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Hydrodynamics of Shallow Water Habitats in the Sacramento-San Joaquin Delta

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Abstract

Over the past 3 years, we have pursued extensive research into the hydrodynamics of shallow water habitats in the Sacramento-San Joaquin Delta. The goal of these studies was to evaluate the relative importance of the various physical forcing mechanisms and influences, while developing the research tools required to address the dynamics of the systems. This work has led to larger-scale grants from CALFED and collaborations with the U.S. Geological Survey, which has facilitated extensive research into the hydrodynamics of shallow water habitats through a combination of field observations and numerical modeling.

Data from two sites has allowed us to begin to contrast the dynamics of different shallow water habitats in the Delta. The first site, Mildred Island, is influenced by forcing from the tides, wind and diurnal heating and cooling. The Island as a whole is a low energy environment, but the details of transport throughout the system are exceptionally subtle and complicated. To further evaluate the relative importance of each of these forcing mechanisms, an existing numerical model, TRIM-3d, has been applied to Mildred Island. After modification to allow for heating and cooling, the model has reproduced the primary trends in temperature over the timescales of several weeks. Using this model, we have evaluated residence times under various forcing conditions to conclude that wind and diurnal heating and cooling play an important role in determining the flushing of particular subregions within the Island.

The second site, Franks Tract, is dominated by tidal forcing and the interaction of tidal flows with vegetation, which develops on a seasonal timescale. Emphasis to this point has been on data analysis, and we have defined representative mean velocity profiles and surrogates for exchange between the vegetated and unvegetated regions of the flow. It appears that these exchanges are driven by intermittent flow instabilities which are likely to develop along the interface between vegetated and unvegetated regions of the flow.

Introduction and Problem Statement

The restoration of shallow water habitats in the Delta has involved and will continue to involve the inundation of Delta islands. Once inundated, these islands become tidal lagoons, with levee breaches providing the connection between the shallow habitats and the Delta channels. What role the shallow water habitats play in the Delta ecosystem is of critical concern in their design and construction, due to CALFED's emphasis on habitat restoration. In order to address the ecological significance of the shallow habitats, the hydrodynamics of these regions must be considered, due to the dominant role that transport plays in the biology of the Delta. First, the tidal exchange at the levee breaches controls the net transfer of biota and sediment between Delta channels and the shallow habitats. Then, within the shallow basins, the hydrodynamics of the interior determine the distribution and concentration of contaminants, nutrients, biota and sediment. While the exchange between channels and shallows is likely to be dominated by tidal forcing,

the dynamics in the interior of shallow water habitats will also be influenced by wind, diurnal heating and cooling, and the presence of aquatic vegetation. The project outlined here was focused on developing the necessary tools to analyze the hydrodynamics in these systems and to compare the relative importance of each of these forcing mechanisms.

Objectives

The specific objectives of the research program described here were to:

- (1) Compare the dynamics of two Delta shallow water habitats characterized by different features. The first, Mildred Island, is unvegetated and has limited tidal influence from the surrounding channels. The second, Franks Tract, is highly vegetated, and is characterized by extensive levee breaches providing connections with the Delta channels.
- (2) To evaluate the roles of wind, diurnal heating and cooling, and vegetation in transport in Delta shallow water habitats.
- (3) To develop capabilities and equipment for making extensive field observations in the shallow water habitats of the Delta.
- (4) To apply an existing hydrodynamic model, TRIM-3d to the systems to evaluate its ability to resolve the dynamics observed in the field.

