SAN DIEGO BAY CIRCULATION

A Study of the Circulation of Water in San Diego Bay for the Purpose of Assessing, Monitoring and Managing the Transport and Potential Accumulation of Pollutants and Sediment in San Diego Bay.

FINAL REPORT

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1. INTRODUCTION.

As part of Phase IV of the San Diego Bay Cleanup Project, the University of California agreed to 'investigate water levels, current profiles, and water temperatures to determine dominant factors controlling bay circulation, flushing and movement of pollutants. The data will be used to validate water circulation models and to make them more predictive.' This is the final report on that work.

Guided by an overall commitment to improving the water quality of San Diego Bay, this project was perceived as a part of a broader community initiative to measure, understand and model the circulation and associated water quality issues of the Bay. Since the original conception of this study in 1990, the research activity on San Diego Bay circulation has increased remarkably and the original specifications of this contract have been exceeded and eclipsed by the present research activity on the Bay. Much of this work was stimulated by my activity during the period before the contract was signed (work performed in good faith). Following completion of this contract, the community of San Diego Bay researchers continues with an exciting and productive array of studies on water circulation and water quality - instruments are deployed, computer models are run and problems are addressed. The total dollar amount invested in this research is at least an order of magnitude more than that made available through this contract. Much of this activity can trace its original stimulation to the early days of this contract. In that way, this contract has been successful way beyond the original expectations in that it has acted as a seed for the rapid growth in our knowledge of the circulation relevant to water quality in San Diego Bay. It is suggested that the Water Quality Control Board may invite active researchers from a variety of agencies to participate in a workshop on San Diego Bay circulation and pollutant transport. This would provide a forum in which ideas can be exchanged and developed and in which the Water Quality Control Board can update its information on this crucial topic - thus reaping the full dividends of the investment in this one contract. Some of this information will be presented at the Oceans '95 meeting in San Diego this October (eg., Chadwick, et al., 1995).

Given the extensive range of activities that have developed in collaboration with this contract, it is difficult to summarize all that we have learnt about the circulation of water in San Diego Bay. In this report, I will limit my comments to those field activities in which the University of California played a lead role. Nevertheless, reference will be made to associated activity and relevant documents will be indicated. Our project team at the University of California (San Diego) consisted of John Largier (project leader & scientist), Kimball Millikan (field research specialist), Ron George (post-doctoral scientist), Bart Chadwick (graduate student scientist) and various engineering, field and clerical staff. The key field experiments consisted of:

(1) deployment of instrumented drifters within the Bay,
(2) surveys of longitudinal temperature and salinity structures,

(3) cross-sectional surveys of current, temperature and salinity structure over a tidal cycle,
(4) survey of current, temperature and salinity structure as well as deployment of drifters in the Bay outflow, and
(5) participation in a multi-agency deployment of an array of current meters, thermistors and water level recorders throughout the Bay.

These data have been used as the basis for ongoing improvements of numerical models of Bay circulation. Further, the data are also used in tests of theoretical models of Bay hydrodynamics and flushing.

From a scientific viewpoint, the primary issues relevant to pollutant transport and potential accumulation in San Diego Bay are Bay-ocean exchange, stratification and shear, trapping in low-velocity regions and the strength of longitudinal dispersion in the Bay. Through reference to earlier studies and data sets, through collaboration with the studies of other researchers and through our own collection of data, we have characterized these processes and estimated the residence time of water in San Diego Bay.

2. BACKGROUND

San Diego Bay is a naturally formed, crescent-shaped embayment in the southwestern corner of California. It is separated from the sea by a sand spit extending from Imperial Beach almost to Point Loma. This spit has now been stabilized, as have the shifting sand islands in the outer Bay (now known as Shelter Island and Harbor Island). In its current configuration, the axial length of the Bay from the tip of Point Loma to the mouth of the Otay River is about 24.5 km. The outer half of the Bay is relatively narrow, averaging 1-2 km, whereas the inner Bay is broader, between 2 and 4 km wide (Figure 1). This broad, shallow region lies south of the narrowest section of the Bay off Sea Port Village (near the Coronado Bridge) and we refer to it as South Bay. Deep water is only found in South Bay where shipping channels have been dredged along the northeastern shore. The remaining areas are 1-4 m deep. In contrast, the North Bay (north of the constriction and bridge) is deep, on average 12 m. The small boat harbors are shallower, about 3-5 m deep. The mouth of the Bay is about 1 km wide and aligned north-south, between the rocky Point Loma and the constructed Zuniga Jetty (Figure 1). Immediately outside the Bay, there are shoals (2-4 m) on either side of the approach channel - a rocky kelp-covered ridge to the west and a smooth sand depositional feature to the east. Offshore of the mouth, the bottom slopes away gently (slope of about 1:200).

The climate of San Diego is characterized as semi-arid, with a low average annual rainfall of about 0.25 m. The period of winter rainfall extends from November through March, with average monthly rainfalls of 0.05 m. The summer rainfall is negligible (Peeling, 1975). Evaporation exceeds precipitation during spring, summer and fall with an annual evaporation of about 1.6 m (Lenz, 1976). Our measurements reflect this seasonally arid climate, with hypersalinity being observed in South Bay every summer (ie., the water is saltier than the sea). Winds over the Bay and coastal regions are typically less than 5 m/s (10 knots). In summer, the wind over San Diego Bay exhibits a strong diurnal cycle - a typical 'sea breeze' (cool sea air moving in over the land) is observed most afternoons. In winter, stronger winds are observed at times, during the passage of a cold front associated with a propagating mid-latitude low pressure system. In fall, strong easterlies may occur during 'Santa Ana' conditions (inland high pressure). Mean air temperature for the region is 16.4°C, with an annual range of only about 8°C (Lenz, 1976). Warmest temperatures are experienced during easterly Santa Ana winds, when cool oceanic air is pushed out to sea. Coldest temperatures occur in winter, under clear skies.

Tides in San Diego Bay are classified as mixed diurnal/semi-diurnal, with a dominant semi-diurnal component. The interaction of diurnal and semi-diurnal tides is such that the higher high tide precedes the lower low tide, resulting in strongest currents being observed on this large ebb tide. The interaction of the lunar M2 and solar S2 tidal components results in a spring-neap cycle with a period of 14.3 days. The tidal range (difference between mean lowest low water MLLW and mean highest high water MHHW) is about 1.7 m with extreme tidal ranges of 3 m. Water level and current meter measurements indicate that the tide behaves approximately as a standing wave, with high and low water occurring in phase throughout the Bay and with inflow velocities leading the tidal water level by about 75-80 degrees (ie., 2.6 to 2.7 hours for the semi-diurnal tide). These estimates are based on current-meter data (Aanderaa instruments) collected by the National Ocean Survey of NOAA at 12 sites over a 1-2 month period in August-September 1983. In general, currents are strongest near the mouth with maximum velocities of 0.5-1.0 m/s. Historical observations (Smith, 1970; Hammond, 1976) suggest a net near-bottom inflow at the mouth, with flood-tide bottom velocities leading those at the surface by 10-30 minutes. While Hammond (1976) and Hammond and Wallace (1982) attributed this to a net northward bottom transport offshore, based on sea-bed drifter data, we show clearly that this near-bottom inflow is strongest during neap tides and is primarily due to buoyancy forcing (see later discussion of Figure 13). Such a thermal exchange flow, as we have observed in San Diego Bay (Chadwick, et al., 1996), has not been described nor explained previously, in spite of the likelihood that such exchange flows occur in a number of other California bays (eg., San Francisco Bay, Largier, 1995). Towards the head of the Bay, current velocities generally decrease owing to the reduction in upstream tidal prism volume (relative to the cross-sectional area). Variations on this trend are due to constrictions and expansions at various locations - eg., current velocities are strong in the narrow region between North Bay and South Bay (Figure 1). In South Bay, currents are typically less than 0.1 m/s.

Aspects of the offshore flow, stratification and water quality near the mouth of San Diego Bay have been studied in relation to the siting of the wastewater outfalls at Point Loma, Tijuana and Ocean Beach and in association with studies of the Point Loma kelp forest ecosystem. The general flow patterns, summarized by Hendricks (Engineering Science, 1988) show a broad, warm southward flow along the coast past Mission Bay and Ocean Beach and a large-scale recirculation and localized upwelling region to the south and east of the Point. This recirculation is understood to be generated by horizontal shear associated with flow separation off Point Loma. It is directly into this sheared region that the ebb flow from San Diego Bay is ejected. Variations in the ambient flow show current reversals occurring over periods from tidal time scales to several weeks. The strongest non-tidal fluctuations are in the 5-10 day band. Thermal stratification is well developed in the waters off the mouth of San Diego Bay during summer and vertical temperature differences of about 10°C are observed. In winter vertical temperature differences are about 2°C. The thermocline is typically found between 10 and 20 m, although weak in winter. This shallow thermocline means that the cold, deeper ocean water which is low in pollutants but high in nutrients may move into the Bay on the flood tide (as we have observed). Significant internal wave activity has been observed along the west side of Point Loma, although there is evidence that these waves are damped near the mouth of San Diego Bay.

Further detailed information is contained in our own publications (Appendices 1-6), in the publications of our collaborators and in older publications from which we have extracted some key points. These older publications include Ridley (1959), Federal Water Pollution Control Administration (1969), Simmons and Herrman (1970), Romer (1972), Peeling (1975), Lenz (1976), Hammond (1976), Lentz (1984), Walton, et al. (1986) and Gordon and Rogers (1990).

3. FIELD STUDIES AND RESULTS.

The initial phase of work consisted of a review of existing information. In addition to published reports, we reviewed data that had been collected previously and determined the overall circulation character of the Bay, as summarized in the preceding section. The second phase of this work was to initiate state-of-the-art numerical modeling of the Bay circulation. This was achieved by working with researchers at NRaD, who had an interest in supporting such modeling work, and with researchers at USGS, who had constructed a state-of-the-art model (TRIM) and applied it to San Francisco Bay (Cheng, et al., 1994). This collaboration continues and it has become a significant focus of water quality work on San Diego Bay (NRaD leads this activity). Much of this preliminary work was completed during the year or two prior to the official signing of the contract, and before we could commit real funds to field work. Once funds became available, we started the field work that led to the following results:

3-1. Residence Times from Longitudinal CTD Surveys:

Our first field experiment was to determine the longitudinal and vertical structures of temperature and salinity (and thus density) in San Diego Bay during summer, the period in which weakest flushing is expected. Profiles of CTD (Conductivity-Depth-Temperature) data were collected at 14 stations on a number of occasions during August 1993. Water in the Bay was much warmer and saltier than that in the ocean (Figure 2), indicating surface heating and evaporation. The unambiguous observation of the seasonal occurrence of hypersalinity (Bay salinities greater than ocean salinities) is an important result of this work. Similar concurrent work in Mission Bay, Tomales Bay and historical data from Elkhorn Slough indicate that many of the "low-inflow estuaries" of California exhibit this seasonal hypersalinity, indicative of weak circulation and flushing and long residence times in these bays during the dry Californian summer.

The constant temperature and salinity values observed over this one month period indicate that the Bay had attained a steady state, in which surface heating and evaporation were balanced by longitudinal dispersion of oceanic water into the Bay (Largier, et al., 1995). This situation allowed us to calculate robust, bulk estimates of average "residence time" at various distances from the ocean entrance. This residence time, the time for which water had been resident in the Bay, varies from one tidal cycle at the mouth to over a month in South Bay (Figure 3). Comparable results were obtained from two methods - the first being a simple calculation based on evaporation rates and the second method being an estimate of residence time from estimates of the longitudinal diffusivity in the Bay. Similar results were obtained for residence times in Mission Bay, Tomales Bay and Elkhorn Slough. These results together with the underlying scientific reasoning and theoretical model are described in Largier, et al. (1995), a scientific paper due to be published in a premier international journal. A copy of this paper is appended (Appendix 1).

