

**Coastal Ocean Processes (CoOP): Transport and Transformation Processes over  
Continental Shelves with Substantial Freshwater Inflows.**

**Report on the CoOP Buoyancy-Driven Transport Processes Workshop  
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Salt Lake City, Utah**

**by**

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## Executive Summary

Coastal Ocean Processes (CoOP) is a program that seeks to plan and implement multi-investigator, interdisciplinary research in the coastal ocean. The CoOP Buoyancy-Driven Transport Processes Workshop was held from October 6-8, 1998, in Salt Lake City, Utah. As requested by the workshop participants, the title of the workshop report was changed to "Transport and Transformation Processes over Continental Shelves with Substantial Freshwater Inflows", since even in coastal regions with large freshwater inflows, much of the transport can be due to other processes, such as wind. The overall question addressed by the workshop was: How do processes on shelves with large freshwater inflows affect cross-margin transport of biologically, geologically, and chemically important materials? This question is important because coastal ocean regions with large freshwater inflows are major gateways for the transfer of materials from continents to oceans. In part due to nutrients supplied with the freshwater, these areas tend to be highly productive and to support major fisheries. Shelves with large freshwater inflows are among those most affected by human activities, with impacts including eutrophication and accumulation of toxic metals in sediments and biota. Climatic warming due to anthropogenic greenhouse gases could lead to marked alteration in freshwater discharge and material transport these in shelf regions.

The workshop was open to all interested scientists. About 40 attended, representing all disciplines but mainly drawn from the field of physical oceanography. This report includes summaries of the five keynote addresses to the workshop participants, reports of the five Working Groups, and a Science Prospectus prepared by the Workshop Committee. The Science Prospectus has been reviewed by an interdisciplinary group of scientists who did not participate in the Workshop.

Workshop participants drafted three broad questions:

1. How does freshwater inflow interact with winds, topography, and tides to produce across-margin transport of materials?
2. How are primary and secondary production influenced by freshwater inputs?
3. How are transport and transformation of dissolved and particulate materials affected by freshwater inflows?

Within these, more specific questions were developed, as described in the Science Prospectus section of this report.

Workshop participants did not reach a consensus on the optimal study region for the investigation of processes related to freshwater inflows. It was agreed that several criteria should guide the selection of a study site, including: buoyancy-influenced flow should be a major component of the coastal current, the dissolved and particulate material delivered by the river(s) in the study region should be in sufficiently large quantity to make detection and quantification of cross-margin transport possible, and there should be evidence that biological communities are influenced by the freshwater inflow. Further, the study will necessarily be constrained by the resources available,

and a site or sites appropriate to those constraints should be chosen. Limited resources can be augmented by collaboration with other ongoing or planned programs.

Certain areas should be considered for funding before a major process study is initiated. Retrospective syntheses of existing knowledge of buoyancy-influenced systems are needed to help identify critical regions and processes for further study of cross-margin transport. Targeted modeling studies should examine the relative influences of buoyancy inflows, winds, and tides in several different systems. Models of the interactions of plumes with the surrounding ocean need improvement. Analyses of sediment cores or other long-term records could better define the location and temporal variation of terrestrial materials in continental margin sediments or changes in precipitation or winds. A synthesis of satellite data, to gain a better understanding of buoyant water dynamics, would be helpful.

The components of a study of transport and transformation processes over continental shelves with substantial freshwater inflows will vary with the specific questions and regions being investigated. However, the following were identified as likely elements: characterization of the boundary conditions, including the freshwater inflow and wind forcing; characterization of the buoyant water and its biological communities with a variety of approaches suited to a range of spatial and temporal scales, including moored instruments, shipboard observations and experiments, drifters, and remote sensing; studies of the benthic boundary layer and sea bed; tracer studies of cross-margin transport; and interdisciplinary modeling.

## **Introduction**

### **A. CoOP Background**

The coastal ocean is a complex zone where biological, chemical, geological and physical processes are strongly influenced by the land, bottom sediment, and atmosphere boundaries, as well as interactions with the open sea. While coastal ocean studies from the perspectives of single disciplines have yielded a valuable body of knowledge, essential for the design of future research, they have also revealed that many important questions must be addressed using an interdisciplinary approach. The need for improved understanding of the coastal ocean is urgent, since this ocean region has special importance to society. For example, humans need to make wise use of coastal ocean fishery and petroleum resources, while coping with the hazards the ocean can pose to the 50% of the U.S. population that lives near the coast. Humans must understand the coastal ocean to minimize adverse impacts due to coastal engineering projects, changes in freshwater drainage, pollution, and introduction of exotic species.

Coastal Ocean Processes (CoOP) is a program that seeks to plan and implement multi-investigator, interdisciplinary research in the coastal ocean. CoOP planning and research activities have included scientists from the disciplines of Biological, Chemical, Geological, and Physical Oceanography and Marine Meteorology. CoOP defines the

coastal ocean as extending from the surf zone to the continental rise. CoOP also includes large, inland bodies of water, such as the Great Lakes, that exhibit processes similar to those in the oceans. The overall CoOP goal is to "obtain a new level of quantitative understanding of the processes that dominate the transports, transformations, and fates of biological, chemical, and geologically important matter on the continental margins" (Brink et al., 1992).

The coastal ocean is too diverse and vast to allow comprehensive study of all regions. The original CoOP Steering Committee decided that the most cost-effective and fruitful approach would be to intensively study coastal regions where one physical process dominates cross-margin transport, so that the effects of that process could be identified and quantified in relative isolation. CoOP-sponsored research includes process studies and well-integrated modeling that aim to produce an interdisciplinary synthesis of the results of each regional study and a means of generalizing those results to other areas. The CoOP Science Prospectus (Brink et al., 1992) originally proposed five shelf types for study:

- Wind-driven shelf regions: Currents and current variability are primarily caused by winds, either local or remote, on time scales longer than one day. Seasonal upwelling is found over many of these shelves, including those off Washington and Oregon, Portugal, Southwest Africa, and western South America.
- Tidally-driven shelf regions: Over these shelves, strong tides determine mixing processes and mean flows. Examples include Georges Bank and the Bering Sea.
- Buoyancy-driven shelf regions: Fresh-water discharge from rivers creates an alongshore flow. In areas where the freshwater influx is large, such as the coastal Gulf of Alaska or the northeastern Gulf of Mexico, the effects can dominate the entire shelf.
- Western boundary current shelves: Transport over these shelves is influenced by strong offshore ocean currents, such as the Kuroshio or the Gulf stream, and by eddies that originate from these currents. The Atlantic coast of the U.S. is a prime example.
- Ice-covered shelves: The Great Lakes and the Bering, Chukchi, and Beaufort Sea coasts of Alaska are seasonally ice-covered. Ice strongly affects air-sea exchange of heat and momentum. Sea ice formation results in formation of dense water masses with elevated salinities due to brine rejection.

Although the ideal is to study regions dominated by one of these physical processes, in reality winds and tides are present to some degree everywhere. So, CoOP has attempted to select areas where other influences are minimized compared to the target process of a particular study. To date, CoOP has initiated major process studies of cross-margin transport processes in the Great Lakes and wind-driven transport processes in the northeastern Pacific. Both of these studies were initiated with a

community workshop, open to all interested in the regional coastal ocean processes. Based on input received at these workshops, plus reviewer comments, reports describing the important regional questions and possible research approaches to those questions were prepared by a committee selected by the CoOP Steering Committee.

The CoOP Steering Committee chose buoyancy-driven shelf regions as the topic for the next community workshop. The Buoyancy-Driven Transport Processes Workshop was held in Salt Lake City, Utah, October 6-8, 1998. This report includes synopses of five keynote presentations; summaries of working group discussions at the workshop; and a science prospectus. The prospectus was written by the Workshop Committee, based on working group and plenary discussions and modified in response to reviewer and community comments on a draft version of this document.

## **B. The Workshop Goal and Charge**

The overall question addressed by the workshop was: **How do processes on shelves with large freshwater inflows affect cross-margin transport of biologically, geologically, and chemically important materials?** More specifically, the charge to the Working Groups was to identify the most important questions relative to processes within their purview. The Working Groups were originally organized around themes related to boundaries and processes, and the reports they generated were titled: "Wind Effects on Freshwater Outflow Plumes", "Freshwater Input", "Fronts and Eddies", "Benthic-Pelagic Coupling", and "Biogeochemical Processes on Shelves with Large Freshwater Inflows". In addition to addressing the overall question of buoyancy effects on cross-margin transport, the Working Groups were asked to explicitly address the following in their discussions and eventual report:

- Identify and prioritize (and provide justification for the ranking) of the most important science issues. Working Groups should arrive at a group of top-priority questions, plus a list of other important issues.
- Identify appropriate locations for studying the questions you identify as important. What are the generic characteristics of the "ideal" site. Which real-world sites approach this ideal?
- What data are essential? What will data gathering require in terms of platforms and instruments (especially if the requirements are unusual)? What frequency/duration of data gathering is necessary to characterize key processes?
- What needs to be done to develop appropriate physical models of buoyancy-driven transport? Can current models adequately describe key biogeochemical processes, and can these models be incorporated in appropriate physical models?

## **C. The Workshop Structure**

The workshop was open to all interested scientists; an invitation was widely distributed via the CoOP Newsletter and website (<http://www.hpl.umces.edu/coop/>). About 40 scientists attended. Most attendees (see Appendix I) were from the field of physical oceanography, but all disciplines were represented.

