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ARTICLE 1

Open Water Processes of the San Francisco Estuary: From Physical Forcing to Biological Responses

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An additional flow-related variable is X2, the distance from the mouth at the Golden Gate up the axis of the estuary to where tidally-averaged bottom salinity is 2 practical salinity units (psu) (Jassby et al. 1995). [Note regarding salinity units: strictly speaking salinity on the Practical Salinity Scale (UNESCO 1981) is a ratio and therefore unitless, but many authors use psu or practical salinity units where needed for clarity]. This variable, used to index the physical response of the estuary to changes in freshwater flow, is closely and inversely related to outflow with a time lag of about two weeks (Figure 8). The response of X2 to flow is discussed below.

Much has been written on seasonal and interannual patterns of freshwater flow and the influence of the water projects on these patterns (Nichols et al. 1986; Peterson et al 1989; Fox et al. 1990). Oddly, there is not general agreement on the nature of these influences, partly because the water projects were developed concurrently with trends in regional climate and patterns of precipitation (Dettinger and Cayan 1995; Arthur et al. 1996). However, there are also clear differences in perception of the roles of the water projects in altering the rate of freshwater flow into the estuary (e.g., Fox et al. 1990; Peterson et al. 1995).

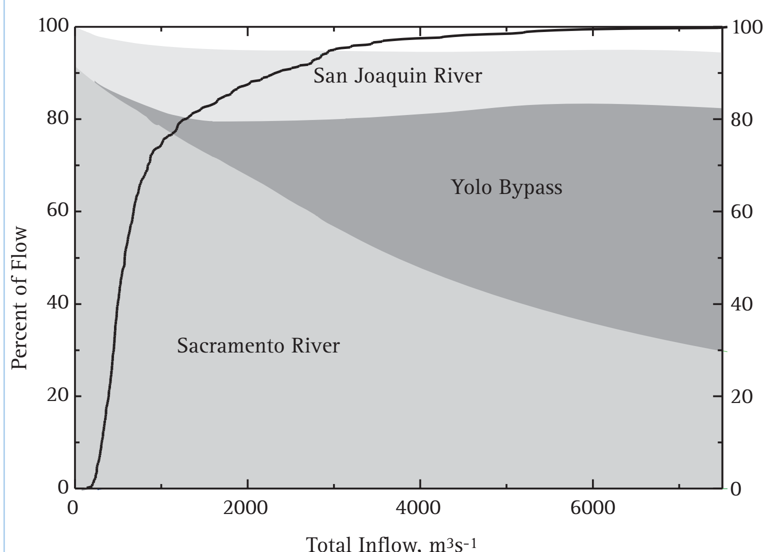

Figure 5. Proportion of inflow to the Delta from different sources based on monthly flow from water years 1956-2002 from the Dayflow program (http://iep.water.ca.gov/Dayflow). Remaining inflow is from small tributaries on the east side of the Delta (e.g., Mokelumne, Cosumnes). The black line is the cumulative percent frequency, i.e. the percent of inflow less than or equal to that value.

It is tautological that exports of freshwater from the basin reduce the quantity of water that would otherwise flow into the estuary on an annual basis, under the current level of development in the Central Valley. Prehistoric salinity records suggest an annual average inflow to the estuary over the last two millennia of ~1250 $m^3\ s^{-1}$ (Ingram et al. 1996a), similar to the current unimpaired flow of about 1195 $m^3\ s^{-1}$ (mean of estimated values from 1906 through 2002). Export flow averaged 185 $m^3\ s^{-1}$ from 1975 through 1999, or about 16% of unimpaired flow during that period.

Some confusion also exists in the literature regarding the relationship between export flow and Delta outflow. For example, Peterson et al. (1996) implied that exported water would otherwise have flowed into the estuary, i.e., there should be an inverse relationship between export flow and outflow. In fact, export flow is weakly and nonlinearly related to inflow (Figure 9), decreasing when inflow is either very high, presumably because of lack of demand, or very low, because of lack of water, or to meet outflow or salinity standards in the Delta. There is no inverse relationship between outflow and export flow at the lower end of the outflow range.