Following our success with these data, NRaD personnel have started a regular longitudinal survey of temperature and salinity conditions over the course of the year. These new data will allow a full seasonal characterization of spatio-temporal variations in longitudinal dispersion.

<u>3-2. Stratified Exchange Flows from Longitudinal CTD Surveys:</u>

These same longitudinal CTD survey data gave us our first clear indication of the presence of significant vertical shear in the tidal flows to and from San Diego Bay. As is observed on 10 August (Figure 2), there is now general evidence that on the flood tide dense, cold oceanic water intrudes into the Bay at depth - note the shape of the water mass with temperatures less than 18°C. Conversely, on the ebb tide the warmer Bay water moves seaward over the cold deeper oceanic water. This vertical exchange process, which appears to have an effect on tidal exchange processes throughout North Bay, has been investigated further in subsequent field studies (see below). A full discussion of this process is given in Chadwick, et al. (1996), a paper presented last year at the 7th International Conference on the Physics of Estuaries and Coastal Seas. A copy of this paper is appended (Appendix 2).

In addition to this thermal exchange flow at the mouth of the Bay, where the cold ocean waters interact with the warm Bay waters, there is evidence of vertical exchange flows associated with the strong gradients in salinity observed in South Bay. The seaward flow of dense hypersaline water underneath less dense water is evident at the southernmost end of South Bay (Figure 2). The importance of these salinity-stratified exchange flows in South Bay depends on the state of the tide, the strength of the wind and the season of the year. Largier, et al. (1996) have explored this process in a paper presented at the7th International Conference on the Physics of Estuaries and Coastal Seas in Woods Hole last November. While this process may be important at the landward extremities of low-inflow estuaries as observed in Figure 2, it is recognized that this process is a negative feedback process that in itself prevents a large buildup of hypersaline dense water in the Bay. In other words, this exchange process will not enhance summer longitudinal dispersion rates enough to change the expectation that the longest residence times will be observed in San Diego Bay during summer and fall. In Largier, et al. (1996), four hydrodynamic regions are identified in low-inflow estuaries - San Diego Bay being a prototype example. A "marine region", dominated by tidal exchange with the ocean, is found in the outer bay. Landward of this, a "thermal region" is found where surface heating controls the buoyancy forcing and results in the thermal exchange flow observed in North Bay. Towards the head of the Bay, a "hypersaline region" is observed. Here evaporation dominates the buoyancy forcing and salinity-stratified flow may be observed. At times, an "estuarine region" may be observed where small freshwater inflows occur (eg., the region where the Otay River enters the Bay). The full detail of the buoyancy exchange model and the characterization of these regions is given in Largier, et al. (1996), a copy of which is appended (Appendix 3).

3-3. Tidal Velocities and Water Levels - Observation & Modeling:

Following these initial CTD observations of longitudinal structure, we participated in a multi-agency deployment of an extensive array of time-series instruments within and immediately outside of the Bay. In this work, the USGS, Army Corps of Engineers and NRaD also deployed instruments. Acoustic Doppler Current Profilers (ADCP's) were deployed for more than a month at three locations in the Bay. Strings of mechanical current meters were deployed at a further four sites in the Bay and one string of current meters was deployed offshore to monitor the influence of oceanic flow on the Bay-ocean exchange process. In order to calibrate the high-resolution TRIM model of Bay circulation, detailed water level data on tidal phase and amplitude were obtained from five locations inside and immediately outside of the Bay. In addition to these current meters and water level recorders, recording thermistors were deployed on the navigation markers along the axis of the Bay and on the offshore current-meter mooring.

While the prime purpose of this data set is to calibrate the numerical model of circulation, we have also used these data to refine our estimates of tidal velocity. In particular, these tidal velocities are used to obtain a scale estimate of the longitudinal tidal diffusion, which varies from about 260 m^2/s at the mouth to less than 10 m^2/s near the head of the Bay (Figure 4). These values compare favorably with those deduced from the CTD observations of salinity in the Bay (Figure 3). Further, the vertical resolution of the data on tidal variations in current velocity and temperature near the mouth has proved to be a valuable complement to the cross-sectional surveys of tidal exchange at the mouth (see below). In particular, these time-series data confirm the generality of the result that the flood tidal flow is strongest near-bottom where cold water moves in underneath the warmer Bay water. On the ebb tide, however, stratification is observed to break down in strong ebb flows, although it may persist through weaker ebb tides. These features are described in detail by Chadwick, et al. (1996) - Appendix 2.

3-4. Langrangian Drifter Data - A New Look at Bay Circulation.

Motivated largely by this project to study water circulation in the context of pollutant transport, we obtained independent funding in 1992 to develop a set of instrumented drifters. Rather than mooring a current meter to obtain "Eulerian" data on water motions, we decided that it would be more appropriate to study dispersive fluid motion with “drifters”, which are large drogues that are designed to move with a given blob of water (Figure 5; also George and Largier, 1995b). Such data on water motion is known as "Langrangian" data. Owing to the difficulties and amount of labor required to obtain these measurements, this approach is seldom adopted and no similar data exists for San Diego Bay. However, as the gradients in water velocities may be large and of small spatial scale in a tidal bay like San Diego, one would need countless current meters to obtain a comparable estimate of tidal dispersion. We designed a drifter that recorded its position by way of GPS (the satellite-based Global Positioning System for navigation). After some very frustrating problems associated with the heavy traffic of electromagnetic radiation in San Diego Bay, we obtained a set of unique and exciting data from these drifters. This work continues.

Drifters have been used in three studies so far. The first was a study of the outflow of water from San Diego Bay. Where did Bay water go and was it simply returned to the Bay on the next flood tide? Drifters were deployed together with ADCP and CTD surveys of the outflow and inflow (described in section 3-5). Secondly, drifters were deployed in lines across the Bay at various distances from the mouth. This was done in combination with ADCP/CTD cross-sectional surveys (described in section 3-6). Thirdly, drifters were deployed in the vicinity of Coronado Bridge to investigate their dispersion over a tidal cycle and to investigate the extent to which drifters would be trapped in embayments like Glorietta Bay (described in this section). The data from all drifter experiments conducted so far are described and plotted in a report to the co-sponsors of this work (NRaD and the Regional Board). This report (George and Largier, 1995) is appended (Appendix 4).

In the vicinity of Coronado Bridge, a remarkably large tidal separation of drifters was observed. Drifters that were deployed in close proximity at low tide would separate dramatically during the course of the tidal cycle (Figure 6). If taken as being representative of a initial spill of pollutant, these drifters indicate that the pollutant spill would be stretched out over 5 km after a single tidal cycle (half a day). This distance is even greater than the tidal excursion in this region. This separation of drifters (dispersion) is due to the presence of the Glorietta Bay trap and the difference in water depth between the channel on the northeast side of South Bay and the shoal on the southwest side of the Bay. Water that moves landward over the shoal during flood tide then moves towards the channel during ebb tide. Similarly, water that moves into Glorietta Bay may be retained and not return to its starting point. In contrast, water that moves landward along the channel moves back seaward to a position near its starting point at the end of the ebb tide. Some water, however, stalls near the entrance to Glorietta Bay on the flood tide and then moves a full tidal excursion seaward during the ebb tide. This set of alternatives leads to a very dispersive tidal flow in this region and one can expect rapid spreading of localized pollutant sources. At the same time, one can expect pollutants to be retained in Glorietta Bay longer than at nearby locations outside of the embayment. The large longitudinal diffusivity (dispersion) indicated by these drifter data, is in agreement with the bulk predictions from a model that we have constructed from scaling arguments (Figure 4). The detail of these dispersive motions in the vicinity of the Bridge is being described and explained in a paper in preparation by Largier, et al. (in prep.). We have planned further drifter studies for this summer.

<u>3-5. Outflow Surveys - How is Water Ejected from the Bay?</u>

The most important process in flushing San Diego Bay of its water, and water-borne pollutants, is the process by which Bay water is ejected into the ocean. Under favorable conditions, the full volume of the tidal outflow will be replaced by new and presumably less-polluted oceanic water. Under less favorable conditions, much of the Bay outflow will be returned to the Bay on the subsequent flood tide. In 1993 and again in 1994, we conducted a series of experiments to describe the outflow and to determine the mechanisms by which it was removed from the mouth, mixed with ocean water and/or returned to the Bay. Ironically, one of the Bay pollutants was a great help in these experiments. The high levels of fluorescence in the Bay, indicative of dissolved hydrocarbons, provided a clear tracer of Bay water relative to ocean water which has very low fluorescence. This fluorescence tracer is described in more detail by Chadwick, et al.(1995).

A series of observations were collected over 3 days: ADCP and CTD/fluorescence surveys of the outflow jet, drifter deployments in the outflow jet, longitudinal CTD/fluorescence surveys of the Bay prior to the outflow measurements, cross-sectional ADCP and CTD/fluorescence surveys at the mouth, ADCP and CTD/fluorescence surveys along the axis of the jet and the outer Bay and moored current-meters and thermistors in the outflow jet. Some of these data are reported by Chadwick, et al. (1996) in the context of thermal exchange flows at the mouth. The full analysis of these data, and further data to be collected this summer/fall, is underway and will be published in the form of Bart Chadwick's Ph.D. thesis.

Some preliminary plots of the outflow show that it is typically ejected in the form of a long straight jet (Figure 7). The unusual lack of widening of the jet with distance from the mouth is understood to be due to the sloping bottom and convergent flow thus induced in the deepening jet. At a distance of about 3 km from the mouth, the jet starts to curve eastward and much of the high-fluorescence water is caught in a tidal eddy that forms between the jet and the shoreline. The sudden eastward turn is well illustrated by the drifter data (Figure 8) and the resultant eddy is seen in the ADCP velocity and fluorescence data (Figure 7). As the tide turns, an inward pressure gradient drives an inflow of oceanic water at the sides of the channel while inertia maintains the outflow jet in mid-channel. Thus, the outflowing Bay water is pinched off from the Bay and cold oceanic water may be seen at the surface during the early flood tide, prior to warm oceanic surface water being drawn into the Bay. It appears that it is only that Bay water which mixes downward into the oceanic water underlying the outflow jet that will be drawn back into the Bay on the flood tide. Estimates of the tidal exchange ratio (the proportion of inflowing water that is new oceanic water; Fischer, et al., 1979 and Largier, 1995) typically exceed 0.5 at the mouth.

Based on initial surveys, our hypothesis was that the key process in tidal exchange at the mouth is "tidal pumping", the temporal asymmetry between a jet outflow and a potential sink inflow in the region immediately seaward of the mouth channel. This idea was confirmed by conducting a series of cross-sectional ADCP/CTD/fluorescence surveys over a full tidal cycle at the mouth (Figure 1). Calculations of the relative contributions of temporal asymmetry (eg., jet-sink), vertical asymmetry (eg., thermal stratification) and lateral asymmetry (eg., reversed flow at sides) indicated that the temporal jet-sink asymmetry accounted for the majority of the tidal exchange between bay and ocean. This result is plotted in Figure 9. Recognizing the importance of the jet and sink geometries, we have developed a theoretical model (Figure 10) that can explain the bulk changes in Bay-ocean exchange due to changes in the forcing due to tidal range and offshore cross-flow. Changes in the tidal exchange ratio as a function of these independent variables is plotted in Figure 11. This work is being written up in a manuscript for submission to a scientific journal (Chadwick and Largier, in prep. - Appendix 6).