A plenary session was held the first day. It included a brief welcome and introduction to CoOP, the five keynote talks (see Section 3. of this report), and the charge to the Working Groups. The Working Groups met that afternoon, with the charge to identify the most important scientific issues that should be addressed by an interdisciplinary research program in a coastal region with substantial freshwater inflow. The Working Group chairs or Rapporteurs briefly reported their discussions at a plenary session beginning the second day. Then, participants adjourned to the Working Groups for more specific discussions on prioritization of research questions, likely study locations, data needs, and modeling requirements. All participants except the Chairs and Rapporteurs were free to attend a new group the second day. The discussions were reported at a plenary session beginning the third day, followed by a general discussion that reached substantial agreement on an outline of key elements of the workshop report. No agreement was reached on the optimal study site or sites. The workshop recommendation, followed in the Science Prospectus, was to include criteria that should guide site selection and examples of potential process study locations, without indicating a preferred site.

The Workshop Committee prepared a draft Science Prospectus and submitted it to the CoOP steering committee for review, along with the Working Group Reports. After revision in response to comments of the Steering Committee, the draft Science Prospectus was sent to reviewers selected to represent a broad cross-section of the coast marine science community. The draft was also placed on the CoOP website for public review and comment. This final version incorporates, as much as possible, all input that the Workshop Committee deemed relevant to this report.

## **I. Science Prospectus**

### **A. Motivation**

#### **1. Introduction**

Coastal ocean regions with large freshwater inflows are major gateways for the transfer of materials from continents to oceans. These coastal regions include vast deposits of terrigenous sediments that accumulate much of the dissolved and particulate materials delivered by streams and rivers. Large natural variations in the quantity and timing of freshwater inflow, winds, and other factors lead to great variability in the amount and location of sediment deposition. Such natural variability also affects the quantities of dissolved and particulate material that are transported across the margin to the open sea. In part due to nutrients supplied with the freshwater, these areas tend to be highly

productive and to support major fisheries that exhibit poorly understood variability. Some of these fisheries have declined due to overfishing, poor water quality, habitat destruction, and natural environmental change.

Shelves with large freshwater inflows are among those most affected by human activities. Lands bordering most major rivers and river mouths are human population centers, due to the fertile river floodplain soils and the ready access to shipping. Human impacts include eutrophication, caused by nutrients originating mainly in fertilizers and sewage. Eutrophication has led to near-bottom hypoxia over large areas of the northeastern Gulf of Mexico shelf (Rabalais et al. 1996). Anthropogenic nutrient inputs may also be a cause of increased duration or frequency of harmful algal blooms (Smayda and Shimzu 1993; Smayda 1997). Toxic pollutants, including pesticides, herbicides, petroleum components, and heavy metals, are often carried by the freshwater discharge. The freshwater influx itself, and the associated sediment load, have been greatly altered in some regions by agricultural irrigation, dams, and construction of levees and dikes that prevent natural flooding and migration of the river channel. Draining and filling of coastal wetlands has destroyed critical habitat for some marine species and has changed the character of freshwater inflow that no longer passes through coastal marshes. Large oil spills have impacted the Prince William Sound/Gulf of Alaska Region (*Exxon Valdez* oil spill) and the southeastern Gulf of Mexico (*Ixtoc II* well blowout). Oil and gas extraction has been suggested as one cause for gradual subsidence of the Mississippi Delta region.

Long-term, natural variations in climate, through changes in precipitation, ice volume, and sea level, have caused large variations in the location of freshwater discharge and sediment accumulation over the continental shelf and slope during the Pleistocene. Climatic warming, due to anthropogenic greenhouse gases, is projected to lead to a sea level rise of about 30 cm during the next century, with potentially much greater changes occurring over the next millenium (Warrick et al. 1996). Even the modest sea level change projected for the next 100 years will have marked effects on coastal erosion and wetlands for low-lying coastal regions such as the Gulf of Mexico. Substantial changes in global precipitation patterns are likely to occur in association with global warming (Kattenberg et al. 1996). Such changes could lead to marked alteration in freshwater discharge and material transport in continental margins with substantial freshwater inflows.

## 2. Characteristics of selected U.S. shelf regions with substantial freshwater inflows

The northern Gulf of Alaska, the Texas-Louisiana shelf, and the Washington-Oregon shelf are the U.S. regions receiving the largest freshwater inflows; the Delaware River and adjacent shelf is an example of a smaller system. The characteristics of the northern Gulf of Alaska, the Texas-Louisiana shelf, the Washington-Oregon shelf, and the Delaware are summarized in Table 1. An expanded table is given in Appendix I. Comparison of these specific cases is not intended to indicate that CoOP is uninterested in the impact of the many smaller rivers that were not specifically included. Small rivers can exert a pronounced influence over a small area, and their flood discharge can be comparable to that of major rivers, greatly expanding their regional

impact for short periods. Numerous small rivers draining into a coastal region can produce a strong, buoyancy-driven coastal current, as occurs in the Gulf of Maine. However, it is not possible here to comprehensively review all of the available information about smaller rivers; there are many examples discussed in the Working Group Reports and the summaries of several Keynote Talks. Most of the processes highlighted in this limited comparison also occur due to smaller river discharges.

The freshwater entering the northern Gulf of Alaska is supplied by numerous small rivers draining steep, mountainous terrain. The main source of freshwater to the northern Gulf of Mexico is the Mississippi-Atchafalaya River system, which drains 41% of the continental U.S. The Columbia River is the predominant source of freshwater to the west coast of the continental U. S., and the Delaware to the mid-Atlantic bight. The Alaska Coastal Current, flowing counterclockwise along the eastern and northern boundaries of the Gulf of Alaska, integrates the freshwater discharge along more than 1500 km of coastline. Indeed, the low-salinity coastal circulation in the Northeast Pacific is apparently continuous from the Columbia River to the Bering Sea (Royer, 1998). The Mississippi-Atchafalaya discharge also influences shelf waters over large regions both west and east of the Mississippi River delta (Dinnel and Wiseman, 1985; Wiseman and Garvine, 1995). As a result of entrainment by the Loop Current, low salinity water linked to the Mississippi discharge has been observed as far away as the Straits of Florida (Gilbert et al. 1996). The salinity minimum associated with the Columbia River plume often extends to the Strait of Juan de Fuca in winter, merging with freshwater sources there and farther north. In summer, the plume extends south, influencing the region off Oregon and reaching northern California waters (Barnes et al. 1972). All of the regions show pronounced seasonal variation in discharge; the maximum is in spring for the Mississippi (Murray 1998) and Delaware, fall for the Gulf of Alaska rivers (Royer 1981), and winter and early summer for the Columbia (Hickey et al. 1998).

**Table I. Characteristic parameters for selected buoyancy-influenced systems.**

Parameter	Alaska Coastal Current	Columbia River and Coastal Current	Delaware River	Mississippi River and Texas-Louisiana Coastal Current
Type of freshwater inflow	Distributed	Point	Point	Point
Estuary?	Varies	Yes	Yes	Mississippi, salt wedge Atchafalaya, Yes
$T_{fw}$ , annual mean freshwater volume flux	23,800 m <sup>3</sup> /s	7,000 m <sup>3</sup> /s	650 m <sup>3</sup> /s	19,000 m <sup>3</sup> /s
D, water depth beneath plume	180 m	20-100 m (winter) >1000 m (summer)	20 m	20 m
H, buoyant plume thickness	10-50 m	20 m	10 m	10 m
$r_i$ , internal Rossby radius <sup>a</sup>	8 km	15 km	6 km	12 km
W, shelf width	160 km	40 km	120 km	200 km
dz/dy, offshore bottom slope	0.012	0.004	0.001	0.001
U, typical current speed	0.25 m/s	0.40 m/s	0.08 m/s	0.22 m/s
Typical tidal velocity	0.08 m/s	0.5 m/s	0.24 m/s	0.06 m/s
$V_E$ , Typical Ekman transport <sup>b</sup>	1.4 m <sup>2</sup> /s	1.0 m <sup>2</sup> /s	1.0 m <sup>2</sup> /s	1.6 m <sup>2</sup> /s
X, alongshore length scale <sup>c</sup>	1500 km	300 km (winter) 500 km (summer)	100	50-100
Suspended sediment concentrations	200 mg/liter <sup>d</sup>	10 to 40 mg/liter	Low	10 to 300 mg/liter
Nitrate conc. in freshwater	5 $\mu$ M	<5 $\mu$ M	50 to 150 $\mu$ M	20 to 200 $\mu$ M

<sup>a</sup>  $r_i = (g'H)^{1/2}/f$ , the internal Rossby radius. The across-shelf scale of the buoyant water tends to be similar to  $r_i$ .

<sup>b</sup> The across-shelf Ekman volume flux  $V_E = \tau^w/(\rho f)$ , where  $\tau^w$  is the magnitude of the alongshelf wind stress and  $\rho$  is the water density. An appropriate scaled version of the Ekman flux is  $V_E / (HU)$ . For large values of this parameter, wind forcing should dominate over buoyancy forcing, while for small values, the reverse is true.

<sup>c</sup> The buoyant water influences different areas of the Washington-Oregon margin during summer and winter, due to a seasonal shift in prevailing winds. The plume extends to the north of the estuary in winter and to the south in summer.

<sup>d</sup>This estimate was obtained by dividing the regional shelf and slope sediment accumulation rate (Jaeger et al., 1998) by the annual freshwater discharge. As biogenic components are minor, this is a reasonable estimate of the mean sediment concentration in the discharge; however, the concentration is highly variable.

