OFFPRINTS FROM TIDAL HYDRODYNAMICS
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NONLINEAR HYDRODYNAMICS OF SHALLOW TIDAL INLET/BAY SYSTEMS

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ABSTRACT

This study reviews recent research on estuarine characteristics responsible for distortion of the barotropic tide in shallow well-mixed estuaries. In addition, a particular class of flood-dominant estuary is described in which estuarine channels shoal over short distances to depths less than the offshore tidal amplitude. Tidal distortion in general results from the nonlinear interaction of the offshore tide with the estuary, and is reflected in the growth of harmonics and compound tides of the principle astronomical constituents. In this study, the amplitude ratio and relative phase of M_4 and M_2 are used to indicate the magnitude and sense of the tidal asymmetry within the estuary. Tidal distortion in the specific class of flood-dominant estuaries investigated here in detail can be identified by low M_2 to M_4 relative phases (~ 5° to 35°) and high M_4/M_2 ratios (~ 0.3 to 0.4) over distances of a few kilometers. These systems (common along the New England (USA) coast and elsewhere) appear to result from a combination of small physical scale and large offshore tidal amplitude relative to distal channel depths. Shoaling channels effectively truncate the lowest portion of the tide, resulting in an extended falling tide and a slow shallow ebb flow. These systems are analogous to tides propagating up rivers, but important distinctions exist. This study investigates tidal distortion in detail at six such systems, using multiple tide records within individual systems, variations in offshore tidal forcing, and numerical modeling.

INTRODUCTION

Net bedload and suspended load sediment transport in shallow estuarine systems is controlled to a significant degree by distortion of the co-oscillating estuarine tide (e.g., Postma, 1967; Aubrey, 1986; Dronkers, 1986a,b). Distortion is defined as duration asymmetries in the rise and fall of the tide, as well as duration and magnitude asymmetries in tidal currents. As is well known, tidal distortion results from the nonlinear interaction of the offshore tide with the estuary, and is reflected in the growth of harmonics and compound tides of the principal astronomical constituents. The problem of tidal asymmetry in shallow estuaries and rivers recently has received a great deal of attention (e.g., LeBlond, 1978; Boon and Byrne, 1981; Parker, 1984; Speer and Aubrey, 1985; Dronkers, 1986a; DiLorenzo, 1988; Friedrichs and Aubrey, 1988). The primary thrust of these studies has been to examine the mechanics of tidal propagation in shallow estuaries and to identify estuarine characteristics responsible for producing different types of asymmetry. A second goal has been to relate the asymmetry to patterns of estuarine sediment transport and observed estuarine morphology. The result of this work has been to clarify the general causes of and mechanics involved in the generation of "flood-dominant" and "ebb-dominant" tidal asymmetries in shallow estuaries. "Flood dominance" indicates the duration of falling tides exceeds that of rising tides, producing longer lags at low water than high water, and leading to a tendency for stronger flood than ebb tidal currents. "Ebb dominance" refers to the opposite situation.

Only the barotropic tidal response is investigated here. Estuaries of interest are shallow and well-mixed. The ratio of offshore tidal amplitude to mean channel depths is typically greater than 0.1, and generally little streamflow impacts these systems. These systems may have longitudinal salinity gradients and can be geometrically quite complex. They are often connected to the ocean via a narrow inlet and tend to consist either of broad shallow bays or a series of meandering channels (widths 10's to 100's of meters, lengths 1 to 10 km) which often terminate in broad bays. The channels and bays are bordered by tidal flats and marshes which, in many cases, store large volumes of water at high tide. An important feature of these systems is the significant change in estuarine surface area produced by the flooding and uncovering of flats and marshes. This feature helps control the type of asymmetry (flood or ebb-dominant) an estuary develops. Estuaries of this type occur along 80-90% of the US east and Gulf of Mexico coasts, and are present on most continents.

This study reviews recent work on estuarine characteristics responsible for producing flood and ebb-dominant tidal asymmetries (Aubrey and Friedrichs, 1988; Friedrichs and Aubrey, 1988). Harmonic analyses of sea surface elevation measurements from a number of estuaries along the US east coast, together with numerical modeling, are used to elucidate the physics responsible for producing different types of tidal distortion. Additionally, the study investigates a particular class of flood-dominant estuary, one in which estuarine channels shoal over short distances to depths less than the offshore tidal amplitude. In general, these systems are relatively small with bay surface areas of order 10^6 m^2 and tidal prisms of order 10^6 m^3. Examples are presented from Cape Cod, Massachusetts (US) and the coast of Maine (US). Although they may appear to be atypical, along some coastlines (Maine, for example) they are quite common (Lincoln and FitzGerald, 1988). Tidal propagation in these systems is also studied by analysis of sea surface elevation measurements and numerical modeling.

TIDAL ASYMMETRY

The distorted co-oscillating estuarine tide can be represented by the nonlinear growth of harmonics and compound constituents of the principal astronomical constituents (Dronkers, 1964; Uncles, 1981; Parker, 1984; Aubrey and Speer, 1985). Along much of the world's coastlines, the offshore tide is principally semidiurnal in character with M_2 the largest constituent. Even harmonics and compound tides formed from these constituents are capable of generating both time and magnitude asymmetries in the observed tide. When M_2 is the dominant semidiurnal constituent, M_4 is the largest quarter-diurnal tide formed within the estuary. Consequently, we use the ratio of M_4 to M_2 amplitude in both sea surface elevation and velocity to indicate the magnitude of the tidal asymmetry generated within the estuary. Similarly, the relative phase of M_2 and M_4 determines the sense of asymmetry (ebb- or flood-dominant). The relative phase ($2M_2$-M_4) is defined as twice the phase of M_2 minus the phase of M_4. Relative sea surface phases between 0° and 180° indicate a longer falling than rising tide, and hence a tendency towards flood dominance of estuarine tidal currents. Longer rising tides and ebb-dominant conditions are indicated by a ($2M_2$-M_4) relative phase between 180° and 360°.