Procedure

The Mildred Island experiments were performed in August-October, 2001. In-situ measurements were made by the U.S. Geological Survey over this entire period, and involved the deployment of several acoustic Doppler current profilers (ADCPs), conductivity-temperature-depth sensors (CTDs) and chlorophyll fluorometers, each logging time-series for the study period (see Figure 1a for distribution of instruments). These observations allow us to examine the variability of flows, temperature and scalar concentration over the tidal, diurnal, spring-neap and longer timescales. With this data, we will be able to address how the dynamics of shallow water habitats are influenced by tides, winds, and diurnal heating and cooling, as well as the influence of larger scale forcing, such as freshwater flow or delta operations

In the midst of this deployment, again in collaboration with scientists from the U.S. Geological Survey, we also performed several days of intensive sampling in early September. For a 24-hour period (2 tidal cycles), the velocity distribution in the vicinity of the primary opening between the shallow habitat and the channel was by repeatedly transecting the region with a boat-mounted ADCP. In addition, we also measured the density structure across the shallow habitat throughout the same 24-hour period using a profiling CTD. With this data, we can examine the details of the tidal exchange, including the asymmetry between flood and ebb tides created by the interaction with the

local bathymetry. By looking at a 24-hour period, we can also address how wind forcing and diurnal heating modify these exchanges.

To complement the field data collection, we have also modified and applied an existing hydrodynamic model, TRIM-3d, to the region surrounding Mildred Island. TRIM-3d is a semi-implicit free surface hydrodynamic model that predicts flow structure and variability as well the transport of scalars. For the application to the Mildred Island data set, we defined the model grid to include all of the Island plus a tidal excursion along each of the four adjoining channels. The open boundary conditions along these four channels are defined by the tidal stage predicted by a Delta-scale simulation of the study period performed by Nancy Monsen of the U.S.G.S. Scalars are allowed to freely advect out of the domain, but a no-flux condition is imposed for inflows. Several modifications to TRIM-3d were required to model the observed conditions. First, temperature was included as a dynamic scalar (i.e., affecting density). Second, a heat flux model was applied at the free surface which accounted for heating from solar insolation and heat loss due to convective and radiative cooling. Third, we generalized the wind input to allow for a variable windstress based on observations. Finally, a third, passive scalar was added to facilitate residence time calculations. The model runs are described further below in the Results section.

At our other field site, Franks Tract, the emphasis was on identifying the influence of vegetation on tidal transport and mixing. To address this issue, we performed five studies, each of about 2-week duration, between March 2002 and March 2003. While most of this work was funded by CALFED, this WRC grant facilitated the background activity which led to these studies. Each experiment consisted of a 2-week in-situ deployment of an ADCP near a connection with the Delta channels and a suit of acoustic Doppler velocimeters (ADVs: high-resolution current meters to examine velocity at a point). In addition to the in-situ deployments, flow and temperature mapping studies were carried out during daylight hours to examine the structure of the tidal jet and how it may interact with the surrounding vegetation (see Figure 2). By comparing the measurements from each of the studies to one another, each characterized by different levels of vegetation development, we can examine the affects of vegetation on the hydrodynamics.

Results

The observations in Mildred Island indicate that tides, wind and heating cooling are all important to the overall dynamics of the habitat, but with a relative importance that varies spatially. In the south part of the Island (Figure 1b), diurnal stratification develops under the influence of daytime heating of the surface waters. The daytime currents are dominated by wind-driven flows, with flow to the southeast at the surface and a return flow at depth. At night, this current pattern reverses, suggesting a relaxation of the density gradients established during the daytime. The influence of tidal forcing is minimal here, and the dominant timescale for both the currents and the scalars is diurnal.

In the northern part of the Island, however, tides are a dominant consideration. Here, the water column remains well mixed due to the influence of tidal mixing (figure 1c), and the dominant timescale is the 12.4 hour tidal cycle. Nonetheless, the influence of winds and diurnal heating can be seen in the structure of the tidal flows. As is illustrated in figures 1d-i and 1d-ii, the tidally-driven flood tide jet is very different between night (figure 1d-i) and day (figure 1d-ii). During the day, winds from the west deflect the near-surface portion of the jet to the east, while at night, the flood tide jet retains its structure well into the interior. One implication of this structure is that during the day, the flood-ebb asymmetry near the channel opening will be reduced.