The ratio of export flow to inflow, or E:I ratio, has been used in management as a measure of the relative magnitude of pumping. Analyses of the combined effects of flow conditions on salinity (Peterson et al. 1995) and survival of striped bass (Jassby et al. 1995) and salmon (Newman and Rice 2003) have used the E:I ratio as a covariate with outflow. The rationale for using export:inflow ratios for these analyses is that export flow should be scaled to the quantity of water flowing into the Delta. However, this scaling implicitly assumes an advective environment in which river-derived net flows dominate, which is not the case when freshwater inflow is low. Furthermore, since export flow is weakly related to inflow, the ratio of export flow to inflow is strongly correlated with inflow and therefore outflow (Figure 6 C, 6D). Thus putting both variables in a statistical model can make results difficult to interpret. Both salinity (Peterson et al. 1975, 1989; Jassby et al. 1995) and striped bass

Net flows were negative (southward) in Middle River because of the influence of net flows toward the export pumps. Even here, however, tidal flows were many times larger than net flows. This means that tidal dispersion effects are likely to be important.

The functioning of the tidal lakes in the Delta has received attention recently. These areas may have long or short residence times depending on the peculiarities of configuration such as number, size, and orientation of breaches in their levees (Lucas et al. 2002). These differences have implications not only for conditions within the tidal lakes, but for their influence on surrounding channels and on movement of salt and other constituents. These tidal lakes are less able to retain the sediments that generally cause shallowing in normal lakes.

In spite of efforts to ensure that Delta levees can withstand variations in water level, storms, and earthquakes without failure, it seems likely that one or more Delta levees will ultimately fail because of seismic activity. Levee failure within the Delta would result in significant salinity intrusion because of the increase in area of the Delta and volume of the tidal prism (Enright et al. 1998).

The Interaction of Freshwater Flow with Tides and Salt

One of the greatest challenges in estuarine physics is to understand and model the interaction among tidal flows, buoyancy, stratification, and transport. These factors are the focus of active research in the San Francisco Estuary, at least partly because of the perceived importance of physical conditions to the estuarine ecosystem. As with flow in the Delta, our views of the physical dynamics of brackish regions of the estuary have changed substantially in the last ten years. Again, the major shift appears to be from a static view dominated by consideration of net flows to a dynamic view in which the tides play a major role.

Movement of the Salt Field

Freshwater flow entering any estuary increases the mean slope of the water's surface, resulting in a barotropic residual flow toward the sea (e.g., Officer 1976). An opposite density gradient due to the salinity gradient results in a tendency for landward density-driven or baroclinic flow. The position of the salt field can be thought of as the net result of these opposing forces, though greatly modified by the tides and by the complex bathymetry of the estuary (Lacy et al. 2003).

In the San Francisco Estuary, the tidally-averaged mean penetration of salinity up the estuary depends primarily on freshwater flow, and to a lesser extent on spring-neap tidal oscillations and meteorological variation (Peterson et al. 1975, 1989, 1996; Knowles and Cayan 2002; Knowles 2000). The degree of penetration can be indexed by X2 (Jassby et al. 1995; Monismith et al. 2002), a convenient index of the physical response of the estuary to freshwater flow. The 2 psu isohaline is most often found in Suisun Bay, and in spring is constrained by regulations to be west of the confluence of the Sacramento and San Joaquin rivers.

Several features of X2 are important here. First, the value 2 psu is not arbitrary but has a physical basis. It is high enough to unambiguously result from dilution of ocean water, and is higher than salinities in the southern Delta elevated by agricultural drainage (Schemel and Hager 1986). It is low enough to mark the landward limit of salinity stratification. Thus, X2 represents the approximate landward end of the salt field and the longitudinal density gradient.

Second, X2 responds to freshwater flow with a time constant of about two weeks (Peterson et al 1975; 1989, Jassby et al. 1995), which may differ somewhat between rising and falling hydrographs (Peterson et al. 1989). This lag can be seen in the response to salinity that occurred during the 1997 flood event (Knowles et al. 1997). It is also consistent with models in which salinity at a point is related to flow with a lagged term to account for antecedent conditions (Denton 1993).

