CIRCULATION OF TWO MULTIPASS ESTUARIES

IN THE GULF OF MEXICO

by

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1. Introduction

An important class of estuaries which has received relatively little attention is the barrier-island-contained multi-inlet one. Cases range in scale from the tidal rivers common along the S.E. coast of the U.S.A. to the very extensive embayments found on the Gulf of Mexico. A sound knowledge of the dynamics of the type of estuary is important for enlightened management of the resource. In the Culf of Mexico region these estuaries tend to be significant spawning areas for marine fishes, and also support important local fisheries and oyster beds. Fortunately (or not) they are also geomorphically associated with coasts underlain by nearly-horizontal sedimentary rocks which often yield petroleum. Finally, in the Culf of Mexico area of the U.S.A. the relatively attractive setting and climate of the barrier islands induces dense human development. (Surprisingly this attraction does not seem to occur in Latin America where the Gulf Coast is relatively unpopular and sparsely populated). Petroleum extraction and residential development, and the civil appurtenances needed to support them, can pose significant threats to the water quality, and hence marine life, of these estuaries. Local economic and social impacts can be severe since the fishing economy is usually marginal and traditional (even in the U.S.), while the oil and real estate businesses are usually strongly linked to wealthier portions of the exogenous economies. Because of this, regulation is probably necessary to prevent excessive adverse impacts, and sound knowledge is required for proper and enforceable water quality regulation.

As occurs in many disciplines from time to time, Carter, Najarian _et al._ (1, p. 1586) pointed out that rigorous estuarine analysis has suffered from the nature of its origin in Chesapeake Bay:

> "One of the most extensive and most thoroughly analyzed set of observations for any estuary was that of Pritchard ... taken in the James River in 1950. ..Although this set of measurements and their analysis by Pritchard resulted in vastly improved understanding of estuarine physical (_sic_) processes, it so influenced subsequent estuarine studies that measured circulation patterns that were at variance, at least for part-

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ially mixed estuaries, were viewed as measurement artifacts, which they were not rather than .... real events, which they probably were"

A particular mental constraint resulting from the notion of the classical estuary (i.e., James River, VA) was that tidally-averaged water flux equals freshwater inflow and tidally-averaged salt flux is zero, under steady state conditions. Further, tidal motion was considered to be the most important variable affecting estuarine dispersion, and the source of most of the ambient turbulence available for mixing. A review of the literature indicates these notions only came to be questioned, disproved, and then incorporated into more sophisticated models after about 1975. Two significant papers appeared around that time. Weisberg (2, also 3) showed that meteorological forcing caused a significant portion of the total turbulent energy even in a narrow tidal river. It has subsequently been realized that wind forcing can almost completely overwhelm tidal effects in broad shallow embayments of the Gulf of Mexico which has minimal tidal amplitude (of the order of a foot). (In all honesty it appears that this may have been appreciated by field biologists before coastal engineers and oceanographers).

The second significant paper was that of van de Kreeke and Dean (4) (followed later by 5, 6, 7), in which the principles of Stokes velocity, as discussed in an earlier theoretical paper by Longuet-Higgins (8), were applied to the engineering analysis of circulation of shallow bays with 2 inlets. The essence of the paper was that non-linear flux terms resulting from periodic tidal motion do not disappear upon tidal averaging (even for single inlet estuaries(9)) and residual flows will typically occur. This will be discussed in more detail anon.

The environmental engineering and biological implications of these results are extremely significant, and, in the author's opinion, almost totally unappreciated by workers in these fields despite some efforts by van de Kreeke (5, 7) to point them out. The effect of net nontidal residual flows caused by wind or nonlinear tidal residuals is to induce an advective component which can greatly reduce the flushing time of the estuary, and change distributions of water quality parameters (7). Since coastal engineering projects can change these renewal rates (10), or at least require them to be evaluated for EIS's, it follows that they should be studied in detail so that adverse environmental impacts can be avoided wherever possible by engineers working in these estuaries.