Both the modeling results and harmonic analyses of sea surface from real estuaries are interpreted in terms of the M_4 /M_2 amplitude ratio and the ($2M_2$-M_4) relative phase. In many shallow systems, a rich spectrum of harmonics and compound constituents is observed in the estuarine tide (e.g., Parker, 1984; Aubrey and Speer, 1985). In particular, the compound constituents MN_4 and MS_4 can reach significant amplitudes. Complex interactions between the parent tides and forced constituents may contribute to amplitudes and phases of shallow estuarine tides. For example, recent modeling of shelf and estuarine tides has demonstrated the importance of correctly modeling the interaction of tidal constituents through the friction term (e.g., Walters, 1984; Le Provost and Fornerino, 1985). These modeling efforts have included complex spectral decomposition of the quadratic friction term in the depth-averaged equations of motion to account for the interactions of the forced constituents with themselves and with their parent tides. The approach taken in this paper, however, is to consider only the M_2-M_4 interaction. This simplified approach is justified for two reasons. First, the numerical modeling approach employed is diagnostic, not predictive. Several studies (e.g., Pingree and Griffiths,1979; Boon and Byrne,1981; Speer and Aubrey,1985) have shown that the essential features of tidal asymmetry in strongly nonlinear systems can be represented by the M_2-M_4 interaction. In particular, the sense of tidal asymmetry developed in a shallow estuary can be explained. Second, field evidence from a number of estuaries supports this approach, and indicates that in the quarter-diurnal species other shallow-water constituents (principally MN_4 and MS_4) reinforce the tidal asymmetry imparted by M_2 and M_4. This last point is illustrated by the relative phases of the three principal quarter-diurnal constituents at two estuaries along the US east coast (Price, SC; Murrells Inlet, SC) and three in Korea (Figure 1). The significant feature is the consistency in relative phase among the three constituents at each location. This finding suggests that the smaller quarter-diurnal constituents simply act to reinforce the sense of asymmetry imparted by the M_2-M_4 interaction.

Two non-dimensional parameters represent the principal estuarine characteristics responsible for different types of asymmetry. The first parameter, a/h, is the ratio of the offshore M_2 tidal amplitude to mean estuarine channel depth. This parameter measures the relative shallowness of

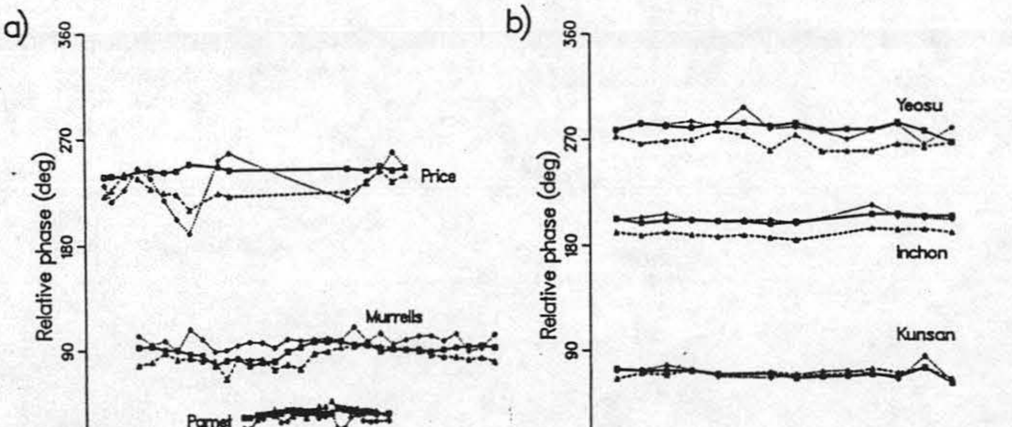

Figure 1. Sea-surface phases (relative to their parent constituents) of the three most significant quarter-diurnal components in: (a) three shallow estuaries from the US Atlantic coast; and (b) three tidally dominated estuaries in South Korea (data from Choi, 1983). [$2M_2$-M_4 , □—□— ; (M_2+S_2)-MS_4 , △—△— ; (M_2+N_2)-MN_4 , ◇····◇···] Similar relative phases among M_4, MS_4 and MN_4 at each estuary indicate that the quarter-diurnal band shallow-water components produce similar tidal asymmetries.

the estuary. It is well known that strongly nonlinear behavior can be exhibited by long waves when the ratio of wave amplitude to water depth is large. For the estuaries considered in this study, a/h typically exceeds 0.1. The second parameter, V_s/V_c, measures the capacity of the estuary to store water as the tide rises from low to high water. This parameter is the ratio of the volume of water stored between mean high and low water in tidal flats and marshes divided by the volume of water contained in channels at mean sea level (Friedrichs and Aubrey, 1988). This parameter is important because within estuaries, tidal channels transport momentum while tidal flats and marshes principally tend to store water. The volume of water that channels must carry to flood areas of tidal flats has an important effect on the sense of asymmetry produced.

One-dimensional numerical modeling (e.g., Uncles, 1981; Speer and Aubrey, 1985) was used to investigate the impact of estuarine geometry on the development of tidal asymmetries. Assumptions implicit in one-dimensional modeling include a small horizontal aspect ratio (channel depth/width << 1), long narrow channels (width/length << 1), and a well-mixed water column (all common for many estuaries of interest). The effects of tidal flats and marshes are modeled by dividing an ideal shallow estuary into two components: (1) trapezoidal channels that transport momentum and (2) shallow sloping intertidal flats that act only in a storage capacity. Numerical calculations were made for a range of the non-dimensional ratios a/h and V_s/V_c to identify estuarine characteristics responsible for producing ebb and flood-dominant tidal responses. Results are presented in Figure 2 in terms of the sea surface M_4/M_2

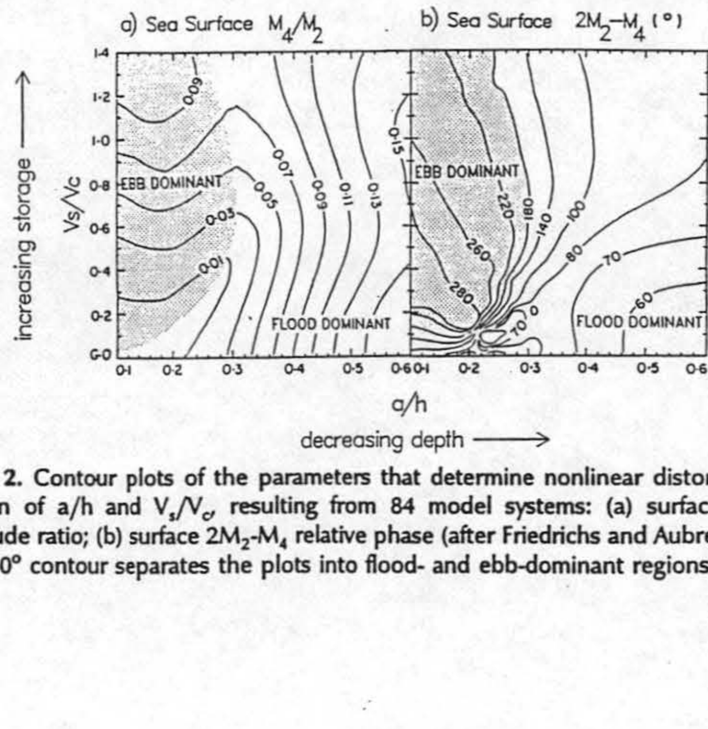

Figure 2. Contour plots of the parameters that determine nonlinear distortion as a function of a/h and V_s/V_c, resulting from 84 model systems: (a) surface M_4/M_2 amplitude ratio; (b) surface $2M_2$-M_4 relative phase (after Friedrichs and Aubrey, 1988). The 180° contour separates the plots into flood- and ebb-dominant regions.

ratio and the $2M_2$-M_4 relative phase. Each model "estuary" consisted of a 7 km long channel (a representative length for these systems) forced by a the M_2 tide. Estuarine geometry was changed by varying a/h and V_s/V_c; model results were analyzed by harmonic analysis.