The further collection of data this year is designed to provide the empirical basis for resolving the complex interplay between vertical, lateral and temporal structures in this mouth region. In particular, we will not be able to predict Bay-ocean exchange and possible future scenarios until we fully understand why the flood tide is characterized by strong stratification without significant shear whereas the ebb tide is characterized by strong shear without significant stratification. Although model simulations from TRIM may resolve the jet and sink flow structures, this TRIM model is only 2-dimensional (vertically averaged) and it cannot resolve the subtle importance of vertical shear associated with lift-off of the outflow and plunging of the inflow. Considering the coherent nature of the thermal exchange flow at the mouth (section 3.2), we anticipate that these vertical structures contribute somehow to the strength of the temporal flux term by separating the tidal outflow and inflow.

3.6 Cross-Sectional Surveys - What are the Dominant Tidal Exchange Terms?

In a similar way to the tidal survey of cross-sectional structures at the mouth of the Bay, we have surveyed the cross-sectional velocity and water-type structures over a tidal cycle at a number of other locations in the Bay (Figure 1). In addition to moored instruments on these transects, drifters were also deployed at these cross-sections during the ADCP/CTD/fluorescence surveys (Appendix 4). At locations away from the mouth and the Seaport Village constriction, where the channel width increases dramatically, the tidal exchange ratio is small as the jet-and-sink tidal pumping process is not well developed. This result can be seen in the relative strengths of the tidal flux terms at the Shelter Island and Harbor Island transects (Figure 12). At these locations, longitudinal exchange depends more on the vertical structure, the lateral structure and on shear dispersion. The cross-sectional structure of the tidal exchange flux terms tends to be complex, with qualitative changes over short along-axis distances. While there is a tendency for water types to stratify off Shelter and Harbor Islands (thermal exchange structures), the dominant velocity structures are lateral in that faster flow is observed on the outside of the curve. At the cross-sections near the Bridge, the velocity does not exhibit laterally skewed structures as the channel is relatively straight, but there is evidence for tidal pumping mechanisms associated with both the changes in channel width and channel depth. Vertical stratification and shear is still observed at this cross-section. Being distant from the oceanic mouth, however, the ebb and flood tidal structures are much more like mirror reflections of each other than is observed at the mouth. Comparing the moored ADCP data at the Bridge with that at the mouth, one can see this trend towards more symmetrical flows at locations away from the mouth (Figure 13).

The drifter data reveal the importance of lateral shear and circulation to enhancing longitudinal dispersion in San Diego Bay. In addition to the dramatic examples offered by tidal traps like Glorietta Bay (see section 3.4 and Figure 6), curvature in the channel leads to secondary circulation in the vertical-lateral plane and to separation flows in the longitudinal-lateral plane. Evidence for both of these flow structures is given by Figure 14. Not only do these secondary circulation features directly enhance longitudinal dispersion, but they also enhance the lateral exchanges required for effective longitudinal shear dispersion.

4. CONCLUSIONS.

The recent and ongoing study of water circulation in San Diego Bay has led to many new insights into how this circulation works and into the dispersive nature of this circulation. From a conceptual, statistical and modeling viewpoint, we are now in a much-improved situation regarding our knowledge of how water motions will move pollutants introduced to the Bay. This improved knowledge should be invaluable in the management of water quality in San Diego Bay.

Many of the new ideas on water motion in San Diego Bay (not all reported here) have developed from the research effort funded by the Regional Board or they have developed through research conducted in collaboration with the research funded by the Regional Board. Based on this observation, one can declare this research contract an unqualified success. In summary, this research contract has played a major role in the following achievements:

(i) We have been instrumental in a collaborative effort to apply and verify a detailed numerical model of Bay circulation (the 2-dimensional TRIM model of the USGS). This model can be expected to perform well within the Bay, at locations away from the ocean entrance and in the absence of significant stratification. Our ongoing field studies are directed at describing and explaining the complex exchange processes at the mouth and in the presence of stratification. Based on our anticipated results, it can be hoped that a well-calibrated 3-dimensional model of Bay circulation will be able to perform well throughout the Bay.

(ii) We have estimated the residence times of water in San Diego Bay as a function of the distance from the ocean entrance (Figures 3 and 12). These estimates are key to determining the capacity of the Bay for receiving and dispersing (flushing) water-borne pollutants to the ocean. Not only are these residence times empirically derived (thus real, not just theoretical), but they have also been explained in terms of the dominant processes of longitudinal dispersion in the Bay (Figure 4). Through a combination of theoretical and field studies, we have developed a thorough understanding of the dominant dispersion processes and how they may change with changes in the fundamental characteristics of the Bay. These results indicate that residence times in the North Bay are short and one need only be concerned with pollutant retention problems in the side basins ("tidal traps") such as the commercial and marina basins. The detailed conditions in these side basins should be predictable with the 2-dimensional TRIM model with some limited field verification. In South Bay, however, long residence times occur everywhere. Extreme residence times occur towards the landward end of the Bay and they are expected in the side basins of South Bay.

(iii) We have shown the seasonal development of hypersalinity in the landward parts of the Bay (ie., South Bay) and we have investigated the feedback process by which this hypersalinity may lead to inverse density gradients and stratified exchange flows in the fall (Largier, et al., 1996). In addition to being key to the understanding of San Diego Bay hydrodynamics, the seasonal occurrence of hypersalinity and the associated density-driven flushing of the landward parts of low-inflow basins is found to be common to many coastal bays/estuaries in California. In this respect, San Diego Bay compares with Mission Bay (San Diego), Penasquitos Estuary (San Diego), Elkhorn Slough (Moss Landing), South San Francisco Bay and Tomales Bay (Marin County), amongst others.

(iv) We have shown the importance of Bay-ocean temperature differences in Bay-ocean exchange flows (Chadwick, et al, 1996), a dynamic previously overlooked by researchers working on bays and estuaries in mediterranean climates. Comparable work in San Francisco Bay, Mission Bay and Tomales Bay indicates that this thermal exchange flow may be common to a number of Californian waters. An interesting aspect of this flow structure is the frequent presence of cold and clean ocean water at depth in outer San Diego Bay - explaining the mussel watch result that the mussels at the mouth of San Diego Bay are the cleanest in the County!

(v) We have directly observed and evaluated the flux of petroleum hydrocarbons (UV fluorescence) from San Diego Bay (Chadwick, et al., 1995 - Appendix 5). In addition to its obvious importance, this observation has allowed us to describe the temporal, vertical and lateral structures of the tidal exchange flows at a number of cross-sections in the Bay. From this we know how Bay pollutants are flushed out and how ocean pollutants may be flushed in.

(vi) We have direct observations of dispersion in the Bay, with groups of drifters acting as pollutant mimics. These drifters indicate the likely paths and dispersive spreading of pollutants introduced at the mouth, in the vicinity of Harbor or Shelter Islands and in the vicinity of Coronado Bridge (George and Largier, 1995 - Appendix 4). Tidal trapping in Glorietta Bay is observed directly.

(vii) We have obtained high-resolution data on the structure of the tidal outflow jet during ebb tides and the near-radial tidal flow towards the mouth during flood tides. In the absence of a large river inflow to San Diego Bay, these offshore water motions within a tidal excursion of the mouth of the Bay are the key factor in Bay-ocean exchange in that changes in these motions bring about large changes in the tidal exchange ratio at the mouth. Changes in the effectiveness of tidal exchange at the mouth of the Bay propagate through the Bay, increasing or decreasing residence times at all locations. Our present activities are directed at quantifying these hydrodynamics.

It is anticipated that our work will continue for another few years as Bart Chadwick completes his thesis work at Scripps Institution of Oceanography (SIO) and also in collaboration with other ongoing studies in San Diego Bay. In addition to purely hydrodynamical research, we have also initiated collaborative research on the ecology of the Bay and the Point Loma kelp forest. In the Bay, we have recently received support for work on the dispersal of crab larvae to and from the Bay in which trace elements will be used as a larval tag indicating its origin. This work is collaborative with Lisa Levin and Claudio di Bacco at SIO. Concerning the kelp forest at the mouth of San Diego Bay, we have been collaborating with Mia Tegner and others at the SIO in determining the effect of Bay outflows on the health of the kelp forests.

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6. FIGURE CAPTIONS.

Fig. 1: Chart of outer San Diego Bay, illustrating the coastline and 5-m isobath. The regions of drifter investigations are indicated by boxes and dated. The across-bay ADCP/CTD/Fluorometer transects are indicated by bold lines and labeled M (mouth), SI (Shelter Island), HI (Harbor Island), CBN (Coronado Bridge North) and CBS (Coronado Bridge South).

Fig. 2: San Diego Bay CTD data from 10 August 1993 - plotted as a function of distance from the head of the bay and of depth. Cool ocean water, warm lower salinity mid-bay water and warm hypersaline inner Bay water is evident. Further, note the density minimum in mid-Bay.
(a) water temperature; (b) water salinity; (c) water density.

Fig. 3: Longitudinal distribution of normalized salinity (vertical and temporal average), longitudinal diffusivity K and residence time of water in San Diego Bay (based on August 1993 CTD data, see Appendix 3 for full details). In this diagram, San Diego Bay is compared with other mediterranean-climate Californian bays (and one southern African bay) with little freshwater inflow, exhibiting their common character.

Fig. 4: Scale estimates of the longitudinal variation in various component terms for the longitudinal diffusivity K (cf. empirically derived values in Figure 3). The combined (total) longitudinal diffusivity K is plotted as a bold line.

Fig. 5: Schematic illustration of the "drifter" system. (a) communication system for differential GPS; (b) the shape of the drifter itself.

Fig. 6: The tracks of three groups of drifters released near Coronado Bridge (see Appendix 6 for more detail). Each group was released simultaneously, at times indicated in the plot of tidal water level in the bay. The separation distance after just one tidal cycle is remarkable.
(a) Group 1; (b) Group 2; (c) Group 3.

Fig. 7: Observed velocity structure and fluorescence distribution in the tidal outflow from San Diego Bay (31 July, 1993). The velocity is near-surface ADCP data. (a) slack high tide showing southeastward offshore flow and residual high-fluorescence water from previous ebb tide; (b) mid-ebb tide, showing the formation of a tidal jet and the ejection of high-fluorescence water from the bay; (c) slack tide at the end of the ebb, showing the residual momentum of the tidal jet, the band of high-fluorescence bay water and the tidal eddy that forms southeast of the mouth.

Fig. 8: The tracks of three groups of drifters released at the mouth during an ebb tide (see Appendix 6 for more detail). Each group was released simultaneously, at times indicated in the plot of tidal water level in the bay. The drifters exhibit remarkably little separation. The anti-clockwise turning at the end of the tidal outflow jet is dramatically clear.

(a) Group 1; (b) Group 2; (c) Group 3.

Fig. 9: The relative strength of major flux terms at the five transect locations (Figure 1), indicating the importance of tidal pumping at the mouth and near the Coronado Bridge. The total longitudinal diffusivity K is also plotted and this can be compared with the scale estimates of K (Figure 4) and with the observations of K based on salinity structure in the bay (Figure 3).

Fig. 10: Schematic of the tidal-jet outflow and potential-sink inflow, as occurs off San Diego Bay. This geometry leads to the greatest bay-ocean exchange. The tidal outflow jet lifts off as it moves into deeper water - as illustrated in the schematic in the lower panel.

Fig. 11: Theoretical values of the tidal exchange ratio, based on the model illustrated in Figure 10. Details are given in Appendix 7. Tidal exchange ratio ("fraction of bay water returning") is plotted as a function of cross-flow strength Ua and ...
(a) ... a function of outflow velocity (related to tidal range) Uo;
(b) ... a function of non-dimensional bottom slope Ho;
(c) ... a function of lift-off tendency as expressed by the internal Froude Number Fr.