A distributed freshwater source can be idealized as a line source and a discrete inflow idealized as a point source. Other well-known distributed sources besides those of the Alaska Coastal Current (Royer, 1982) are associated with the Norwegian Coastal Current (Mork, 1981) and the freshened nearshore waters in the South Atlantic Bight (Blanton and Atkinson, 1983). Additional examples of discrete sources include the Amazon, the Rhine plume (Simpson and Souza, 1995) and the extremely variable Eel River (Geyer et al., 1998). The term "plume" is commonly applied to the buoyancy-influenced water extending from a discrete source, but this terminology is not appropriate for distributed sources. In the following discussion, "buoyant water" is used to refer to marine waters influenced by either a line or point source.

Another property of the inflow is the discharge angle, the angle between the direction of the exiting freshwater and the regional coastline. Commonly this angle is about  $90^\circ$ , but natural sources often differ substantially. The Changjiang River discharge angle is about  $45^\circ$  (Beardsley et al., 1985), while that of the Delaware is about  $35^\circ$ . Models indicate that the plume is closer to the coast when the discharge angle is less than  $90^\circ$  (Garvine, 1987) and the discharge angle can also affect plume response to winds (Thompson et al., 1991). The discharge angle, along with other factors, influences whether the plume has a significant turning region or bulge near its source.

Currents result both from the positive buoyancy inputs and winds. Royer (1981, 1998) has reported current speeds of  $180 \text{ cm s}^{-1}$  in the Alaska Coastal Current, but the relative contributions of wind and buoyancy forcing are unknown. The prevailing winds, on average, reinforce the buoyancy component of the coastal current (positive wind stress curl), but are strongest in winter, which corresponds to the minimum in freshwater inflow. The average coastal winds in the Gulf of Mexico are also downwelling favorable and tend to reinforce any buoyancy-driven flow, but the mean basin-scale wind stress curl is negative. Northerly wind events occasionally force the Mississippi plume directly southward across the Gulf of Mexico. Such cross-shelf winds are rare in the Gulf of Alaska because of the coastal mountains, although wind-blown dust plumes from the Copper River Valley have been observed crossing the shelf and extending well out to sea. Hickey et al. (1998) showed that the coastal current resulting from the Columbia River outflow was of similar magnitude to the wind-driven current,  $20\text{-}40 \text{ cm s}^{-1}$ . The winter-summer reversal of Columbia plume direction is attributed partly to changes in wind direction. All river plumes also show short-term variations, on time scales of 3-10 days, in response to changing winds.

If the freshwater discharges onto a continental shelf, the shelf width,  $W$ , can vary from about 25 km, for the Columbia plume on the Washington shelf, to 100 km for the U.S. east coast and 500 km for the Bering Sea shelf. Dynamically,  $W/r_i$  (shelf width/internal Rossby radius) is the important characteristic. Because  $r_i$  sets the across-shelf scale for the buoyant water, if  $W/r_i$  is approximately one, the buoyant water should interact with shelf break processes. For large values, the buoyant water should behave independently of the shelf break. The across-shelf length will generally be a few  $r_i$ . For a discrete source, the alongshelf length is controlled by the mixing processes (Garvine, 1999), while for distributed sources, the source buoyancy distribution itself may control

the alongshelf length. Two prominent examples of the latter are the Alaska Coastal Current (Royer, 1982) and the Norwegian Coastal Current (Mork, 1981).

The degree of buoyant water bottom contact is clearly significant, for it determines whether benthic processes are directly coupled to buoyant water processes. The range of shelf bottom slope is huge, about  $10^{-3}$  for the U.S. east coast, but  $10^{-2}$  for the west coast. If bottom slope is large compared with the isopycnal slope, bottom contact is minimal and the buoyant water will be surface trapped, while if it is much smaller, bottom contact will be extensive and the buoyant water will tend to extend from surface to bottom. The Connecticut plume is a prime example of the former type (O'Donnell et al., 1998 and Garvine, 1974), the Rhine plume of the latter (Simpson and Souza, 1995).

The processes and magnitude of nutrient supply to the northern Gulf of Alaska, Mississippi, Columbia, and mid-Atlantic shelves differ greatly. The rivers draining the Alaskan coast have very low nutrient concentrations and are probably not a significant source (Sambrotto and Lorenzen, 1986). On the other hand, the bordering Gulf of Alaska is a HNLC (high nutrient, low chlorophyll) region where surface water nutrients are generally not depleted, apparently due to iron limitation of diatoms. The northern Gulf of Alaska experiences seasonal downwelling, not upwelling. Although the precise mechanisms are unclear, it seems that the relatively high shelf primary productivity results from nutrients supplied from offshore. The Columbia River has moderate nutrient concentrations that supplement nutrients from other sources, such as wind-driven upwelling in summer. The Mississippi River has very high nutrient concentrations, predominantly due to anthropogenic inputs that have doubled the annual average concentrations over the past 35 years (Turner and Rabalais, 1991; Bratkovich et al., 1994). The increase in nutrient concentrations has been accompanied by a change in the composition of nutrients (Justic et al., 1995). The Mississippi is a major source of nutrients to primary production in areas affected by the plume, although the relative magnitude of other inputs such as upwelling and benthic or water column regeneration are not well known (Lohrenz et al. 1997). Despite low light in the sediment-laden water, primary productivity can be high within the plume, though it is greatest just outside the plume boundary where light penetration is greater (Lohrenz et al., 1999). The mid-Atlantic bight is also a region of substantial anthropogenic nutrient sources, but there suspended sediment concentrations are low. Much of the nutrient influx may be trapped, at least initially, within estuarine sediment organic matter. Biogeochemical processes in estuaries can result in nutrients reaching the coastal ocean in different forms (such as DON and PON) and at different times than delivered by the freshwater sources.

All three of the U.S. regions with the highest freshwater inflows have significant fishery resources. The Gulf of Mexico has great diversity at higher trophic levels, and this diversity is reflected in its fisheries, which include annual landings of >\$10,000,000 for blue crab, red grouper, spiny lobster, Atlantic menhaden, oysters, several shrimp species, and tuna. There has been substantial recent concern about the potential ecosystem effects of summer hypoxia in the near-bottom waters of the Louisiana shelf, due to elevated nutrient levels in the Mississippi (Rabalais et al. 1996). Other fisheries-related concerns include losses of wetland habitat, which is essential to over 90% of

commercially or recreationally important marine species at some life stage. Decreases in fishery productivity and yield are also occurring, apparently due to overexploitation and bycatch (Kumpf et al., 1999). The continental shelf of the northern Gulf of Alaska is very productive at higher trophic levels (Sambrotto and Lorenzen, 1986). It serves as the nursery area for many commercially important species, including salmon and pollock (NOAA Atlas of Biological Resources). The shelf's mesozooplankton assemblage is homogenous over most of the Gulf's coastline and reflects exchange between oceanic and shelf populations (i.e., exchange across the two current systems, the Alaska Coastal Current and the shelf break/continental slope Alaska Current; Cooney, 1986; Napp et al., 1996, Incze et al., 1997). In the open Gulf of Alaska, decadal scale change in zooplankton standing stock has been documented and hypotheses attribute the change to climate variability associated with the Regime Shift, a late 1970s change in the intensity of the Aleutian low pressure system, wind patterns, and sea surface temperatures (Brodeur and Ware 1992; Hare and Francis, 1995). The Regime Shift has also been correlated with changes in several major Gulf of Alaska and Bering Sea fisheries. The 1977-78 Regime Shift appears to be part of a longer-term climate pattern exhibiting variation on decadal scales. Despite the evidence that the open regions of the Gulf respond to changes in climate, climate-induced change has not been documented for the coastal region. Historically, salmon catch has varied in a seesaw pattern between the Pacific Northwest and Alaska, with highs in one region being associated with lows in the other. Presumably, this correlation stems from a regional climate pattern, but its origins are unknown and are one subject of a recently initiated fisheries oceanographic study (GLOBEC). Pacific Northwest salmon fisheries have been severely damaged by human activities in or near freshwaters where migration and spawning occur, such as logging and the construction of hydroelectric dams.

The Mississippi, Gulf of Alaska rivers, and the Columbia all carry substantial loads of suspended sediment. In the case of the Gulf of Alaska rivers, the sediment is partly derived from glacial weathering and partly from intense physical weathering of the mountainous coast. Both the Columbia and the Mississippi drain farmlands, where tilling of the soil increases its erosion rate. Sediment transport by the Columbia has been more affected by dams for hydroelectric power generation, while the channel of the Mississippi has been extensively modified by a variety of engineering projects directed toward flood control, improved access by ships, and other ends. Sediments from the Columbia are found in extensive shelf mud deposits extending mainly to the north of the mouth. Upwelling conditions result in offshore transport of sediments in surface waters; under downwelling conditions most sediment transport is in the bottom boundary layer. Mississippi sediments accumulate in a vast delta relatively near the mouth, but relative rates of deposition, redistribution, and burial may vary on time scales of days to decades (Dagg et al. 1991). The Atchafalaya, which carries about 30% of the combined Mississippi- Atchafalaya discharge, supplies sediments to a coastal mud stream which extends westward along the Texas coast. The fate of sediments in the northern Gulf of Alaska varies with location. The largest quantity accumulates in the Copper River Delta, and the remainder is trapped within fjords, accumulates in glacially-cut troughs in the shelf and slope, or is transported westward by the Alaska Coastal Current (Molnia, 1989; Jaeger et al., 1998).