2. Scopes of Apalachicola and Terminos Projects

Apalachicola Bay is a large (550 km^2) 4-inlet embayment on the Florida Panhandle. Laguna de Terminos, the largest (2000 km^2) estuary on the Gulf of Mexico, is a 2 inlet-embayment located at the base of the Yucatan Peninsula. See Figures 1 and 2. Both support significant local fisheries. Apalachicola is being impacted by nonpoint pollution from silvicultural activities near its head (11-15), and by residential development in St. George Island. Terminos is being affected by intensive petroleum exploration offshore in the Gulf of Campeche and by associated growth of the barrier island city of C. de Carmen. There

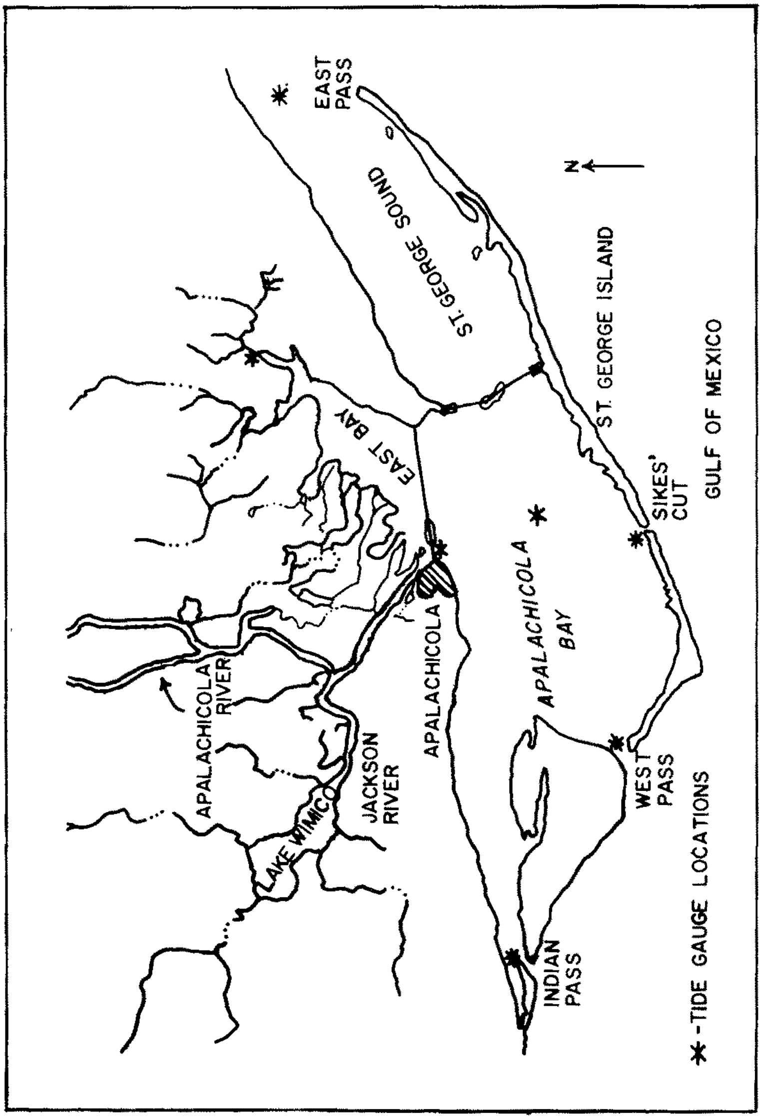

Figure 1 GEOGRAPHY OF APALACHICOLA BAY

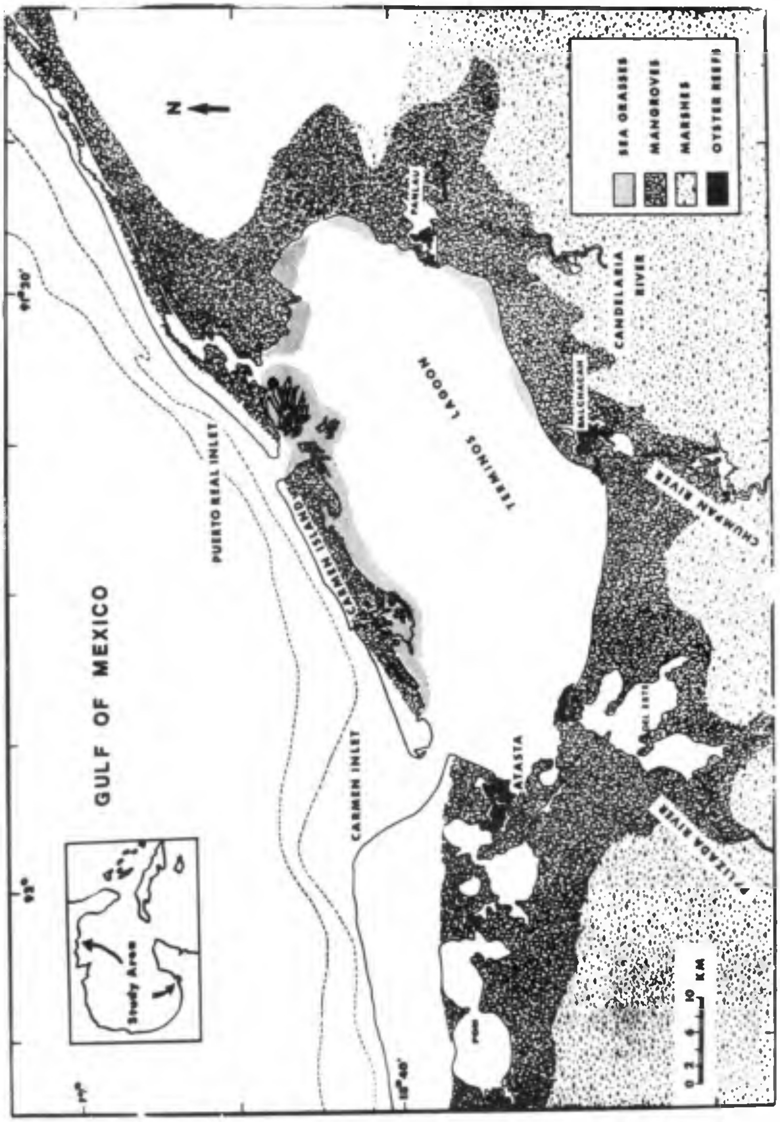

Figure 2 Geography of Laguna de Terminos, Mexico

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is concern over the fate of another large oil spill or blowout. In both cases the vertically-averaged 2-dimensional real-time finite-element circulation model CAFE-1 (16) was applied to provide information about the macro-circulation features of the estuaries. Both projects were consulting jobs essentially in support of biological studies and hence were limited in scope and funding. Some field data for model verification were obtained for Apalachicola Bay, none was specifically available for Terminos. The purpose of the paper is to discuss the general results of the two model applications to geomorphologically and dynamically similar estuaries on the Gulf of Mexico, and the relate these to the comments made in the introduction. It is emphasized that these were engineering projects limited in scope and not exhaustive scientific programs.

