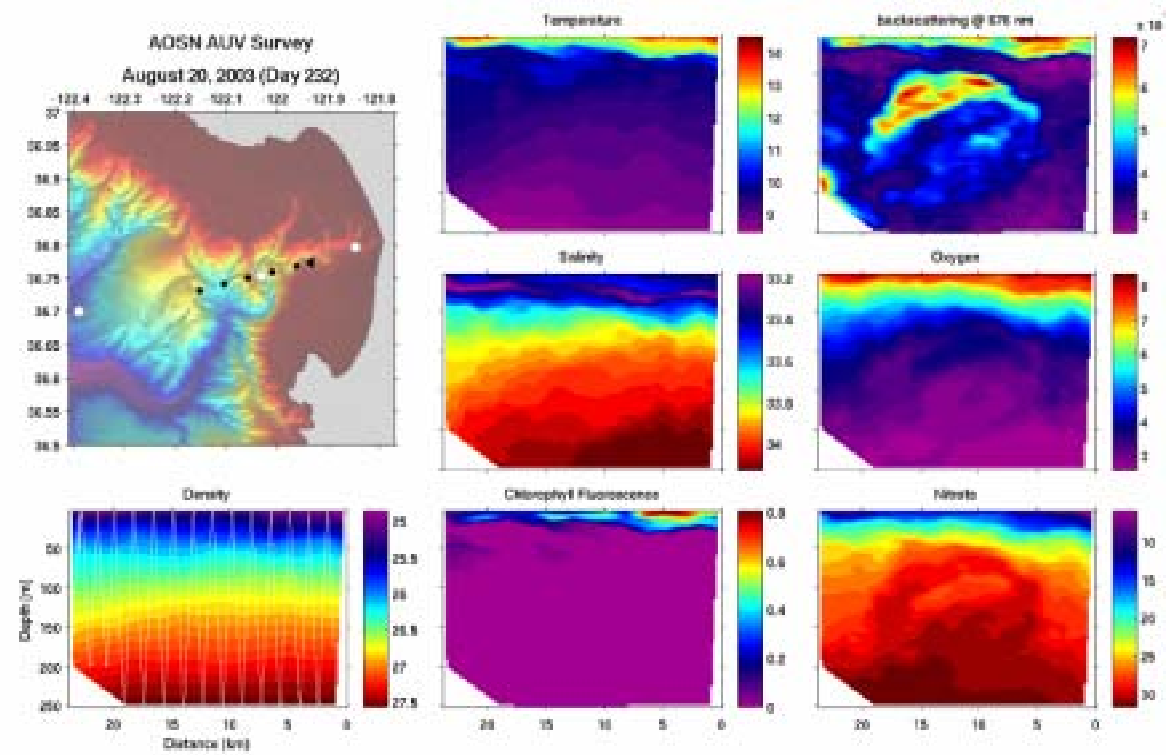
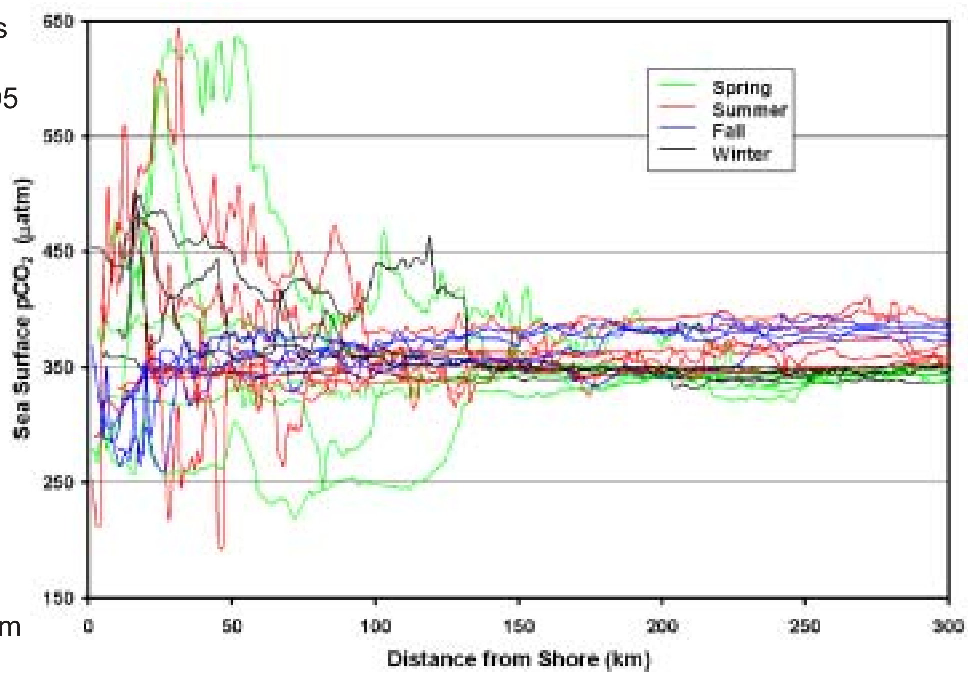


Figure V.E.5. Vertical sections of temperature, salinity, chlorophyll fluorescence, optical backscatter, oxygen, nitrate and density made with a Dorado AUV over a 25 km section (surface to 250 m depth) past the M1 mooring. These sections will extend from Moss Landing to the M2 mooring (far left dot) and back to Moss Landing in 2004.

Two moorings are now in place. A third will be deployed in 2004 in the northern part of Monterey Bay. A fourth mooring will be deployed offshore in 3500 m of water near the Sheperd Meander in Monterey Canyon. Both of these moorings will be of an advanced design that will automatically configure itself (Plug and Work) when new sensors are added. All of the moorings telemeter data to shore in real time. The MOOS 2005 mooring will also provide power and communications to the seafloor to enable real time connections to benthic experiments (respirometers, sediment traps, benthic stress sensors, eddy flux sensors, etc.). A Dorado AUV will be regularly transecting to the M2 mooring and efforts are underway to design a docking system that will allow AUV's to operate from offshore, cabled nodes.

Figure V.E.6. Measurements of sea surface pCO_2 made on regular transects along the CalCOFI Line 67 (dots in Figure V.E.1) (Friederich et al., 2002).



Two additional Endurance Array Line locations are recommended in subsequent implementations. Both Lines would define processes at boundaries shared with other West Coast regions. An Endurance Line at the northern boundary of the Central California region, south of Cape Blanco and north of Cape Mendocino is described in the Pacific Northwest section. An Endurance Line at the southern boundary of the Central California region at Point Conception, is described in the Southern California Bight section.

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F. The Pacific Northwest

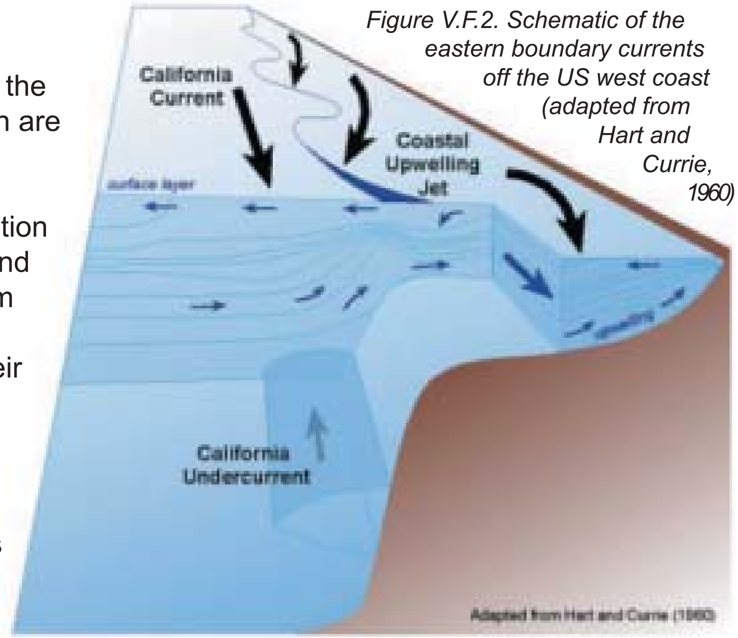
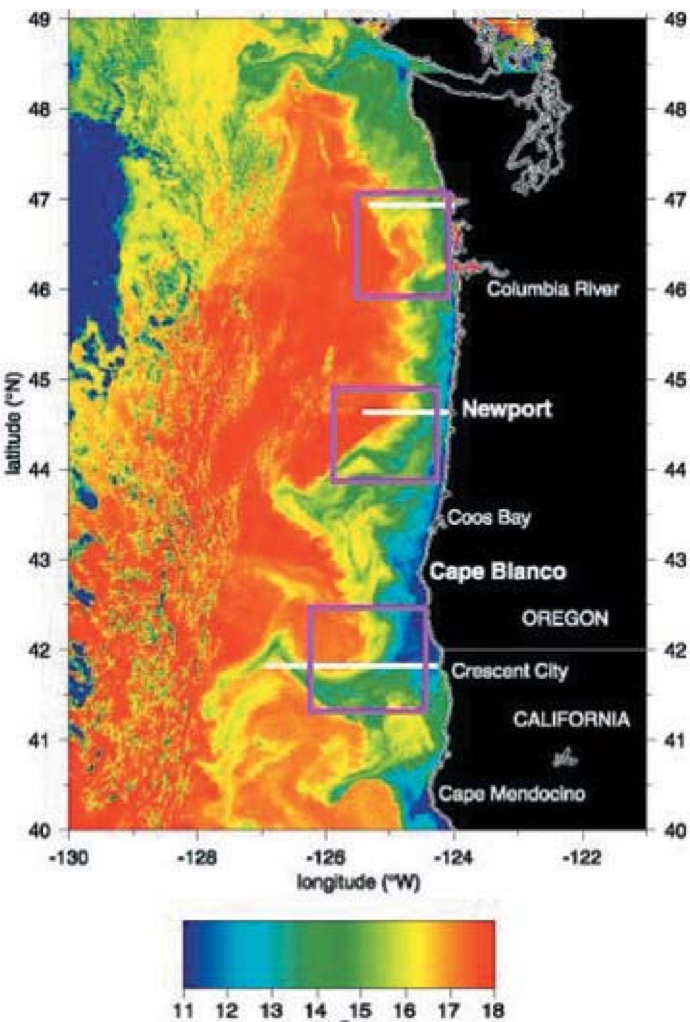


Figure V.F.2. Schematic of the eastern boundary currents off the US west coast (adapted from Hart and Currie, 1960)

Circulation and water mass properties over the Pacific Northwest (PNW) continental margin are influenced by a variety of processes which include the large-scale North Pacific gyre, strong wind and buoyancy forcing, propagation from the south in the coastal wave guide, and flow-topography interaction including bottom boundary layer processes. The beach processes of the Northwest are unusual for their long-period, high-energy waves, large tidal excursions, and dramatically high material transport rates. These shelf and nearshore processes span a large range of time and space scales, from interdecadal to seconds and from gyre scale (1000 km) to turbulent mixing scales (1 cm) . This range of time and space scales presents a wealth of coastal ocean dynamics and processes that can be addressed by a combination of long-term, multi-parameter cross-shelf lines (Endurance Array Lines) and higher-resolution arrays (Pioneer Arrays) (Fig. V.F.1). After a short overview of processes in the PNW coastal ocean, we highlight a number of science issues ready to be addressed with a coastal ocean observing system.