An area of emphasis for us in our analysis of the system has been exchange flows. First, the exchange between South and North Island, appears to be dominated by wind-driven flows and associated density (relaxation) currents at night. The exchange between north island and the Delta channels is clearly tidally dominated, but may be modified by the presence of wind-driven surface currents. The hydrodynamic model of the system has been used to examine these exchanges in more detail, using a passive scalar to measure the net exchange directly. To be clear, we initialized the interior of Mildred Island with a uniform concentration (normalized to 1) and then simulated its transport through the study period under different forcing assumptions. The cases considered included 2d and 3d model runs with 3 forcing scenarios: (1) tides only; (2) tides and wind; and (3) tides, wind and heating/cooling.

Figure 3 illustrates this process for three of the cases. In each case, the distinction between North and South Island is clear, with North Island being rapidly flushed through tidal exchange with the adjoining channel. South Island, in contrast, retains high concentrations of the scalar for much longer periods, but with varying degrees of exchange for each of the cases shown. In the two-dimensional case (figure 3a), the rapid flushing of North Island has little effect on South Island, and exchange between the two subregions is severely limited (note that this simulation included wind and heating and cooling, but little effect of these processes is seen). In the three-dimensional cases, much more scalar (as much as 20%) is exchanged between South and North Island, most likely under the action of the vertical exchange flows driven by wind and temperature gradients. Comparison of figure 3b and 3c suggests that diurnal heating and cooling (3c) is effective at increasing the exchange along the axis, resulting in an increase in the exchange by about 20% over the case with just wind (3b).

To aggregate these scalar concentrations into a measure of overall exchange, we have calculated the average concentration in the entire island as a function of time, as well as in the subdomains of North and South Island. The decay of these concentrations defines the flushing (or residence) time of each region. In figure 4, these concentrations are shown as a function of time. Exponential fits to these curves would produce estimates of the residence time (or, equivalently, the volumetric exchange flow), but for now we present the raw timeseries. Comparison of Figure 4a and the green lines in Figure 4b and 4c demonstrate the importance of vertically sheared currents in establishing the flushing time for the system. For the three-dimensional models (figures 4b and 4c), the interior concentration in Mildred Island is approximately 0.68 on September 17, while the two-dimensional model predicts a concentration of 0.75. While this is just a 10% difference in concentration, it is actually a 25% difference in the amount of flushing. To assess the

role of heating and cooling in the flushing of South Island, we compare the red lines in figures 4b and 4c. By September 17, the model with heating and cooling (figure 4b) shows a concentration in South Island of 0.86, which compares to a concentration of 0.88 for the case without heating and cooling (figure 4c). This difference represents a 14% increase in the degree of flushing, and indicates that predictions of exchanges in South Island requires inclusion of atmospheric heat fluxes.

While not as thoroughly analyzed at this time, the observations from Franks Tract do suggest an important interaction between the vegetation and the hydrodynamics. First of all, as is seen in the flow mapping data (Figure 2b), the flood tides are channelized by the vegetation, producing jets that extend well into and across the shallow water habitat. This flow structure would produce a ‘short-circuiting’ of the habitat, and the effective residence time of a particle carried in one of these jets, while not quantified at this time, could be extremely short. Retention of particles in the shallow water habitat may depend on intermittent exchanges into the vegetated regions along the edge of the jet, which would be driven by the instability of the jet flow structure. On the ebb tides (Figure 2c), the flow is less channelized and is more distributed across the entire basin, even extending into and across vegetated regions. This suggests an important tidal asymmetry in transport across the vegetated-unvegetated interface, with channelized flood tides providing only intermittent exchanges and uniform ebb tides that carry waters across the vegetated regions. The implications for residence time are likely to be profound, and continue to be an area of emphasis for us.

