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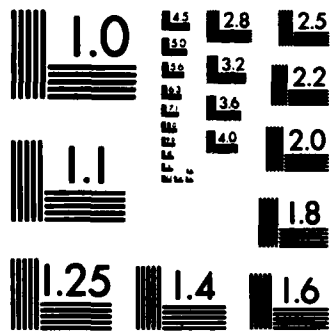
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ESTUARINE-SHELF INTERACTIONS

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## ESTUARINE-SHELF INTERACTIONS

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**Abstract.** The gravitational pattern in estuaries is often perturbed, at subtidal scales, by flows resulting from other processes. Wind forcing is the most familiar of these. Subtidal estuarine flow variability appears to be ubiquitous, but no predictive framework for these circulation patterns has yet been proposed. The estuarine-shelf exchanges driven at subtidal scales result in buoyant effluent plumes, which influence shelf chemistry and biology as well as physics. The dynamics of these plumes remains a fertile area of research, principally because of a lack of knowledge concerning mixing in stratified flows.

### Introduction

Estuaries are, by definition, semienclosed coastal bodies of water, but it is becoming increasingly clear that they cannot be treated in isolation. Their dynamics and impact depend, to a large extent, on their interaction with the inner shelf.

Morphologically, they are perturbations to the large-scale coastline variability, allowing free exchange of water with the adjacent shelf. As such, they have a pronounced effect on tidal characteristics over the adjacent shelf, tending to delay the longshore propagation of the tidal wave [Munk et al., 1970]. Because estuaries are, generally, regions in which seawater is diluted by land runoff, baroclinic pressure gradients drive a net flow of light water seaward over the heavier coastal water that is intruding into the estuary along the bottom [Pritchard, 1955]. This two-layered pattern of light surface effluent and heavier, deep inflow will be referred to as the classical estuarine circulation pattern. The evolution of this conceptual flow pattern has recently been reviewed [Beardsley and Boicourt, 1981]. The estuarine effluent plumes represent a major source of interaction between the estuary and shelf. The fronts at the plume boundaries are strong convergence and mixing zones [see Simpson and James, this volume], but as the fronts dissipate, the associated pressure gradients cause local perturbations to the shelf circulation patterns [Beardsley and Winant, 1979]. Dissolved and

particulate species carried within these plumes are also important to the shelf. Sediment carried by the effluent can cause major perturbations to the nearshore bathymetry and occasionally alter the nearshore circulation patterns [Murray et al., 1981]. The importance of outwelling, the export of carbon and nutrients from a marsh/estuarine system, to the shelf ecosystem is still being actively debated by ecologists, but it appears clear that progress will be made only when one fully understands and can accurately measure the transports between the shelf and the estuary [Nixon, 1980].

Many isolated estuarine plumes are of sufficient strength locally to be a dominant mode of forcing for the shelf, e.g., the Mississippi, Amazon, and Columbia river plumes. Elsewhere, though, effluent plumes from numerous smaller rivers may interact to form a region of low salinity along the coast [e.g., Blanton, 1981], the coastal boundary layer [see Pettigrew and Murray, this volume]. The inner shelf is the mixing zone for these effluents, an area in which their salinity is brought up to that of the outer shelf. Whereas the estuary proper is often thought of as the region where fresh water derived from runoff mixes with oceanic water, this mixing is rarely completed within the estuary proper. In some situations, e.g., the Amazon [Gibbs, 1970] and the mouths of the Mississippi during flood stage [Wright, 1971], essentially no mixing takes place until the effluent is outside the confines of the river mouth. Once the effluent plume has been released from the estuary, the principal dynamic balances controlling its movement and mixing with its surroundings are altered.

Estuarine-shelf exchanges are not a unidirectional process. Significant mass and momentum transports occur from the shelf to the estuary [Elliott and Wang, 1978]. Again, such exchanges are not limited to the physical characteristics of the estuary, but include biological [Garside et al., 1978] and geological [Wright et al., 1972; Wright and Sonu, 1975] as well.

In the following, I shall attempt to summarize briefly our present understanding of estuarine-shelf exchanges at the subtidal scale and our knowledge of effluent plumes.