Figure V.F.1. Locations of Pacific Northwest Endurance Array Lines (east-west white lines) and Pioneer Arrays (magenta boxes) plotted on top of a satellite SST image from 2 September 1999.



The North Pacific Current (aka the West Wind Drift) approaches the North American continent from the central Pacific and splits into the poleward Alaskan Current and the equatorward California Current (CC) at a latitude of about 50° N (Fig. V.F.2) (Hickey, 1979). During spring and summer, time-averaged surface velocities over the continental shelf and slope in the northern CC off the PNW are equatorward. Velocities are strongest (up to 1 m s^{-1}) in the core of wind-driven equatorward upwelling jet. The alongshore flow is correlated for long distances (100~km or more) along the coast (Kundu and Allen, 1976). Nearshore reversals, i.e. poleward flow, can occur in response to wind relaxations or periods of northward wind (Fig. V.F.3).

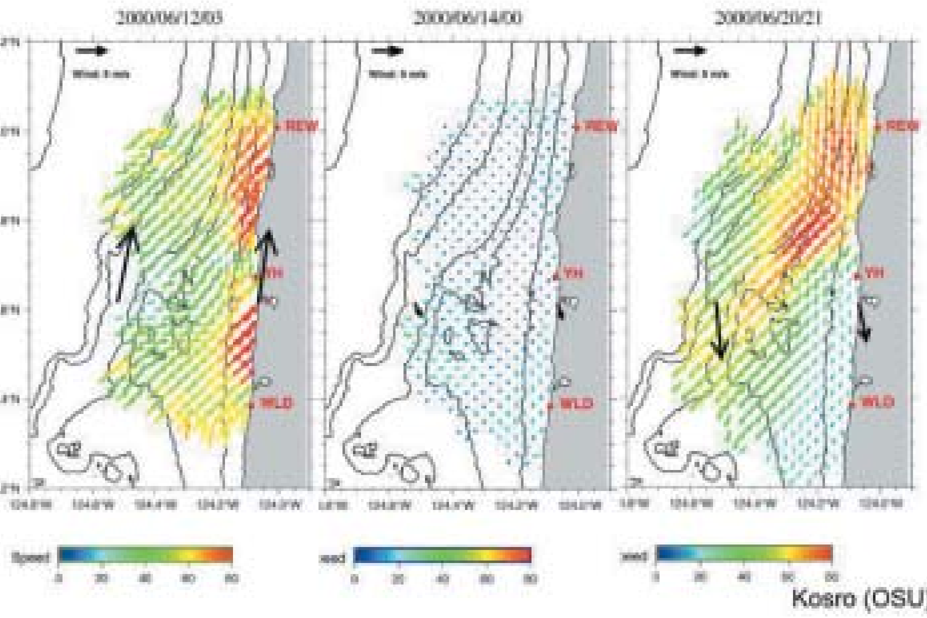


Figure V.F.3. Surface currents from land-based high-frequency radar from off central Oregon showing the coastal ocean response to downwelling (left panel; northward winds) and upwelling (right panel, southward winds) favorable winds. Winds, indicated by bold black arrows, are measured on land near Newport, Oregon, and at an offshore NDBC buoy (P.M. Kosro, unpublished data).

The poleward California Undercurrent flows continuously year-round from at least 33-51° N at an average depth of 200 m and speeds of 0.15 m s^{-1} (Pierce et al. 2000). During the winter, flow over the shelf and slope is poleward in the Davidson Current with surface flows sometimes reaching 1 m s^{-1}.

The Columbia River and Strait of Juan de Fuca contribute significant amounts of freshwater, sediment, and micronutrients to the northeast Pacific region (Fig. V.F.4). The Columbia River is the nation's third largest river with 11 major dams and countless minor dams throughout its 260,000 mi^2 watershed. The Columbia River watershed and continental margin is historically subjected to catastrophic events, the most recent being the 1980 eruption of Mount St. Helens with its ensuing high-volume debris flow along the Toutle River.

Within the seasons, the currents and sea level respond to local wind forcing on a 2-10 day time scale, the so-called "weather band." Strong, time-varying wind events in the PNW drive "classic" upwelling and downwelling on the shelf, and result in significant alongshore flows (Fig. V.F.3) (Huyer, 1983). Spring and summer upwelling of cold, nutrient-rich subsurface water into the euphotic zone over the continental shelf leads to strong phytoplankton growth and production of organic carbon which is then either transported offshore, consumed by higher trophic levels or exported to the sea floor. Sometimes the phytoplankton produced may be "harmful" and occasionally production levels are so high that respiration of this material at depth can drive shelf bottom waters anoxic (Fig V.F.5).

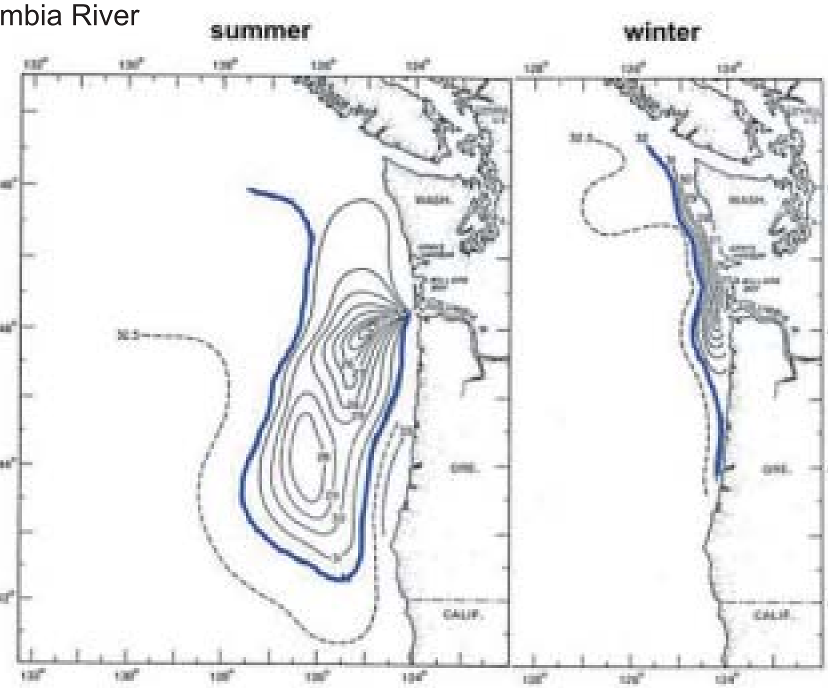


Figure V.F.4. Distributions of surface salinity showing the influence of the Columbia River in summer and winter. The 32 isohaline is bold.

Mesoscale meanders and eddies resulting from hydrodynamic instability and flow-topography interaction are associated with the strong equatorward upwelling jet over the continental shelf and slope (Fig. V.F.1) (Barth, 1994). As the wind-driven currents gain strength, they interact with alongshore variations in the bottom and coastline topography. This causes shelf and slope flows to separate from the margin, carrying with them nutrients and shelf-type biological communities (Barth, 2000). Significant flow-topography interaction takes place at coastal promontories and at submarine banks and canyons (e.g., Cape Blanco, Cape Mendocino, Heceta Bank, Astoria Canyon).

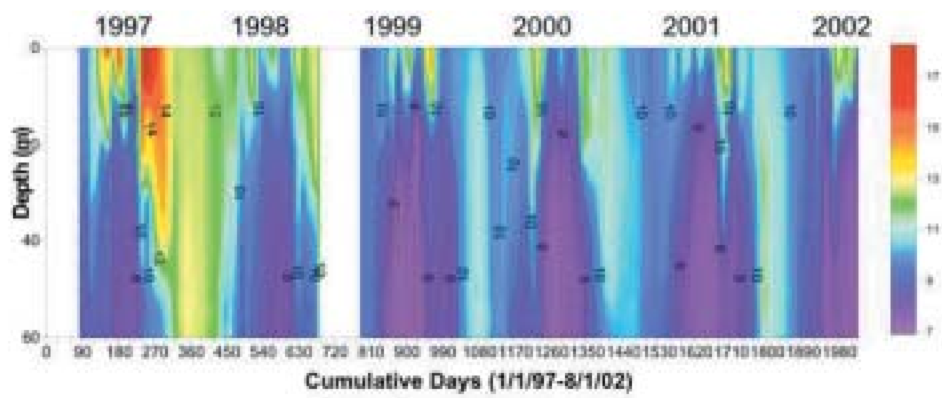


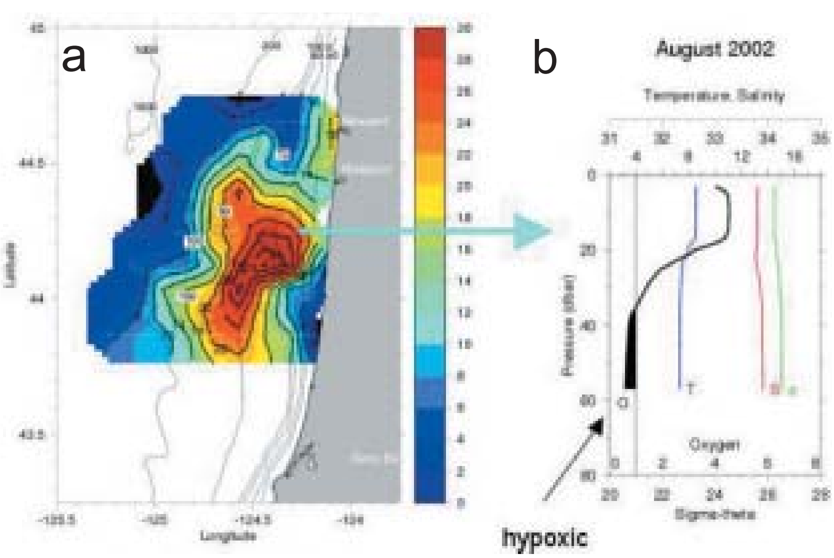
Figure V.F.6. Temperature-depth section at Station NH-5, 9.3 km offshore of the coast at 44.65 N. Measurements indicated by white dots (1997-1999 data from Peterson et al. 2002; 2000-2002 data courtesy of B. Peterson and L. Feinberg).