Differences between flood and ebb-dominant estuaries are clarified by these results. For the scales of systems considered in this study, virtually all estuaries having an a/h ratio greater than 0.3 are flood-dominant. Ebb-dominant systems are characterized by relatively deep channels (a/h < 0.2). Between these two values either response can be found depending on the relative amount of water stored in flats compared to that transported in channels. Friedrichs and Aubrey (1988) explained these results by suggesting that tidal distortion in shallow estuaries is a compromise between two primary effects: (1) frictional interaction of the tide with the channel bottom and (2) intertidal storage on flats and marshes. The former is reflected in the parameter a/h and leads to time delays between the ocean and estuary low water exceeding the delays at high water. A similar argument is presented by Dronkers (1986a). This explanation is also consistent with the theoretical analysis of tidal propagation in rivers presented by LeBlond (1978). LeBlond explained the tendency of longer lags at low water than high as being related to a momentum balance between bottom friction and barotropic pressure gradient. Tidal propagation is best described as a diffusive process when this balance holds. The second effect is reflected in the parameter V_s/V_c and can be interpreted as an inefficient exchange of water in the estuary around high water (Boon and Byrne, 1981). This particular effect is enhanced in estuaries having relatively deep channels and extensive amounts of intertidal storage. The magnitude of distortion (M_4/M_2) is controlled by different parameters for each type of tidal asymmetry. The M_4/M_2 ratio is controlled primarily by a/h in flood-dominant cases and V_s/V_c in ebb-dominant ones.

A comparison between model results and field observations from estuaries along the US east coast supports the modeling conclusions (Figure 3). Field observations were decomposed by harmonic analyses of 29-day records into M_2 and M_4 constituents. Despite the complicated geometries of natural estuaries, results of numerical model runs employing simple geometries are consistent with the data. Discrepancies result from several factors: simplifying assumptions used in modeling (e.g., the one-dimensional approximation); treatment of all systems as equal in length (7 km); and neglect of asymmetry in the tidal forcing. For the geometries modeled, ebb/flood asymmetry in tidal currents (and hence bedload sediment transport) is consistent with duration asymmetries in the rise and fall of sea surface. To first order, this is a consequence of continuity constraints (see Fry and Aubrey, in press). The result is important because in natural estuaries, long term sea surface records are easier to obtain than long term current meter records. The combination of shallow water, strong flows, high sediment transport rates, and bio-fouling complicate current measurement deployments for periods longer than a few days.

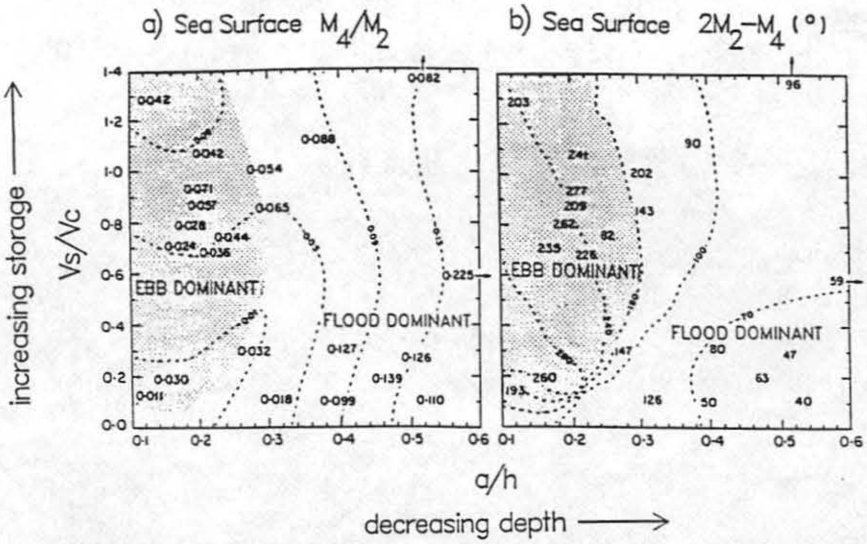

Figure 3. Mean values for parameters which determine nonlinear tidal distortion in 22 shallow estuaries along the US Atlantic coast (superimposed on results of numerical modeling) as a function of a/h and V_s/V_c: (a) surface M_4/M_2 amplitude ratio; (b) surface $2M_2$-M_4 relative phase (from Friedrichs and Aubrey, 1988). Considering the simplicity of modeling and geometric approximations, the field results agree well with model predictions.

A SPECIAL CLASS OF FLOOD-DOMINANT ESTUARIES

A recent investigation of tidal distortion at several estuaries along the Maine coast revealed examples of strongly distorted estuarine tides characterized by low values of sea-surface $2M_2$-M_4 relative phase (Lincoln and FitzGerald, 1988). A feature common to these estuaries is the shoaling of their channels to depths less than the offshore tidal amplitude along short distances, in one case a few hundred meters over the ebb-tide delta. Table 1 summarizes sea surface harmonic analyses of M_2 and M_4 constituents from three of the Maine estuaries and three on Cape Cod (MA). All six systems display $2M_2$-M_4 relative phases indicative of flood-dominant behavior (i.e., longer falling than rising tide). The exact values of these phases, however, are lower than those observed in other flood-dominant estuaries (e.g., Friedrichs and Aubrey, 1988) and indicate different dynamics may be present. In addition, the tide tends to be strongly distorted with the M_4/M_2 ratio reaching ~ 0.3 to 0.5 at distances of a few kilometers.

A detailed comparison between Pamet River (MA) and Murrells Inlet (SC) was conducted to highlight the differences between this class of flood-dominant estuary and those more common. Murrells Inlet (Figure 4) is characteristic of most flood-dominant shallow estuaries found along the US east coast as reported in the literature (e.g., Boon and Byrne, 1981; Aubrey and Speer, 1985). Compared to Pamet River, it is a longer and deeper system forced by a smaller offshore tide. The sea surface M_4/M_2 ratio increases from 0.07 to 0.1 moving from the inlet to far reaches of the estuary, compared to range of 0.07 to 0.4 at Pamet (Table 1). In addition, the $2M_2$-M_4 relative phase at Murrells displays values (83° to 98°) characteristic of frictional flood-dominant systems. By contrast, Pamet has relative phases consistent with flood-dominant behavior but considerably lower than typically observed. Both estuaries have high a/h values (>0.3) characteristic of flood-dominant systems. As discussed earlier, the parameter a/h determines the magnitude of the distortion for flood-dominant systems.