## Subtidal Exchange Between Estuaries and Shelves

In his pioneering work on estuarine dynamics, Pritchard [1955] clearly identified the role of baroclinic pressure gradients within the estuary in driving the classical pattern of nontidal exchange with the coastal ocean. Although there were data collected during the next two decades that showed circulation patterns in direct contrast to Pritchard's model, these were generally treated as measurement artifacts rather than real phenomena [Carter et al., 1979]. Pritchard ignored wind stress effects in his analysis of the James River data [Pritchard, 1956], because in his data the stress spanned the compass rose and averaged to a near-zero value. The effects of low-frequency, time-varying wind stress, though, were ignored for many years. The influence of local wind stress was suggested in data from short field studies [Pickard and Rogers, 1959] and later, in model studies [Hansen and Rattray, 1965], distinctly identified as potentially important to estuarine dynamics. Weisberg and Sturges [1976] clearly identified the importance of such forcing for the first time from extended field records. During the analysis of 39 days of current meter data from the west passage of Narragansett Bay, they estimated coherence squared values greater than 0.8 between the flow and the along-channel winds at periods of 2 to 3 days. Their data plots suggest that both unidirectional flows and sheared regimes with opposing flows in the upper and lower layers occur at these frequencies, but the unidirectional pattern is the most important. (In a similar study of the Providence River estuary, a tributary to Narragansett Bay, the dominant subtidal response to wind forcing was found to be strongly two layered [Weisberg, 1976].) Since the transport is largely unidirectional, such a flow regime would tend to violate continuity if it were not for the peculiar geometry of the area. A connection with the east passage of the bay at the inshore end of both passages permits exchange of water between the two basins.

Similar subtidal, wind-driven exchanges are noted elsewhere, being detected primarily from tide gage records. Kjerfve [1975] suggested that Louisiana estuaries exchange water with the shelf on time scales greater than 1 day in response to Ekman convergences at the coastline driven by the alongshore wind stress. His data sets, though, are extremely short, and the statistical significance of his data is minimal at low frequencies. In a somewhat longer study, of exchanges between Corpus Christi Bay and the shelf, the transports appeared to be driven by the cross-shelf wind stress at periods of 2 to 4 days, while they were driven by the alongshelf wind stress at longer periods [Smith, 1977]. These exchanges are extremely important volumetrically; the volumes of water exchanged during meteorologically driven events are an order of magnitude larger than exchanges driven by astronomical tides. The rela-

tive importance of alongshelf wind to cross-shelf wind in driving exchange processes appears to be a function not only of the strength of the relative stress components but also of the relative water depth in the nearshore region and of frequency [Chuang and Wiseman, 1983].

Chesapeake Bay is a long, narrow coastal plain estuary whose axis runs north-south. At its mouth it opens onto the continental shelf to its east, although the thalweg is oriented more to the southeast. Through careful analysis of tide gage records from the bay [Elliott and Wang, 1978; Wang and Elliott, 1978], subtidal disturbances within a number of well-defined frequency bands have been identified. At periods of 2 to 3 days, significant exchanges with the shelf take place. These are coherent with the along-estuary wind but incoherent with the coastal sea level. The fluxes appear to be seiches within the bay with a node at the bay entrance. At periods longer than about 4 days, water levels within the bay are coherent with coastal water levels. Furthermore, events appear to propagate up the bay from the mouth. Forcing of these events by processes over the shelf thus appears probable. When the net volume flux is determined from water level records within the bay, the largest exchanges occur at periods between 4 and 10 days. The volume flux decreases rapidly at longer periods. In the 4- to 10-day band, volume exchanges are coherent with the east-west, cross-bay wind stress. Such winds apparently drive Ekman flows within the bay in the north-south direction (the direction of the bay's longitudinal axis) and also directly drive flow east-west (out of and into the bay) at the bay's mouth. It seems that the north-south wind is ineffectual at driving very low frequency exchanges because a wind that would drive water down the bay and out onto the shelf is in the same direction as one that would cause Ekman convergence at the coastline, an increased water level, and a pressure gradient that would induce flow into the bay. These two counteracting processes would tend to cancel.

A related study [Elliott and Wang, 1978] analyzed data from a yearlong current meter mooring maintained in the Potomac River estuary. The Potomac is a tributary to the Chesapeake Bay, and as such, the bay plays the role of shelf waters for the Potomac. The annual mean flow structure within the Potomac exhibits the classical estuarine circulation pattern, but the tidally averaged flow shows this pattern only 47% of the time! The remainder of the time, the patterns observed include the opposite of the classical pattern, storage or flushing (inflow or outflow at all depths), and three-layered circulation. Empirical orthogonal function analysis further shows that the variability in the exchange patterns is due not only to local forcing by the wind but also to nonlocal forcing by processes that occur in the coastal ocean (in this case, Chesapeake Bay).