Fig. 12: The tidal exchange ratio calculated from transect data collected at the five locations indicated in Figure 1. Note the large difference in the exchange at the mouth and that farther into the bay, more than a tidal excursion from the ocean entrance. Associated residence time estimates for the bay water landward of these transects is plotted in the second panel. It is not clear why Harbor Island region should exhibit a residence time that is so much longer than that near Shelter Island. It is clear, however, that the inner bay should exhibit long residence times and these values are consistent with those derived from a salt-balance estimate (Figure 3).

Fig. 13: Time-series of current at three locations (mouth, Shelter Island, Coronado Bridge), as observed by fixed ADCP's during July 1993. At the mouth, the vertical shear is strong on ebb tides and negligible on flood tides. The ebb-tide shear is strongest during neap tides (small tidal range), indicating that buoyancy exchange is more important at that time. In contrast to the mouth data, vertical shear appears more symmetrical in the data taken farther into the bay. Near the bridge, the near-bottom current is very weak.

Fig. 14: The tracks of four groups of drifters released near Shelter Island during flood tide (see Appendix 6 for more detail). Each group was released simultaneously, at times indicated in the plot of tidal water level in the bay. The drifters exhibit remarkably little separation. There is a qualitative change in drift tracks as the tidal velocity increases, with drifters initially curving around the bend and later separating from the inner wall of the channel.
(a) Group 1; (b) Group 2; (c) Group 3; (d) Group 4.

7. APPENDICES.

APPENDIX 1: Copy of research paper on hypersalinity (Largier, et al, 1995: "Seasonally Hypersaline Estuaries in Mediterranean-Climate Regions").

APPENDIX 2: Copy of research paper on thermal exchange (Chadwick, et al., 1996: "The Role of Thermal Stratification in Tidal Exchange at the Mouth of San Diego Bay").

APPENDIX 3: Copy of research paper on inverse density structures (Largier, et al., 1996: "Density Structures in Low-Inflow Estuaries").

APPENDIX 4: Copy of field data report on drifter tracks (George and Largier, 1995: "Lagrangian Drifter Observations in San Diego Bay: Data Report").

APPENDIX 5: Copy of research paper on the flushing of petroleum hydrocarbons from San Diego Bay (Chadwick, et al., 1995: "Contaminant transport measurements in San Diego Bay").

APPENDIX 6: Copy of draft research paper on a model of the dominant bay-ocean exchange process (Chadwick and Largier: "A generalized jet-sink model for tidal exchange in coastal inlets").

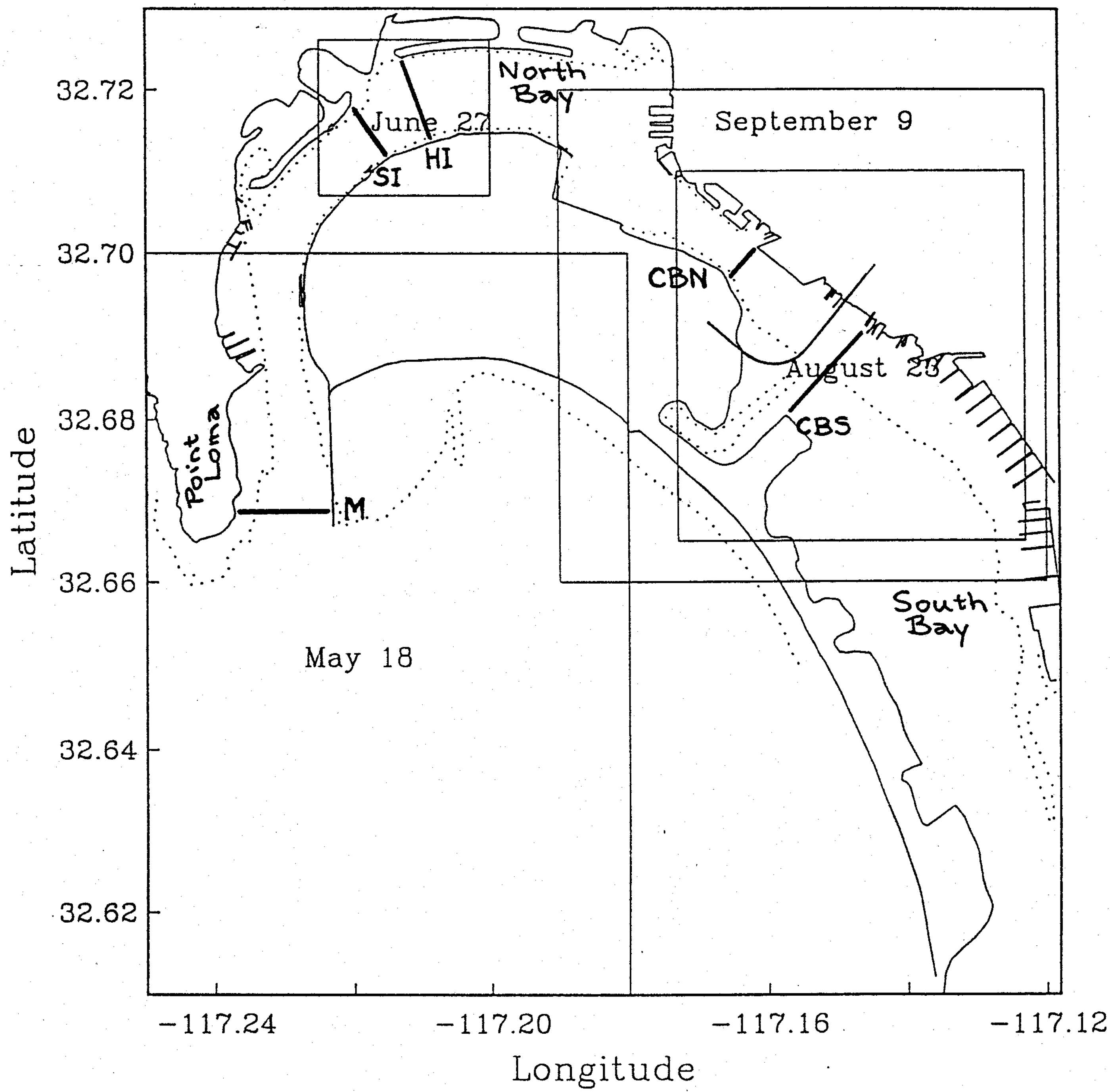

North Bay
June 27
HI
SI
September 9
CBN
August 23
CBS
Point Loma
M
South Bay
May 18
32.72
32.70
32.68
32.66
32.64
32.62
Latitude
−117.24
−117.20
−117.16
−117.12
Longitude

FIGURE 1

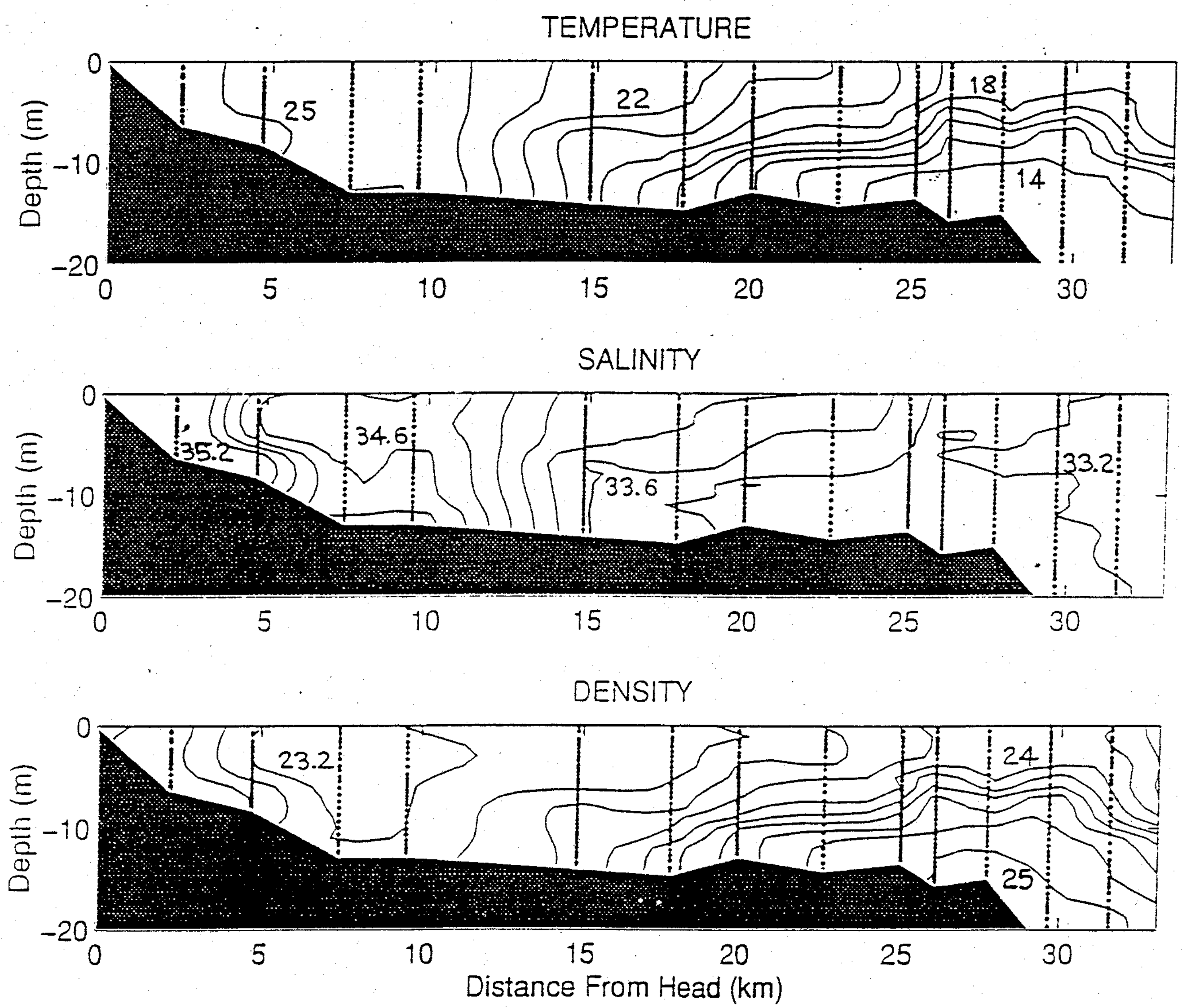

TEMPERATURE
SALINITY
DENSITY
Depth (m)
0
-10
-20
0
5
10
15
20
25
30
25
22
18
14
35.2
34.6
33.6
33.2
23.2
24
25
Distance From Head (km)