The essential physical difference between Pamet River and Murrells Inlet is shown by channel cross-sections for both estuaries (Figure 5). Levels of mean low water (MLW) and mean high water (MHW) for the offshore tide are superimposed on each section. The channel at Pamet River shoals to an elevation approximately two meters above MLW of the offshore tide over a

Table 1. M_2 and M_4 analysis results for seven U.S. east coast estuaries. ([1] Moody, 1988; [2] Lincoln and FitzGerald, 1988).

Estuary	Length (km)	Gauge (km)	Start date	Duration (hours)	M_2 (m)	M_4/M_2	$2M_2$-M_4 (deg)	Set-up (m)
Herring River, MA[1]	2.4	2.4	10/08/75	697	1.11	0.098	15	n.a.
Little Namskaket, MA	2.0	Ocean	05/04/88	359	1.48	0.023	180	0
		0.7	18/03/88	697	0.78	0.335	14	0.16
			16/11/88	146	0.91	0.349	13	0.16
		2.0	18/03/88	359	0.65	0.424	16	0.16
			16/11/88	146	0.80	0.370	13	0.16
Little River, ME[2]	4.3	'inlet throat'	27/07/82	13	1.16	0.092	44	n.a.
Ogunquit, ME[2]	4.0	Ocean	n.a.	697	1.29	0.008	226	0
		0.7	n.a.	697	1.09	0.083	28	n.a
		2.2	n.a.	697	0.72	0.263	29	n.a
Pamet, MA	3.4	Ocean	20/07/88	1400	1.51	0.016	232	0
		0.2	20/07/88	359	1.26	0.070	7	0.24
velocity		*0.2*	*20/07/88*	*62*	*0.42*	*0.097*	*342*	
		0.8	07/02/87	4000	1.18	0.105	38	0.25
		3.4	18/11/88	2100	0.58	0.411	9	0.51
Sprague, ME[2]	3.4	'inlet throat'	14/07/82	12	0.63	0.404	27	n.a.
Main Creek, SC	8.0	Ocean	01/10/74	9000	0.73	0.008	124	0
		1.2	01/10/74	11000	0.59	0.092	83	0.05
		4.7	15/10/74	2000	0.58	0.070	98	0.05
		8.0	01/10/74	12000	0.56	0.101	90	0.05

distance of three kilometers. The smaller offshore tide amplitude at Murrells results in MLW being above the channel floor at the estuary's landward reaches. The shoaling channel at Pamet effectively truncates the lowest portion of the tide, producing a sea surface signal considerably different than that observed in a deeper system like Murrells (Figure 6a). The tide at Murrells displays features typical of a damped flood-dominant response to ocean forcing, i.e. attenuation of the tidal range and longer lags at low water than high water. The tide at Pamet shows truncation of low tide levels as well as longer lags at low water. The truncation of the tide at Pamet is similar to that described by Lincoln and FitzGerald (1988) for the Ogunquit River estuary of Maine. A detailed examination of the tide at Pamet (Figure 6b) shows a relative $2M_2$-M_4 phase tending towards 0°. Relative phases actually observed (approximately 30°) reflect a compromise between typical values for flood-

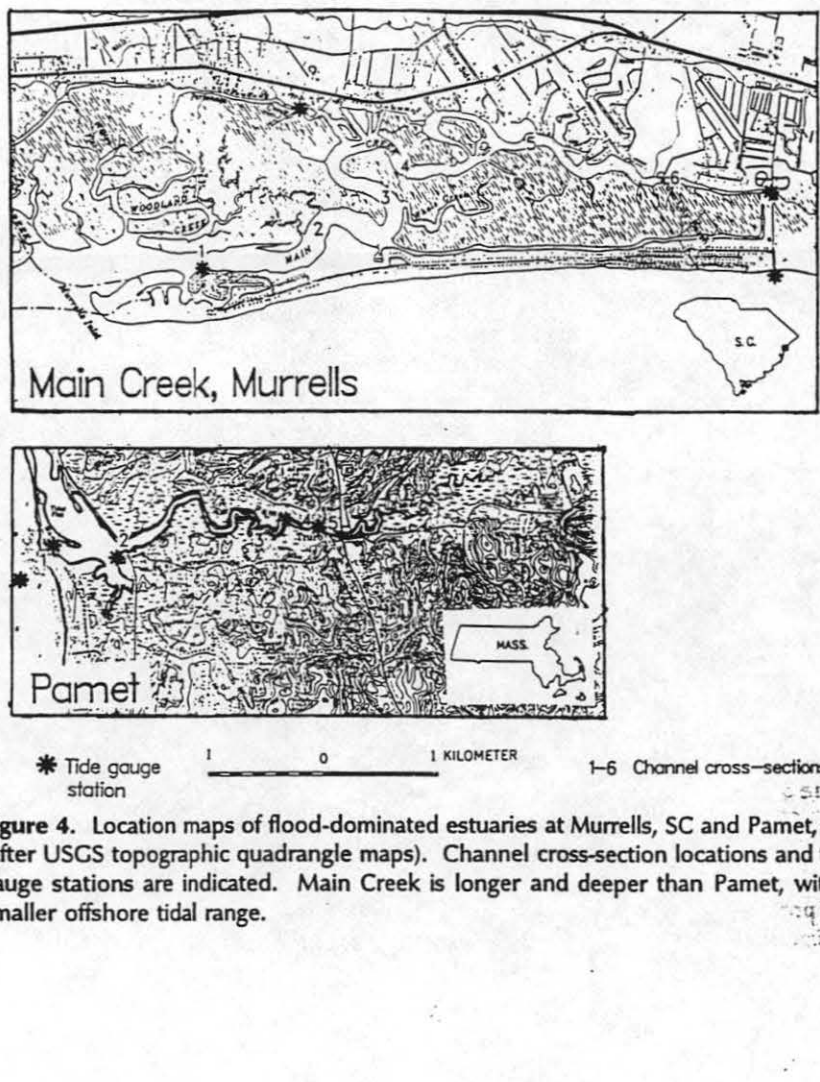

Figure 4. Location maps of flood-dominated estuaries at Murrells, SC and Pamet, MA (after USGS topographic quadrangle maps). Channel cross-section locations and tide gauge stations are indicated. Main Creek is longer and deeper than Pamet, with a smaller offshore tidal range.

dominant systems (60° to 90°) and those required to represent a truncated tide (0°). The evolution of the tide as it propagates down channel is summarized for shallow estuaries where truncation of low tide appears to occur (Ogunquit ME, Little Namskaket and Pamet, MA) in Figure 7. The principal differences between more common flood-dominant estuaries and the shallower flood-dominant systems are clear: the latter have more highly distorted tides ($M_4/M_2 > 0.25$, Figure 7a), lower values of the $2M_2$-M_4 relative phase ($2M_2$-$M_4 < 40°$, Figure 7b), and increased mean sea level inland (Figure 7c).