As longer records have become available, seasonal variability in the subtidal exchange pat-

terns has been identified. Using both spectrum analyses of seasonal records of net volume flux across Chesapeake Bay mouth and complex demodulation of a yearlong record of the same variable, a seasonal contrast is noted between the winter season, when the wind systems are strong and well organized, and the summer, when they are weak and poorly organized [Wang, 1979]. Using a multiple coherence analysis to separate local wind effects from shelf effects, it is seen that while shelf processes control the shelf-estuarine net fluxes at periods longer than 4 days during the winter, shelf processes dominate the fluxes only at periods longer than 16 days during the summer.

In the northwestern Gulf of Mexico the barometrically adjusted sea level exhibits strong semianual and annual signals. The amplitude of this seasonal signal approaches that of the tidal signal. Part of this very low frequency variation is due to steric effects, part is due to local Ekman effects over the shelf, and the remainder is suspected of being caused by seasonal variations in the curl of the large-scale wind stress field [Blaha and Sturges, 1981]. Smith [1978] maintained two month-long near-bottom moorings in the ship channel connecting Corpus Christi Bay with the shelf, one deployment during a period of falling mean sea level and the other during rising mean sea level. In both cases the signal shows significant wind-driven subtidal transport. Rarely, though, is this variability sufficient to reverse the direction of the subtidal exchange, which is into the bay during rising mean sea level and out during falling mean sea level.

Less well studied are the seasonal variations in baroclinic subtidal exchanges. Obviously, seasonal river floods, which change the freshwater flow to an estuary, will consequently alter the stratification and the baroclinic patterns of exchange between the estuary and the shelf [McAllister et al., 1959; Hanson, 1965]. Another way, though, to alter the longitudinal baroclinic pressure gradients that drive the baroclinic flow within an estuary is to alter the density of the shelf water at the mouth of the estuary. This can be accomplished, among other ways, by upwelling of dense water onto the shelf or by lateral advection of water past the mouth of the estuary. The latter process occurs at the mouth of the Magothy River, an estuary tributary to Chesapeake Bay [Pritchard and Bunce, 1959]. During the spring freshet, low-salinity runoff from the Susquehanna flows southward along the western shore of the bay. Runoff to the Magothy proper is minimal. Thus the density within the Magothy reflects that of the waters that were outside the mouth of the Magothy in the immediate past. As the density front associated with the Susquehanna flood flows past the Magothy, the longitudinal pressure gradients within the estuary reverse, as does the subtidal exchange pattern with the bay. Along the Louisiana shelf, similar processes occur when the Mississippi River floods. Runoff from the Mississippi and Atchafalaya rivers flows westward

along the shelf. The meteorological events that control this flood occur over the states of the northern Mississippi Valley. The meteorology that controls runoff to the smaller Louisiana estuaries is more local in nature. At times during the Mississippi flood, the waters outside the mouth of these smaller estuaries are fresher than those inside (B. Barrett, personal communication, 1973; F. Kelly, personal communication, 1983). The baroclinic pressure gradient thus reverses direction. Similar events may occur on a shorter time scale. The increased particle displacements associated with spring tides can move light water to the mouth of the estuary and alter the longitudinal pressure gradients at specific phases of the fortnightly cycle [Hayward et al., 1982]. The fortnightly cycle in stratification observed in the subestuaries of the lower Chesapeake Bay was initially thought to be due to local mixing. Increased currents during spring tides appeared to result in increased turbulent mixing and decreased stratification, thus modulating the longitudinal baroclinic pressure gradients within the estuary [Haas, 1977]. While this process now appears not to have been solely responsible for the observed patterns in the lower Chesapeake Bay, mixing is important elsewhere. The role of tidal mixing in driving the mean circulation of estuaries tributary to the Bay of Fundy was early recognized and modeled in the laboratory [Hachey, 1934]. Vertical mixing was later noted to greatly reduce the flushing time of Baltimore Harbor below what would have been expected in the absence of such mixing [Carpenter, 1960]. The stratified upper layers of the Chesapeake Bay fill the harbor and are vertically mixed within it. The resultant water mass is heavier than the surface waters at the harbor mouth and denser than the deeper waters. The resultant longitudinal pressure gradients result in a three-layered circulation with inflow at the surface and bottom and outflow at mid-depth. This pattern, which Hachey [1934] modeled in the laboratory and Carpenter [1960] observed, has since been modeled analytically as well [Hansen and Rattray, 1972]. Other numerical studies have indicated the modified circulation patterns which result from assuming that the eddy coefficients in circulation models depend directly upon the strength of the flow rather than being specified a priori [Bowden and Hamilton, 1975] including a modulation of the circulation pattern during the course of the spring-neap cycle [Godfrey, 1980].