3. Discussion of Significance of van de Kreeke's Results

Numerical model outputs for both Apalachicola Bay (10, 17) and Laguna de Terminos (18, 19, 20) both showed residual nontidal flows with windless conditions. Frankly, we thought that either the model results might be erroneous or that we had discovered something new, particularly since drowning victims and loose boats at Apalachicola were known to drift west. Dr. Tavit Najarian kindly brought van de Kreeke's work to the attention of the author. This material appears to be germane, although it does not seem to have been applied to such large systems before. It will be compared to numerical results herein.

In terms of unit discharges the equations of motion used by van de Kreeke (4, 6) were

$$\frac{\partial \eta}{\partial t} + \frac{\partial q}{\partial x} = 0 \qquad 1.$$

$$\frac{\partial q}{\partial t} + gh\frac{\partial \eta}{\partial x} + g\eta\frac{\partial \eta}{\partial x} + \frac{2}{h}\, q\, \frac{\partial q}{\partial x} + \frac{gh^2}{\rho 2} * \frac{\partial \rho}{\partial x} = - Fr \qquad 2.$$

$$\text{where } Fr = \frac{F_1\, q\, |q|}{(h+\eta)^2} \qquad \text{quadratic} \qquad 3.$$

$$\text{or} \qquad Fr = \frac{F_2 q}{h} - \frac{F_2 q\eta}{h^2} \qquad \text{quasi-linear to second order} \qquad 4.$$

where η - tidal were amplitude, q - unit discharge, h - mean depth, ρ - density, Fr - bottom friction term, F_1 - constant and F_2 - constant.