A numerical simulation of tidal motion in an idealized representation of Pamet clarifies the physics of tidal propagation in shallow systems having shoaled channels. The numerical model employed is the one-dimensional

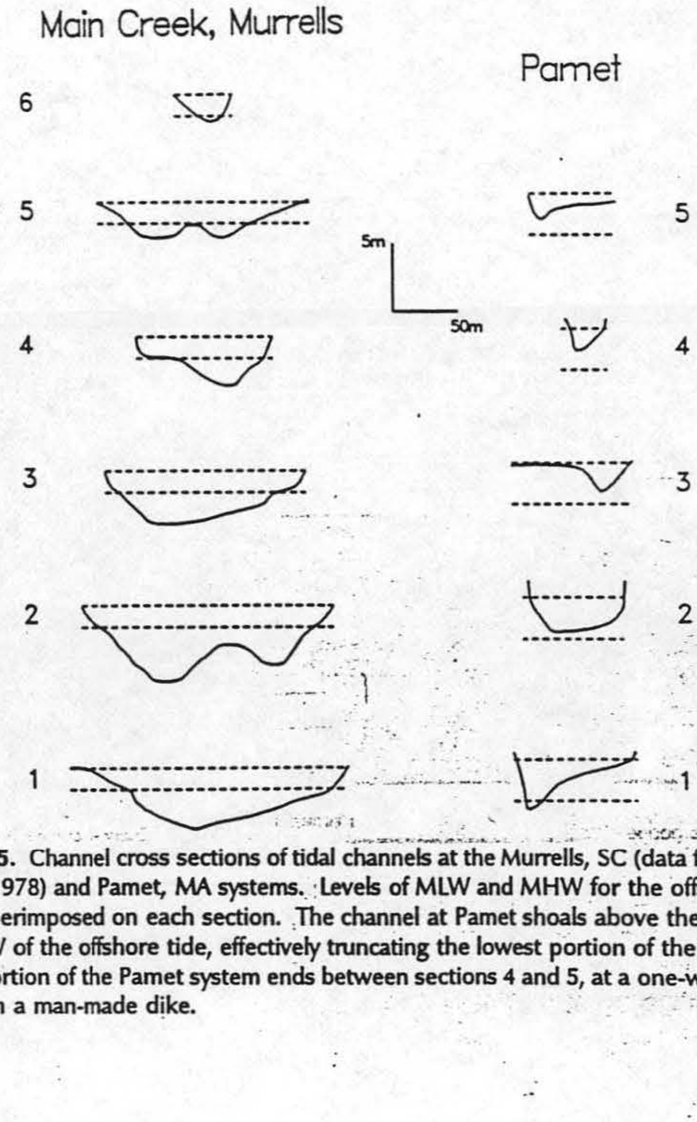

Figure 5. Channel cross sections of tidal channels at the Murrells, SC (data from Perry *et al.*, 1978) and Pamet, MA systems. Levels of MLW and MHW for the offshore tide are superimposed on each section. The channel at Pamet shoals above the elevation of MLW of the offshore tide, effectively truncating the lowest portion of the tide. The tidal portion of the Pamet system ends between sections 4 and 5, at a one-way culvert through a man-made dike.

scheme described earlier. The dimensions of the modeled system include a length of 2.75 km and a channel depth ranging from 2.5 m for the channel on the ebb tide delta to 0.65 m at the farthest reach of the estuary. In addition, the width gradually contracts from 50 m near the inlet to approximately 20 m near the end of the channel (compare with Figure 4 showing the Pamet system). The model was forced by a 1.5 meter M_2 tide.

A series of longitudinal profiles of channel sea surface elevation produced by the model illustrates the basic dynamics of an estuary like Pamet River (Figure 8). Consistent with the field observations of tidal elevation, high tide is nearly synchronous at all locations in the estuary. The reason for this behavior is the short length of the system and the relatively small tidal prism. (Significant intertidal storage in large areas of tidal flats and marshes would tend to make tidal exchange inefficient near high water, leading to lags of high water through the system.) As the tide at the inlet falls towards low water, the flow in the interior of the estuary eventually becomes uncoupled from the ocean tide (Figure 8). The momentum balance during ebb becomes a balance between the pressure gradient produced by the channel slope and bottom friction, as opposed to one between sea surface pressure gradient and bottom friction. This situation persists in the far reaches of the estuary until well after

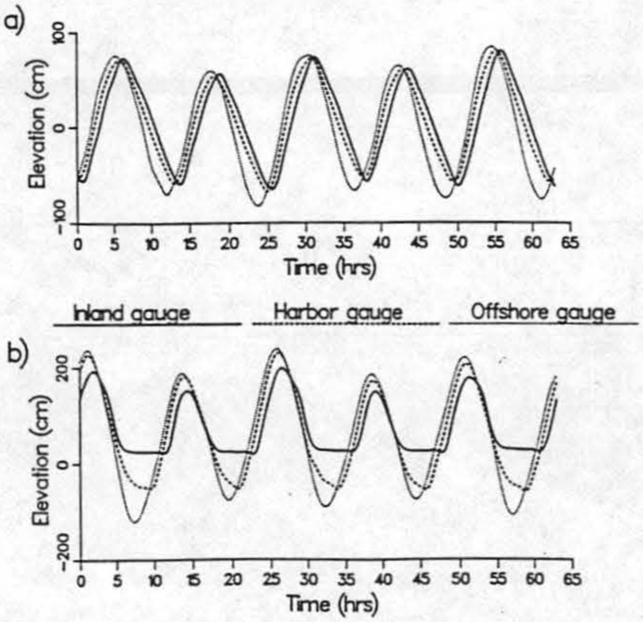

Figure 6. Tidal elevations over six tidal periods at three locations along the tidal channel at **(a)** Murrells, SC beginning 00:00 EST, November 16, 1975 and **(b)** Pamet, MA beginning 10:00 EST November 24, 1988. The truncation of low tide at Pamet is apparent.