Another type of flow topography interaction is the creation of strong baroclinic tides by barotropic tidal flow over varying topography, in particular near the continental shelf break. The baroclinic tide can have important consequences for ocean mixing, creating convergence and divergence zones capable of concentrating prey, and in causing onshore transport of material (e.g., planktonic larvae). The interaction of internal waves and sloping bottom topography may lead to intensified mixing along the continental slope. The form and level of this boundary mixing is crucial to the mixing of fluid properties (heat, salt, nutrients) in the world's oceans.

The hydrographic, velocity, nutrient, phytoplankton and zooplankton fields all vary interannually in response to the El Niño, La Niña cycle (Fig. V.F.6) (Huyer et al. 2002; Peterson et al., 2002). On interdecadal time scales, these fields are strongly influenced by the Pacific Decadal Oscillation (Fig. V.F.7).

Boundary layer processes are important at both the sea surface and near the sea floor. Wind-driven mixing near the sea surface has a strong influence on the physics and ecosystem response in that region. Near the bottom, currents and waves combine to form bottom mixed layers. Friction at the sea floor influences the strength and form of the currents above. Resuspension of sediment, nutrients and organic material from the bottom has important implications for the biogeochemistry of the continental margin. These resuspension events are often episodic and difficult to capture with traditional ship-based sampling.

Figure V.F.5. a) Chlorophyll-a concentration (mg m^{-3}) at 5 m depth over Heceta Bank off the central Oregon coast from 9-11 August 2002. Measurement locations indicated by white dots; isobaths in meters (from Grantham et al. 2003). b) Vertical profile in core of high-chlorophyll region showing hypoxic bottom water (J. Barth, unpublished data).



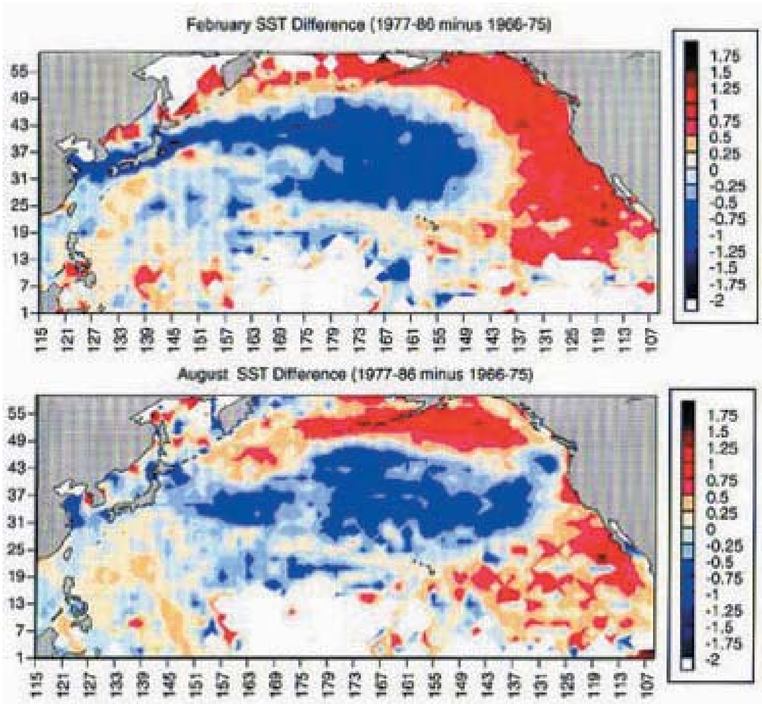


Figure V.F.7. Sea surface temperature difference between the warm (1977-1986) and cold (1966-1975) phases of the Pacific Decadal Oscillation (top: February, bottom: August) (following Mantua et al. 1997).

Wind waves along the Pacific Northwest coast are predominantly incident from the southwest, but local reversals close to shore, in the inner shelf and surf zone (shoreline to 30m depth), occur near headlands, offshore islands or sea stacks, and where there are changes in the coastal orientation. Mean wave heights are nominally 2m with periods of 10sec. During extreme storm events, waves can be as high as 10m and periods as long as 20sec. Tides are mixed semi-diurnal with a 2 to 4m range. Strong El Niño events can influence wave direction and shoreline water excursion levels.

The fluid dynamics on the inner shelf (nominally 10 to 30m depth) is driven by local winds, tides, and breaking ocean waves; the fluid dynamics in the surf zone (shoreline to 10m depth) is driven primarily by the breaking waves. The breaking waves force local currents that are distinct from the coastal current (e.g., the California Current) described above. Longshore currents flow along the shore and can be quite strong in the surf zone (1-2 m s^{-1} with weak vertical shear. Cross-shore currents (also called the undertow) are typically weaker (order 30 cm s^{-1}) but have a large vertical shear; the flow is predominantly onshore near the surface and offshore in the lower part of the water column. Both waves and surfzone currents are responsible for sediment resuspension and transport.

Pacific Northwest beach morphology influencing these currents, and consequently the local transport of both sediments and biology (e.g., plankton), has regional differences. For instance, the region from the Columbia River, north to the Copalis River, has remarkably alongshore uniform beaches that are characterized by low-sloping (1:100), unusually wide surf zones (of order 1 km) with multiple low-crested longshore sand bars. Two very large estuaries, Willapa Bay and Grays Harbor, interrupt this otherwise linear part of the coast. Both estuaries are protected from ocean waves by large sand spits. The beach sand is fine grain and is derived from a northward net drift of Columbia River sediment discharge. Local currents, and sediment and plankton transport, are expected to be uniform in this region with local variations about the mouths of the estuaries. Plankton found in the surf zone may be derived from nonlocal upstream sources.

In contrast, the beaches north of Copalis River, and south of the mouth of the Columbia River, are a mix of long, straight, low-sloping sandy beaches composed of fine to medium sand and sea cliffs with steep-sloping pocket beaches composed of coarse-grain sand. Very little Columbia River sediment reaches these beaches; most sediment is derived from rivers that empty onto this part of the coast and from local sea cliff erosion. Local beach currents along these regions are expected to vary at a local scale in direction and magnitude due to the nonuniformity of this coastline. Plankton found in the surf zone are likely to be derived from local offshore sources.

In summary, outstanding progress could be made on the following science issues in the Pacific Northwest through a coastal ocean observing system:

wind-driven coastal upwelling and downwelling (cross-shelf transport; ecosystem dynamics; 2-10 day event scales; seasonal differences)

eastern boundary current transports (north-south flux of water, heat, salt, water properties; modulation by wind-driven coastal processes; influence of longer time scale phenomena)

interannual and interdecadal variability (El Niño/La Niña cycles; Pacific Decadal Oscillation; Subarctic water invasion; ecosystem impacts; changes in productivity; changes in species distributions and diversity)

major buoyant inputs (Columbia River; Fraser River via Strait of Juan de Fuca)

sediment input by rivers (Columbia River, Eel River, Umpqua River) and sediment transport and sinks

energetic beaches (high material transport volume, large tidal ranges; high wave energy; modulation by interannual variability, e.g., El Niño/La Niña)

chlorophyll blooms (upwelling-driven, diatom dominated; CO_2 sink; harmful algal blooms; nearshore hypoxia)

flow-topography interaction (alongshore flow with banks and capes; internal tide generation, propagation and mixing; enhanced mixing on slope via internal wave interactions)

Suggested Endurance Array Line locations:

Cross-shelf arrays of heavily instrumented, multiparameter moorings should be located off central Oregon along the historic Newport hydrographic line (44.6° N). The array line should extend from the beach to the continental slope. Vertical profiling systems and acoustic Doppler current profilers should span the shelf and slope, for example at the 15, 50, 100, 150, 800, 1200 and 3000-m isobaths. Of particular interest is the connection of the shelf observations (> 15 m water depth) with those in the nearshore and right up on the beach. The Newport line is south of the Columbia River, hence only influenced by it during summer. This line together with lines across the continental margin both north and south (Fig. V.F.1) will allow the study of alongshore transport and wave propagation along the entire US west coast.

Another highly desirable location for an Endurance Array Line is off central Washington, north of the Columbia River so that a study of wintertime sediment input by the river can be done.

A third desirable location is south of Cape Blanco and north of Cape Mendocino. The purpose of this line is to study coastal ocean processes where wind forcing is strong and where the coastal ecosystem occupies a larger offshore region. This line will also be useful for studying transport of water and materials through the PNW into the remainder of the California Current System farther south during spring and summer (Fig. II.A.1).

It is hoped that through international cooperation that the Canadians might occupy a cross-shelf transect off Vancouver Island in order to extend the US-based coastal ocean observing system farther north. This would allow better study of the split of the North Pacific Current, input through the Strait of Juan de Fuca and alongshore correlation of variable ocean currents.

Suggested Pioneer Array locations:

Suggested locations for intensive, high-resolution arrays of instruments designed to capture episodic and short-length scale phenomena (the Pioneer Arrays) are:

off central Oregon to study wind-driven upwelling and downwelling, flow-topography interaction, ecosystem dynamics, shelf-nearshore interaction

off the Columbia River to study buoyancy, sediment and micronutrient input onto the nearshore, and inner and outer shelf

off northern California/southern Oregon to study ecosystem dynamics and flow-topography interaction in a region of strong wind-driving

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G. The Gulf of Alaska/Arctic

The coastal waters surrounding Alaska offer three logical regions to center coastal observatory development. These are the Gulf of Alaska, Bering Sea, and the Chukchi/Beaufort seas of the Arctic Ocean. The physical characteristics of each of these shelves differ from one another resulting in substantially different shelf ecosystems. Nevertheless, each of these ecosystems shares a common feature because waters from the Gulf of Alaska flow northward across the Bering-Chukchi shelves and into the Beaufort Sea. This pathway provides a means by which these shelves communicate with one another transmitting climate signals, contaminants, and organisms from the south to the north (Fig. V.G.1).