In the Gulf of Alaska, eddies are an important mechanism for cross-margin transport. They provide a connection between the narrow (15-20 km) Alaska Coastal Current (ACC), augmented by river runoff as it flows along the coast, and the Alaska Current that carries oceanic water above the continental slope. Past, sporadic observations show that eddies are of sufficient scale to cross the shelf. Maps of suspended matter concentrations by Feely et al. (1979) in the Gulf of Alaska bight illustrate terrigenous material extending up to ~100 km seaward of the shoreline. Ahlnas et al. (1987) showed how suspended glacial sediments reveal complex eddy structures near Kayak Island which protrude seaward and force the ACC to separate from the coast. The eddies extended at least 50 km seaward to the 1000-m isobath and 50 km landward over the submerged Copper River delta. Utilizing NOAA-14 AVHRR images, Thomson and Gower (1998) produced a composite map of sea surface temperature for the entire Gulf which showed six anticyclonic eddies stretching along the coast from Vancouver Island in the south to Kodiak Island in the north. The eddies had an average radius of 80 km and a spacing of 250 km. It is clear that because of the eddies' ability to sweep material off the continental shelf, investigations of buoyancy-forced flow along the margin of the Gulf of Alaska must be conducted on spatial scales large enough to quantify and separate this effect.

Eddies of the Loop Current occur in the Gulf of Mexico and some of these interact with the continental margin. When this occurs, cyclone-anticyclone pairs can be generated and such features may transport high chlorophyll shelf waters offshore, in the form of a jet or squirt (Biggs and Muller-Karger, 1994). Vertical entrainment of nutrients may occur with such circulation features. Recent studies have suggested that small eddy interactions on the upper slope may play a role in movement of water on and off the shelf in the central and western Gulf of Mexico (Berger et al. 1996).

The northern Gulf of Alaska, Washington-Oregon margin, northeastern Gulf of Mexico, and mid-Atlantic bight are representative examples of regions with substantial freshwater inflows. In all cases, the freshwater appears to be responsible for a component of flow, but this is modified by wind-driven circulation. It is likely that there are times and locations where the buoyancy influx strongly influences alongshore flow, but also likely that there are times when wind is an important or even dominant influence. These sites have large differences in nutrient supply by the rivers, minimal for the Gulf of Alaska rivers, moderate for the Columbia, and large for the Mississippi and Delaware. The differing nutrient regimes probably have an important influence on the coupling of primary production to higher trophic levels. The regions also differ, in the same order, in the extent of human impact on the characteristics of the river inflow.

### 3. Need for a CoOP Process Study

There is a general lack of well-integrated, fully interdisciplinary studies in continental margin regions with substantial freshwater inflows. For example, the influence of the Mississippi-Atchafalaya discharge on the northern Gulf of Mexico has recently been the subject of major research efforts including NECOP (Nutrient Enhancement of Coastal Ocean Productivity), LATEX (Louisiana-Texas Shelf Experiment), the Gulf Hypoxia study, and others. However, NECOP and Hypoxia focused mainly on biology and

biogeochemistry, while LATEX emphasized physical oceanography. Similarly, the Columbia discharge has been studied mainly by small teams of investigators focusing on physical oceanography and sediment transport processes (Kachel and Smith 1989; Hickey et al. 1998), but there have been no major biological or geochemical studies in the past 30 years. The physics of the Delaware coastal current has been examined (e.g., Munchow and Garvine 1993; Sanders and Garvine 1996), but not in conjunction with biogeochemical studies. The situation for the northern, particularly the northeastern, Gulf of Alaska is somewhat different; there is a dearth of most types of oceanographic data.

It is a CoOP priority to study coastal regions with substantial freshwater inflows because these areas also offer a unique opportunity to address CoOP's broad goal of quantitative understanding of cross-margin transport. Freshwater delivers large quantities of many tracers useful for identifying and quantifying materials that traverse the continental margin. These include terrigenous organic matter, with molecular and isotopic composition distinct from that produced by marine phytoplankton, various radiotracers, and even simply the salinity decrease resulting from the freshwater itself. Another, related reason is that freshwater flow is the main process transferring materials from continents to the coastal ocean. Thus, regions with large freshwater inflows represent the likeliest areas for substantial cross-margin fluxes of terrigenous materials.

## **B. Questions**

### **1. How does freshwater inflow interact with winds, topography, and tides to produce cross-margin transport of materials?**

The system characteristics outlined in the previous section frame this question. Table 1 shows that there is a tremendous range among different systems in parameters that are likely to have a strong influence on the physical dynamics (Garvine, 1995). Below are examples of some of the more specific questions raised during workshop discussions.

*How do winds and buoyancy interact to produce cross-margin transport?* The along-coast pressure gradient associated with river inflow can drive a coastal current. However, wind also is generally important in driving the alongshore flow, as evidenced by observations and modeling studies (e.g., Fong, 1998). The interactions of wind and buoyancy forcing will substantially determine cross-margin transport as well. Away from river mouths, wind-driven upwelling and downwelling are the main mechanisms of cross-margin transport, as they are on most other shelves. However, the freshwater-influenced layer decreases the thickness of the Ekman layer, so that velocities are greater than in cases without such stratification. Downwelling promotes attachment of the buoyant water to the bottom and thus affects bottom boundary layer processes.

*What physical processes determine the mixing of buoyant water and its dissolved and suspended materials with ambient water?* Fronts are defined as regions where the horizontal gradient of a property, especially of water density, is large compared to

elsewhere, such as within the plume's interior. Much of the transfer of dissolved and particulate material presumably occurs through mixing across frontal boundaries. However, mixing processes in fronts have been studied relatively little, in part because they occur on temporal and spatial scales that are difficult to resolve with available instruments and sampling devices. The Connecticut River plume has very strong frontal boundaries (O'Donnell et al., 1998), and resolving the Connecticut plume front required sampling on less than 1 m intervals in the horizontal. The mixing processes commonly cited in the literature are tidal mixing, wind mixing, Ekman circulation, barotropic and baroclinic flow instabilities, and internal waves. The stirring action of the barotropic tides, especially near the bottom, tends to promote mixing of buoyant water and to reduce stratification. Simpson and Souza (1995) show a particularly clear example for the Rhine plume. Direct mechanical stirring by wind stress, including the effect of breaking wind waves, produces mixing near the surface. Simpson et al. (1993) show evidence of this mechanism for the Rhine plume. Straining of the plume by coastal Ekman circulation is also due to along shelf wind, but the stirring mechanism differs from that of direct wind mixing (Fong, 1998). Both barotropic and baroclinic flow instabilities are sometimes observed in large scale buoyancy driven coastal currents. The best known example is the Norwegian Coastal Current (Mork, 1981). Breaking of internal waves is an additional process. The relative importance of these mixing processes has not been assessed in a single system.

*What mechanisms lead to cross-margin transport via eddies?* Eddies can be of sufficient scale (similar to the Rossby radius) to span a shelf. Their quantitative importance in cross-margin transport depends on the frequency of occurrence and persistence of these features, as well as the quantities of material that they entrain from the buoyant water, and the shelf width. Shelf eddy formation is often attributed to fundamental instability in the along-shelf motion, and this hypothesis is consistent with model results. However, irregularities in bathymetry and the coastline are also important. Certain features are known to have associated, semi-permanent eddies such as those found near Kayak Island (Ahlnas et al., 1987), which protrudes into the Alaska Coastal Current. Such localized eddies are readily studied, but remote sensing of eddies via suspended sediment, temperature, or other signature properties will be essential to locate and study those that do not occur predictably. All-weather, near real time monitoring can be conducted using satellite microwave altimetry from TOPEX Poseidon and ERS-2 satellites.

*How do rare, extreme events impact cross-margin transport in regions with substantial freshwater inflows?* Severe storms, floods, and other extreme events may result in large transports of materials from land to the coastal ocean, and may also impact cross-margin transport. Shelves with substantial buoyancy inflows are particularly susceptible to extreme precipitation events, including those that occur inland, and in some systems these events dominate transport. By their nature such events are very difficult to study; even intensive monitoring programs may not document them, because conditions may preclude sampling or even data collection by moored instruments. In some systems, extreme events are fairly predictable (i.e., seasonal flooding) and are more amenable to study. For most systems, sedimentary and other long-term records may be the best tool for assessing impacts of extreme events.

*What are the characteristic dissolved and suspended materials in the freshwater?* The extent of characterization of dissolved and particulate materials carried by rivers ranges from substantial for the Mississippi to almost none for rivers draining into the Gulf of Alaska. Since the composition certainly varies markedly in time, and also among rivers when more than one is important, complete characterization of these sources is not feasible. It is clear that seasonal and other temporal variability must be addressed, especially during times of high discharge. Key properties must be identified that include those materials whose cross-margin transport is intrinsically important, and substances that are sensitive tracers of terrigenous materials.

*How does the coupling of buoyant water and benthic processes affect material transport?* The degree of buoyant water bottom contact determines whether benthic processes are directly coupled to buoyant water processes. Yankovsky and Chapman (1997) address whether a plume will be, in their terminology, surface advected, bottom advected, or intermediate. Surface advected plumes are the same as surface trapped plumes, while bottom advected plumes extend from surface to bottom and have dynamics controlled by the offshore advection of buoyancy in the bottom boundary layer. They find that if the ratio ( $\tau$ ) of typical buoyant water across-shelf isopycnal slope to the shelf bottom slope is less than 1, the plume is surface trapped and its surface front extends offshore in the anticyclonic turning region at least as far as  $4r_i$ . If  $\tau > 1$ , there are two possibilities. The isobath depth at which the plume bottom is trapped is  $(\tau)^{1/2}H$  (where  $H$  is the thickness of the buoyant water). If  $(\tau)^{1/2}H$  corresponds to an offshore distance greater than  $4r_i$ , then the plume is bottom advected. If the corresponding offshore distance is less than  $4r_i$ , then the plume is intermediate. The plume will have substantial bottom contact, but its farthest seaward extent will be found in the turning region at about  $4r_i$ . Yankovsky and Chapman addressed plumes that were unforced by wind stress, but alongshelf wind stress greatly impacts the plume vertical structure. Downwelling favorable winds tend to push the plume against the coast and to increase  $dy/dz$  appreciably, while upwelling winds tend to do the opposite (Fong, 1998).