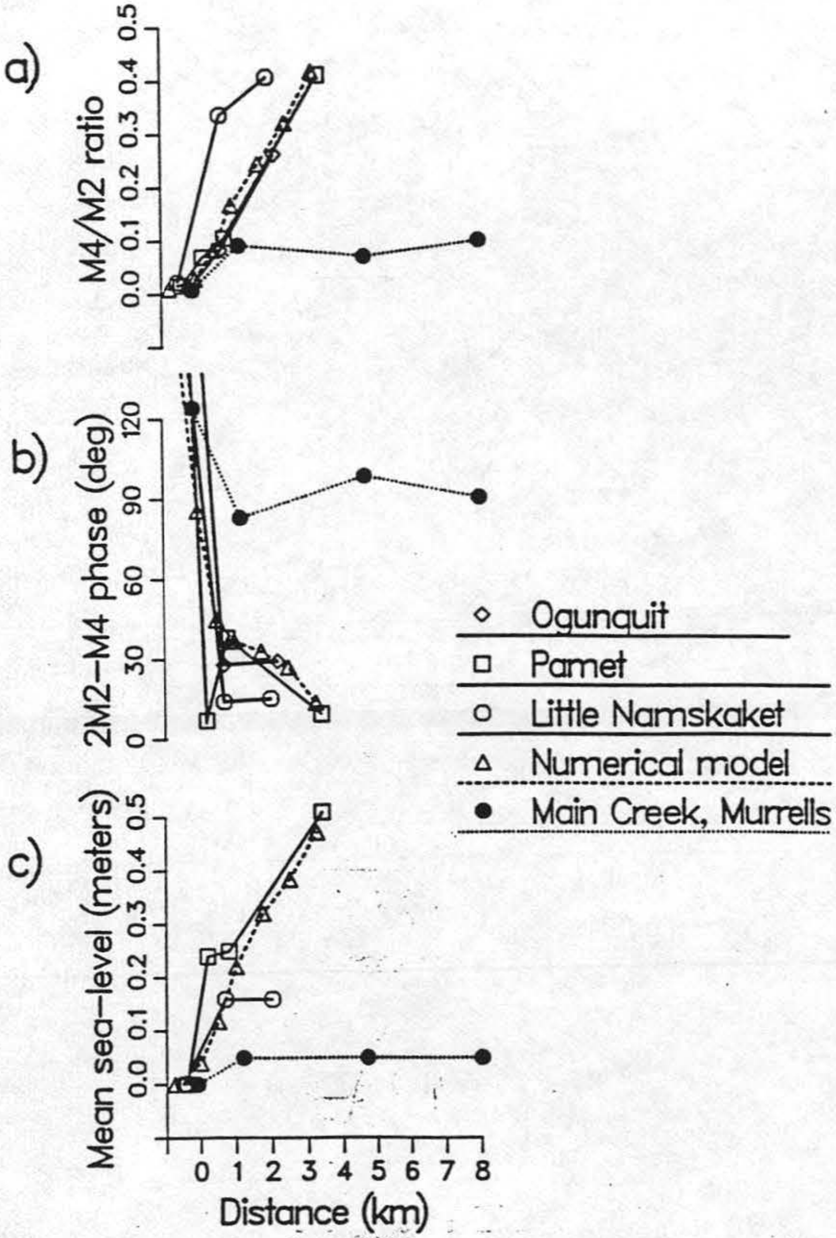

Figure 7. Parameters which describe tidal distortion as a function of distance along channel for four "truncated" systems (three natural, one numerical) and the tidal channel at Murrells, SC: (a) surface M_4/M_2 amplitude ratio; (b) surface $2M_2$-M_4 relative phase and (c) mean sea level. Tidal properties of the truncated systems are distinct from more common flood-dominant systems such as Murrells.

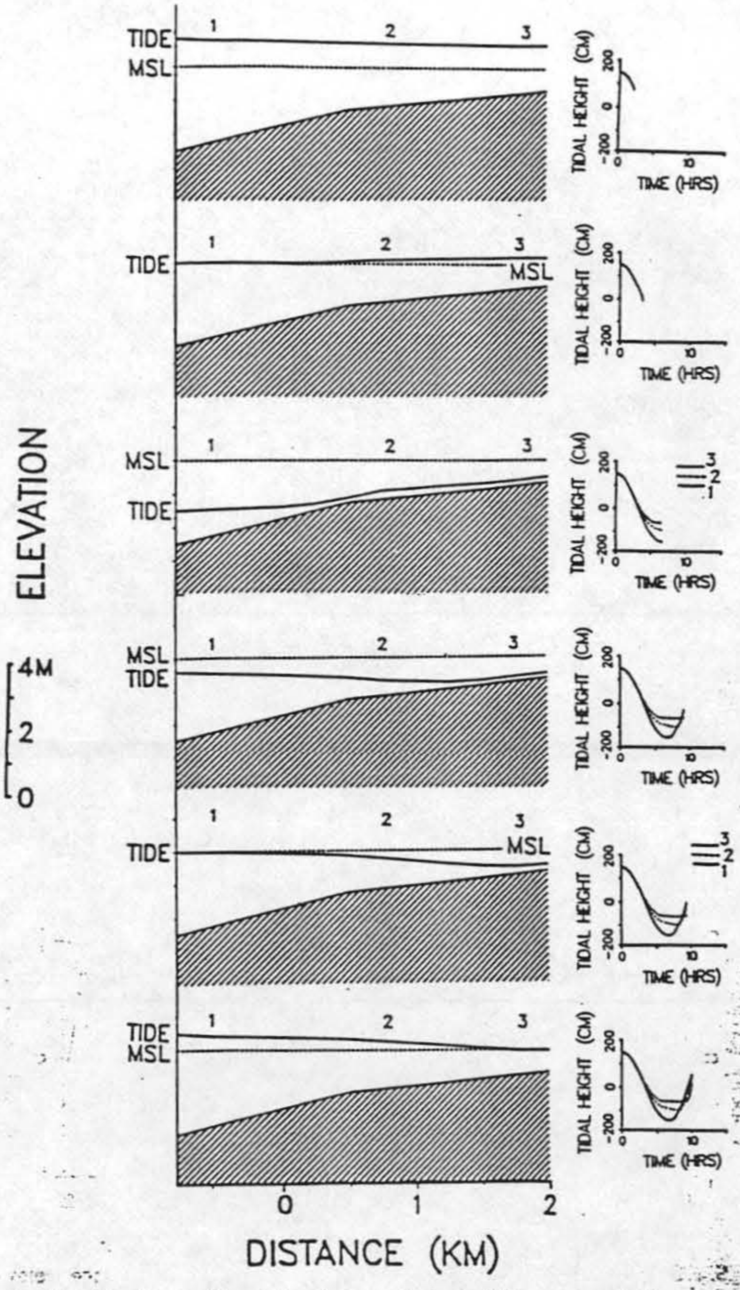

Figure 8. Results of one-dimensional numerical modeling presented as a series of longitudinal profiles of channel sea surface elevation during the tidal cycle. 1,2,3 indicate locations of tide gauge stations, the results of which are displayed adjacent to each profile.

the tide has turned to rise at the inlet. The resulting tidal propagation produces the characteristic truncated signals observed in the Pamet records.