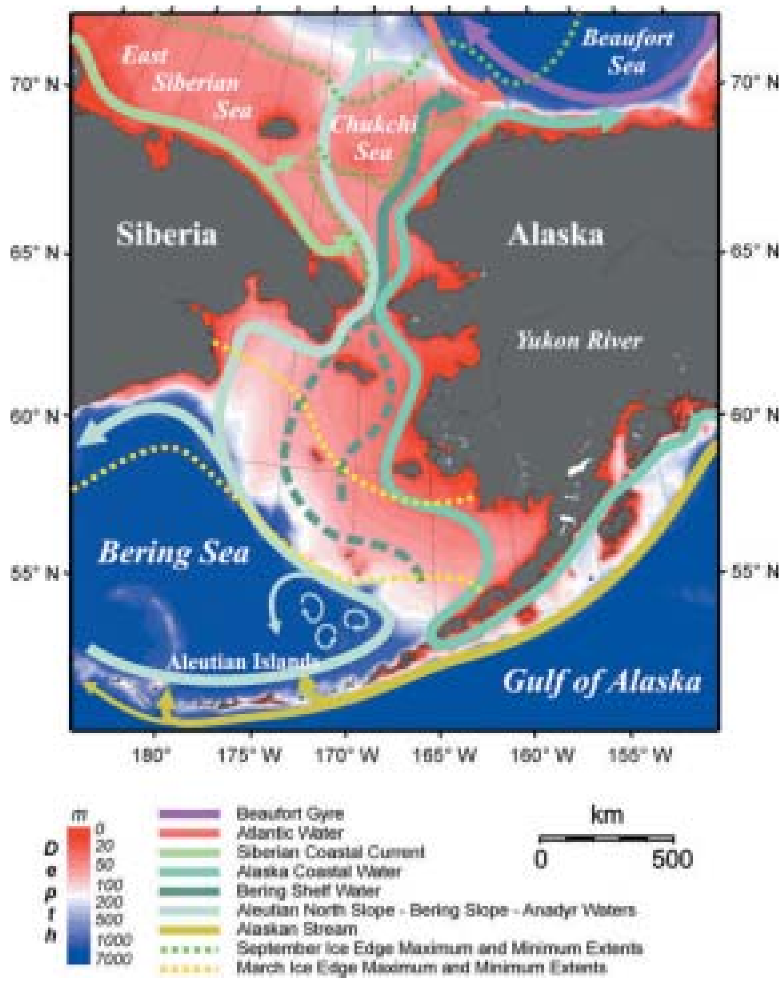

Figure V.G.1. Schematic of water masses and predominant currents surrounding Alaska.

Global climate models consistently predict and observations support that high latitudes are very sensitive to climate change and will probably respond to changes earlier than mid- and low-latitude shelves. Indeed, there is already compelling evidence that the Arctic and Bering marine ecosystems are undergoing dramatic change. Hence detecting, quantifying, and identifying the symptoms and sources of this change is of fundamental importance for understanding global climate variability and its effects on marine resources.

Gulf of Alaska:The Gulf of Alaska (GOA) continental shelf extends for some 2500 km from British Columbia in the southeast to the tip of the Alaska Peninsula in the southwest (Royer, 1998). The shelf width varies from being quite narrow in the eastern gulf (<20 km) to very broad in the northwestern gulf (~150 km) (Fig. V.G.2). The bathymetry and coastline are exceedingly complex being punctuated by numerous capes, bays, canyons and banks. Storm systems associated with the Aleutian Low generate a mean cyclonic wind stress and heavy coastal precipitation rates that result in a wind- and buoyancy-forced shelf circulation (Royer, 1982; Stabeno et al. 1995; Stabeno in press). Over the inner shelf this consists of the swift, narrow (~40 km) coastally-trapped Alaska Coastal Current (ACC), while the middle shelf supports a weaker but highly variable flow (Niebauer et al. 1981; Stabeno et al. 1995).

Flow along the continental slope includes the Alaska Current, which is broad and rich in eddies and meanders in the eastern gulf and transforms into the narrow, swift Alaska Stream in the western gulf (Schumacher and Reed, 1986). These currents interact with the complex topography and likely induce vigorous mesoscale activity that could be critical to biological production and cross-shelf exchange. There is large seasonal and interannual variability in winds and precipitation, which lead to similarly large variations in the coastal ocean (Stabeno et al. in press; Royer et al. accepted; Weingartner et al. accepted).

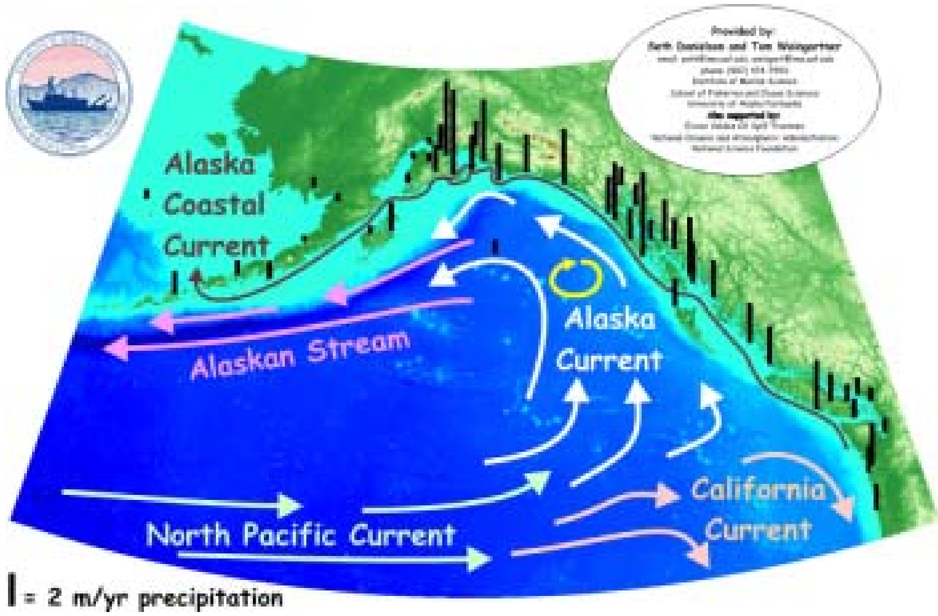

Figure V.G.2. Circulation in the Gulf of Alaska. Vertical black bars on the coast indicate precipitation rate.

The dynamics of the GOA basin and the shelf are tightly linked to the position and strength of the Aleutian low pressure system. Storms propagating into the gulf are blocked by coastal mountains, resulting in very high precipitation and persistent, cyclonic winds. The wind stress forces a cyclonic circulation in the deep GOA and causes an onshore surface Ekman drift. The drift establishes cross-shelf pressure gradients that force the ACC. The high precipitation feeds an enormous freshwater flux (~20% larger than the Mississippi River discharge) that enters the shelf as a distributed "coastal line source" around the gulf's perimeter (Royer, 1982).

The seasonal variability in wind stress and freshwater discharge is large. Cyclonic winds are strongest from November through March and feeble or even weakly anticyclonic in summer when the Aleutian Low is displaced by the North Pacific High (Royer, 1975; Wilson and Overland, 1986). The seasonal runoff cycle is maximum in early fall, decreases rapidly through winter when precipitation is stored as snow, and attains a secondary maximum in spring due to snowmelt (Royer, 1982). The winds and discharge jointly force a mean cyclonic alongshelf flow over the GOA shelf and slope (Reed and Schumacher, 1986). The flow interacts with a complex bathymetry and coastal geometry to generate mesoscale variability that enhances cross-shelf exchanges.

Three Endurance Line locations are recommended for the Gulf of Alaska. An Endurance Line would be useful downstream of Prince William Sound but upstream of Kodiak Island in the northwestern gulf (Fig. V.G.3). This line would monitor the outflow from Prince William Sound and eastward flow south of Montague Island and provide the infrastructure for shelf/slope exchange processes in the northwest gulf where the bathymetry and the structure of the slope flow field differs considerably from the eastern gulf. This line would build upon the historical observations made during OCSEAP in the 1970s and that were continued under GLOBEC. It would also take advantage of planned CODAR coverage for the area (D. Musgrave, pers. comm.; Fig. V.G.4).

Figure V.G.3. Close-up of the Gulf of Alaska shelf near the GAK station and suggested Endurance Line.

An Endurance Line would also be valuable in the eastern gulf perhaps at the juncture of southeast and southcentral Alaska to measure the confluence of the outflow from the Southeast Alaska island archipelago with the northward flow along the continental shelf. Regional circulation models (Hermann et al. 2002) suggest that this portion of the shelf might preferentially transport nutrient-rich slope waters onto the shelf. A line here would also monitor the enormous freshwater discharge entering southeast Alaska and serve as a basis for shelf-slope exchange studies in a region where the continental shelf is relatively narrow and the slope flow is relatively weak. It would also serve as a link between the northern Alaska shelf and any Endurance Lines that the Canadians might establish along the British Columbian continental shelf. This line would also provide important boundary conditions for ecosystem models being established through the GLOBEC program for the northern Gulf of Alaska and Prince William Sound.

The third location would be across the western exit of Shelikof Strait. Transport at this location strongly influences flow patterns on the shelf to the east and the portion of the Alaska Coastal Current that eventually flows through eastern Aleutian Passes into the Bering Sea (Stabeno et al. 2002). These moorings would build upon historical observations comprised of approximately seven years of moorings deployed sporadically over a 20 year period and 20+ years of biological observations from net tows and hydrographic surveys that have been collected as part of NOAA research programs.

Suggested locations for Pioneer Arrays include areas where bank/trough topography is thought to be critical to biological productivity and cross-shelf exchange (northwest gulf, Kodiak Island, northeast gulf), processes controlling exchange between the shelf and Prince William Sound through Hinchinbrook Entrance, large troughs/canyons (e.g., Shelikof Sea Valley and Amatouli Trough) that strongly influence on/off shelf fluxes of salts, nutrients and biota, Unimak Pass which is the primary pass connecting the shelves of the GOA and Bering Sea and mesoscale motions generated by flow-coastline interactions.

Bering Sea: The Bering Sea shelf, ~600 km wide and ~1000 km long, is an enormously productive region, sustaining the world's largest groundfish fishery and vast populations of birds and mammals. Although depths grade smoothly from the coast to the shelfbreak, it contains a diversity of biological habitats because the bathymetry divides the shelf into three distinct biophysical domains (the outer domain, the middle shelf domain, and the coastal domain), with a frontal system or transition zones separating each domain from the other.