Third, salinity at any point in the northern estuary is related to X2 (Figure 22). This relationship is most nearly linear in mid-estuary where salinity is far from its limits (e.g., USGS station 11 in central San Pablo Bay). At both the low- and high-salinity ends of the distribution there is a noticeable flattening as the relationship approaches its limits. This means that the steepest salinity gradient, and the greatest tidal variability in salinity, will usually be where salinity is near 15 psu. Note, however, that these relationships are time-averaged, whereas on any given transect up the suppress the destratification part of the SIPS cycle, resulting in "runaway" or persistent stratification. This positive feedback cycle occurs when the tendency for baroclinic flows overcomes the tendency for vertical mixing by the tidal shear stresses. This mode of stratification depends on the steepness of the baroclinic density gradient (related to X2), and the strength of turbulence, which is related to tidal velocity and water depth. Monismith et al. (1996, Eq. 18) proposed the use of a "horizontal Richardson number" to identify the transition between periodically and persistently stratified conditions. This dimensionless number is the ratio of the potential energy of the longitudinal density gradient to the tidal kinetic energy that drives mixing. A high value indicates a tendency for stratification to persist. This ratio increases linearly with increasing density gradient and the square of water depth, and decreases with the square of tidal velocity. In contrast with the estuarine Richardson number (Fischer et al. 1979), which explicitly includes freshwater flow, the horizontal Richardson number varies with the steepness of the salinity gradient. Thus, we expect persistent stratification in deep locations with a strong salinity gradient and weak (i.e., neap) tides. Persistent stratification has been observed in 3D model studies (Cheng and Casulli 1996) and in field investigations of deeper channel areas in both the northern and southern estuary during neap tides (Huzzey et al. 1990; Monismith et al. 1996). Strong wind can also eliminate stratification by enhancing vertical mixing (Koseff et al. 1993; May et al. 2003).

Stratification may also be found in association with fronts formed by the joining of different water masses, e.g., saltier channel water with fresher water from shoals. The resulting interaction can have complex influences on stratification (Lacy et al. 2003).

Strong stratification is associated with the development of gravitational circulation, in which net (tidally-averaged) flow is up-estuary near the bottom and down-estuary near the surface. Although gravitational circulation may be possible in unstratified conditions, it generally occurs in the presence of stratification (Hansen and Rattray 1966; Festa and Hansen 1976; Geyer 1993; Monismith et al. 1996; Cheng and Casulli 1996). Gravitational circulation is an important mechanism for upstream salt penetration, thereby providing a negative feedback that limits the seaward movement of the salt field (Hansen and Rattray 1966; Monismith et al. 2002, see "Movement of the Salt Field", p. 27). It is also an important mechanism for the transport of organisms and materials, particularly negatively buoyant particles. Gravitational circulation has been observed in deeper locations, particularly under neap tidal conditions, e.g., in the Central Bay and Golden Gate (Conomos et al., 1970; Conomos 1979a; Petzrick et al. 1996), Carquinez Strait (Smith et al. 1995), and the lower Sacramento River in summer (Nichol 1996).

The Entrapment Zone

The landward limit of gravitational circulation, or null zone (Peterson et al. 1975), has been the subject of considerable interest in the San Francisco Estuary because of its potential role in entrapment of particles (Arthur and Ball 1979). The conceptual model of the entrapment zone (Postma and Kalle 1955; Festa and Hansen 1976, 1978; Peterson et al. 1975, Figure 14 in Arthur and Ball 1979; Figure 25A) holds that gravitational circulation produces a net seaward (barotropic) current at the surface and a net landward (baroclinic) current at the bottom. Through continuity these currents must result in an upward net current near the null zone, which is the landward limit of gravitational circulation. This net flow pattern traps negatively-buoyant particles and downward-swimming organisms near the null zone. The null zone was believed to occur consistently at around 2 psu salinity, which is frequently in Suisun Bay (Peterson et al. 1975; Arthur and Ball 1979).

This appealing idea seemed to match observations of maxima in turbidity and abundance of some planktonic organisms. However, recent analyses from a variety of estuaries suggest mechanisms may be more complex and dynamic than suggested in these earlier studies (e.g., Jay and Musiak 1994; Grabemann et al. 1997; Guezennec et al. 1999). A recent series of studies in Suisun Bay using modern oceanographic sensors failed to support the entrapment zone model. The key finding was that gravitational circulation was rare in Suisun Bay except in fall (Burau 1998; Kimmerer et al. 1998; see also Figure 3 in Peterson et al. 1975) because of the shallow depth and consequently low horizontal Richardson number. Furthermore, vertical turbulent motions are much larger than the upward