Conclusions

In addition to establishing our ability to effectively observe and model the hydrodynamics of shallow tidal flows in the Sacramento-San Joaquin Delta, our research over the past three years has provided insights into those same flows. As a general result, we can conclude that multiple forcing mechanisms – specifically tides, wind, diurnal heating and cooling and vegetative drag – are all important in defining the dynamics of shallow water habitats. The relative importance of each mechanism varies spatially, both within an individual shallow water habitat and between habitats. In nearly enclosed basins, such as MI, wind and diurnal heating and cooling dominate, except near specific openings (where the interaction of tides with the local bathymetry is most important). In more open basins, tidal interaction with bathymetry and vegetation dominates transport throughout the interior, such as was seen in Franks Tract.

In the design of shallow water habitats, therefore, all of these forcing mechanisms should be considered. For example, the orientation of the basin and its openings relative to the dominant wind-direction should be a consideration in order to either encourage or prevent the formation of ‘dead zones’ with high retention times. Similarly, hydrodynamic models of shallow water habitats in the Delta must also include the influence of diurnal heating and cooling and local wind forcing.

Taken as a whole, I hope that this research effort illustrates the fact that transport and mixing, even in these very shallow flows, are driven by the subtle interaction of multiple forcing mechanisms, and the three-dimensional flow structures they produce.

