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Introduction

Carl T. Friedrichs
Virginia Institute of Marine Science, carl.friedrichs@vims.edu

D. G. Aubrey

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C. T. Friedrichs and D.G. Aubrey

Part I: The Importance of Buoyancy in Estuarine and Coastal Environments

The shores and resources of estuarine and coastal waters have attracted human settlement for millennia. Though not obvious to most of these "settlers," buoyancy dynamics contribute to the attraction of these estuarine and coastal waters. The combination of intermittent stratification with sufficient shallowness for frequent nutrient delivery by complete vertical mixing favors a convenient, productive fishery. Strong density gradients in coastal waters usually indicate a connection between rivers and the sea, often providing a natural highway for trade or a harbor for protection. And land bordering the coast may well have been a flood plain in recent geologic time, leaving soils well-suited for agriculture. As human population has mushroomed during the past two hundred years, environments dominated by buoyancy dynamics have also been among those most severely altered. Strong buoyancy gradients often imply restricted water exchange or restricted mixing, indicating an environment susceptible to over-enrichment by agricultural runoff or sewage, or one easily contaminated by industrial waste. Restricted exchange also favors ecological isolation and areas particularly sensitive to over-fishing or to introduction of new species by human activities. Shallow regions whose dynamics respond most strongly to buoyancy input are often those most easily affected by dredging, diking or changes in relative sea level. In recent years, the competing interests of commerce, agriculture and industry versus sustainable fisheries, quality of life and tourism have come to a head and helped accelerate the impetus for study of coastal and estuarine buoyancy dynamics.

Study of estuarine and coastal environments during the last four decades has highlighted many physical processes influenced by buoyancy at first order. In the 1950's, the first process-oriented classification systems for estuaries (salt wedge, partially mixed, homogeneous) were based on buoyancy distribution, whereas in the 1960's dynamical models for estuarine circulation treated the along-channel density gradient as the dominant forcing. The important role of gravitational circulation in the transport of larvae, contaminants and sediment (e.g., the turbidity maximum) was recognized early on. About the same time, a separate but similarly simplified view of buoyant flows on the inner shelf developed based on the interaction of the coastal wall, the earth's rotation and idealized density gradients, while neglecting bottom friction and intra- and infra-tidal effects. In the 1970's and 1980's, it became increasingly apparent that the restrictive assumptions of two-dimensional circulation, idealized density fields, and simplistic tidal averaging represented the lowest order behavior of only a small fraction of environments strongly influenced by buoyancy input. Lines of research developed investigating topographic control and transverse circulation, the roles of spatially-varying density gradients and fronts, intra- and infra-tidal exchange and mixing processes, controls on tidally-averaged dispersion, and alternative sources and sinks of buoyancy, to name just a few. More subtle aspects of buoyancy dynamics were found to be highly applicable in both channelized estuaries and less confined coastal seas, such as intratidal mixing, rapidly

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evolving fronts, differential advection and straining of the density field, and controls on dispersion by interacting spatial and temporal scales.

1. Prominent Themes

This volume represents a maturation of several lines of research beyond the classical regime of estuarine and coastal circulation driven by steady, idealized density gradients. Three themes which receive particular attention in this volume and cut across the traditional geographic distinctions between estuaries and coastal seas are: (i) topographic steering and hydraulic control of buoyant flows; (ii) dispersion and time-scales of shear and mixing; and (iii) estuarine and coastal systems influenced by negative sources of buoyancy.

1a) Topographic Steering and Hydraulic Control of Buoyant Flows

Many of the papers in this volume emphasize the role of irregular bathymetry in influencing coastal and estuarine circulation and exchange in a variety of dynamic settings. In deeper environments such as coastal seas (tens to hundreds of meters), conservation of vorticity under near geostrophy requires flow driven by buoyancy to closely follow irregular isobars, as is the case in Hannah and Loder's modeling of the Scotian Shelf and Gulf of Maine region. An extension of this simple lateral balance also explains why estuarine plumes follow the curves of the coastline with the shoreline on the right in the northern hemisphere (Blanton; Mavor and Huq; Visser) and suggests a preference for northern hemisphere mean flow along the right side of relatively deep estuaries. However, three papers in this volume which address intermediate depth, partially-mixed estuaries (Friedrichs and Hamrick; Valle-Levinson and O'Donnell; Wong), observe the influence of Coriolis on the lateral distribution of along-channel mean velocity to be minor. Rather, mean buoyancy-driven flow over channel-parallel shoals tends to be seaward, whether on the left or right side of the channel, whereas flow over deeper areas tends to be landward. Lateral segregation of mean flow in these systems appears to be explained largely by a laterally invariant baroclinic pressure gradient acting over a depth-varying cross-section.