It is clear, from work completed to the present, that significant subtidal variability in shelf-estuarine exchange processes exists at both synoptic and longer periods. It is also clear, though, that significant geographical variability exists. Those processes which are important along the Texas coast are not necessarily the dominant processes along the Washington coast. Our ability to predict, a priori, the amplitude of exchange, or even whether exchanges will be one layered or two layered, is minimal. We have, at best, begun to define the problem and describe the pheno-

mena. There is still room for much fruitful research in the near future.

#### Plume Morphology

Once the light estuarine water leaves the confines of the estuary proper, it spreads and flows as a buoyant plume. It still possesses the inertia it acquired while in the estuary. It also stands higher than the surrounding shelf waters because of its low density, thus generating a pressure gradient both laterally and downstream. As the plume flows over the shelf waters, it acquires momentum from the wind and also exchanges momentum with the shelf waters through entrainment/detrainment or mixing. Furthermore, its dynamics are influenced by the local bottom topography. A number of descriptive studies of effluent plumes indicate the relative importance of these processes in different settings.

In small estuaries adjacent to a coastal ocean with a sufficiently large tidal range, the direction of the shelf-estuarine exchange reverses during the course of a tidal cycle. At the mouths of large rivers or small rivers in flood [Garvine, 1974], the exchange may be unidirectional for many tidal cycles, although still modulated by coastal tides. It is principally these large unidirectional exchanges that have been the objects of field observation programs.

The areal extent of the identifiable plume is dependent on the rate at which fresh water is being supplied to the estuary [Donguy et al., 1965; Rouse and Coleman, 1976; Garvine, 1974]. Once on the shelf, the plume is often observed to approach and attach itself to the coast rather than to continue to flow seaward in an unbounded fashion. Donguy et al. [1965] attributed the tendency to track the coastline to the Coriolis effect. A rather important exception is the Amazon outflow, which often pinches off, leaving large boluses of low-salinity water far offshore of its mouth [Ryther et al., 1967; Nof, 1981]. Frequently, though, the plume flows coherently, but in a fashion other than that which would be dictated by Coriolis effects alone. Ambient currents on both tidal [Garvine, 1974] and seasonal scales are known to correlate with plume trajectory, a pattern discussed in detail and modeled by Garvine [1982]. Wind stress also correlates with variability of plume trajectory on synoptic [Rouse and Coleman, 1976; Bowman, 1978] and seasonal scales [Duxbury, 1965]. Whether this correlation is due to direct momentum transfer to the plume or to larger-scale forcing of the ambient coastal currents, though, is not totally clear.

Buoyant expansion is known to be important to the spreading of the plume [Bondar, 1972], but this will vary as ambient water is mixed with or entrained into the plume, or plume water is detrained. Unfortunately, our knowledge of the associated mixing processes in these highly stratified situations is very poor. In fact, we often do not even know the direction of mass flux across

plume boundaries, since water is entrained across such boundaries into the region of greatest turbulent intensity [Garvine, 1979].

Finally, local shelf topography may influence the plume's characteristics. Where the shelf is shoal and significant mixing has already occurred within the estuary, such that the buoyancy of the effluent is slight, the plume may travel an appreciable distance before separating from the bottom. Such may be the case for small tidal inlets. In the case of larger river mouths, the river mouth bar frequently provides the perturbation necessary for plume detachment. In each case, further vertical entrainment or mixing is eliminated until the plume separates from the bottom.