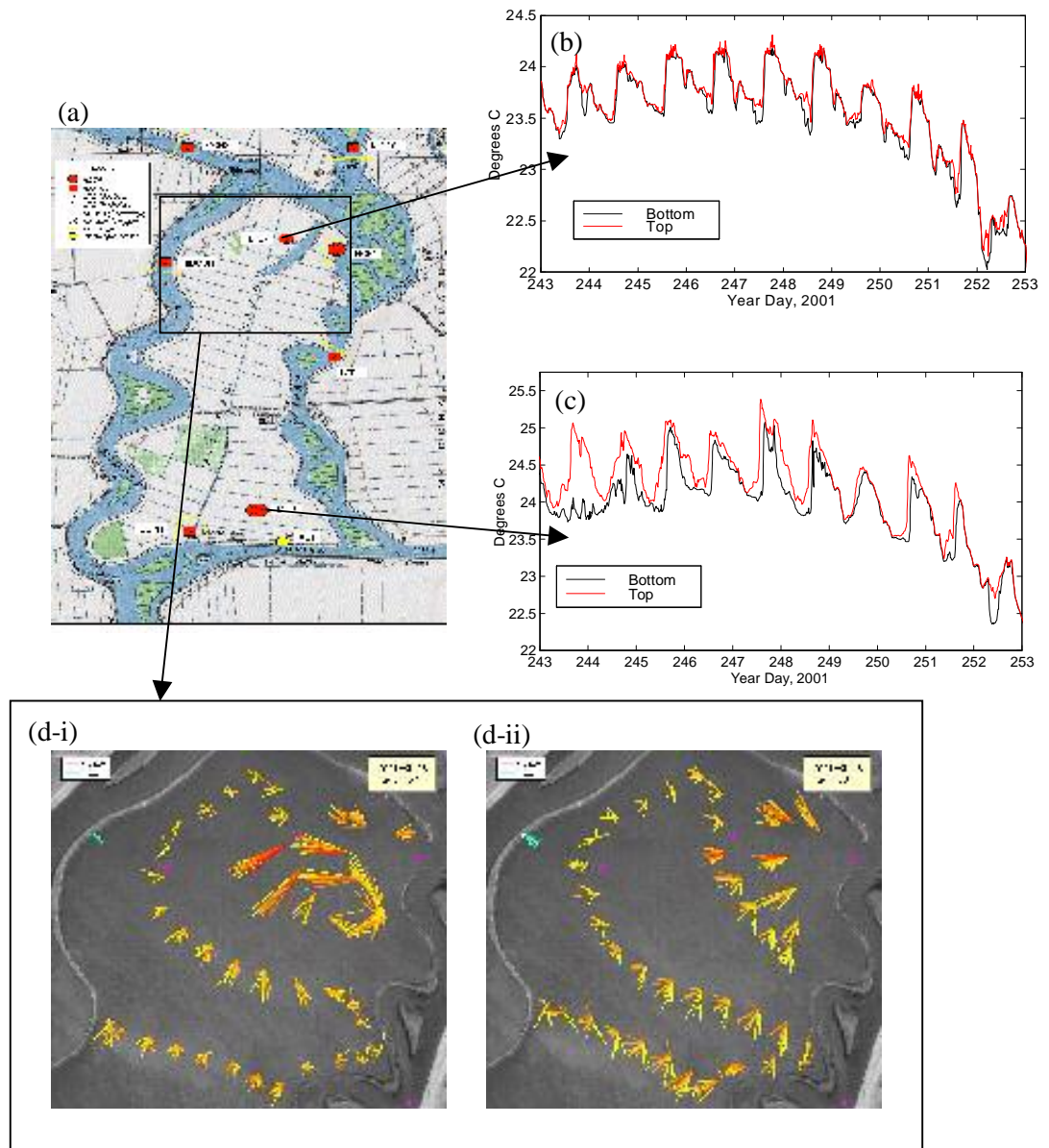


Figure 1: Mildred Island experiment and observations. (a) Field site. Location of in-situ instruments marked by red circles. (b, c) Time series of top and bottom temperatures at North Island (b) and South Island (c) stations. Note the persistent stratification in South Island (c), and the fact that North Island remains unstratified (b). (d) Flow mapping results showing nighttime flood jet (d-i) and daytime flood jet (d-ii), which has been modified by wind influence.