FIGURE 2

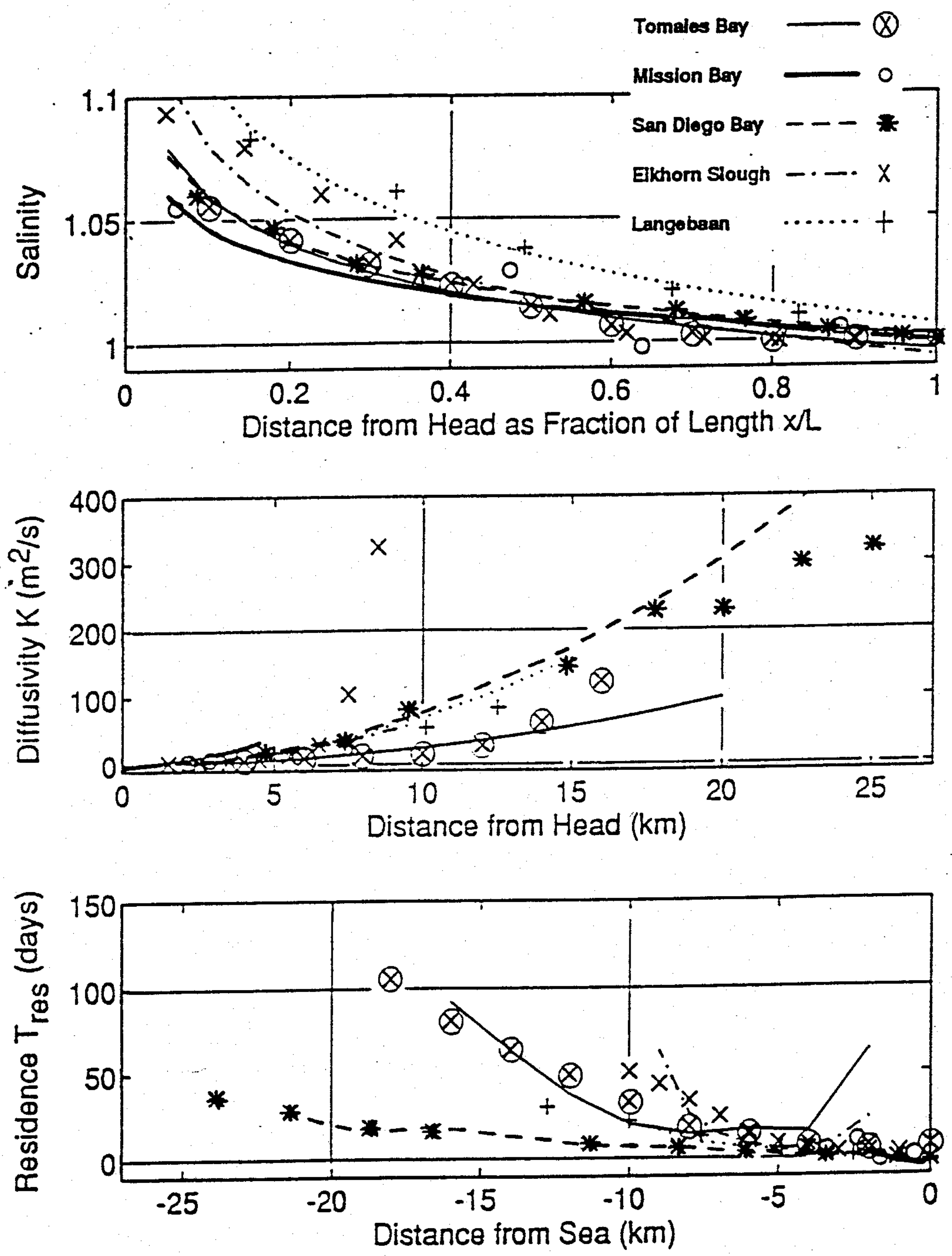

Tomales Bay
Mission Bay
San Diego Bay
Elkhorn Slough
Langebaan
Salinity
1.1
1.05
1
0
0.2
0.4
0.6
0.8
1
Distance from Head as Fraction of Length x/L
Diffusivity K (m^2/s)
400
300
200
100
0
0
5
10
15
20
25
Distance from Head (km)
Residence T_res (days)
150
100
50
0
-25
-20
-15
-10
-5
0
Distance from Sea (km)

FIGURE 3

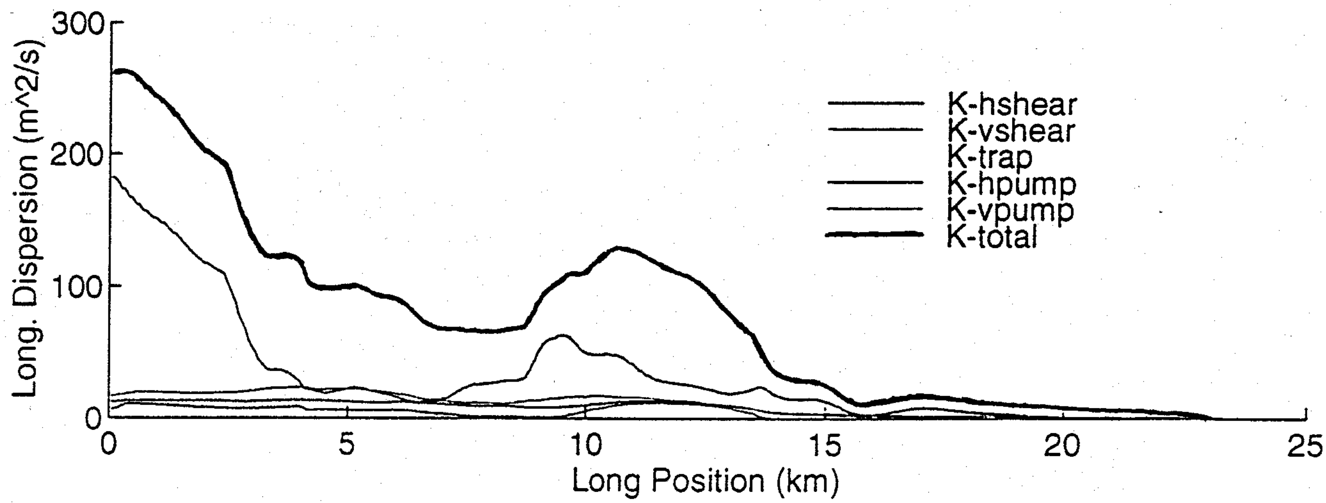
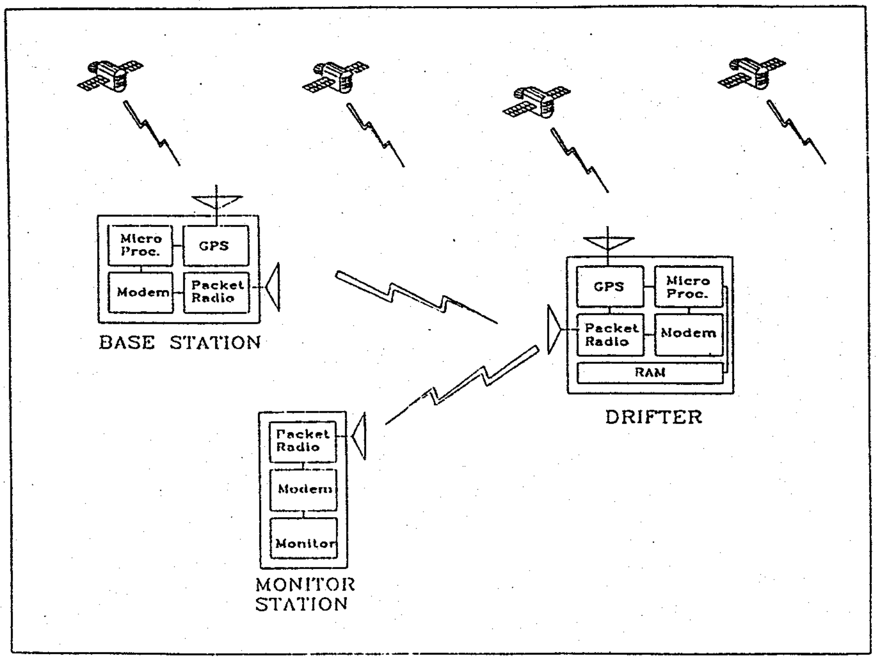

300
200
100
0
Long. Dispersion (m^2/s)
K-hshear
K-vshear
K-trap
K-hpump
K-vpump
K-total
0
5
10
15
20
25
Long Position (km)

FIGURE 4


Micro Proc.
GPS
Modem
Packet Radio
BASE STATION
GPS
Micro Proc.
Packet Radio
Modem
RAM
DRIFTER
Packet Radio
Modem
Monitor
MONITOR STATION