## **2. How are primary and secondary production influenced by freshwater inputs?**

Freshwater inflows affect primary production and its linkages to higher trophic levels. Both phytoplankton and zooplankton can be influenced by stratification, mixing, and advection. Such processes will affect the distribution and abundance of organisms and the time-varying nature of environmental variables affecting growth and physiology. Key environmental variables such as temperature, salinity, light, and nutrient concentrations are subject to modification by inputs of freshwater. Such modifications can influence physiology at the level of individual organisms and ultimately affect the rates of biological processes such as photosynthesis, respiration, growth, grazing, and sinking.

The dynamic nature of systems subject to freshwater inputs poses a special challenge for the precise characterization of primary production and trophic interactions. Variations in rates of primary production are the result of variations in both biomass (e.g., chlorophyll) concentrations and biomass-specific photosynthetic rates (i.e., carbon

fixation, oxygen production). The amount of biomass at a given location is the result of a balance between inputs of biomass (i.e., in situ growth, advective inputs) and losses (i.e., sinking, grazing, advective losses). Four dimensional (space and time) characterizations of primary production must include some capability for extrapolation or prediction of the time-varying nature of biomass and photosynthetic rates as influenced by physical dynamics (advection), environmental conditions (temperature, salinity, light, nutrients) and their impact on biological variables (biomass, photosynthesis, respiration, growth, sinking, grazing).

Major issues related to trophic coupling between primary production and zooplankton include how primary production is processed by zooplankton and how zooplankton respond to spatial and temporal variations in primary production in the highly advective environments of freshwater-impacted ecosystems. Grazing losses can represent a substantial fraction of total primary production in these ecosystems (Dagg 1995; Fanenstiel et al. 1995). Food webs may be highly nonlinear as a result of interactions at a variety of trophic levels. Different approaches are required for the study of the different major zooplankton groups including microzooplankton, mesozooplankton and gelatinous zooplankton.

With these considerations, we pose the following subset of questions:

*How do sources and transformations control the availability of micro- and macro-nutrients?* Freshwater inputs differ both in the concentrations and composition of nutrients compared to that of coastal waters. High levels of nutrients associated with some large rivers can contribute to enhanced primary and secondary production. The extent to which such inputs are supplemented by other sources (e.g., upwelling, nitrogen fixation) and regenerated sources (benthic and pelagic) is a critical question for regions subject to freshwater inflows. Differences among sources in the concentrations and composition of both micro- and macro-nutrients may affect the degree and type of nutrient limitation, and influence spatial and temporal patterns of nutrient limitation. In addition to dissolved inorganic forms, dissolved organic matter and suspended particles may provide significant sources of nutrients. In systems having high phytoplankton productivity, nutrients introduced by freshwater inflows can be depleted within a limited spatial region. In such cases, the terrestrial nutrients impact the adjacent continental shelf and oceanic waters largely in regenerated forms. Thus, assessments of the influence of freshwater inflows on coastal and oceanic productivity should include efforts to understand mechanisms of along-shelf and cross-margin transport of organic matter, the associated nutrient regeneration rates, and the relative importance of regenerated nutrients for primary production in relation to other nutrient sources. Export of nutrients or biomass from continental margin waters to the deep ocean may be especially important in regions of freshwater inflows with narrow continental shelves. The cross-margin export of terrestrial nitrogen is especially important, as this may contribute to an enhanced uptake of atmospheric carbon dioxide by oceanic waters in which nitrogen is limiting. Both denitrification and burial lead to removal of fixed nitrogen in continental margin sediments, and these losses are greater in highly productive areas with large terrigenous nutrient inputs. Both of these processes should be considered in efforts to

determine the mass balance of nitrogen and its influence on carbon cycles (Christensen 1994).

*How is light availability affected by stratification, mixing, and turbidity?* Strong horizontal and vertical gradients in irradiance will occur in surface waters impacted by freshwater inputs due to the presence of high concentrations of optically active constituents associated with terrestrial run-off. These materials include suspended mineral and biogenic particles, plant pigments and colored dissolved organic matter (CDOM). As salinity increases along the mixing gradient, the attenuation of irradiance decreases due to particle settling, dilution of turbid freshwater with clearer coastal waters, and photochemical breakdown of pigments and CDOM. Biomass and productivity may reach maximal levels at intermediate salinities where irradiance attenuation decreases and nutrients remain high enough to support growth. Enhanced stratification of surface waters influenced by freshwater inflows may restrict the vertical excursions of materials within relatively thin surface layers and lead to elevated rates of photosynthesis and photochemical reactions.

*Why do rates of biological processes in river-influenced regions differ from those where there is no freshwater inflow?* Regions of large freshwater inputs represent particularly difficult environments in which to characterize primary and secondary production, because of strong gradients over relatively small spatial scales and rapid temporal change. The relative importance of physical and biological factors in determining biomass distributions and rates of biological processes remains a challenging problem. This is due primarily to two reasons. The first is that the highly resolved characterization of the three dimensional circulation of dynamic coastal environments, such as those associated with large freshwater inputs, represents a difficult physical problem. The second reason has to do with a historical lack of ability to sample biological distributions and processes on scales that complement physical measurements. It is likely that successful approaches to deal with the question of interactions between biology and physics problem will necessarily involve combinations of observations and modeling.

*How do processes of entrainment and transport of organisms interact with behavioral and physiological responses in influencing their distribution and abundance in regions of freshwater outflow?* The mechanisms whereby certain organisms maintain their distributions within dynamic regions of freshwater input are, in many cases, poorly understood. The sharp gradients in physical and chemical properties along mixing gradients of freshwater inflows are frequently associated with dramatic transitions in species composition as communities develop from freshwater to marine. Processes by which individual species become entrained within regions of mixing and the tolerance of individual organisms for growth over widely varying conditions will ultimately be important in determining the community composition. In addition to physiological tolerances of organisms, the role of factors such as phytoplankton motility and the ability to regulate sinking speeds through changes in buoyancy are poorly understood. These factors may be important in explaining accumulation of phytoplankton along density gradients subject to vertical shear. Similarly, zooplankton capable of active swimming may exploit the multidirectional nature of circulation in regions of freshwater outflow for

maintaining their locations within zones of optimum conditions for growth and recruitment.

*What is the nature of trophic interactions within convergence zones of buoyant water?* Accumulation of organisms in convergence zones is a common observation in regions of freshwater inflow (Grimes and Finucane, 1991; Govoni and Grimes, 1992). The enhanced concentrations of phytoplankton and other organisms frequently observed in these regions makes them potentially important zones for grazing. Yet studies of grazing and productivity of organisms within convergent fronts in regions of freshwater outflow are rare, and the significance of these features for coupling of primary production to higher trophic levels is uncertain.

*To what extent are community level changes in productivity and trophic interactions related to associated changes in community composition?* Because individual taxonomic groups will respond differently to the widely varying conditions, successful efforts for predictive modeling of community level primary and secondary production will ultimately require an understanding of responses to environmental variables at the level of individual algal and zooplankton taxa. Variations in productivity are often correlated with differences in species composition. For example, diatoms are frequently found to be prevalent in the region of high biomass and productivity of buoyant water (Cadee, 1975; Dortch et al., 1992), while cyanobacteria and phytoflagellates may be more important in regions of higher salinity and lower nutrient concentrations. Differences in phytoplankton community composition may also be accompanied by differences in zooplankton community composition. This, in turn, influences grazing and food web structure. For example, protozoan populations can respond rapidly to changes in phytoplankton abundance, but feed primarily on smaller phytoplankton (Dagg, 1995). Gelatinous zooplankton (larvaceans, salps, doliolids) can also have high population growth rates and may represent an important component of the grazing community (Zeldis et al., 1995). Mesozooplankton (e.g., copepods) grow more slowly and feed more efficiently on larger phytoplankton (Dagg, 1995).

*What is the significance of subsurface biomass maxima to water column primary and secondary productivity?* Subsurface biomass maxima are common features found in regions of freshwater inflow (Lohrenz et al. 1999). In many cases, multiple maxima occur at a given location and may be associated with different vertically interleaved water masses or their interfaces. Reasons for the existence of such features are not well known. The relative role of these features in contributing to integrated water column primary production has rarely been examined. Similarly, the significance of these features for grazers is not well understood, but may represent regions of high zooplankton activity. The origin and significance of these subsurface maxima can only be understood through comprehensive study of the three dimensional circulation and time-varying nature of biological processes.

#### **4. How are transport and transformation of dissolved and particulate materials affected by freshwater inflows?**

A combination of physical, chemical, geological, and biological processes in systems with substantial freshwater inflows transform materials as well as transport them. The questions below highlight the complexity of such problems and serve as a guide to some of the outstanding problems.

*What are the processes that affect the rates and locations of particle aggregation, disaggregation, and sinking?* Often 80-90% of the particulate material delivered to the coastal ocean from rivers is fine, suspended sediments. Due to the small settling velocity of fine particles, many reach the seafloor only after repackaging, and it is probably rare that fine particles reach the seabed as individual grains. Particle aggregation due to electrochemical processes has largely been considered a function of salinity, concentration of particles, and shear in the transporting fluid (Dyer 1986). Particles in the marine environment at low salinities tend to flocculate due to the suppression of the repulsion of the charged particle surfaces. However, aggregation can continue at higher salinities as a function of concentration and turbulent shear in the water column. The concentration of particles must be high enough that particles will come into contact with one another, and the turbulent shear acts to bring particles together, and if strong enough can also act to disaggregate particles. Organic coatings can enhance aggregation, and zooplankton can repackage particles into fecal pellets. Ultimately, the settling rate of particles is due to their size and density (and to a lesser extent their shape). Thus, the factors that influence aggregation act as an initial control on whether or not particles remain suspended in a plume or deposit to the seabed close to the river mouth. Information on these processes in buoyant plumes is limited (Syvitski et al. 1985; Hill et al. 1998), but it is clearly an area of primary importance for the transport of materials.