In comparing these with the basic equations in the CAFE-1 model (see 16, or 14, 17, 19) the primary differences are i) the dimensionality, ii) the exclusion of Coriolis and wind-stress terms, and iii) the inclusion of a baroclinic term. A 2-D analog of equations 1-4 is given by van de Kreeke in (7), but ii) still holds. The quadratic resistance relation, eq. 3, is used in CAFE, while van de Kreeke uses the quasi-linear form (4) for his illustrations. As shown in (4) the differences are great enough to warrant using full quadratic formulation, but the results are similar and of the same order. Substituting eq. 4 in eq. 2, a tidally-averaged form of eq. 2 can be derived in which second-order terms are retained as residuals and are balanced by the net bottom stress (see 4, 5, 6, 7). Assigning boundary conditions at each inlet of the channel of

$$\eta = a_0 + a_1 \sin\sigma t \text{ and } \rho = \rho_a \text{ at } x = -L/2 \qquad 5.$$

$$\text{and } \eta = b_0 + b_1 \sin(\sigma t - \delta) \text{ and } \rho = \rho_b \text{ at } x = +L/2 \qquad 6.$$

and denoting the tidally averaged unit discharge as q_*, it is shown (4, 6) that

$$\frac{q_* T}{hL} = P\left(\frac{\lambda}{L}, \frac{F_2 L}{C_0 h}\right) \frac{a_1 b_1}{h^2} \sin\delta + Q\left(\frac{\lambda}{L}, \frac{F_2 L}{C_0 h}\right) \frac{a_1{}^2 - b_1{}^2}{h^2}$$

$$+ \frac{C_0 h \lambda}{F_2 L L} \frac{a_0 - b_0}{h} - \frac{C_0 h}{F_2 L} \frac{\lambda}{L} \frac{\rho_a - \rho_b}{\rho_0} \qquad 7.$$

where T - wave period, λ - wave length, $C_0 = \sqrt{gh}$, P and Q are functions (see 4). Eq. 7 is given in (6), while only the first two terms on the rhs appear in (4). The contributions represent, respectively, net flow induced by phase differences, amplitude differences, differences in mean water level, and baroclinic effects. The nature of the latter is reasonably well known and will not be given further consideration here. Also, $\partial\rho/\partial x$ effects are not used in CAFE. Note that terms in the rhs of eq. 7 are of order a^2/h^2, so q_* would be expected to be largest in shallow lagoons, such as Apalachicola and Terminos.

In other words, if the tidal wave at each inlet has a different amplitude and phase lag, caused by differences in offshore shelf topography, then a net nontidal flow will be set up in shallow multi-inlet estuaries. Further, if the mean sea level varies along the coast, a net-flow will be induced, as expected. The latter is not uncommon and van de Kreeke (6) found this to be the largest contribution at Marco Island, Florida. Unfortunately we did not have the capability of finding mean sea level at either Apalachicola or Terminos, although we expect there is a difference at Apalachicola since superior model results were obtained by inputting a gradient of mean sea level.

A final comment is made that van de Kreeke and Chiu (7) found similar residual currents with a 2-D finite-difference model. Residual flow eddies were also present but it could not be readily determined to what extent these were real or numerically-induced. Tee (21) claimed residual eddy currents computed for the Minas Basin, NS, were real. At the April 1980 AGU convention in Toronto van Zant and Hsueh (see 22) presented a finite difference Leendertse-type model of Apalachicola Bay which they had developed contemporaneously, but independently, from our own CAFE application. Using similar boundary conditions, but cruder boundary representation, they computed residual eddies near East and West Passes. CAFE, on the other hand did not (although a (real) residual eddy can appear near East Bay under some circumstances). Further, our field work and satellite images showed no evidence of such eddies existing under these conditions. Consequently, residual eddies in numerical models must be viewed with skepticism until proven. As shown in (19), satellite images confirmed the existence of the central eddy in Terminos calculated by CAFE.

4. Selected Apalachicola Results

Since most of the Apalachicola and Terminos material has been published, only selected results germane to the foregoing comments will be presented. Interested readers are referred to the original papers for more details.