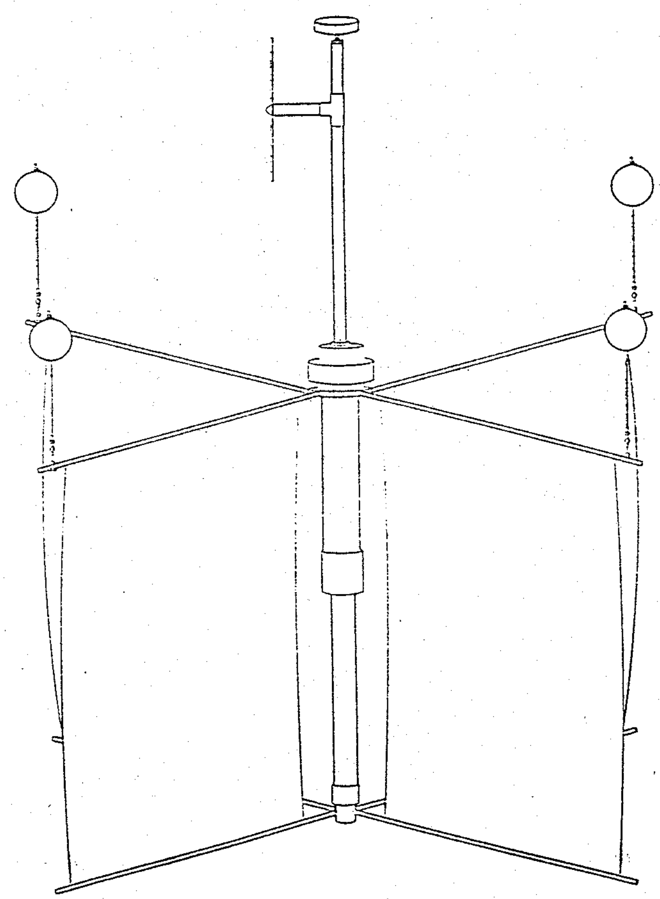


FIGURE 5

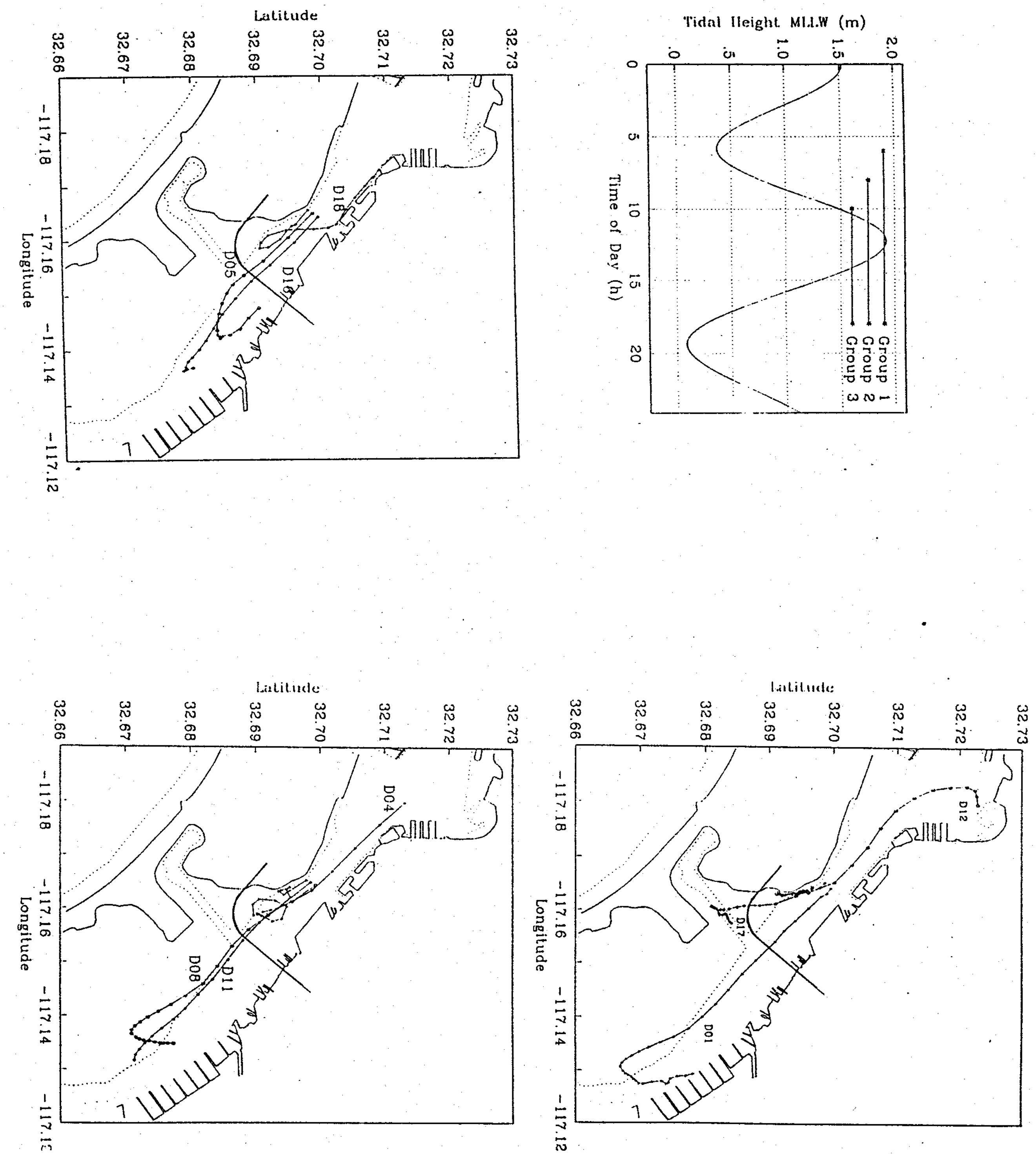
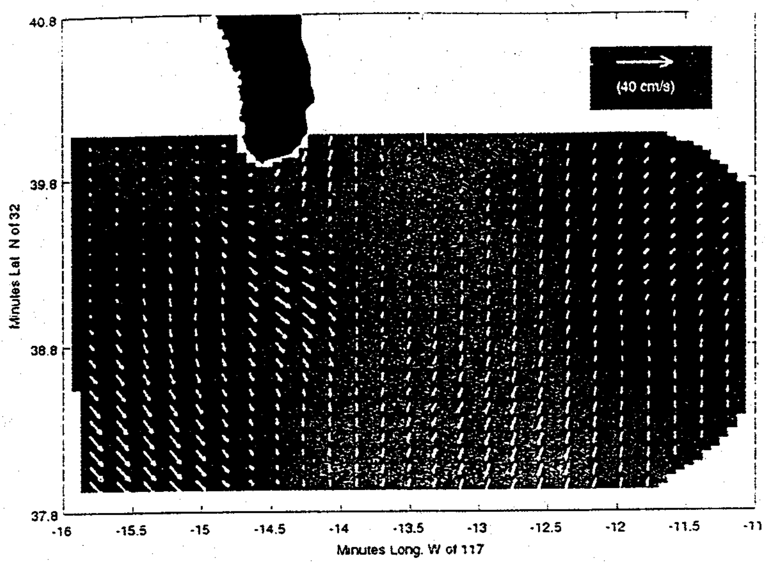
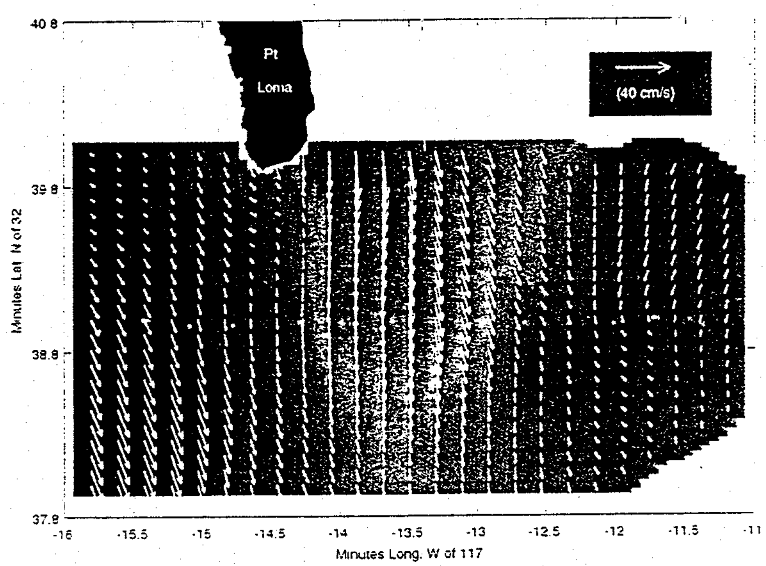

Tidal Height MLLW (m)
Time of Day (h)
Group 1
Group 2
Group 3
Latitude
Longitude
D18
D05
D16
D04
D08
D11
D12
D17
D01

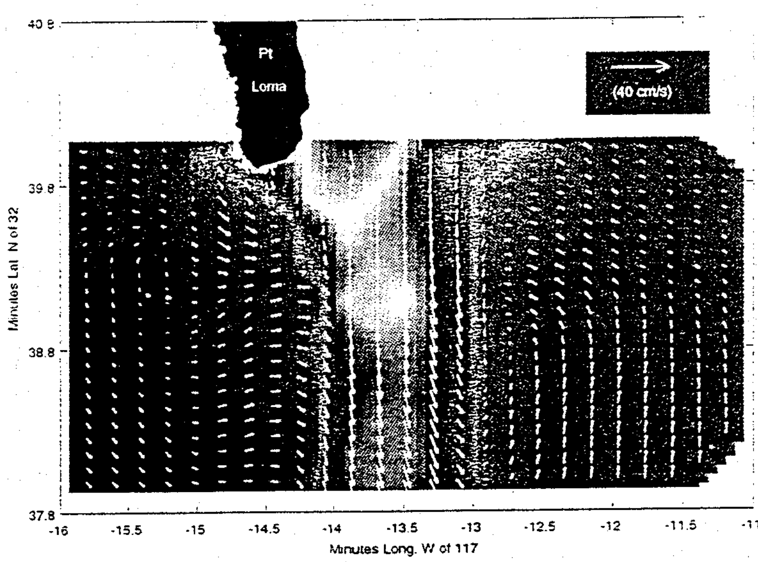
FIGURE 6



(40 cm/s)
40.8
39.8
38.8
37.8
Minutes Lat N of 32
-16
-15.5
-15
-14.5
-14
-13.5
-13
-12.5
-12
-11.5
-11
Minutes Long. W of 117

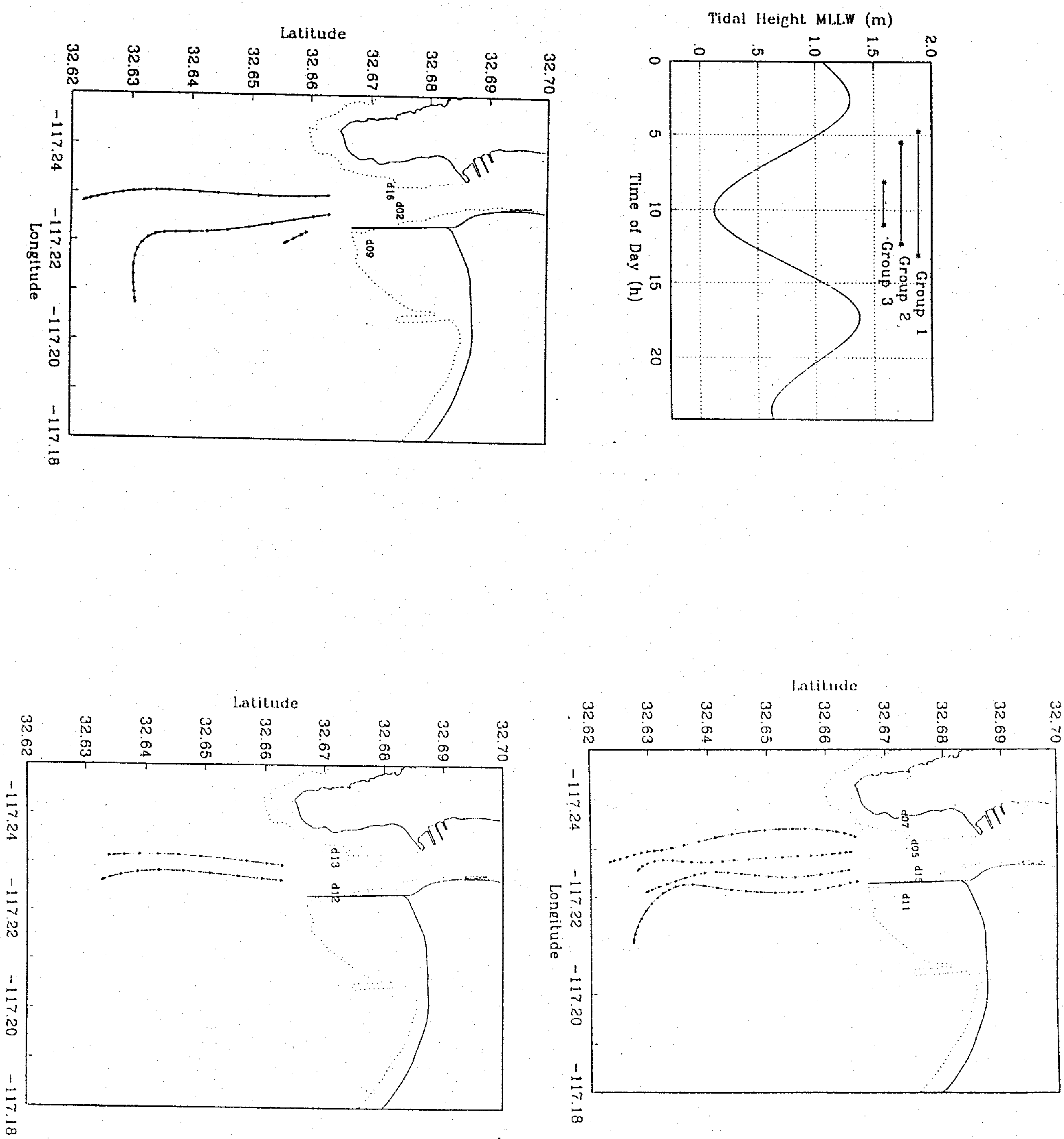


Pt
Loma
(40 cm/s)
40.8
39.8
38.8
37.8
Minutes Lat N of 32
-16
-15.5
-15
-14.5
-14
-13.5
-13
-12.5
-12
-11.5
-11
Minutes Long. W of 117



Pt
Loma
(40 cm/s)
40.8
39.8
38.8
37.8
Minutes Lat N of 32
-16
-15.5
-15
-14.5
-14
-13.5
-13
-12.5
-12
-11.5
-11
Minutes Long. W of 117

FIGURE 7



Tidal Height MLLW (m)
Time of Day (h)
Group 1
Group 2
Group 3
Latitude
Longitude
d16
d02
d09
d07
d05
d11
d13
d12