*What factors influence the rate and extent of adsorption and desorption reactions?* The processes of adsorption and desorption occur continuously and simultaneously and are likely a function of concentration (of both particulates and dissolved substances), salinity, and the degree of mixing due to turbulence. The removal of chemical species from dissolved to particulate phase, or the reverse, has been shown to be a function of salinity and may vary for different chemical species (e.g. trace elements, Shiller and Boyle 1991). The rates of these processes and where they occur will directly influence the delivery of materials to the seabed or the release to the water column in the coastal ocean. Salinity dependent interactions may occur rapidly in surface waters with initial mixing. Subsequent resuspension of bottom sediments will have an additional influence. Cycling of particle-reactive chemical species will be a function of how frequently sediments are introduced into different water masses. Time scales of many of the chemical processes are unknown, but could be coupled to time scales of sediment transport processes like resuspension.

*How are photochemical reactions affected by turbidity and stratification within the buoyant water?* Plume waters exposed to wind stresses will mix, continuously exposing waters of the plume to ultraviolet radiation (UV). The effects of mixing on UV absorption by dissolved substances are not well understood. Dissolved organic matter discharged by rivers includes photosensitive substances that are degraded and, sometimes, converted to more chemically reactive substances when exposed to light. River water may carry nutrients associated with DOM. If exposed to UV the nutrients could be transformed to a more available species (e.g., ammonium) in the plume and become available for phytoplankton uptake (Bushaw et al., 1996). Photochemical reactions can also change the oxidation state of metals. Clearly, it is an oversimplification to consider only light dependence of photosynthesis in assessments of biogeochemical cycling of materials.

*What are the dynamics of the benthic boundary layer?* In many cases, the greatest flux of sediment occurs within the bottom boundary layer, even with a pronounced muddy surface plume. On the Amazon shelf only ~15% of the sediment dispersal is via the surface plume or the shallow coastal mudstream and possibly 60-70% is via near-bottom transport in the form of fluid muds (Kineke et al. 1996). Recent observations on the California shelf as part of STRATAFORM show a mismatch between the locus of the flood deposit and the pathway of the surface plume (Wheatcroft et al. 1997, Geyer pers. comm.), again implying a subsurface dispersal route for the majority of sediments. For some cases the boundary layer engulfs the entire water column (e.g. a plume in contact with the bottom), but in other cases the stratification is great enough at the base of the surface plume that bottom stress has no effect on surface plume (e.g. the Amazon shelf, Lentz 1995, Lentz and Limeburner 1995). The Atchafalaya and Mississippi Rivers potentially provide examples of both situations within the same dispersal system.

*Where and how does sediment resuspension occur, and how does this process affect transport of particulate materials?* Storm waves are known to cause sediment resuspension to depths greater than 50 m on open shelves. Sediment resuspension can also result from a variety of other causes, such as bottom currents, including tidal currents; turbidity flows; and ice gouging. Except in the case of ice, which is nonselective, resuspension is a function of particle size, particle cohesion and the consolidation of the sediment deposit, and biological reworking and structuring. Sediment resuspension can result in further transport and redistribution of the sediment particles, but is also important because it enhances solute transfers from porewaters to the water column.

*What factors govern the formation, transport, and deposition of fluid muds?* High concentration sediment suspensions (fluid muds) have been commonly observed in estuaries worldwide. They can also occur on continental shelves and could serve as a major mechanism for dispersal of sediments (Wright et al. 1990, Kineke et al. 1996). Observations on the Amazon shelf dispelled the idea of sediments passively settling from the surface plume and creating a deposit in a region where bottom stresses due to waves or tides are low enough to allow accumulation (Kineke et al. 1996). Rather, sediments from the river are trapped at bottom salinity fronts forming dense, ~2 m thick

suspensions which migrate offshore to serve as the conduit for delivering sediments to the subaqueous delta in deeper water. Formation of fluid mud in the coastal ocean can be through fluidization of the seabed from pumping due to surface waves, or, perhaps more commonly, through a combination of processes that result in particles settling rapidly enough to inhibit self-weight consolidation. These processes include increased settling velocities of particles due to aggregation, settling due to relaxation of stresses (i.e. decrease in wind speed), or strong stratification at a plume liftoff point inhibiting turbulence generated at the seabed to be transmitted to surface waters.

*What is the role of hyperpycnal flows in material transport?* Besides the positively buoyant, hypopycnal plumes that carry sediment and are easily visible (and relatively easy to sample), plumes can also be negatively buoyant, or hyperpycnal. Although previously it has been thought that these are somewhat rare and are exclusive to hypersaline lagoons, rivers of extremely high sediment discharge, or extreme events (Wright 1985), Mulder and Syvitski (1995) identified over 70 moderately “dirty” rivers that probably produce a hyperpycnal plume every 100 years or less. The hyperpycnal plumes may form from elevated sediment concentrations during times of flood, causing the river to become denser than the water in the receiving basin. Hyperpycnal flows on shelves can result from other mechanisms including the trapping of sediments at salinity fronts as on the Amazon shelf (Kineke et al. 1996) or rapid settling at the river mouth. Once formed, the near bed flow is governed by bottom boundary layer processes. The Mississippi River could be a candidate for forming a hyperpycnal flow during the spring freshet when the salt wedge is pushed from the river mouth and sediments trapped at the nose of the salt wedge are flushed from the estuary. The occurrence of slumping from oversteepened sediments just off the mouth of the Mississippi implies rapid sedimentation rates, possibly too rapid to occur from passive settling from the surface plume. Hyperpycnal flows could be a mechanism to deliver sediments rapidly to the shelf edge.

*Where and how does remobilization of materials within sediments occur, and how does this process affect net and gross material fluxes at the sediment-water interface?* The decomposition of organic matter within sediments results in return of dissolved organic matter and inorganic carbon, nitrogen, and phosphorus to the water column, primarily via diffusion and bioirrigation, although upward advection of porewaters due to sediment compaction can play a role where accumulation rates are very high. Because the organic matter oxidation rate exceeds the rate of supply of oxygen via diffusion or bioirrigation, most coastal sediment deposits are anoxic within a few cm of the sediment-water interface. Within anoxic sediments, bacteria utilize nitrate, manganese, iron, sulfate, and finally organic molecules or carbon dioxide as electron acceptors, which can result in the release of reduced metals, sulfide and other reduced sulfur species, and sometimes methane from the sediment deposit (e.g., Henrichs and Reeburgh 1987). One broad effect of organic matter decomposition processes is that materials deposited to the sediments are often returned to the water column, if they are associated with organic matter or if they are more soluble in reduced than oxidized form. However, sediments topped with a relatively thick (several cm or more) oxic layer release much less of these reduced species, since they are generally oxidized by

bacteria within this layer. Metal-enriched surface sediment layers can form in these circumstances. Globally, the burial efficiency (net/gross burial flux) of organic matter is broadly correlated with sediment accumulation rate, a pattern that may be due to protective organic matter associations with clay mineral surfaces, but this relationship does not generally apply in deltas, where the accumulation rate of detrital clay minerals is extremely high (Mayer, 1993). The accumulation and decomposition rates of organic matter, the sediment accumulation rate, the extent and frequency of sediment resuspension, and the biomass and species composition of the benthic community are among the many variables that affect the quantity and nature of materials remobilized from the sea bed.

### **C. Plan of Action**

#### **1. Criteria for the Selection of Research Areas**

Although no consensus on the optimal study site or sites emerged, there were several criteria suggested that could help to guide selection.

- a. Buoyancy-influenced flow should be a major component of the coastal current, at least at certain times and places within the proposed study. It is recognized that there is probably no "pure" case of buoyancy-driven flow.
- b. The dissolved and particulate material delivered by the river(s) in the study region should be in sufficiently large quantity to make detection and quantification of cross-margin transport possible.
- c. There should be evidence that productivity or structure of biological communities or cross-margin transport of organisms is influenced by the freshwater inflow.
- d. The spatial and temporal scale of the study will necessarily be constrained by the resources available, and a site or sites appropriate to those constraints should be chosen.
- e. Limited resources can be stretched by collaboration with other ongoing or planned programs, funded through NOAA, EPA, MMS, ONR or a collaborative mechanism such as NOPP.

#### **2. Preliminary Research**

- a. Retrospective syntheses of existing knowledge of buoyancy-influenced systems are needed to help identify critical regions and processes for further study of cross-margin transport. Most of the existing literature describes single systems, and the few intercomparisons (e.g., Garvine, 1995) focus on physical oceanography. Such syntheses will be most useful to CoOP if, collectively, they address biological, chemical, and geological processes as well as physical oceanography and meteorology.