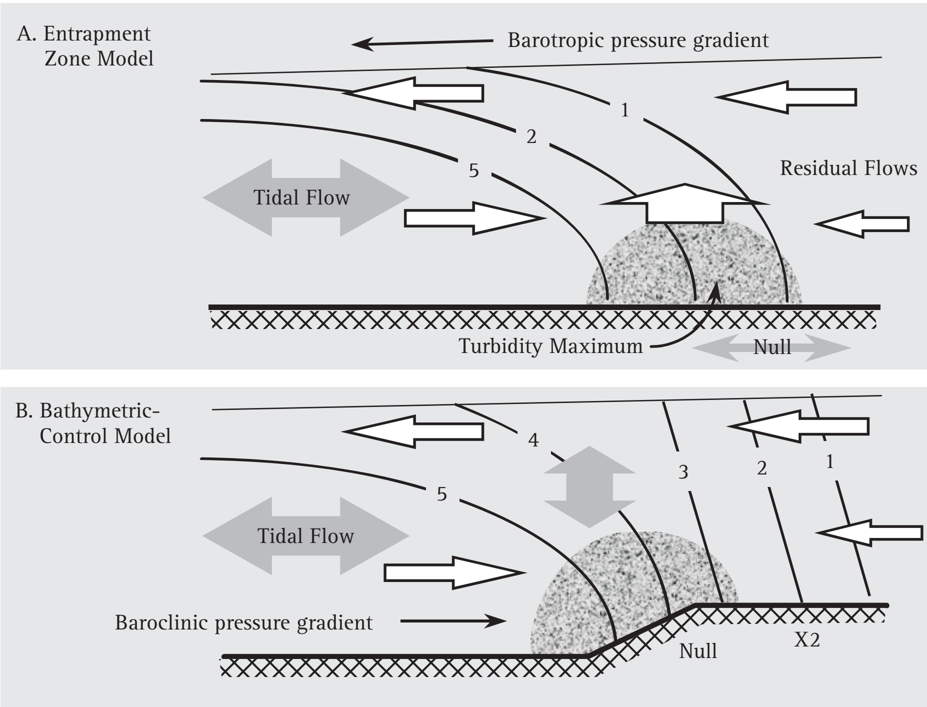

Figure 25. Alternative models of dynamics of the Low-Salinity Zone. Tidal motions are depicted as solid gray arrows, and residual motions as open arrows. In both models, seaward residual currents result from the barotropic pressure gradient, and landward residual currents result from the baroclinic pressure gradient. A., Entrapment-zone model: a null zone exists at approximately 2 psu salinity, representing the landward limit of stratification and gravitational circulation. Residual currents are unidirectional landward, and bidirectional seaward of the null zone, where bottom currents move particles landward. A vertical residual current in the vicinity of the null zone is responsible for maintaining particles in suspension, resulting in a turbidity maximum. B., Bathymetric-control model: gravitational circulation depends on water depth and steepness of the baroclinic pressure gradient. When the LSZ is in Suisun Bay, the baroclinic pressure gradient is insufficient to stratify the water column because of strong turbulent mixing. Stratification and gravitational circulation are strong in deeper areas such as Carquinez Strait. The landward limit of this circulation occurs at the shoal, resulting in a bathymetrically-fixed null zone and turbidity maximum.

current calculated from continuity and believed responsible for maintaining particles in suspension (Peterson et al. 1975; Arthur and Ball 1979). When the salt field moves further up the estuary, it produces a steeper longitudinal salinity gradient in Suisun Bay, since the gradient begins to flatten out below about 2 psu (see Figure 2B in Jassby et al. 1995). This can result in gravitational circulation in Suisun Bay in fall, but only when the 2 psu isohaline is further landward, which is not consistent with the entrapment zone model.

Because the putative entrapment mechanism has not been observed in Suisun Bay, a less ambiguous or misleading term for this hydrologic zone of the estuary may be the Low-Salinity Zone (LSZ), essentially the same as the oligohaline zone of the Venice classification system (Cowardin et al. 1979). The revised conceptual model for this region (Figure 25B) shows that stratification and gravitational circulation in the LSZ persist only in deeper waters, e.g., in Carquinez Strait. There is no null zone associated with the LSZ in Suisun Bay, although a persistent, spatially fixed null zone with a turbidity maximum has been noted where Carquinez Strait abruptly shoals into Suisun Bay at Benicia (Schoellhamer 2001).