The Bering shelf is connected to the GOA via Unimak Pass. Over the shelf, the mean flow is northward linking the southern shelf to Bering Strait and the Arctic Ocean. Cross-shelf differences in the currents and water properties primarily reflect differences in depth but also regional influences of the continental slope, rivers, sea ice formation and melting and variations in tidal currents, which are particularly important as a source of energy for mixing (Kinder and Schumacher, 1981, Schumacher and Kinder, 1983; Coachman, 1986; Stabeno et

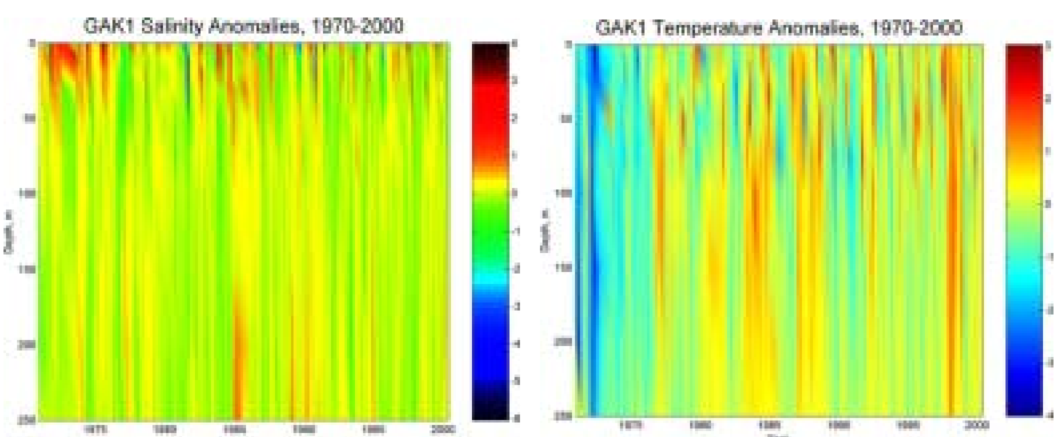

Figure V.G.4. Temperature and salinity time series from GAK 1.

al. 1999). There are also enormous interannual differences in water temperature, sea ice cover, vertical stability and cross-shelf transfer (Stabeno et al. 1998), which induce dramatic changes in the structure of this ecosystem on interannual and longer time scales (Hunt et al. 2002).

The Bering Sea is connected to the GOA through the porous boundary of the Aleutian Arc (Fig. V.G.1). The shallow passes to the east of Samalga Pass permit the introduction of shelf waters onto the Bering Sea shelf. The deeper western passes permit the northward transport of warm, saline water into the Bering Sea basin. In total, the eastern passes (those east of the date line) permit the transport of ~8 x 10^6 m^3 s^{-1} of north Pacific water into the Bering Sea (Stabeno et al. submitted). Bering Strait is the sole connection between the North Pacific and Western Arctic oceans. The sea level difference between these basins drives a mean northward transport of ~0.8 x 10^6 m^3 s^{-1} (Roach et al. 1995).

The flow contains the time-varying and integrated output of the physical and biogeochemical components of the Bering Sea. The salt and nutrient loads of this flow represent the net effects of upwelling from the Bering Sea basin, biochemical cycling on the Bering shelf, and freshwater fluxes associated with the freezing and melting of sea ice (Springer at al. 1996; Walsh et al. 1989), river runoff, and inflow from the Gulf of Alaska (Weingartner et al. accepted; Stabeno et al. 2003).

This inflow of low-salinity, but nutrient-rich waters sustains the high productivity of the Western Arctic shelf (Walsh et al.1989), and conditions the density structure of much of the Arctic Ocean. It also affects the ice cover (Aagaard and Carmack, 1989) of the Arctic Ocean and is an essential link in the global freshwater cycle, balancing the water budget of the North Pacific and the North Atlantic (Wijffels et al. 1992). It might even augment the global wind-driven circulation through its role in the Goldsbrough-Stommel haline circulation (Huang and Schmitt, 1993). The strait is also a migratory corridor for a rich and diverse annual movement of marine mammals and birds over broad distances (Ainley and DeMaster, 1990; Tynan and DeMaster, 2004) and it is an important pathway by which anthropogenic contaminants from the North Pacific enter the Western Arctic (Macdonald and Bewers, 1996).

Given the vast extent of the Bering Sea, there might be practical problems associated with establishing cabled observatories in the region. Nevertheless, Endurance-type systems should be established in the southeast Bering Sea with these distributed within each of the distinct biophysical domains. Ideally, a series of four moorings would be deployed along the 70 m isobath (the center of the middle shelf domain). These could build on existing mooring sites. The southern site (56.9° N, 164° W) has been occupied nearly continuously since 1995 and a second site approximately 150 km northwest has been occupied more sporadically for 6 years.

Both moorings are heavily instrumented measuring biological, chemical and physical parameters. Two other mooring sites, one near St. Mathews Island and the other south of St. Lawerence Island, are planned. While long term funding does not exist for these moorings, they have been discussed by other programs. Associated with each of the four moorings of the middle shelf domain should be a mooring in the coastal domain and another in the outer shelf domain. These would provide necessary coverage to this broad shelf with moorings in each of the three cross-shelf domains at four locations north to south.

Cabled observatories are probably achievable in Bering Strait (although some care will be required where sea ice scours the sea floor nearshore) and in some of the Aleutian Passes. While the deeper Aleutian Passes are beyond the scope of this program, the shallow eastern passes (e.g. Unimak, Tanaga and Samalga) are critical in determining the northward flux of heat, salts (including nutrients) and zooplankton, just as Bering Strait is the critical connection to the Arctic through which heat, salts and biota pass.

Pioneer systems will be useful to examine and measure cross-shelf and slope transfer processes related to the bathymetry and slope eddies and ecosystem processes related to sea-ice and river runoff. The Bering Sea ecosystem is strongly influenced by the extent and timing of sea-ice formation. Pioneer systems designed to measure changes in salinity, temperature, primary production and baroclinic flow over the shelf are critical to understanding how this ecosystem functions. Other suggested areas for focused investigations include the rich habitats around the Pribilof Islands on the outer shelf, St. Matthew Island on the central shelf, and Nunivak Island on the inner shelf. Onshelf fluxes occur at a number of canyons and particularly at Bering Canyon in the south, Pribilof Canyon and Zymchug Canyons farther north. In addition, Pioneer systems could investigate the effects of the huge sediment and freshwater influxes from the Yukon River (northern shelf) and Kuskokwim River (southern shelf) on the Bering Sea ecosystem.

Chukchi and Beaufort shelves: The outflow from the strait crosses the vast (~800 km in meridional extent, 900 km in zonal along its northern boundary) and shallow (~50 m) Chukchi Sea (Fig. V.G.1). The flow splits into three branches arrayed across the western (Herald Valley), central (Central Channel), and eastern (Barrow Canyon) portions of the shelf (Weingartner et al. submitted; Woodgate et al. submitted). Water mass modification processes include cooling and salting, which increases the density of the Pacific waters flowing across this shelf. The magnitude of these changes depends upon the seasonal evolution of the sea ice freeze and thaw cycle, which varies substantially from year-to-year in response to the regional wind field (Maslanik, 1999). This interannual variability likely affects slope processes and the transport of Pacific waters into the Arctic Ocean interior where these waters play an important role in maintaining the stratification of the upper Arctic Ocean. Some of the outflow from the Chukchi shelf appears to form eddies that propagate into the Arctic Ocean interior and some flows eastward as part of a circumpolar slope subsurface current carrying water derived from the Atlantic Ocean and Eurasian shelves (Aagaard, 1984). All of these various outflows consequently influence the potential vorticity structure along the Beaufort Sea continental slope, (Pickart, in press) and thereby affect shelf-slope exchange processes.

The Alaskan Beaufort Sea shelf is an approximately 100 km wide by 600 km long shelf that extends from Pt. Barrow to the Canadian boundary. Its western boundary is influenced by the outflow through Barrow Canyon and its eastern boundary is affected by the massive outflow from the Mackenzie River. Circulation on the outer shelf appears to be mainly wind-driven and westward in the upper layers, but eastward at depth due to the influence of the slope undercurrent. Wind-driven upwelling along the slope can advect eastward momentum onto the outer shelf and temporarily reverse the westward wind-driven flow there (Aagaard, 1984).

The shelf circulation is complicated by landfast ice that covers the shallower (<25m) portion of the shelf from fall through early summer. The ice is an immobile lid, effectively limiting the transfer of momentum between the atmosphere and ocean. The circulation field within the landfast ice zone and its connection with the outer shelf remains poorly known. River runoff begins before the landfast ice recedes and the plume flows seaward beneath the ice cover. Initially at least the inner shelf is highly stratified because there is little wind or tidal energy available for mixing. Depending upon wind conditions and the rapidity with which the ice melts, the freshwater is either swept offshore through Ekman transport or transported eastward in a coastal current. Satellite imagery suggests that these flows are often accompanied by vigorous instabilities similar to those observed by Weingartner et al. (1999).

The NSF is currently sponsoring the Shelf-Basin Interaction Program, a major field and modeling program in the Chukchi Sea, to address the physical and biogeochemical processes associated with inflow of Pacific Ocean waters onto the Chukchi continental slope. Nevertheless, a candidate site for an Endurance Line would be at the Chukchi-Beaufort juncture, with instruments monitoring the variable flows and water properties along the continental slope. Such an emplacement would be a useful monitor of the integrated forcing over the Chukchi shelf and of signals advected into the region from the Atlantic Ocean and Eurasian shelves. Measurements should include chemical tracers such as barium and $\delta^{18}O$ that provide useful inferences on water mass origins (Falkner et al. 1994; Cooper et al. 1997). In addition, ice thickness and ice distribution measurements should be incorporated into any long-term measurements made in the Arctic. It seems imprudent to recommend an Endurance array on the Beaufort slope until the studies currently being planned have been completed.

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H. The Great Lakes

The Great Lakes represent the second largest coastal region in the US after Alaska, and many of the arguments for coastal ocean observatories are also applicable to the Great Lakes. The need to understand terrestrial - littoral - pelagic transfers of material and energy is as great in the Great Lakes as in the coastal ocean, and is relevant to current management issues such as eutrophication, exotic species impacts, and fish recruitment.

CO_2 fluxes between the sediment, water and atmosphere are poorly understood in the Great Lakes - we do not even know if Lake Michigan is a net source or sink for carbon. The implications of climate change for the Great Lakes are of great concern, but predictive capacity is currently poor. Better spatial and temporal measurements provided by observatory arrays will not only improve the quality of predictive models, but because the Great Lakes are more responsive than the oceans to climate change (due to their size), they can serve as sentinels for the impact of climate change on aquatic systems.