Several articles address the importance of bathymetric irregularities in the form of rapid along-channel changes in channel depth or width via their role in hydraulic control of two-layer flow (Chadwick et al.; Cudaback and Jay; Kay et al.; Geyer and Nepf; Uncles and Stephens). Plunging intrusion fronts are observed on the flood tide near sudden increases in channel depth or width where the associated decrease in tidal velocity can no longer push back the more buoyant estuarine water found up-estuary (Uncles and Stephens). On the ebb, tidal outflow is observed to lift off the bottom near an expansion when the reduced inertia no longer prevents denser water downstream from nosing underneath (Chadwick et al.). If the local acceleration term becomes large in comparison to the convective term, however, the quasi-steady approximation begins to break down, and the dynamic effects of time-dependence on the hydraulic response must be considered (Cudaback and Jay). Significant salt transport due to tidal pumping may result if the hydraulic responses triggered by a constriction during flood and ebb are asymmetric (Geyer and Nepf; Kay et al.). Under high discharge conditions in the Hudson, for example, Geyer and Nepf observed strongly sheared conditions to persist on the ebb, causing the sharp pycnocline to deepen within a lateral constriction. During the flood, the hydraulic response was subdued due to reduced shear, and the tidally-averaged transport of salt due to this tidal pumping effect was the same order as that due to gravitational circulation.

1b) Dispersion and Time-Scales of Shear and Mixing in Buoyant Flows

A theme which appears in several articles is the relationship between time-scales for shear and mixing and their control on the magnitude of dispersion. Buoyancy plays various important roles controlling shear and/or mixing in estuarine and coastal environments. Shear and mixing control dispersion, which then feeds back to determine the distribution of buoyancy. For classical circulation in partially-mixed tidal estuaries, the horizontal density gradient brought about by fresh water leads to vertical shear in the along-channel flow, whereas tides and bottom friction create (and stratification inhibits) vertical mixing perpendicular to the shear (Friedrichs and Hamrick; Park and Kuo). In a neat trade of roles in more strongly tidal estuaries, differential tidal advection creates cross-channel shear in the along-channel flow, and the resulting cross-channel density gradient can lead to cross-channel gravitational circulation which "mixes" across the shear (Dronkers; R. Smith; Valle-Levinson and O'Donnell; Uncles and Stephens). In coastal plumes and regions of freshwater influence, vertical shear in the cross-shelf current is provided by wind, the cross-shelf density gradient, and tidal interaction with stratification; by contrast, vertical mixing perpendicular to the shear is provided by the wind and tide (Blanton; Souza and Simpson; Visser).

In each of the above cases, the effective diffusivity in the direction parallel to the sheared flow is determined by the time-scale of the shear relative to the time scale of the mixing. When time scales for mixing are short relative to time scales for shear, shear dispersion becomes larger as mixing decreases (R. Smith; Visser). This property can be seen in the partially-mixed estuary model of Park and Kuo, for which spring-neap modulation of tidal mixing increases dispersion at neaps and decreases dispersion at springs. In the Rhine coastal plume, Visser identifies a similar pattern. Strong cross-shore winds create shear in the plume which alone should eventually spread out the plume in the cross-shore direction. However, strong winds cause strong vertical mixing over a time-scale much shorter than cross-shore advection. This means the cross-shore velocity has very little time to transport density horizontally before it is mixed vertically. R. Smith describes a similar ratio of time-scales in explaining the sensitivity of salt intrusions to the size of tidal estuaries. In small estuaries, where cross-channel mixing is fast, decreased freshwater input reduces cross-channel circulation and increases along-channel dispersion. Thus salt "diffuses" much farther up small estuaries under conditions of low river flow. In large estuaries, the time scale of cross-channel mixing is much longer than the tidal time-scale of cross-channel shear, so the interaction of cross-channel circulation and tidal shear isn't as important to longitudinal dispersion. Thus reduced freshwater input has less effect on the effective diffusion of salt.