Despite truncated sea-surface records within the inner estuary, neither field observations nor results of numerical modeling indicate strongly flood-dominant tidal velocities near the inlet (Figure 9a,b). This is because tidal velocity at the inlet lags behind the changing inlet cross-sectional area. Tidal velocity is in phase with the delayed discharge from the inner estuary, whereas the inlet cross-sectional area is in phase with the ocean tide. The reduced cross-sectional area during ebb forces the ebb at the inlet to be of higher velocity than otherwise would be expected. One-dimensional numerical modeling does suggest strongly flood-dominant tidal currents occur within the inner estuary, with ebb tide existing as a long, slow and shallow flow (Figure 9c). The sources of water for this slow ebb at Pamet are slow drainage

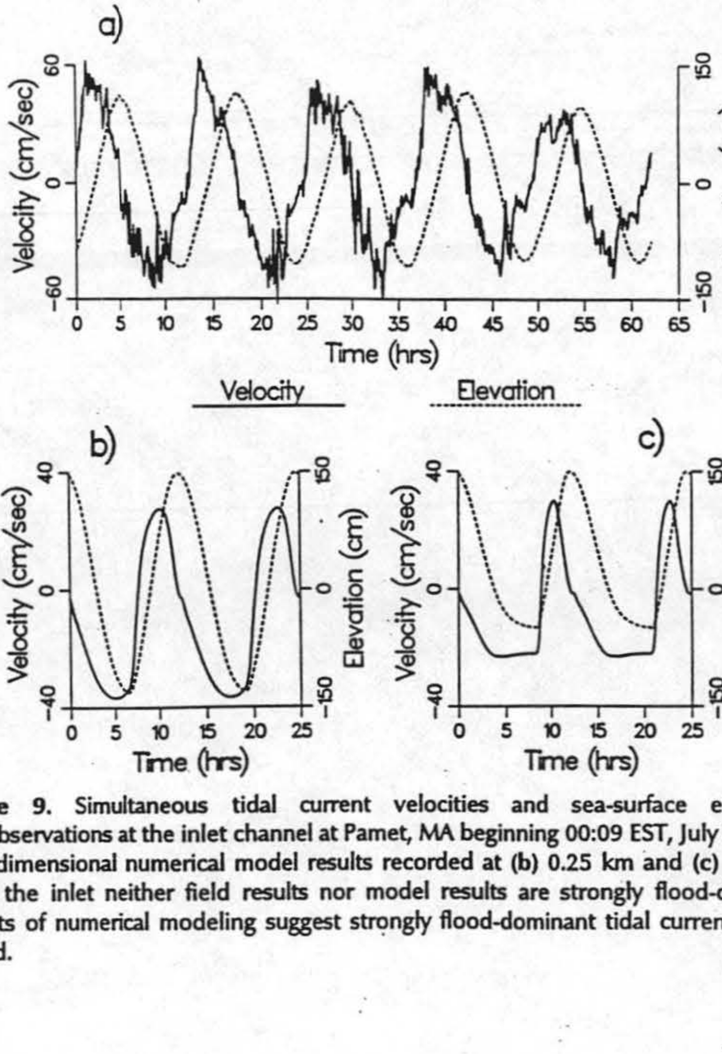

Figure 9. Simultaneous tidal current velocities and sea-surface elevations: (a) Observations at the inlet channel at Pamet, MA beginning 00:09 EST, July 20, 1988. One-dimensional numerical model results recorded at (b) 0.25 km and (c) 1.75 km. Near the inlet neither field results nor model results are strongly flood-dominant. Results of numerical modeling suggest strongly flood-dominant tidal currents farther inland.

from tidal flats and marshes, as well as freshwater which enters both through a dike at the distal portion of the channel and as groundwater along the full length of the system. As a result, flow in the upper reaches of Pamet becomes mostly fresh during late stages of ebb. Despite this, the total freshwater inflow amounts to only a few percent of the tidal prism.

Significant temporal variability occurs in tidal asymmetries in shallow estuarine systems. The variability arises from two principal sources: (1) changes in estuarine mean sea level on which the tide propagates resulting from atmospheric fluctuations and seasonal variability in water density (Aubrey and Friedrichs, 1988; Friedrichs *et al.*, submitted) and (2) the conjunction of a few principal tidal constituents at adjacent semidiurnal and quarter-diurnal bands (Friedrichs and Aubrey, 1988; Boon, 1988). The latter effect is the beating that occurs among M_2, S_2, and N_2, the result of which is to change the amplitude of the semidiurnal tide. This in turn affects the amplitude and relative phase of the daily quarter-diurnal tide producing changes in tidal distortion. Although the $2M_2$-M_4 relative phase may remain reasonably constant, tidal distortion does not remain constant through time. Lincoln and FitzGerald (1988) noted the average duration asymmetry at Ogunquit declined significantly from spring to neap tide. They speculated that during neap tides the offshore tide was no longer truncated at low tide by estuarine bathymetry. In terms of the relative phase between the semi- and quarter-diurnal tide, this would imply a shift from $\sim 0°$ to $30°$ to $\sim > 40°$.

The response of the modeled system to changes in the amplitude of semidiurnal forcing and mean sea level was investigated to examine the time-varying distortion problem. The results were then compared to observations from Pamet River (Figure 10). Observations of varying tidal amplitude effects consist of analyses of successive three-day records covering a spring-neap cycle. Constituents near the frequencies of M_2 and M_4 were extracted from the data. The time variability observed in the results does not reflect temporal variability in the harmonic constants but rather the superposition of unresolved adjacent constituents from the same species. Observations of varying mean sea level effects consist of 29-day averages covering a six-month interval. The results of the numerical modeling and harmonic analyses show that the magnitude of distortion in the estuarine tide increases with increased semidiurnal amplitude or decreased mean sea level. In both cases the tendency of estuarine bathymetry to truncate low tide is enhanced. This truncation is indicated by an increase in the quarter-diurnal-to-semidiurnal amplitude ratio (Figures 10a and 10d) and a shift in the relative phase towards a limit of 0° (Figures 10b and 10e). It is also clear that both the model system and Pamet behave more like a typical frictional flood-dominant system during neap tide and at higher mean sea level. Reduced truncation of low tide during the transition from spring to neap also causes estuarine mean sea level to decrease (Figure 10c). Seasonal fluctuations in offshore sea level likewise are correlated with low-frequency variations in tidal amplitude within