In the Great Lakes, as in the coastal ocean, gradients of many biogeochemically important materials are substantially greater in the offshore direction than alongshore. In the presence of large gradients, cross-isobath circulation is a primary mechanism for material exchange from nearshore to offshore. Along-shore and cross-isobath current components exhibit strong episodic behavior from wind forcing. Alongshore transport has been well studied, but the advective and diffusive mechanisms driving cross-isobath transport remain less well understood (Schwab et al., 2000).

Transient physical processes effect major changes in the biological and geochemical properties of coastal environments. In southern Lake Michigan and off the Keweenaw Peninsula of Lake Superior, storms give rise to turbidity events which have implications in cross-shelf sediment transport and distribution (Schwab et al. 2000; Beletsky et al. 2003; Chen et al.,

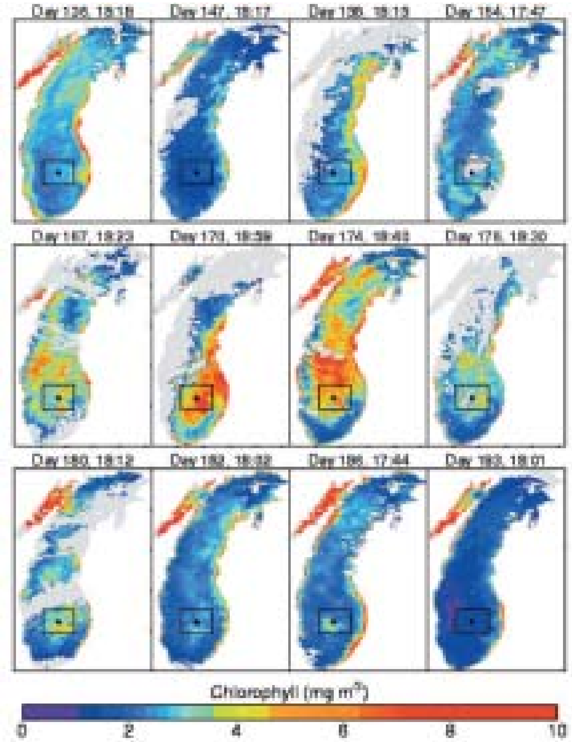

Figure V.H.1. Images of Lake Michigan chlorophyll a from SeaWiFS showing the June 1998 phytoplankton bloom. The dot and solid box in the southern basin indicate the location of the thermistor string and the area enclosed by the 60-km by 60-km box was used to compute the spatially averaged chlorophyll a values. From Lesht et al. (2002).

2001), and excursions in primary production (Fig. V.H.1, Lesht et al. 2002). Sediment resuspension events are also an important mechanism coupling sediment diagenesis to water column food web dynamics (Cotner et al. 2000).

Although many physical processes responsible for material transport offshore are similar in coastal oceans and the Great Lakes, the lakes' enclosure by land makes for significant differences. Material transported offshore can be removed for the long term on oceanic shelves; in the Great Lakes, material is removed only by permanent burial or outflow. Suspended sediments in Lake Michigan have offered an opportunity to examine recurrent episodes of cross-isobath transport.

Mortimer (1988) first reported via satellite imagery a plume of suspended material 10 km wide and 100 km alongshore in southeastern

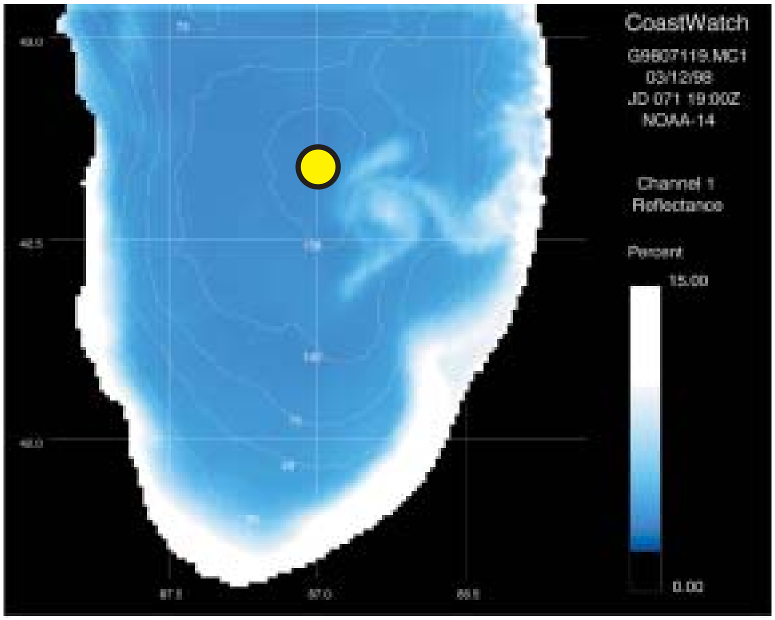

Figure V.H.2. Color-enhanced visible-band satellite image of Lake Michigan sediment resuspension event (from Beletsky et al. 2003). Yellow dot denotes potential Endurance Buoy in the center of the southern Lake Michigan Basin.

Lake Michigan. The plume has been observed every spring since 1992 when the NOAA CoastWatch program began to routinely provide Great Lakes imagery (Eadie at al., 1996). A spectacular plume in March of 1998 originated following intense storms with 17 m s^{-1} northerly winds and basin waves in excess of 5 m high. The plume extended over 300 km alongshore and the feature persisted for six weeks. (Fig. V.H.2). A relatively small-scale observatory effort of moored arrays of current meters, thermistors and sequencing traps coupled with interdisciplinary Lagrangian measurements and shipboard surveys and process studies was employed. The time series results were supplemented by synoptic coverage from satellite imagery and multi-frequency HF radar observations. The results provided a framework of model testing and development using a lake-scale hydrodynamic model coupled with a wave model (Fig. V.H.3). Results were integrated with sediment transport and lower food web models to assess the impact of internal nutrient cycling and nearshore-offshore transport on sedimentary and biological processes.

Endurance Instrumentation

An Endurance Buoy in the southern Lake Michigan basin would build on the current observatory system that is being developed for Lake Michigan (Fig. V.H.2). NOAA/GLERL and the Great Lakes WATER Institute (GLWI) are in active collaboration for the development of extensive sensor deployments. GLWI has deployed a buoy with meteorological sensors, an underwater profiler, and near-real-time data telemetry in Lake Michigan (*http://waterbase.glwi.uwm.edu*). In the coming year, GLWI plans to deploy two more buoys, one of which will be paired with an additional buoy to be deployed by NOAA/GLERL. The data collected by these buoys is complemented by an intensive Lake Michigan monitoring program that the WATER Institute has conducted since

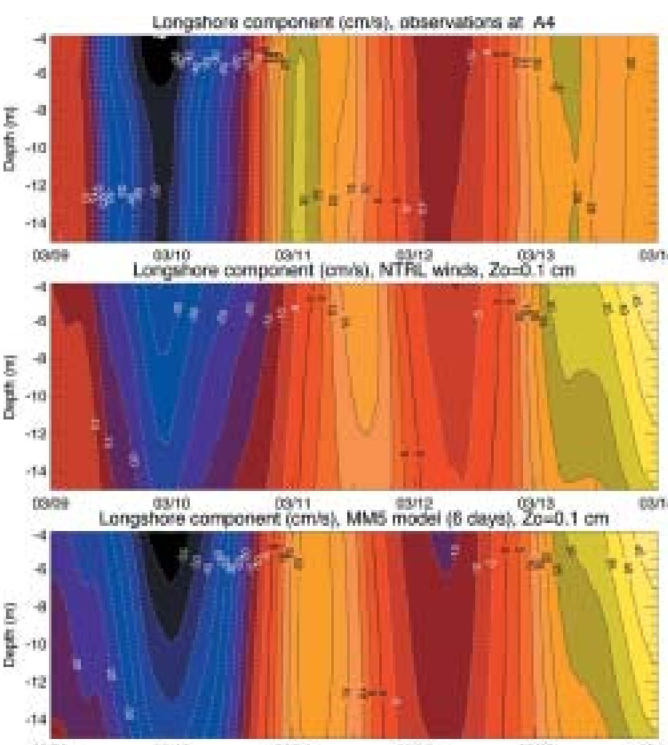

Figure V.H.3. Results of hydrodynamic run (middle and lower panels) compared to observed longshore currents (upper panel) during the Lake Michigan sediment resuspension event shown in Figure V.H.2 (from Beletsky et al. 2003).

1997. This represents an ambitious beginning to a Lake Michigan observatory array, which further coastal observatory plans can capitalize on. These plans would be coordinated with the development of a Great Lakes Observatory System that was recently initiated by NOAA and the Great Lakes Commission (*http://www.glc.org/announce/03/10glos.html*)

Four additional Endurance Buoys at the outlets of Lakes Superior, Huron, Erie and Ontario would allow biogeochemical mass balances to be constructed with a degree of precision virtually impossible on an open coastline. Such observations would tie climatology to long term biogeochemical impacts over a range of response times determined by the unique hydrological structure of the system (e.g., water residence times vary from approximately 190 years in Lake Superior to greater than three years in Lake Erie). The dashed orange line connecting the buoys indicates the active international partnership with Canada (Fig. III.D.10).

Pioneer Instrumentation

Incorporating the existing and planned observatory infrastructure into a more complete Pioneer Array would result in a dataset with high temporal resolution and moderately high spatial resolution that would greatly increase our understanding of the linkages between physical, chemical and biological processes. A recommended configuration is two bisecting transects running west-east and north-south in the Lake Michigan's southern basin. The data collected by this array will facilitate the design of future Endurance Lines in the Great Lakes.