1c) Estuarine and Coastal Systems Influenced by Sources of Negative Buoyancy

All the articles discussed under the two previous topics concern density gradients resulting from inputs of positive buoyancy into estuarine or coastal waters, and nearly all are due mainly to fresh water sources (as opposed to temperature). This is also the most commonly described case in the literature, perhaps because fresh water input dominates along the Atlantic coasts of Europe and North America. But several articles in this volume also address the quite different scenario of negative buoyancy inputs (Hearn & Largier; Largier et al.; Lin and Mehta; N. Smith; Yanagi et al.). Coastal embayments in hotter and/or drier climates are often influenced by removal of buoyancy by evaporation (Hearn & Largier; Largier et al.; N. Smith). Hearn & Largier and Largier et al. discuss estuaries in California which are characterized by longitudinal zones indicative of the locally dominant buoyancy source or sink: Beyond the immediate vicinity of the inlet, a "thermal" regime is entered wherein buoyancy input by heat dominates. Deeper in the basin, an evaporative increase in salinity dominates in the "hypersaline" region. Finally, an "estuarine" regime may be observed closest to the fresh water source.

Another source of negative buoyancy addressed in this volume is surface cooling (N. Smith; Yanagi et al.). N. Smith discusses a phenomena observed on the eastern margin of Great Bahama Bank, triggered by a combination of intense surface cooling and evaporation. Water on the shallow Bank soon becomes denser than the much deeper water to the east, and plunging density currents occur at the break in topography. Even fresh water can be a negative source of buoyancy if it is much colder than neighboring sea water. When this is the case, the usual density contrast associated with an embayment mouth may be largely subdued or reversed, and fronts where fresher water spreads under saltier water may develop (Yanagi et al.). Yet another source of negative buoyancy in estuaries and coastal seas is suspended sediment, which can contribute to vertical density gradients via near bottom turbidity layers (Yasuda et al.).

2. *Organization of the Volume*

This volume contains a subset of the papers presented at the 7th International Biennial Conference on the Physics of Estuaries and Coastal Seas, held in Woods Hole, Massachusetts, 28-30 November, 1994. Like previous PECS volumes published in the Coastal and Estuarine Studies Series, all papers included here were peer reviewed in order to maintain "journal standards." In addition, papers for this volume were selected on the basis on their contribution to the central theme of buoyancy dynamics. This represents a shift from past PECS volumes which have recently been one to two hundred pages longer and presented a less cohesive survey of physical processes. The hope is that this work represents more of a "text" on estuarine and coastal buoyancy dynamics within which complementary papers better foster a unified understanding. Despite the unifying themes discussed above, the contents of this volume follow a quasi geographic organization from buoyancy dynamics of plumes and coastal seas to estuarine exchange/lower estuary physics to buoyancy dynamics of the inner estuary. This choice has been made because several papers address more than one of the major themes highlighted in the previous sections and several others focus on other distinct aspects of buoyancy dynamics. Within each section, papers are organized according to common physical processes and decreasing time scale to provide insight into the potential overlap of the dominant mechanisms considered.

Part II -- Buoyant Plumes and Buoyancy in Coastal Sas

These first six papers address buoyancy dynamics in coastal seas or on inner shelves outside the immediate vicinity of the river mouth or estuary. In the lead off paper, Hannah and Loder diagnostically model seasonal baroclinic circulation in the Scotian Shelf/Gulf of Maine and find circulation to be dominated by along-shelf flows with substantial seasonality and topographic steering by banks and basins. The next three papers examine the behavior of buoyant plumes as they move along the coast. Visser examines the persistence of the Rhine River plume over time scales of months, which Visser credits to vertical mixing by wind shutting down horizontal dispersion. Blanton examines estuarine-like circulation perpendicular to the coast within a lens of low density water observed along the southeastern U.S. inner shelf, and finds the circulation to be strongly modified by upwelling or downwelling favorable winds.