The relationship between X2 (i.e., the location of the LSZ) or flow and the abundance of various biota in the estuary is discussed below. Two important physical features of the estuary bear on how those relationships can be considered and how they might work. The first is the lag time in the response of the estuary to changes in flow discussed above, which means that pulse flows must be large and long-lasting to affect the estuary. The second is that except under very high-flow conditions, the LSZ is vertically well-mixed. This means that there is no way for river flow per se to penetrate the estuary west of Suisun Bay; the degree of stratification and gravitational circulation is directly related to the longitudinal density gradient but only indirectly related to river flow. The implication for biota is that river flow usually does not disperse organisms into seaward areas as previously hypothesized (e.g., Armor and Herrgesell 1985). This may happen under extremely high-flow conditions, however, when much of the area of the estuary is fresh.

helpful to decompose the mathematical description of exchange into terms having known meanings and modes of variation (e.g., mean flow, gravitational circulation) and focus on those likely to be important. For example, longitudinal movement of organisms in the Low Salinity Zone was found to depend on the interaction between vertical movement of organisms and vertical variability in flow velocity at the tidal time scale (Kimmerer et al. 1998).

In the absence of persistent stratification, longitudinal dispersion occurs through tidal pumping and trapping and shear flow dispersion (Fischer et al. 1979). The tidal wave propagates up the estuary by alternative pathways that result in differences in phase because the wave propagation speed increases with increasing depth, and the time of travel depends on speed and the distance traveled. In the case where two channels branch off the main channel and then rejoin, as in Suisun Bay, phase differences may arise because of differences in both depth and distance, so that water masses that initially split apart at the branch will rejoin some distance from each other. Similarly, a wave will propagate up a shoal more slowly than in the nearby channel, resulting in phase differences. Propagation of the tidal wave up a side channel on a flood tide can result in a phase difference at the junction on the subsequent ebb. These phase shifts cause stretching and distortion of the water masses, resulting in longitudinal mixing. This mixing can be strongly affected by changes in the tidal wave speed or excursion due to modification of channel geometry, e.g., by dredging or alteration of estuarine area (Enright et al. 1998).

Another mechanism for exchange depends on the configuration of flood and ebb flows. For example, in both the Golden Gate (M. Stacey, UC Berkeley, pers. comm.) and Franks Tract (J. Burau, USGS, pers. comm.) in the Delta, flood flows occur as a jet resulting in strong mixing of the flooding water with the water in the wider basin just inside the entrance. On the subsequent ebb, the water moves out across the entire basin. The net result is a stronger exchange than would occur without the jet.

Stratification in the channels can have a profound effect on longitudinal transport by uncoupling the surface and bottom layers and promoting gravitational circulation, as discussed above. When stratification is strong, the effective longitudinal eddy dispersion coefficient can increase by an order of magnitude over that seen under unstratified conditions (Monismith et al. 1996; compare to values in Cheng and Casulli 1992). This leads to the paradox that turbulence in an estuary can actually impede longitudinal exchange by eliminating stratification (Nunes Vaz et al. 1989).

Vertical stratification in salinity can appear at the surface as a front. Analogous to meteorological fronts (but upside down), estuarine fronts mark the surface boundaries between water masses of different density (Bowman and Esaias 1978; Largier 1992, 1993; O'Donnell 1993). As with vertical density gradients, fronts impede the exchange of materials, and are often locations of strong downward movement resulting in visible accumulation of foam and debris at the surface and differences in turbidity in the adjoining water masses (Largier 1992). In the San Francisco Estuary, ephemeral shear fronts typically form and dissipate on a tidal cycle because of differences in tidal velocity in shoals and channels (O'Donnell 1993). Because these fronts are ephemeral, they probably contribute little to exchange over subtidal time scales or between embayments, although they are important to exchange within embayments. Numerous fronts are visible in salinity data from an example transect through the northern estuary (Figure 23).

An important mode of exchange in many shallow estuaries is Stokes' drift. This is a net transport of water, salt, and particles up-estuary due to the phase between the tidal height and velocity as the tidal wave progresses up the estuary. This phasing can result in a positive correlation during the tidal cycle between water depth and water velocity, such that particles and water are moved up-estuary. Although this is unimportant in the channels of Suisun Bay (Burau 1998), its importance in other areas of the estuary has yet to be determined. Stokes' drift may be important over shoals, implying that it could be a significant mechanism for longitudinal exchange in most basins of the estuary.