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I. The Hawaii Region

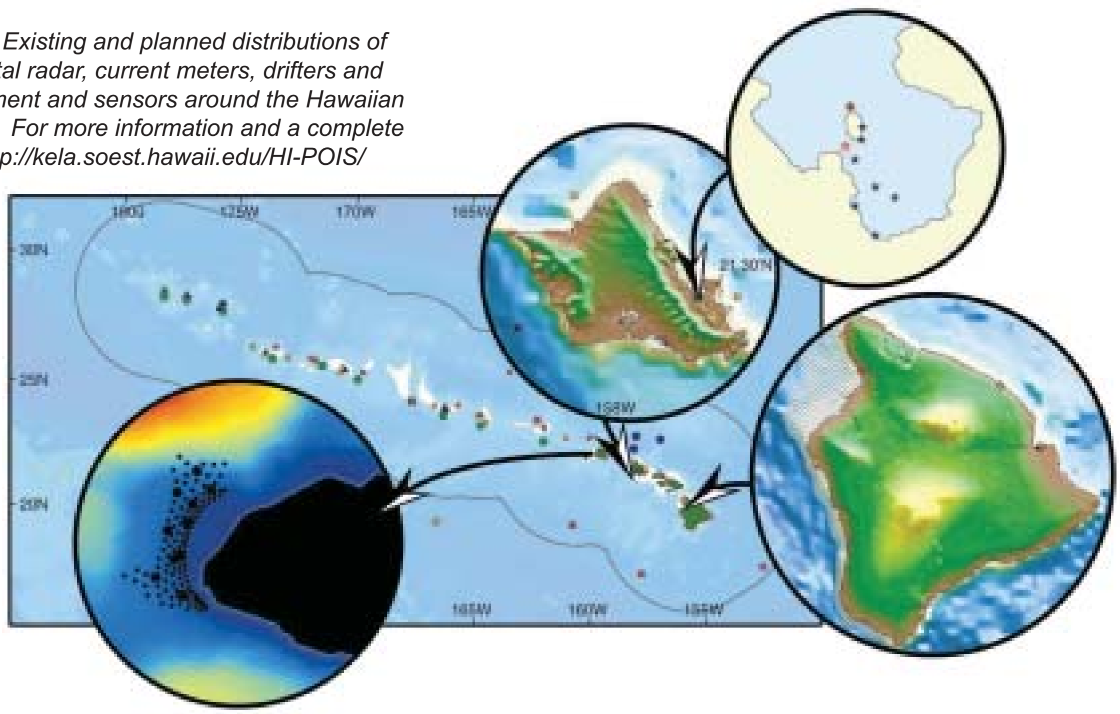
The health and protection of marine ecosystems is of vital interest to the economy and culture in the State of Hawaii. The main islands of the Hawaiian archipelago have nearly 1700 km of tidal coastline. Beaches and nearshore environments are particularly sensitive with potential repercussions on tourism, fishing and public recreation. The coastal zone of the main Hawaiian Islands is heavily burdened in terms of societal impact with point and non-point source pollution regularly affecting water quality. The physical environment around the Hawaiian Islands is also complex with surface and internal tides combining with wind-driven and general oceanic circulation patterns to create three-dimensional flows that render modeling efforts difficult.

A diverse array of delayed and real-time sensors have been deployed in Hawaii coastal regions (Fig. V.I.1). Research groups at the University of Hawaii's School of Ocean and Earth Science and Technology (SOEST) have begun to develop and deploy a set of observational tools that will enable examination of the links between the physical and the biogeochemical environment in coastal areas with a focus on linking physical forcing (storms, waves, tides, currents) and coastal water quality and productivity as affected by land-ocean transfer of materials (Fig. V.I.2). The long-term goal of this work is development of real-time observatories, which, coupled with numerical models will yield a predictive capacity for the nearshore environment and will be of use to the general public through local, State, and Federal agencies concerned with aquatic resources, public health, and water safety.

To date the project has deployed a moored, continuous monitoring instrument package dubbed Coral Reef Instrumented Monitoring Platform (CRIMP, Ringuet et al. 2003; Fig. V.I.3) in southern Kane'ohe Bay, an area with a well-documented history of urban development, anthropogenic nutrient and sediment inputs, and reef degradation. The project has produced a unique continuous record of biogeochemical and physical conditions in the water column of southern Kane'ohe Bay, and a parallel series of synoptic spatial surveys of these parameters, including depth profiles of temperature, salinity, dissolved oxygen, dissolved and particulate species of N and P, chlorophyll, and turbidity.

Historical and contemporary data are combined with laboratory measurements of carbon and nitrogen stable isotopes and phosphorus partitioning in suspended particles and sediments, to continue development of a coupled physical-

Figure V.I.1. Existing and planned distributions of buoys, coastal radar, current meters, drifters and other equipment and sensors around the Hawaiian archipelago. For more information and a complete map, see http://kela.soest.hawaii.edu/HI-POIS/



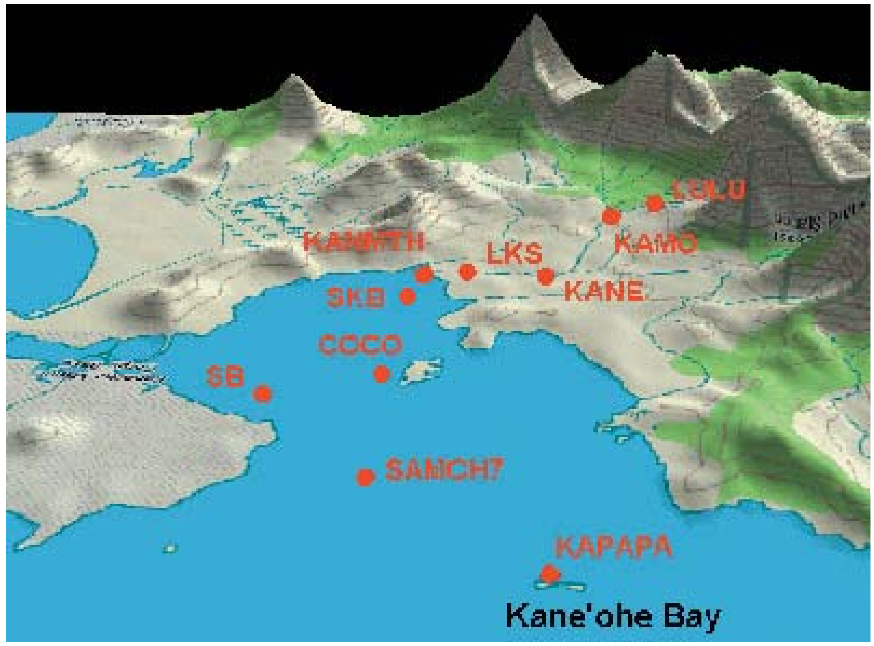


Fig. V.I.2. Stations occupied in ongoing Kane'ohe Bay watershed and bay monitoring study, with monthly monitoring of nutrients, turbidity, T, conductivity, pH , oxygen levels and other parameters. Figure courtesy E. DeCarlo and F. Mackenzie

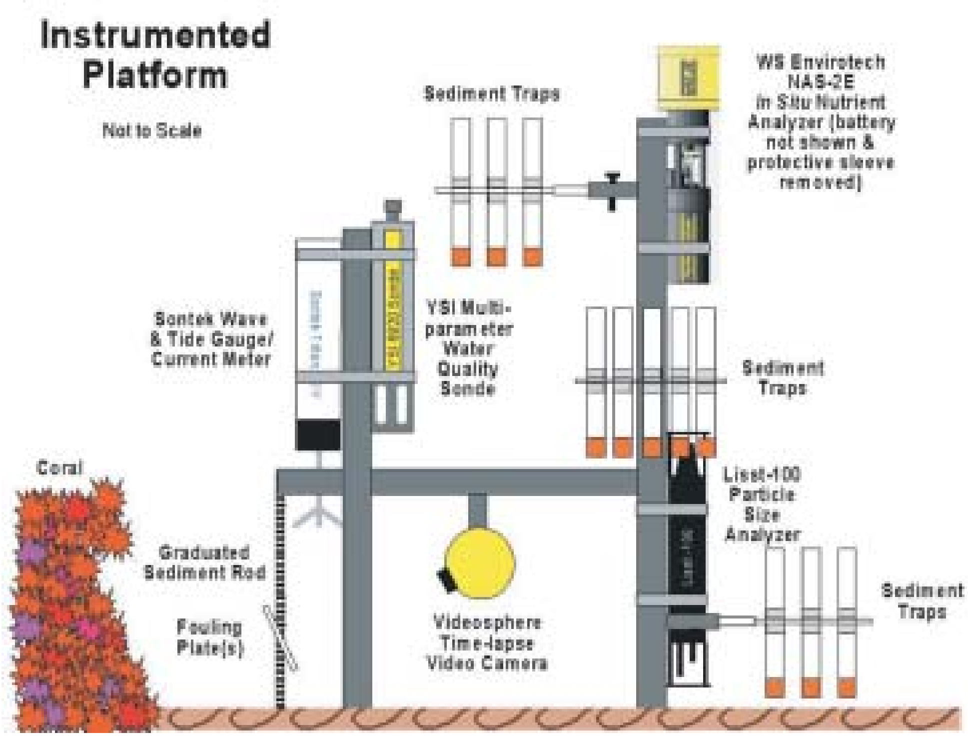
biogeochemical model of nitrogen and phosphorus transport and cycling in southern Kane'ohe Bay that will be applied to other coastal areas in the near future. The model will be used to examine the timing and magnitude of particulate and dissolved terrestrial nutrient fluxes to biota in the proximal coastal zone, providing a management tool that directly ties water quality and reef ecosystem health to land use in the adjacent watershed.

In addition to the above, researchers have started to investigate the direction and magnitude of the flux of CO_2 across the air-sea interface of Kane'ohe Bay and Hilo Bay (Fig. V.I.4), two of the larger coastal marine ecosystems in the state of Hawaii. Aside from considerations related to their size, these two bays were chosen because of their different ecosystem characteristics due to differences in geologic age. The older Kane'ohe Bay is dominated by coral reefs and associated carbonate sediments whereas younger Hilo Bay lacks both features. Thus one would expect that biogeochemical cycling of carbon in the waters and sediments of Kane'ohe Bay and the flux of CO_2 at the seawater-atmosphere interface is controlled by processes related to both production/respiration of organic carbon and calcification/deposition/solution of calcium carbonate. The Hilo Bay carbon cycle on the other hand is dominated by organic metabolism alone. The water columns of both bays have thus far been sampled several times for their marine carbon system parameters (pH, total alkalinity, and dissolved inorganic carbon) plus other physical and biochemical parameters.

Tentatively it appears that the conclusion above is supported by the preliminary data. Both bays during fall 2003 are sources of CO_2 to the atmosphere but in Hilo Bay total alkalinity behaves conservatively with salinity indicating that carbonate mineral formation through the process of calcification is not overly important in that ecosystem. However total alkalinity is not conservative with salinity in Kane'ohe Bay showing that calcification by corals, coralline algae, etc. is important in controlling the behavior of the carbon cycle and the air-sea exchange of CO_2 in that ecosystem. The studies in both bays are being extended to the shelf/slope break and out to the HOT Station ALOHA to tie in with the long-term ALOHA marine carbon system time series (Fig V.I.4).