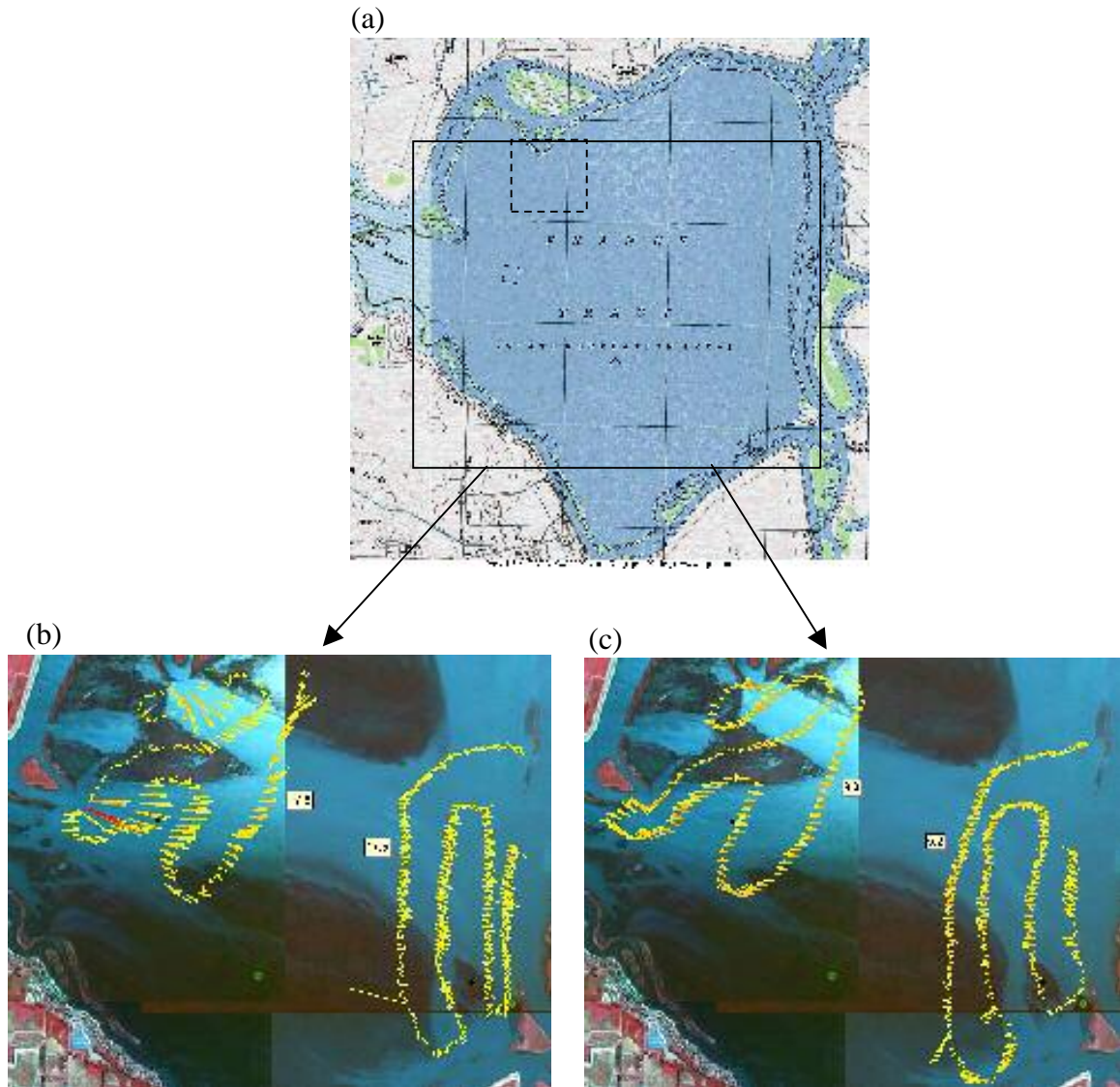


Figure 2: Franks Tract experiment and observations. (a) Study site showing region for flow mapping in (b) and (c). Smaller, dashed rectangle in (a) shows location of high-resolution mapping experiments and in-situ deployments. Comparison of flood tide (b) and ebb tide (c) shows tidal asymmetries. Note two flood tide jets entering from the west and northwest openings (b). On ebb, flow is more uniformly east-to-west (c).