FIGURE 8

Processes Contributing to Longitudinal Dispersion

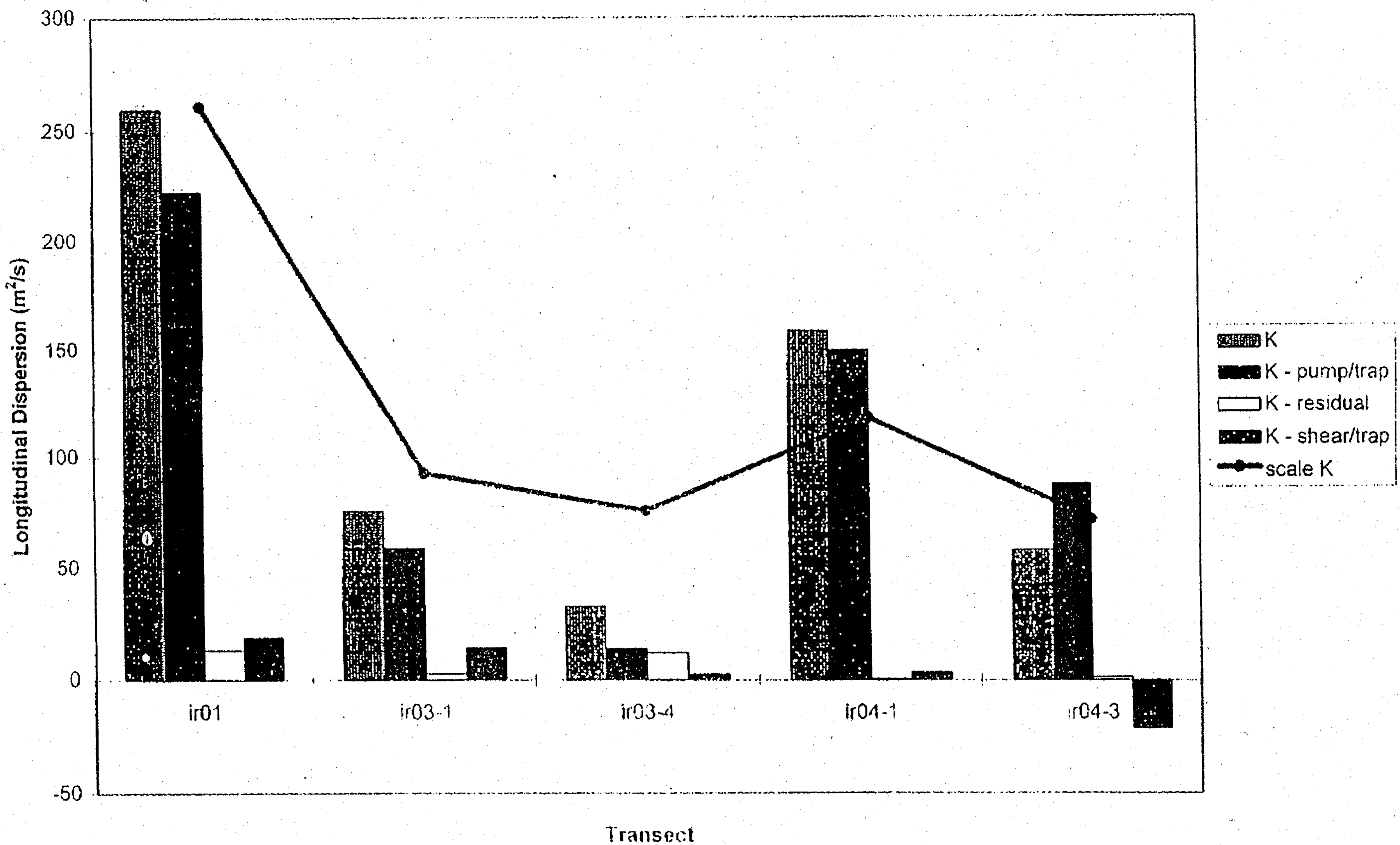
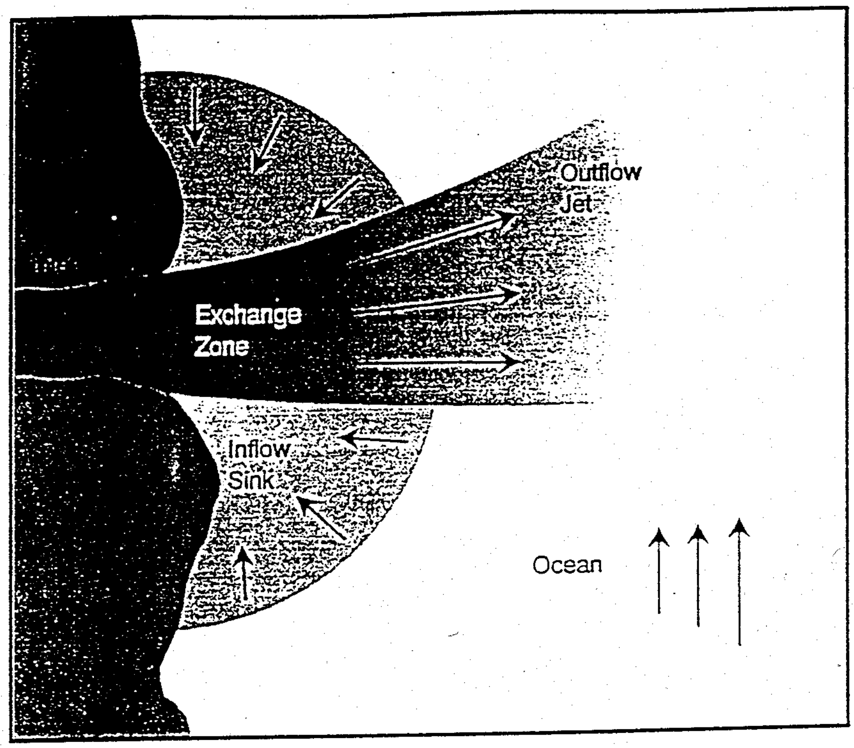


FIGURE 9


Outflow
Jet
Exchange
Zone
Inflow
Sink
Ocean

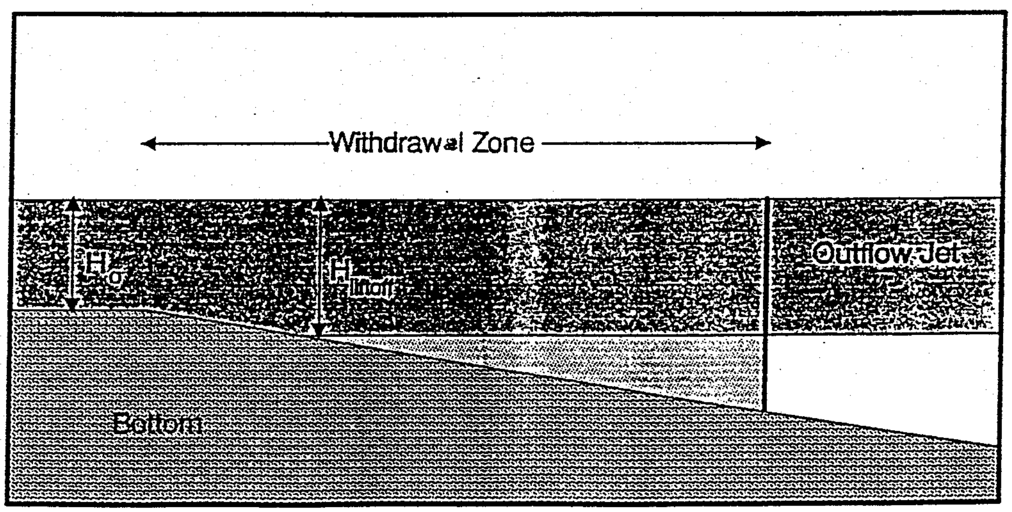

Withdrawal Zone
Outflow Jet
Bottom

FIGURE 10

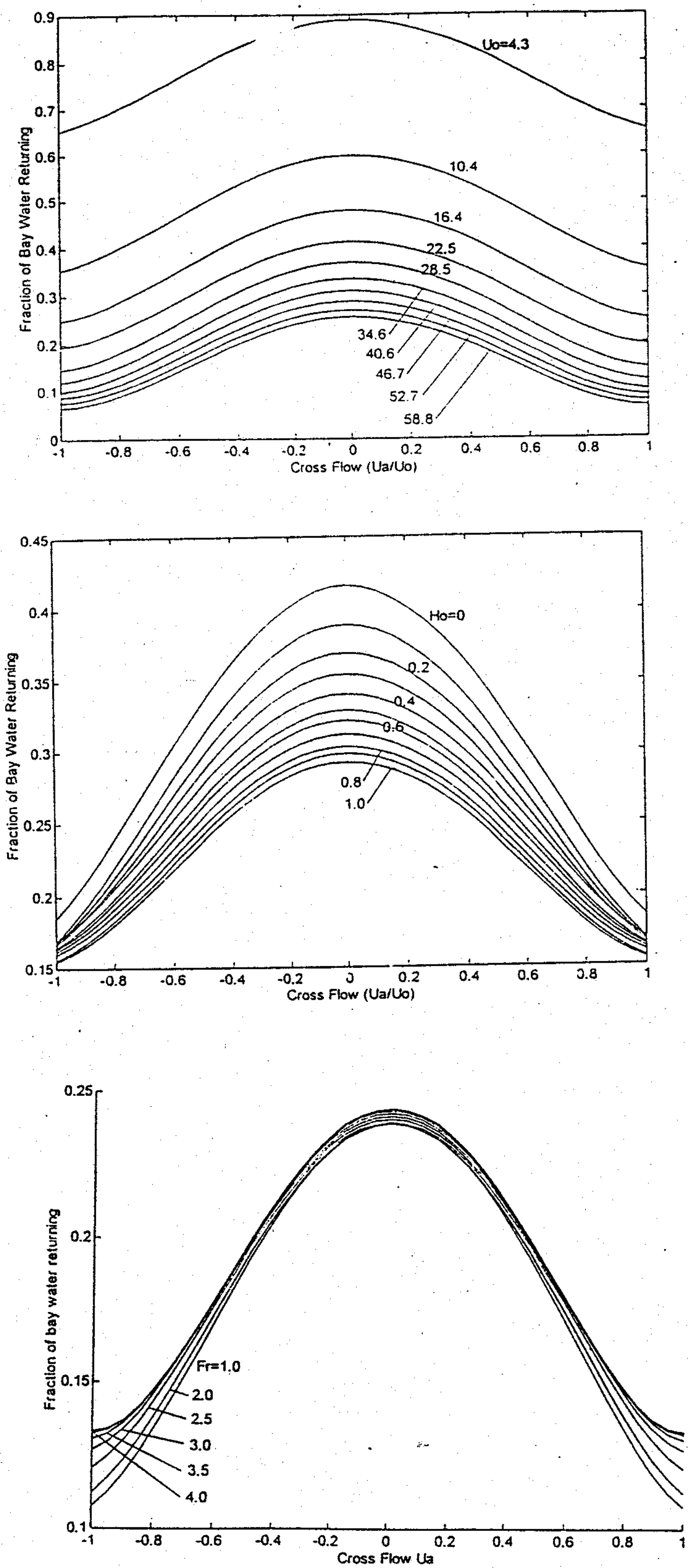

Fraction of Bay Water Returning
Cross Flow (Ua/Uo)
Uo=4.3
10.4
16.4
22.5
28.5
34.6
40.6
46.7
52.7
58.8
Ho=0
0.2
0.4
0.6
0.8
1.0
Fraction of bay water returning
Cross Flow Ua
Fr=1.0
2.0
2.5
3.0
3.5
4.0