- b. Targeted modeling studies are needed to examine the relative influences of buoyancy inflows, winds, and tides in several different systems, and how these vary seasonally. Such studies will serve to clarify when and where buoyancy influence is likely to be strong and transport processes can be examined with lesser influence from other forcings. Conversely, models could identify other times and places where interactions with winds could and should be the focus. Such a synthesis could be very useful in designing the field program.
- c. Models of the interactions of buoyant water with the surrounding ocean need improvement. Problems with current models include the turbulence closure schemes, which are derived from measurements of mixing in boundary layers over fixed surfaces, while the regions of interest here are free shear layers in highly stratified structures. Algorithms are needed to better maintain the integrity of frontal boundaries within models. A non-hydrostatic plume model may be required, since the large vertical velocities at frontal boundaries probably will not be well-resolved by hydrostatic models.
- d. Analyses of sediment cores, glacial ice cores, tree rings, or similar long-term records could better-define the location and temporal variation of terrestrial materials in continental margin sediments or changes in precipitation or winds. These could aid design of the research program, but would provide information useful to only one region.
- e. A synthesis of satellite data, including temperature, chlorophyll, and suspended sediments, in areas of major freshwater discharge, to gain a better understanding of buoyant water dynamics.

### 3. Boundary Conditions

#### *Freshwater source*

A fundamental requirement for this program is a thorough characterization of the freshwater inflow. The necessary data, of course, include the quantity of freshwater inflow, and its temporal (and spatial, in some cases) variability; nutrient concentrations; sediment load; and concentration and composition of potential chemical tracers (see 6. below). If the freshwater enters the ocean through an estuary, then the influence of estuarine processes on the inflow must be studied. Even when an estuary is absent, the monitoring station(s) must be close enough to the mouth (and the nearest shelf stations) so that substantial modification of the signal does not occur.

#### *Winds*

Wind forcing is probably important most of the time, even when freshwater inflows are large. Measurement of local winds during field studies is straightforward. Assessing the climatological winds over large regions is less so. Coastal winds are widely available for most study regions, although they may not strictly reflect offshore winds. The specification of the winds on sufficiently fine spatial scales may require using the

output of a high-resolution numerical weather prediction model. The northern Gulf of Alaska coast is very sparsely inhabited and coastal wind stations are few; further, they are subject to orographic effects. There, moored meteorological instruments could be crucial, although they are needed in all regions.

#### 4. Characterization of the buoyant water

The extreme spatial and temporal variability within dynamic buoyant water environments makes the objective for four-dimensional (space and time) characterization of properties particularly difficult. Innovative approaches using a combination of measurement platforms that sample over various spatial and temporal scales will be required for physical and biogeochemical observations. This could include fixed site measurements (e.g., moored instruments), ship-based underway and profiling instrumentation, autonomous underwater vehicles, drifters, and airborne and satellite remote sensing.

##### *Fixed-site measurements*

Fixed-site measurements, as with moored instrumentation, can be used to provide high resolution time series of properties. The major limitation of this approach is limited spatial resolution. Another limitation of moored observations for buoyant water studies is the difficulty or impracticality of placing sensors near the surface and bottom, where many of the important processes occur. Some acoustic or optical instruments will not function in water with high suspended sediment concentrations. Despite these limitations, time-series observations are invaluable in that they provide temporal continuity lacking in other measurements, which is essential for identifying episodic events and persistence of spatial patterns.

Useful information to be gained from moored instrumentation include observations of currents, tides, CTD (Conductivity-Temperature-Depth), nutrients, dissolved gases, plankton and optical properties. Acoustic Doppler current meters can provide current and zooplankton information, although use in some buoyant water environments may pose special challenges, especially where the buoyant water is confined to the upper 10 m of the water column. Newly available technology for time-series measurements of nutrient and dissolved gases will be invaluable. Newly developed fluorescence sensors for characterizing photochemical processes in phytoplankton may be useful for providing information about the photosynthetic rates and physiological status of the algal population. Optical sensors for determination of inherent and apparent optical properties may be used in a variety of applications, including measuring suspended sediment concentrations, development of remote sensing algorithms for estimation of biogeochemical constituents, and modeling of irradiance and photosynthesis.

##### *Ship-based measurements*

Two important approaches that will be important for ship-based measurements will be to provide quasi-synoptic descriptions of property distributions through rapid underway mapping and the ability to resolve and sample small scale vertical structure in physical

and biogeochemical properties. Underway sampling may include shipboard flow-through systems that characterize primarily surface properties and towed instrument packages capable of depth profiling. The latter may be highly effective in providing two- and three-dimensional visualization of property distributions. Autonomous underwater vehicles may also be particularly well suited to these environments. Although valuable in mapping many important properties, these systems may be limited for some applications. Depending on size and design, towed and autonomous systems may not be able to adequately sample thin surface layers often observed in freshwater plumes. In addition, distinct subsurface layers with high biomass may not be well resolved by these systems. Finally, some critical biological and chemical process rate measurements require stationary sampling for shipboard experiments and use of vertical profiling/sampling systems. Resolution of the highly stratified and vertically heterogeneous environments found in freshwater outflow environments will require innovative designs in profiling instrumentation and sampling gear. Such systems must be able to operate with high vertical resolution and be free of ship motion and perturbations.

### *Drifters*

Drifter studies are extremely valuable in providing information about flow fields in a Lagrangian reference frame. By equipping such platforms with optical and other sensors, additional information regarding biogeochemical properties may be acquired. Lagrangian observations are especially useful for characterization of transit times and temporal scales of variation in properties within different regions of the salinity gradient. The value of such measurements is enhanced if observations are complemented by supporting information such as satellite or aircraft-based observations.

### *Remote Sensing*

Remote sensing has provided unprecedented views of the spatial and temporal patterns of freshwater impact on coastal environments. The information provided on synoptic scales about regional patterns has been particularly useful in relating freshwater distributions to variations in meteorological forcing and regional circulation. Such information can also be invaluable in guiding surface sampling and for interpolation of shipboard and fixed-site measurements. However, a serious limitation is that sea surface temperature and ocean color observations are limited to clear weather. Much work remains in the development of capabilities to derive quantitative information about biogeochemical constituents. The highly turbid conditions of many large freshwater sources require the development of specialized algorithms and extensive “ground truth” validation.

A variety of remote sensing technologies may be applicable to the planned study. Ocean color and sea surface temperature have proven valuable in the study of many systems. Ocean color data is currently available from the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) on board the SeaStar satellite, and many new ocean color sensors, both airborne and onboard satellites, are being developed (IOCCG, 1999). These include several hyperspectral (high spectral resolution) ocean color imaging

systems. AVHRR (Advanced Very High Resolution Radiometer) imagery continues to be enhanced with the newly launched NOAA-15 satellite. In addition to ocean color and AVHRR, there are other promising capabilities in remote sensing that may be useful for this study. Airborne salinity sensors have shown promising results in coastal environments (Miller et al. 1998). Such sensors have the advantages that they are less restricted by cloud cover. In addition, salinity is an important physical variable in these systems as temperature gradients may be relatively small and less important in influence baroclinicity. Finally, other remote sensing technologies may prove useful. For example, coastal high frequency radar may be an especially valuable tool for monitoring surface waves and currents in near shore environments. Synthetic Aperture Radar may also be useful in characterizing waves, currents and internal waves. GOES (Geostationary Operational Environmental Satellite) imagery will be important for meteorological studies.

### *Meteorological and Hydrological Observations*

An essential component of any program attempting to determine the impact of freshwater outflow on coastal processes will be a complete suite of meteorological and hydrological information. Information about winds will be especially important in efforts to develop circulation models. River discharge rates and will be required to characterize source terms. A modest set of additional atmospheric observations will probably be warranted. These observations should be designed to provide direct estimates of the meteorological forcing in selected locations. Perhaps more importantly, they will also provide validation data sets for assessing the fidelity of NWP (Numerical Weather Prediction) models. Once a NWP model is shown to reasonably reproduce the actual meteorological forcing, its output provides a complete and convenient way to drive physical oceanographic models.

### *Numerical Modeling*

Modeling will be an integral part of efforts to characterize the buoyant water environment. An observational program, no matter how extensive, cannot be expected to provide a fully four dimensional characterization of the buoyant water circulation. Coupled physical-biogeochemical models will provide an invaluable interactive tool, which can be used to develop and test hypotheses regarding the roles of physics, biology and geochemistry in giving rise to observed distributions. More specific models will be useful in describing meteorological processes, sediment transport, the optical environment within the buoyant water, the associated rates of primary production and the relationships between optically-active biogeochemical constituents and remotely-sensed observations. Data assimilation techniques may serve as a useful complement to modeling efforts.

It is not clear how well existing turbulence closure schemes will perform in regions with freshwater inflows, where there can be strong stratification and shears in the interior of the water column, since these schemes have previously been used mainly to model surface and bottom boundary layer situations. Models of turbulence closure in such situations need to be developed and verified. Also, a nonhydrostatic buoyant water

model should be developed. The large vertical velocities expected at frontal boundaries are not anticipated to be well resolved by hydrostatic models. Algorithms are needed that better maintain the integrity of frontal boundaries within models; fixed grids tend to rapidly diffuse strong frontal boundaries.

#### 5. Studies of the benthic boundary layer and seabed

Studies of surface sediment properties related to their potential for resuspension or fluidization will be important to evaluate the role of these processes in sediment transport and accumulation. Studies of sediment cores to characterize biogeochemical processes and the sources of material to the sediment (see tracers, below) are also a key element of this study. Collection of undisturbed sediment samples including the poorly consolidated sediment-water interface will be crucial.

The dynamics of the benthic boundary layer (BBL) have been mainly been studied from fixed instrument packages (tripods and similar platforms) deployed on the sea floor. This may not be optimal when the interactions of moving buoyant water with the bottom need to be followed. ROVs or AUVs could potentially be more useful.