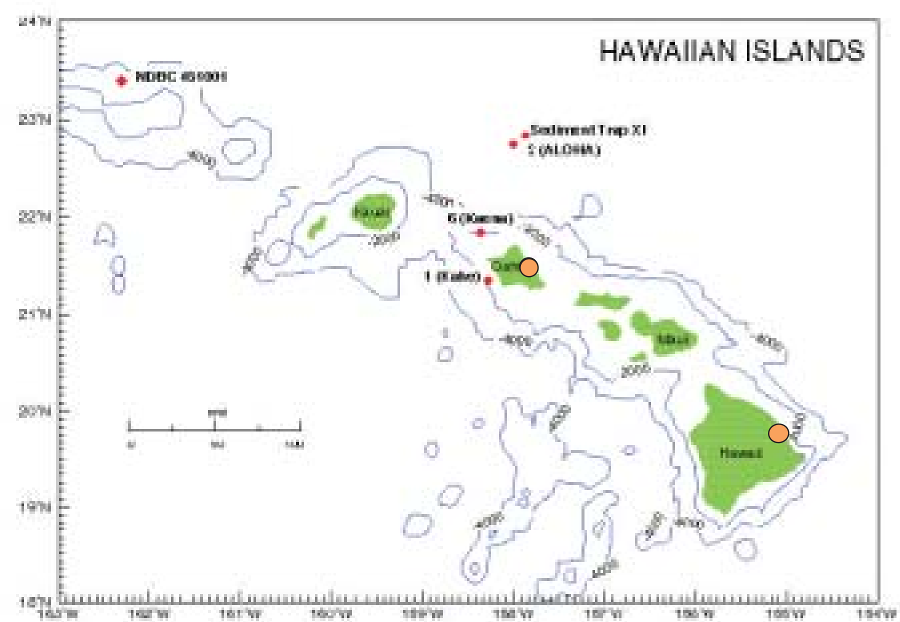
The Hawaii Ocean Time-series (HOT) was developed in 1988 to obtain a long time-series of physical and biochemical observations in the oligotrophic North Pacific subtropical gyre in order to address long-term variability, oceanic carbon cycling and global change (Karl et al. 2001; Karl et al. 2003). Station ALOHA is in deep water (4750 m), sufficiently distant to not be influenced by coastal ocean dynamics and inputs, but close enough to accomodate frequent, short cruises. A coastal analogue site was also established in 1500 m water off Kahe Point on the island of Oahu to allow convenient equipment testing and training of personnel.

Fig. V.I.3. Schematic of Coral Reef Instrumented Monitoring Platform (CRIMP) developed to examine how reef ecosystems respond to new sediment and nutrient inputs and resuspension/ remineralization events. Figure courtesy E. DeCarlo and F. Mackenzie



Funding has been received by SOEST scientists to emplace a fiber optic linked bottom observatory at Station ALOHA and plans are to have a number of optics-linked extensions (up to 150 km each) up to the coast and perhaps inshore for continuous surveillance of onshore to offshore processes including but not limited to nutrient and freshwater inputs and sediment transport. Logical first Endurance Buoy emplacement would be in Kane'ohe Bay, followed by emplacement in Hilo Bay.

Fig. V.I.4. Location of Station ALOHA north of Oahu, and location of Kane'ohe and Hilo Bays. Modified from HOT website http://:hahana.soest.hawaii.edu/hot/.



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VI. Acknowledgements

This report is the result of contributions from a much larger community than the list of authors who attended the CORA workshop in person or by electronic participation. The workshop was conceived in mid August 2003 and occurred in mid November 2003. The draft report was prepared over a subsequent five-week period. This very narrow time window coupled with busy schedules unavoidably excluded some and limited the participation of others. Nevertheless, many individuals generously contributed directly and indirectly to the draft and final versions of this report. Gratitude is due in particular to the following for providing information for regions which were under-represented at the workshop: Steve Lohrenz and Stephan Howden for the Gulf of Mexico; Eric DeCarlo, Fred Mackenzie and Dave Karl for Hawaii; Joe Niebauer, Harvey Bootsma, Val Klump, Dave Schwab, Michael McCormick, Tom Johnson and Steve Colman for the Great Lakes; Dave Musgrave, Tom Weingartner and Phyllis Stabeno for Alaska/Arctic; and Robert Guza, Tim Stanton, Bill Birkemeier, Ed Thornton and James Kaihatu for nearshore processes.

The quilted cover 'framework' was designed by Anna Boyette, Skidaway Institute of Oceanography, with quilt pieces derived from graphics provided by the individual contributors.

Funding for the CORA workshop was provided to the Coastal Ocean Processes Program by the National Science Foundation (OCE-0301872) and the Office of Naval Research (N000140010129). Their support is greatly appreciated.

The views expressed in this report are those of the authors and do not necessarily reflect the views of the National Science Foundation or the Office of Naval Research.

This report is posted on the CoOP website.

CoOP contact:
CoOP Office/DB Jahnke
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411 USA
voice 912.598.2493
fax 912.598.2310
email djahnke@skio.peachnet.edu
http://www.skio.peachnet.edu/coop/

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VIII. Participants

Andrew H. Barnard
Department of Research
WET Labs, Inc.
PO Box 518
Philomath, OR 97370
(541) 929-5650 ext.32
andrew@wetlabs.com

John M. Bane, Jr.
Department of Marine Sciences
University of North Carolina
Chapel Hill, NC 27599-3300
Tel: (919) 962-0172
Fax: (919) 962-1254
bane@unc.edu

Jack Barth
College of Oceanic & Atmos. Sci.
Oregon State University
104 Ocean Admin Bldg
Corvallis, OR 97331-5503
voice 541.737.1607
fax 541.737.2064
barth@oce.orst.edu

Francisco Chavez
MBARI, 7700 Sandholdt Road
Moss Landing CA 95039-9644
voice 831.775.1709
fax 831.775.1620
chfr@mbari.org

Hans G. Dam
University of Connecticut
Department of Marine Sciences
1080 Shennecossett Rd.
Groton, CT 06340-6048
Phone: (860) 405-9098
Fax: (860) 405-9153
E-mail: hans.dam@uconn.edu

Ed Dever
Integrative Oceanography Div. - 0209
Scripps Institution of Oceanography
UCSD, 9500 Gilman Dr.
La Jolla, CA 92093-0209
voice 858.534.8091
fax 858.534.0300
edever@ucsd.edu

Paul M. DiGiacomo
NASA Jet Propulsion Laboratory
California Institute of Technology
MS 300-323
4800 Oak Grove Drive
Pasadena, CA 91109-8099 USA
Phone: 1-818-354-8189
Fax: 1-818-393-6720
Email: pmd@pacific.jpl.nasa.gov

Jim Edson
Woods Hole Oceanographic Institution
MS 12, 98 Water Street
Woods Hole MA 02543
voice 508.289.2935
fax 508.457.2194
jedson@whoi.edu

Rocky Geyer
Woods Hole Oceanographic Institution
MS 12, 98 Water Street
Woods Hole MA 02543
voice 508.289.2868
fax 508.457.2194
rgeyer@whoi.edu

Scott Glenn
Rutgers University
Room111C Marine Sciences Building
71 Dudley Road
New Brunswick NJ 08901
voice 732.932.6555 x544
fax 732.932.1821
glenn@imcs.rutgers.edu

Rick Jahnke
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah GA 31411
voice 912.598.2491
fax 912.598.2310
rick@skio.peachnet.edu

Ken Johnson
MBARI, 7700 Sandholdt Road
Moss Landing, CA 95039-9644
voice 831.775.1985
fax 831.775.1620
johnson@mbari.org

Mark A. Moline
Biological Sciences Dept.
California Polytechnic State University
San Luis Obispo, CA 93407
T: (805) 756-2948
F: (805) 756-1419
mmoline@calpoly.edu

Jim O'Donnell
University of Connecticut
Department of Marine Sciences
Groton CT 06340
voice 860.405.9171
fax 860.405.9153
james.odonnell@uconn.edu

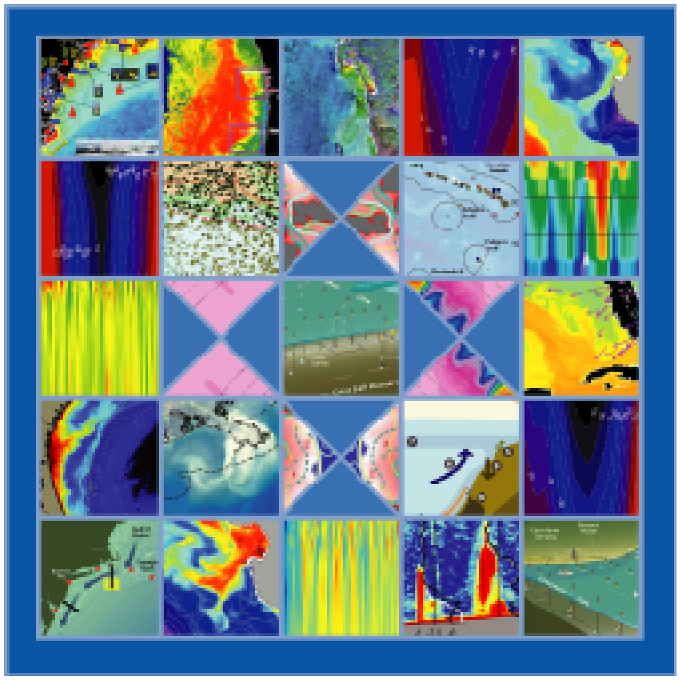
Joan Oltman-Shay
Northwest Research Associates
14508 NE 20th Street
Bellevue, WA 98007-3713
voice: (425) 644-9660 x314
fax: (425) 644-8422
joan@nwra.com

Ola Persson
CIRES/NOAA/ETL R/ET7
David Skaggs Research Center
325 Broadway
Boulder CO 80305-3328
Fax: (303) 497-6101
Work: (303) 497-5078
ola.persson@noaa.gov

Oscar Schofield
Rutgers University
Institute of Marine and Coastal Sciences
Coastal Ocean Observation Lab
New Brunswick NJ 08901
voice 732.932.6555 x548
fax 732.932.4083
oscar@imcs.rutgers.edu

Heidi M. Sosik
Woods Hole Oceanographic Institution
Biology Department, MS 32
Woods Hole MA 02543-1049
voice 508.289.2311
fax 508.457.2134
hsosik@whoi.edu

Eric J. Terrill
Marine Physical Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093-0213
phone 858 822 3101
fax 858 534 7132
et@mpl.ucsd.edu



The Coastal Ocean Processes (CoOP) Program is an interagency effort to conduct large-scale, interdisciplinary research to improve our quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter within continental margin systems.

CoOP Office

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