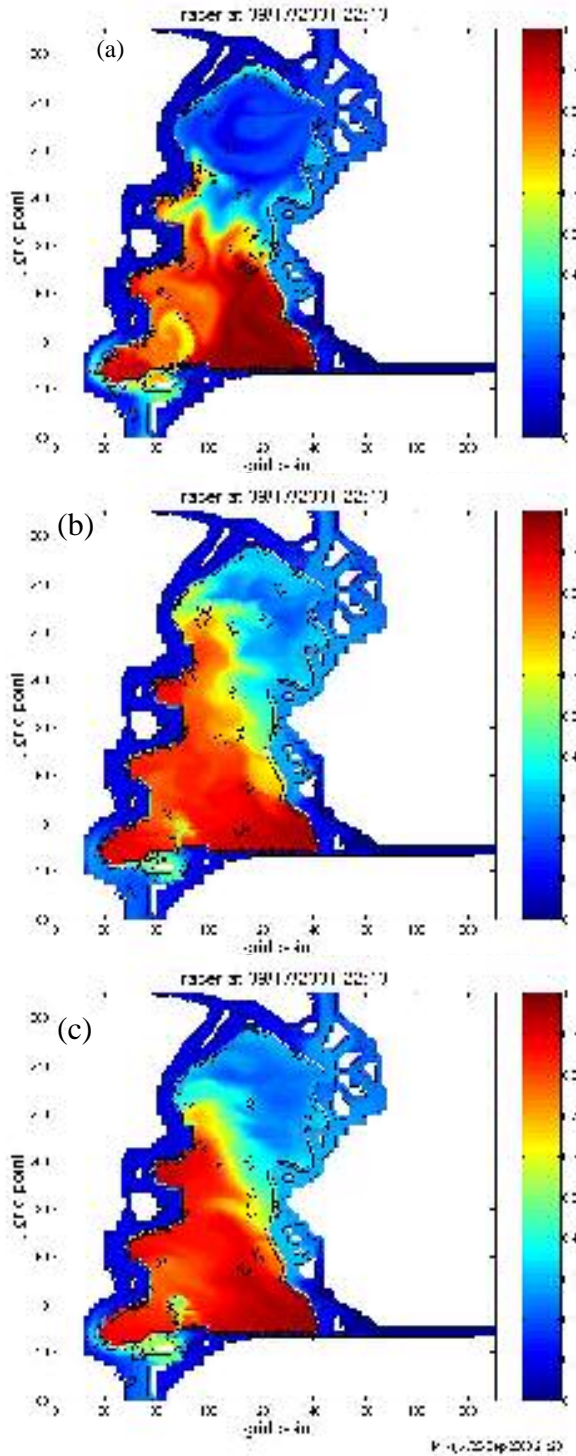


Figure 3: Simulation results for passive tracer flushing after six days (initialized as 1 everywhere on 9/11/2001). (a) Two-dimensional simulation shows little exchange between North and South Island. Three-dimensional simulations allow more exchange to develop due to vertical shear. (b) Includes influence of wind and diurnal heating and cooling; (c) wind only (no heating and cooling). While subtle, differences in these distributions suggest about a 20% increase in north-south exchange when heating and cooling is considered.

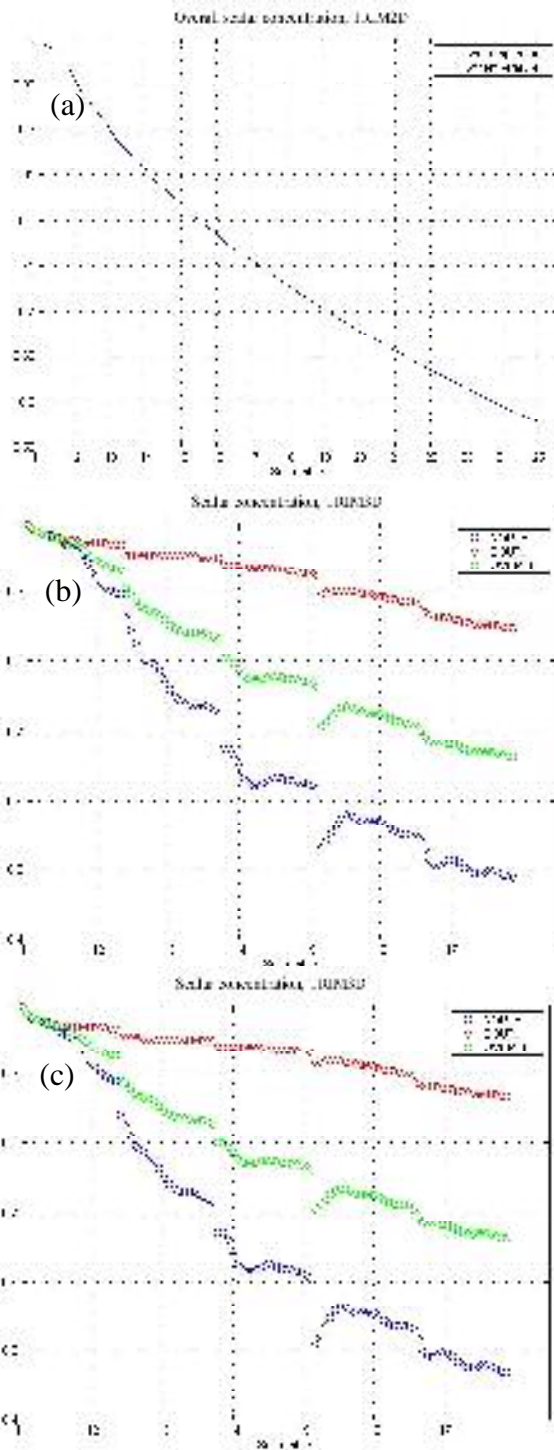


Figure 4: Residence time calculations. (a) Average concentration in Mildred Island for 2-dimensional simulation. (b) Averaged concentrations for three-dimensional simulation including tides, wind and diurnal heating and cooling. Timeseries show average concentration in all of Mildred Island (green), North Island (blue) and South Island (green). (c) Same as (b), but without the effects of diurnal heating and cooling.