Mavor and Huq simulate the behavior coastal plumes using a rotating laboratory tank, and identify dimensionless parameters governing gravity current flow velocities and the behavior of instabilities. The last two papers address the interaction of tides and buoyancy in shelf seas. Sharples and Simpson examine the spring-neap advance of tidal mixing fronts in shelf seas and find lags of several days occur because spring tidal mixing must remove the buoyancy stored since the previous spring tide. Souza and Simpson investigate intratidal properties of Rhine's region of freshwater influence. They find semi-diurnal variability of stratification to be the result of interaction between the mean water column stability and tidal shear.

Part III -- Buoyancy, Salt Transport and Estuary-Shelf Exchange

Eight papers focus on mechanisms for buoyancy exchange near the mouth of an estuary or embayment. Yanagi, Guo and Ishimaru discuss the seasonal flow structure around a front at the mouth of Ise Bay, Japan, where surface cooling of relatively fresh bay water causes it to sink at the mouth of the bay. The remaining papers consider intratidal phenomena, with the first two specifically addressing the influence of shelf density structure. N. Smith discusses tidal exchange between Exuma Sound and the shallow Great Bahama Bank, where denser water from the Bank cascades down the narrow shelf of the Sound on the ebb and is replaced by entirely different Exuma Sound water on the flood. Next, Wong describes the effect of tidal motion on the salinity distribution in the lower-most Delaware Bay. Along with the role of cross-sectional variations in depth, Wong stresses the complex advection and mixing of distinct water masses within and outside the Bay. The next five contributions investigate hydraulic control on estuary-shelf exchange, with the final two emphasizing the ramifications of tidal pumping.

Cudaback and Jay apply a time-dependent hydraulic control model to tidal exchange at the mouth of the Columbia Estuary. Chadwick, Largier and Cheng document the role of thermal stratification in San Diego Bay leading to alternating sub- and super-critical flow at the mouth of the Bay. Along with variations in stratification correlated with the Richardson Number, Uncles and Stephens observe hydraulic control of plunging fronts near the mouth of the Tweed Estuary. Kay, Jay and Musiak perform salt transport calculations for the mouth of the Columbia and find landward transport of salt to be dominated by tidal advection of the tidal salinity field. Finally, Geyer and Nepf find a similar pattern holds along the Hudson River estuary.

Part IV -- Estuarine Dynamics and Buoyancy

Nine papers consider the dynamics of mixing and/or tidally-averaged flow within estuaries, which are presented here in approximate order of decreasing time-scale. Largier, Hearn and Chadwick describe a class of low inflow estuaries found in Mediterranean climates, where buoyancy fluxes during the dry season are dominated by air-water exchange. Under these conditions, positive buoyancy flux by heating nearly cancels negative flux due to evaporation, leading to very weak gravitational circulation. Next Hearn and Largier present a case study of a such an estuary as they document the response of Tomales Bay to historical changes in bathymetry. On seasonal time-scales, Schroeder, Wiseman, Pennock and Noble examine the relationships between river input, flushing time and salinity in Mobile Bay. The next four papers examine controls on tidally-averaged circulation and tidal mixing in partially to well-mixed coastal plain estuaries. Valle-Levinson and O'Donnell perform numerical experiments to investigate the tidally-averaged response of a central channel bordered by shoals and find mean inflow concentrated in the deep channel. Friedrichs and Hamrick find similar results based on analytical solutions and flow observations for a triangular cross-section of the James River estuary. Park and Kuo examine two opposing effects of vertical mixing over the spring-neap cycle in the Rappahannock Estuary. Mixing weakens circulation by enhancing vertical momentum exchange may potentially increase circulation by strengthening the longitudinal salinity gradient. Next, R. Smith discusses the critical relationship between the width of an estuary and the sensitivity of longitudinal dispersion to freshwater discharge. Lewis and Lewis describe vertical mixing events in detail over a tidal cycle in the Tees Estuary. Finally, Dronkers suggests that transverse gravitational circulation enhances erosion of sediment on channel bends and intertidal flats in Volkerak estuary and the Wadden Sea.

3. Conclusions

The 23 papers of this volume focus on the important coastal dynamics issue of buoyancy and its effects. By providing case studies as well as basic theoretical formulation of important processes in the coastal oceans, the topic has been introduced at a level we hope will be of benefit to the reader. Though not an inclusive treatment of buoyancy effects, which can be found in several extant works, this volume produces an update of recent thinking in this arena, and modern observational programs addressing these buoyancy effects.