#### 6. Tracers

For testing inferences from spatially and temporally limited data and validating models, chemical tracers that reflect net transport over time and space could be particularly useful. Field experiments will necessarily be limited to a few months of ship time per year. Though this can be distributed in time to maximize sampling of temporal variability, and temporal continuity of data can be improved using moored instruments, gaps will remain. Likewise, even the combination of shipboard sampling, moored instruments, and remote sensing will provide incomplete spatial coverage. Both added tracers and natural tracers could help to overcome these limitations. Added markers could assist in tracking the buoyant water or its boundaries. Commonly used tracers include dyes, which have the advantage that they can be observed from aircraft, and sulfur hexafluoride, an inert compound that can be measured at extremely low concentrations by a rapid gas chromatographic technique that allows real-time mapping of the labeled water. No attempt will be made to list all of the potential tracers of terrigenous inputs and continental margin processes; rather, a few commonly-used examples will be given.  $\delta^{18}\text{O}$  is commonly used as a tracer of freshwater, since meteoric waters are significantly depleted in the heavy isotope. The waters draining into the northern Gulf of Alaska are very "light" isotopically, and therefore  $\delta^{18}\text{O}$  could offer a more sensitive tracer of freshwater than salinity. Further, certain benthic tunicates appear to incorporate the isotopic signature of the water in which they live (Grebmeier and Cooper, 1992), and this could offer a way of examining longer-term salinity variations over the shelf. Naturally-occurring radium isotopes, which have high concentrations in river water relative to seawater, have been used to examine the kinetics of desorption, and the fate of desorbed ions, in several river plumes (Moore, 1992). Comparison of  $^{234}\text{Th}$  and  $^{210}\text{Pb}$  sediment accumulation rates on the Mississippi shelf found the  $^{234}\text{Th}$  rate to be an order of magnitude greater (McKee et al., 1999). This was attributed to substantial remobilization of sediments on annual time scales.

The carbon and nitrogen stable isotope composition of terrigenous organic matter differs from that produced by marine phytoplankton, and can be used to differentiate the two sources. Biomarkers, particularly lignin oxidation products, can also indicate the presence of terrigenous plant material in sediment deposits (Hedges, 1977)

#### **D. Conclusion**

Freshwater inflow influences the transport and transformation of materials over vast areas of the U.S. continental margins. These shelves are gateways for the delivery of materials from the continents to the oceans. In most cases, human impacts on the amount and composition of the freshwater input to shelves are substantial. Freshwater-influenced shelves are important because of rich fisheries, major mineral and petroleum resources, and vital marine transportation routes, in addition to the large coastal populations found near most major rivers. Shelves with substantial freshwater inflows also offer an excellent opportunity to address the central CoOP goal, the quantitative understanding of cross-margin transport of materials. This is because the large signal provided in river-borne inputs of terrigenous materials will make offshore transport relatively easy to delineate using various natural tracers.

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## Appendix II. Expanded table of characteristic parameters for selected buoyancy-influenced systems.

The magnitude and geographic extent of the freshwater inflow provide some useful information, but the buoyancy effects on coastal dynamics can best be compared using the scaled quantities in Table 1. The dynamically relevant measure of the horizontal scale is  $K_i = L / r_i$ , the Kelvin number. Here  $r_i = (g'H)^{1/2}/f$ , the internal Rossby radius, and  $L$  is the horizontal scale of the source. The across-shelf scale of the buoyant water tends to be similar to  $r_i$ . Another useful scaled property is the freshwater volume flux  $T_i$  divided by the associated source geostrophic transport  $T_g$ , or  $t = T_i / T_g$ , where  $T_g = g'H^2/(2f)$ . Here  $g'$  is the reduced gravity of the source water,  $H$  its depth, and  $f$  the Coriolis parameter. This quantity is essentially the ratio of the freshwater influx to the total coastal current transport;  $t$  plays a prominent role in the modeling papers of Yankovsky and Chapman (1997), Garvine (1987), and Garvine (1999). For a two-layer idealization the stratification is described by the density difference,  $D\rho_s$ , the difference in density between the upper layer and lower layer. A more telling measure is  $D\rho_s / D\rho_i$ , where  $D\rho_i$  is the density difference between the inflowing freshwater and the mean shelf water. Measures of the importance of the tidal circulation are shelf tidal height amplitude /  $H$  or shelf tidal current amplitude /  $U$ , with  $U$  the typical freshwater source current ( $T_i / (HL)$ ). The former ratio can easily reach 0.3 in the Gulf of Maine, while it nearly vanishes in the Gulf of Mexico. The most important dimensional property related to wind mixing is the across-shelf Ekman volume flux  $V_E = \tau^w / (\rho f)$ , where  $\tau^w$  is the magnitude of the alongshelf wind stress and  $\rho$  is the water density. An appropriate scaled version of the Ekman flux is  $V_E / (HU)$ . For large values of this parameter, wind forcing should dominate over buoyancy forcing, while for small values, the reverse is true.

If the freshwater discharges onto a continental shelf, the shelf width ( $W$ ) can be an important parameter. It can vary from about 25 km, for the Columbia plume on the Washington shelf, to 100 km for the U.S. east coast and 500 km for the Bering Sea shelf. Dynamically,  $W/r_i$  is the important characteristic. As  $r_i$  sets the across-shelf scale for the buoyant water,  $W/r_i$  tends to measure the shelf width in buoyant water widths. For values of order one, the buoyant water should interact with shelf break processes, while for large values, the buoyant water should behave independently of the shelf break. The across-shelf length will generally be a few  $r_i$ . For a discrete source, the alongshelf length is controlled by mixing processes (Garvine, 1999), while for distributed sources, the geographic locations of the freshwater inflows may largely control the alongshelf length. Two prominent examples of the latter are the Alaska Coastal Current (Royer, 1982) and the Norwegian Coastal Current (Mork, 1981).

The degree of buoyant water bottom contact is clearly significant, for it determines whether benthic processes are directly coupled to buoyant water processes. A compact measure of this property is the ratio of the typical buoyant water across-shelf isopycnal slope,  $dy_i/dz$ , to the shelf bottom slope,  $a$ . (Usually these slopes will be of opposite sign.) The range of shelf bottom slope is huge, about  $10^{-3}$  for the U.S. east coast, but  $10^{-2}$  for the west coast. If  $(dy_i/dz)/a$  is small, bottom contact is minimal and

the buoyant water will be surface trapped, while if large, bottom contact will be extensive and the buoyant water will tend to extend from surface to bottom. The Connecticut plume is a prime example of the former type (O'Donnell et al., 1998 and Garvine, 1974), the Rhine plume of the latter (Simpson and Souza, 1995).

Parameter	Alaska Coastal Current	Columbia River and Coastal Current	Delaware River	Mississippi River and Texas-Louisiana Coastal Current
Type of freshwater inflow	Distributed	Point	Point	Point
Estuary?	Varies	Yes	Yes	Mississippi, Salt Wedge Atchafalaya, Yes
$T_w$ , freshwater volume	23,800 m <sup>3</sup> /s	7,000 m <sup>3</sup> /s	650 m <sup>3</sup> /s	19,000 m <sup>3</sup> /s
L, horizontal scale of source	50 km	4 km	8 km	42 km
D, water depth beneath buoyant water	180 m	20-100 m (winter) >1000 m (summer)	20 m	20 m
H, buoyant plume thickness	10-50 m	20 m	10 m	10 m
$r_i$ , internal Rossby radius <sup>a</sup>	8 km	15 km	6 km	12 km
W, shelf width	160 km	40 km	120 km	200 km
dz/dy, offshore bottom slope	0.012	0.004	0.001	0.001
U, typical current speed	0.25 m/s	0.40 m/s	0.08 m/s	0.22 m/s
Typical tidal velocity	0.08 m/s	0.5 m/s	0.24 m/s	0.06 m/s
$V_E$ Typical Ekman transport <sup>b</sup>	1.4 m <sup>2</sup> /s	1.0 m <sup>2</sup> /s	1.0 m <sup>2</sup> /s	1.6 m <sup>2</sup> /s
X, alongshore length scale <sup>c</sup>	1500 km	300 km (winter) 500 km (summer)	100 km	50 to 100 km
Suspended sediment concentrations	200 mg/liter <sup>d</sup>	10 to 40 mg/liter	Low	10 to 300 mg/l
Phosphate concent. in fresh water				7 $\mu$ M
Nitrate concent. in fresh water	5 $\mu$ M	<5 $\mu$ M	50 to 150 $\mu$ M	20 to 200 $\mu$ M
Primary Production	200 gC/m <sup>2</sup> yr			1-10 gC/m <sup>2</sup> d

K <sub>i</sub> , Kelvin number	6		1.3	5
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<sup>a</sup>  $r_i = (g'H)^{1/2}/f$ , the internal Rossby radius. The across-shelf scale of the buoyant water tends to be similar to  $r_i$ .

<sup>b</sup> The across-shelf Ekman volume flux  $V_E = \tau^w/(\rho f)$ , where  $\tau^w$  is the magnitude of the alongshelf wind stress and  $\rho$  is the water density. An appropriate scaled version of the Ekman flux is  $V_E / (HU)$ . For large values of this parameter, wind forcing should dominate over buoyancy forcing, while for small values, the reverse is true.

<sup>c</sup> The buoyant water influences different areas of the Washington-Oregon margin during summer and winter, due to a seasonal shift in prevailing winds. The plume extends to the north of the estuary in winter and to the south in summer.

<sup>d</sup> This estimate was obtained by dividing the regional shelf and slope sediment accumulation rate (Jaeger et al., 1998) by the annual freshwater discharge. As biogenic components are minor, this is a reasonable estimate of the mean sediment concentration in the discharge; however, the concentration is highly variable.