As shown in Figure 3, a strong east to west net nontidal velocity was calculated for windless conditions with T = 44640s; at West Pass $a_0 = 0$, $a_1 = 0.21$ m; at East Pass $b_0 = 0$, $b_1 = 0.40$ m; $\delta = 3780$ sec (see eq. 5, 6) from the tide tables. In this case then, L = 39 km, h = 3 m approximately, $C_0 = 5.4$ mps, $\delta = 30.48^{\circ}$, $\sin\delta = .507$, $\lambda = 242$ km. n = 0.018 in the model, so

$$F_1 = \frac{n^2 g}{h^{1/3}} = \frac{.018^2(9.81)}{3^{1/3}} = .00220 \qquad 8.$$

and letting $F_1 \doteq F_2$ (rather than eq. 22 in (4))
we get, from eq. 7, 9.

$$q_* = 2.62\ [P(6.21,\ 5.30)(.008)(.507) + Q(6.21,\ 5.30)(-.014)] \qquad 10.$$

$$P \doteq 1.8, \qquad Q \doteq 1 \quad \text{from (4)} \qquad 11,\ 12.$$

$$\text{so } q_* \doteq 2.62\ (.007 - .014) = -.019 \qquad 13.$$

$$\text{so } v_* = q_*\ h = -0.019 * 3 = 6 \text{ cm/s westward} \qquad 14.$$

Typical values computed (10) are about 20-30 cm/s westward for 3 m depths, hence the results are reasonable and comparable, considering the approximations of eq. 9, 11, 12, lack of Coriolis terms in (4), and the suspicion that $a_0 \neq b_0$ on the average. Hence the net westward flux in Apalachicola Bay can be ascribed to nonlinear interaction of tidal waves. This net flux is surmised to be responsible for the high quality of Apalachicola Bay water, and it was demonstrated in (10) that construction of a mid-Bay island for bridge abutments had probably resulted in an increase in flushing time.

In November 1979 we placed tide gauges at each inlet to Apalachicola Bay and in the Bay center (see Figure 1). Records were correlated by superposing Doodson-filtered signals of mean surface water levels (17). The magnitude of wind-induced (5-10 kt maxima) fluctuations in amplitude and "mean" sea level in this type of estuary is evident in Figure 4. Wind forcing can readily dominate tidal motion. As shown in Figure 5, CAFE produced reasonably good results. It can be seen however that relatively long-term records are needed to establish that $a_0 = b_0$ in eq. 5 and 6.