Exchange processes can be conceptualized in terms of residence time, defined as the average time that a particle of water, salt, sediment, or other material spends within a region (Monsen et al. 2002). Residence time of a conservative property (i.e., one that is not produced or consumed within the water body) is the total quantity of that property (e.g., amount of water or salt in a body of water) divided by the rate of input or output of that property across all boundaries. This concept is most useful when applied to regions of the estuary that are well-defined and have relatively few points of exchange with other regions. Residence time in various basins of the estuary varies inversely with exchange rate, and with the mode of exchange and therefore the nature of the property. Thus, residence time of water in the northern estuary decreases sharply as freshwater flow increases, but residence time of certain kinds of particles may actually increase because of gravitational circulation.

Smith and Hollibaugh (2000) estimated residence times using a salt mass-balance approach. Residence times for the northern estuary, including only part of the Delta, ranged from 2 to 14 days in the wet season and 19 to 29 days in the dry season, while residence times in the South Bay were 8 to 51 days in the wet season and effectively infinite in the dry season. Walters et al. (1985) reported hydraulic replacement times, i.e., volume divided by freshwater inflow, for different regions of the estuary. Unlike residence times, hydraulic replacement times neglect tidal mixing, but are much easier to calculate. Hydraulic replacement times for Suisun and San Pablo bays were 1.2 days under high flow conditions and 60 days under low flow, while corresponding values for the South Bay were 120 and 160 days.

Exchange between the estuary and the coastal ocean is important because the ocean is the source of salt, some organisms, and possibly nutrients and organic matter, and the sink for materials produced in or transported through the Bay including freshwater, sediment, contaminants, organic matter, and organisms. Several analyses have estimated exchange at the Golden Gate; however, the seaward boundary of the estuary from a hydrodynamic perspective may be the sill west of the Golden Gate (Largier 1996), for which relatively little information exists about exchange processes. Exchange through the Golden Gate is complex, with strong vertical stratification and lateral variability in current velocities and tidal phase (Petzrick et al. 1996; Largier 1996). Exchange occurs through tidal flow, gravitational and lateral circulation (Conomos 1979a; Walters et al. 1985), changes in sea level due to the spring-neap tidal cycle, wind stress, and large-scale atmospheric pressure gradients (Walters and Gartner 1985; Largier 1996). Circulation is ebb-dominated on the northern side and flood-dominated on the southern side of the main channel (Petzrick et al. 1996). Gravitational circulation is controlled largely by the salinity gradient due to freshwater flow in winter and spring, and by variation in density due to upwelling of cold, salty water in the adjacent ocean when freshwater flow is low and the estuarine salinity gradient has moved landward (Largier 1996).

Exchange between South and Central Bay is strongly affected by the salt field in the northern estuary. When Delta outflow is high and X2 is seaward, salinity in the Central Bay is reduced. Under these conditions an inverse estuarine circulation cell can be set up in South Bay with residual circulation to the south at the surface and north at the bottom (McCulloch et al. 1970; Schemel 1998). This increases stratification and decreases residence time in the South Bay.

Another area of active research is exchange between shoals and channels, an important mechanism for longitudinal mixing (Walters et al. 1985), and in phytoplankton production (Cloern et al. 1983; Lucas et al. 1999b), sediment transport (McDonald and Cheng 1997), and possibly recruitment of fish and macroinvertebrates. Exchange between shoals and channels is strongly affected by tides and also by longer-scale processes such as spring-neap oscillations, wind, and intrusions of low-salinity water (Huzzey et al. 1990). Recent work in Honker Bay showed that exchange between shoals and channels was very rapid, and that wind and the orientation of the channels resulted in up-estuary residual currents (Warner et al. 1996; Lacy 1999).

Exchange can be estimated using one of three general approaches. The most straightforward conceptually is also the most difficult in practice: measuring velocity and concentration at sufficient temporal and spatial resolution to allow the net flux to be calculated. The principal difficulty is the high degree of variation in velocity, although Acoustic Doppler Current Profilers (ADCPs) permit a much higher resolution of the velocity and turbulence field than was possible with cur-