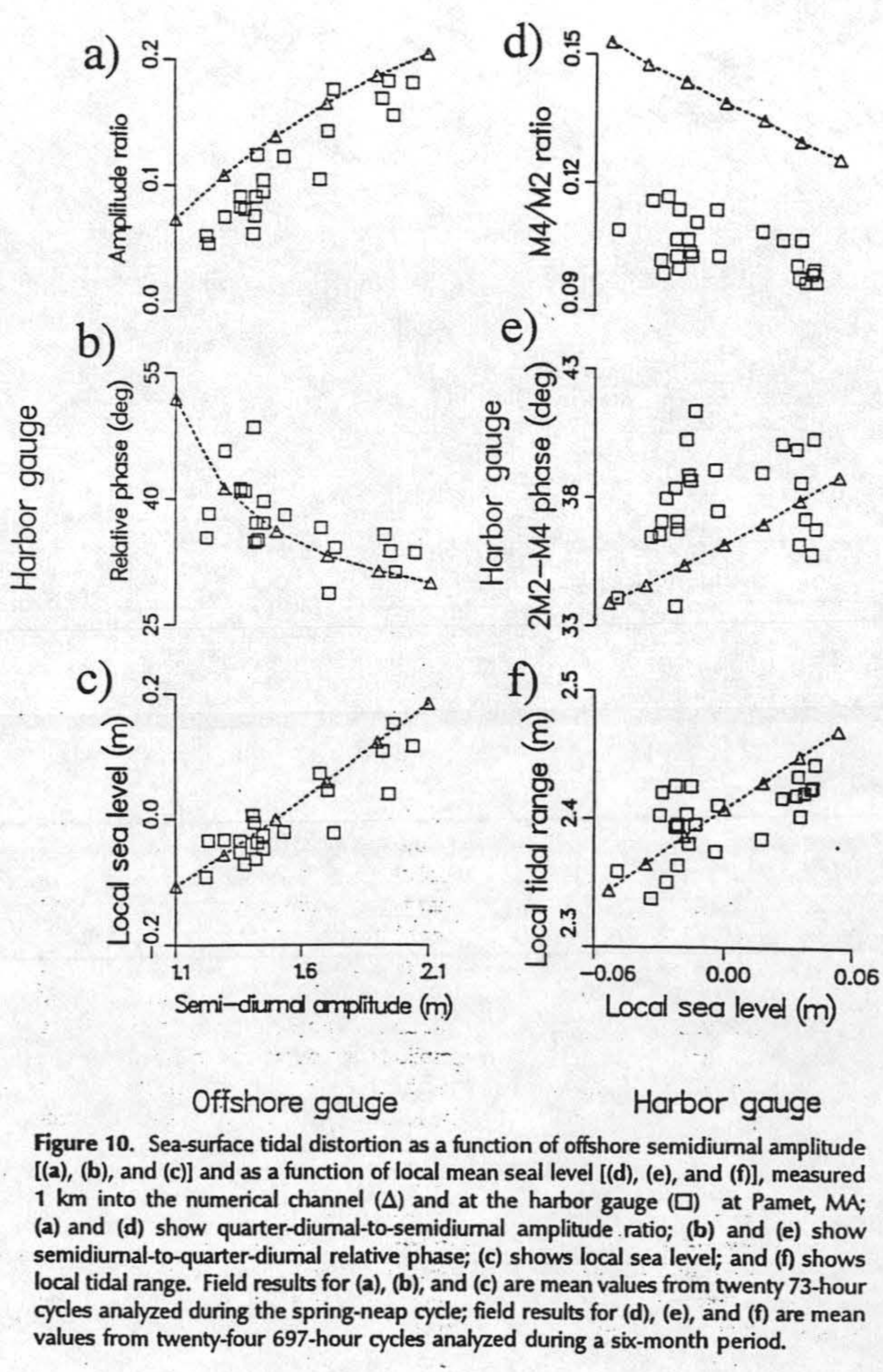

Figure 10. Sea-surface tidal distortion as a function of offshore semidiurnal amplitude [(**a**), (**b**), and (**c**)] and as a function of local mean seal level [(**d**), (**e**), and (**f**)], measured 1 km into the numerical channel (Δ) and at the harbor gauge (□) at Pamet, MA; (**a**) and (**d**) show quarter-diurnal-to-semidiurnal amplitude ratio; (**b**) and (**e**) show semidiurnal-to-quarter-diurnal relative phase; (**c**) shows local sea level; and (**f**) shows local tidal range. Field results for (**a**), (**b**), and (**c**) are mean values from twenty 73-hour cycles analyzed during the spring-neap cycle; field results for (**d**), (**e**), and (**f**) are mean values from twenty-four 697-hour cycles analyzed during a six-month period.

the estuary (Figure 10f). These observations are consistent with those for the Ogunquit Inlet (Lincoln and FitzGerald, 1988).

DISCUSSION AND CONCLUSIONS

This study summarizes a methodology developed earlier (Friedrichs and Aubrey,1988) to examine the different types of tidal asymmetry found in shallow tidally-dominated estuaries. Measurements of sea surface elevation and one-dimensional numerical modeling are combined to define estuarine characteristics responsible for producing flood- and ebb-dominant asymmetries. The method is then applied to a particular class of flood-dominant estuary, one characterized by strongly distorted sea surface tides and low values of the $2M_2$-M_4 relative phase.

Tidal distortion in shallow estuaries results from two principal effects: (1) frictional interaction between estuarine tidal currents and channel bottoms and (2) intertidal storage of water in flats and marshes. Estuaries dominated by the first effect have longer lags at low water than high proceeding into the estuary, and hence longer falling tides. As a result, they tend to develop stronger flood than ebb currents. Flood-dominant estuaries are typically shallow ($a/h > 0.3$) with small to moderate areas of tidal flats. Estuaries dominated by the second effect have longer lags at high water than low water, and hence longer rising tides. These systems generally have stronger ebb than flood currents and tend to be deeper ($a/h < 0.2$) with frequently extensive regions of flats and marshes. In both cases, sediment transport patterns and resulting estuarine morphology are controlled by the type of asymmetry present.

A particular class of flood-dominant estuary is defined by large values of the M_4/M_2 ratio and atypically low values of $2M_2$-M_4 relative phase ($<30°$). These systems, which are common along the New England (USA) coast appear to result from a combination of small physical scale and large offshore tidal amplitude relative to distal channel depths. The distinguishing feature of tidal propagation is the truncation of low tide by estuarine bathymetry, resulting in an extended falling tide and a slow shallow ebb flow. Despite short channel lengths (~ 2 to 3 km), flow in the interior during the latter stages of ebb is effectively decoupled from tidal forcing at the inlet. This decoupling produces a typical riverine momentum balance of bottom friction and channel slope induced pressure gradient. By contrast, many flood-dominant systems are characterized by principal momentum balances between bottom friction and sea surface pressure gradient. As with other causes of tidal distortion, truncation of low tide is enhanced during spring tides and greatly reduced during neap tides. This produces considerable variability in the actual degree of tidal asymmetry a shallow estuary experiences on a day-by-day basis. Transport of dissolved and suspended material is expected to be influenced strongly by this type of flood-dominant behavior.

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