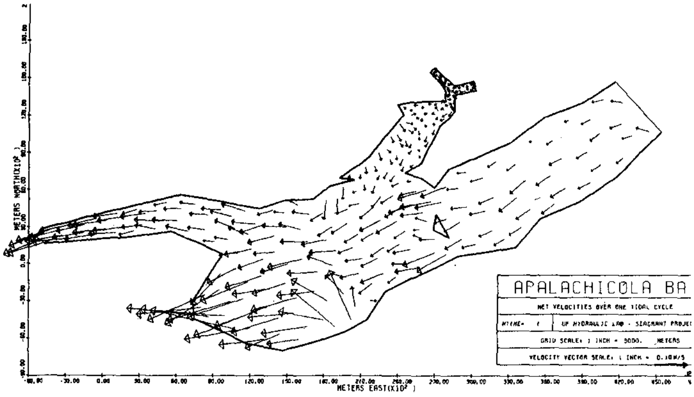

Figure 3 Net Residual Apalachicola Bay Velocities

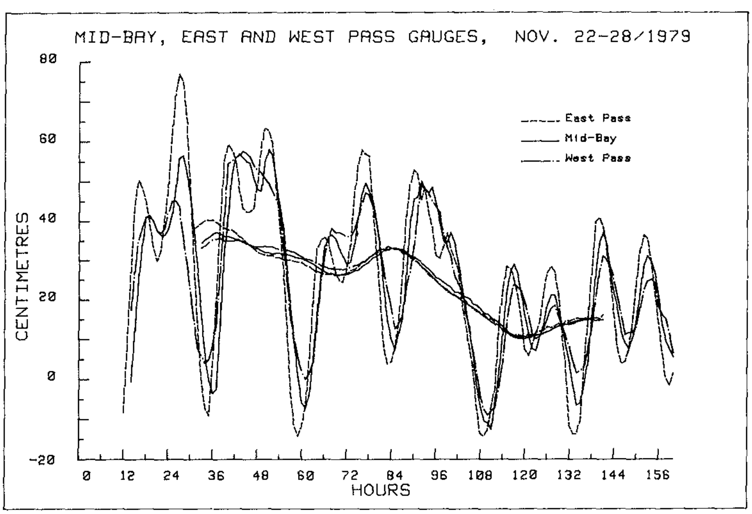

Figure 4 Measured and Doodson- Filtered Tide Records

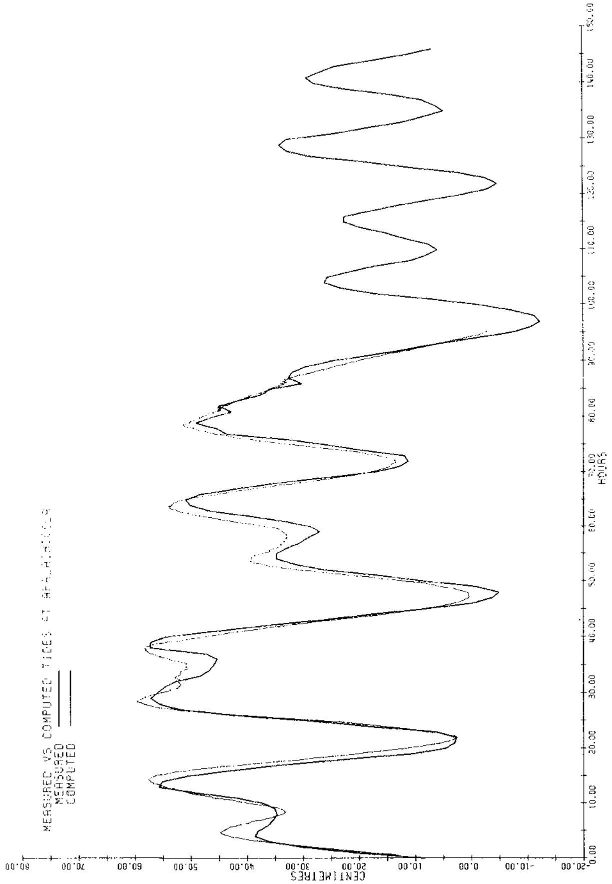

Figure 5 MEASURED VS. COMPUTED TIDES AT APALACHICOLA

5. Selected Terminos Results

Because Laguna de Terminos is morphologically and dynamically similar to Apalachicola, we were asked to apply the CAFE model to it in support of a UNAM - LSU biological assessment. No data were available to us except those in standard tide tables. A crude bathymetry of Terminos was provided by LSU. Terminos lies in Trade Wind zone so that it enjoys a constant breeze from the NE of about 2-5 mps for much of the year. This is surmised to cause the net westward flow , as discussed by Mancilla and Vargas (23), and evidenced by the prominent flood-tidal delta at Puerto Real inlet.

The cases simulated for Terminos are listed below

	Amplitude		Lag		Wind	
	E m	W	E s	W	Speed mps	Direction from
1	.24	.24	0	0	0	-
2	.24	.30	+120	0	0	-
3	.24	.24	0	0	5	NE
4	.24	.24	0	0	10	NW

where E - Puerto Real inlet, W - Carmen inlet. The LSU field biologist said he suspected there was no difference in tidal properties between the two inlets. The differences in Case 2 were the greatest that could be expected by interpolation and extrapolation from the few stations in Tide Tables. The results showing net velocities are depicted in Figure 6. The large eddy for Case 4 also appears in winter satellite images.(19)

Subsequent work by M. C. Julio Candela P. (24) and Crivel et al. (25) appears (to the extent the author understands the Spanish) to yield the following information on the tidal properties. According to Candela the dominant tides at Carmen are O_1(amp = 11.23 cm, period = 25.82h, phase = 317.25^o), K_1 (amp. = 11.04 cm, period = 23.93 h, phase = 321.32^o), and M_2 (amp = 7.51 cm, period = 12.42 h., phase = 88.58^o). This results in a mixed tide with Band 1 dominant. Taking mean values of O_1 + K_1 of amp = 22 cm, phase = 319.3^o for Carmen, the comparable values for Isla Aguda in Puerto Real are, for Band 1, amp. = 22 x 0.92 = 20.2 cm and phase = 319.3^o + 6.7^o = 326^o. Crivel et al. (25) find the same phase difference, i.e. 6.7^o or 27 minutes, to exist.