FIGURE 11

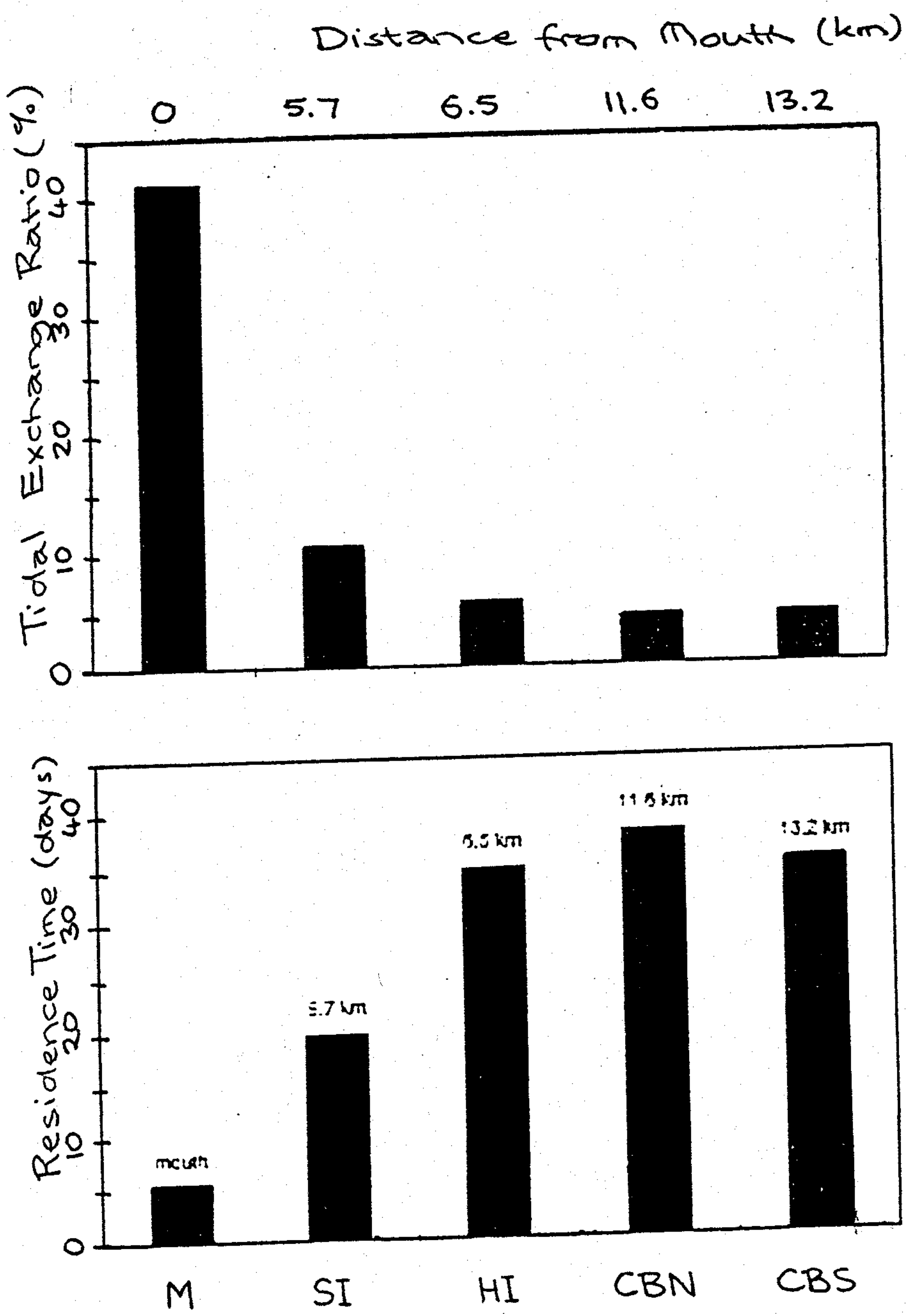
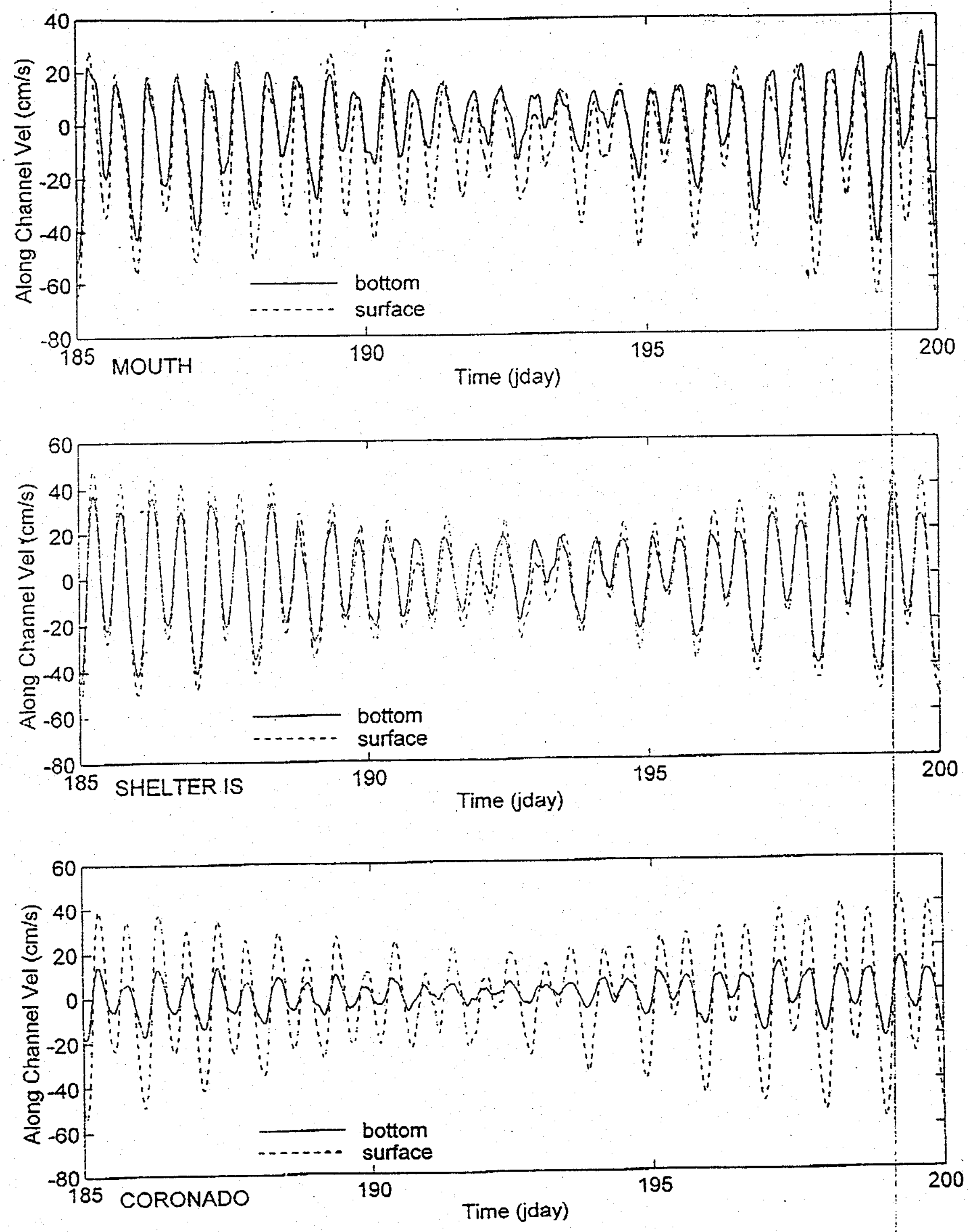
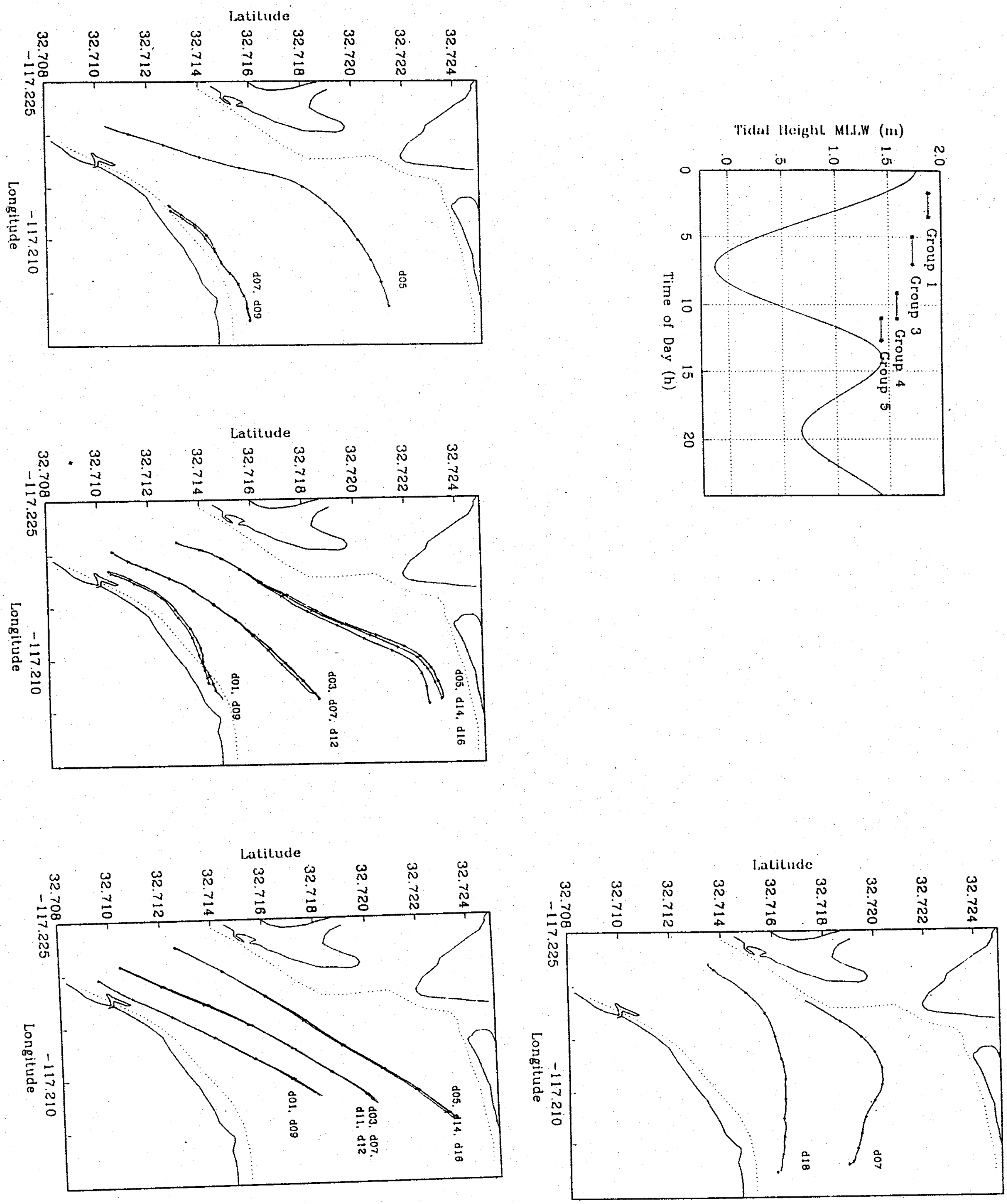

Distance from Mouth (km)
0
5.7
6.5
11.6
13.2
Tidal Exchange Ratio (%)
0
10
20
30
40
Residence Time (days)
0
10
20
30
40
mouth
5.7 km
6.5 km
11.6 km
13.2 km
M
SI
HI
CBN
CBS

FIGURE 12



Along Channel Vel (cm/s)
bottom
surface
MOUTH
Time (jday)
SHELTER IS
CORONADO

FIGURE 13



Tidal Height MLLW (m)
Time of Day (h)
Group 1
Group 3
Group 4
Group 5
Latitude
Longitude
d05
d07, d09
d05, d14, d16
d03, d07, d12
d01, d09
d03, d07, d11, d12
d07
d18

FIGURE 14