Once again, although many observations of plume trajectories and characteristics showing significant variability are available, we have yet to discern a unifying pattern. Many physical processes have been identified as important in different geographical settings. We are, though, unable to specify a priori the dominant dynamical balances in any given situation. This places severe limitations on our ability to solve the very practical problem of predicting plume dynamics.

Initial attempts at modeling the effluent as a two-dimensional jet, while possibly appropriate for tidal inlets adjacent to shallow shelves, are inappropriate for the buoyant effluent from an estuary. Balancing buoyancy effects, Coriolis deflection of the plume, and lateral momentum diffusion [Takano, 1954] has met with some success in explaining observations [Donguy et al., 1965]. This model, though, does not allow for the seaward reduction in buoyancy of the plume, a feature that is characteristic of all estuarine effluents. Wright and Coleman [1971] modified a model produced by Bondar [1969] to allow for vertical entrainment of ambient seawater. They assumed no lateral entrainment because their observations on the Mississippi River effluent showed no lateral gradients across the plume. Momentum diffusion was ignored, and deceleration of the plume was associated with the entrainment of momentum from below. The neglect of lateral entrainment and diffusion does not appear to be universally justified, though [Garvine, 1974; McClimans, 1978]. Some success has been achieved with numerical models of effluent dynamics. Waldrop and Farmer [1974] used the full Navier-Stokes equations to study the near-field plume of the Mississippi River. Their greatest difficulty lay in an inability to maintain the frontal nature of the plume boundaries, probably because of the assumed Fickian diffusion, which is almost certainly inappropriate. Similar time-independent plume models have been developed for the prediction of the fate of thermal effluents from power plants [e.g., Stolzenbach and Harleman, 1971] and are applicable to the prediction of the trajectory and dispersion of estuarine effluents on the shelf. More intuitive representations of the frontal transfer processes [e.g., Garvine, 1979;

Stronach, 1981] have resulted in reasonable agreement of model results with observations.

Many recent efforts at modeling effluents have been predictive in nature, i.e., designed to reproduce observations of plume characteristics from a particular estuary. A notable exception, which is concerned less with prediction and more with understanding, is the work of Beardsley and Hart [1978], who have produced similarity solutions for one- and two-layered source-sink flows over the shelf. Although the model does not deal with the effects of frontal boundaries of the plume, it clearly indicates the steering properties of the lower layer of the ambient shelf waters on the plume through both drag and topographic variations of the "pycnocline," which acts as a bottom for the upper layer flow. In a similar vein, O'Donnell and Garvine [1983] have numerically studied the time-dependent dynamics of a two-dimensional plume. A two-layered model was utilized which solved the long-wave equation in the body of the plume and a shock patching technique at the frontal boundary. Temporal variations of conditions at the river mouth are seen to propagate outward as internal waves, surges, or bores and affect the motion of the frontal boundary.

#### Final Comments

Historically, the influence of estuarine discharge on shelf dynamics has been considered small and, except in the case of major river mouths, modeled as a uniform leakage of salinity deficit at the coastline. Renewed concern for the dynamics of the coastal boundary layer, though, has increased interest in the details of estuarine-shelf exchanges. We have only recently begun to appreciate the importance of modulations of these exchanges at time scales longer than tidal. Recent studies offer much information concerning the variability of these exchanges, but little insight into what controls the mode, amplitude, or spectral variability of this process. Similarly, while significant advances have been made in the ability to predict plume behavior in the vicinity of a given estuary, these advances have been due, in large part, to tuning of the free bulk parameters of the models. Many of these models offer little to our understanding of the underlying processes. Thus, although we now have at our disposal the results of numerous excellent descriptive studies of estuarine-shelf exchanges and their variability, considerable effort will be required to explain coherently these observations.

There are so many avenues for fruitful research that it would be presumptuous to set priorities. From a theoretical viewpoint, one major impediment to further quantitative understanding of these processes appears to be our inability to adequately describe mixing and entrainment in stratified shear flows. It would seem that improved understanding of estuarine-shelf exchange will go hand in hand with our understanding of stratified turbulent flows. On the other hand, on a more pract-

ical note, it is clear that the estuarine and shelf flow regimes are intimately linked. Yet one's interest is usually in one regime or the other, and the cost of simultaneously modeling both is generally prohibitive. It is reasonable to ask how one might, without loss of accuracy, reduce the domain which must be modeled when interest lies solely in the shelf or estuarine circulation.

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