In summary the Band 1 amplitude difference is 1.8 cm and the phase difference is 27 minutes with Carmen leading. These are of the same order as those used by Craham in Case 2, but not close. An analysis using van de Kreeke and Dean's (4) eq. 7 for a_o = b_o (25) with the values: T = 25h = 90000s, h = 3.5 m (24), L = 38.5 km between the inlets (24), C_o = 5.9 mps, λ = CT = 527 km, a1 = 20.2 cm, b1 = 22 cm, δ = 6.7^o, sinδ = .117, F = F2 = .0022, then

$$q_* = 1.5 \,[P(13.7,\ 4.1)(.0036)(.117) + Q(13.7,\ 4.1)(-.00062)] \quad 15.$$

$$P \doteq 0.6,\ Q \doteq 1.8 \text{ from } (4) \quad 16.$$

so $q_* = 1.5\ (.00025 - .00112)$

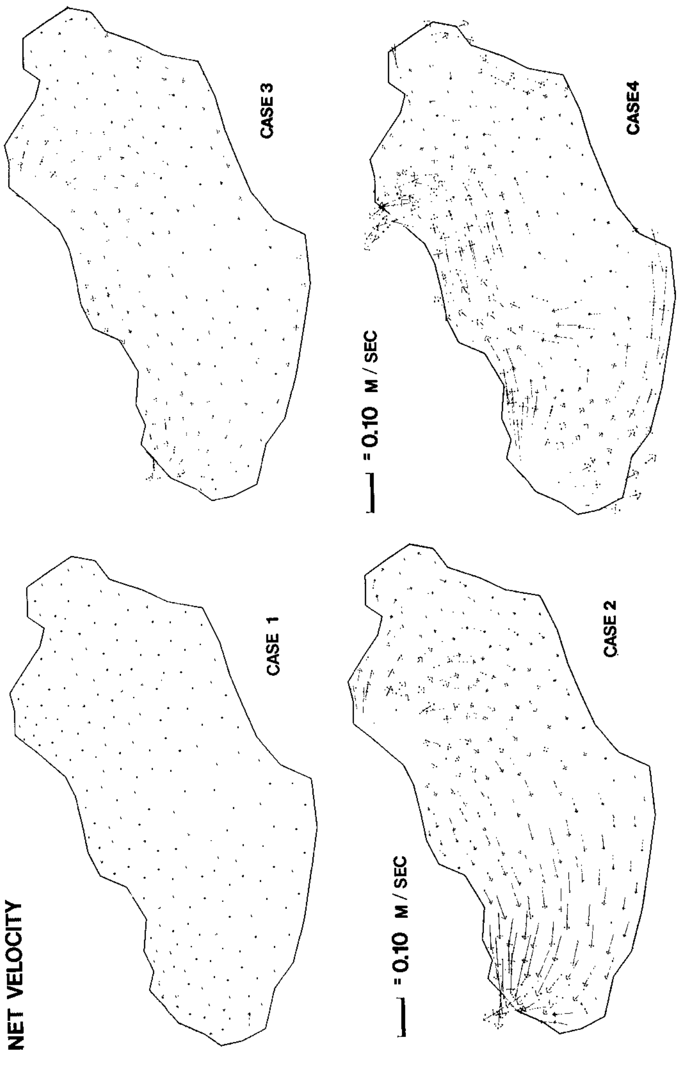

Figure 6 Net Residual Terminos Velocities

$$q_* = -.00082 \qquad 17.$$

so $$V_* = q_* h = -.003 \text{ m/s} = -.30 \text{ cm/s} \qquad 18.$$

eastward. This does not correspond to the computed results of Figure 6 because the phase is lagged in the opposite direction. It also suffers the same caviats as mentioned earlier for Apalachicola. It may be concluded that the net westward drift in Terminos likely occurs because of the steady trade winds and in spite of the nonlinear tidal wave flux. Modification or filling of Puerto Real inlet could severely alter the flushing rate of the Laguna. Conversely, oil spills near Carmen might enter Terminos under windless conditions. It is hoped further cooperative work on Terminos can be done.

6. Summary

The flushing and water quality of shallow multi-inlet estuaries in the Gulf of Mexico appears to be dominated by nonlinear wave flux advection and wind forcing, rather than advection from river inflow and tidally enhanced dispersion. Understanding and managing these systems requires detailed knowledge of their tidal characteristics and response to wind shear. Coastal engineering works could significantly alter the properties of the circulation of these estuaries.

7. Acknowledgements

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