TIDAL CIRCULATION MODELLING OF A GEORGIA COASTAL SOUND

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Abstract- The circulation of a tidally forced Georgia estuary is modeled to provide precise prediction of surface currents. These predictions are useful to determine contaminant plume spread (oil spill potential), the transport routes of (shrimp and crab) larvae into the sounds, etc. In the past, they have been used to assist Savannah's 1996 Olympic yachting events. Using a comprehensive nonlinear finite element model which includes tidal- and wind forcing and generates the three dimensional structure of the circulation of Wassaw Sound, we demonstrate the special boundary conditions needed to correctly account for drainage from extensive marsh systems, typical of the US South Atlantic Bight. Tidal forcing from outside the sound is used to specify the interior response of tidal creeks and channels. By synthesizing the back water areas of the marsh flats, the volume of the tidal prism can be correctly modeled without the artificial specification of interior tidal heights. Model results can be used to predict Lagrangian (tracer) pathways, and identifying the "hot spot" regions of mixing between the sound and coastal ocean. Tracer pathways also demonstrate the large variability of residence time within the marsh and sounds encountered by different water masses.

INTRODUCTION

Of fundamental importance to inner shelf and tidal sounds is the mixing, residence time and cross-system flux of carbon, nutrients, salt, chemicals and pollutants. Transport paths of these solutes and particulates determine whether these systems are net importers or exporters and determine the productivity of these ecological systems. Biological and geochemical exchange and reaction rates depend on quantitative measures of concentration fields and residence times. As a practical solution, most studies within tidal bays, sounds, rivers and estuaries are still based on measurements of tracer gradients to derive bulk gradient mixing factors and residence times. Gradient diffusivity models have oversimplified these measures by ignoring the true variation in concentration and residence time of parcels of water which are exchanged by the diffusion cascade model. Being able to discriminate between the relevant dispersion and mixing processes, an alternative (and quantitatively more correct) measure of exchange can be offered to researchers in the fields of biology, geology and chemistry.

Circulation patterns within the inner shelf and coastal sounds determine the mixing and exchange of materials across the interface between the coastal ocean and neighboring sounds. Understanding the details and the direction of the exchange across the inner shelf/coastal sound interface is essential in determining the seaward transport and fate of land-derived materials (*e.g.*, Windom and Gross, 1989; Signell and Butman, 1992), the landward (onshore) transport of sediments (*e.g.*, Olsen *et al.*, 1989), and the ingress of the larvae of many marine species from their offshore spawning areas into estuarine larval and juvenile nursery areas (*e.g.*, Boehlert and Mundy, 1988).

A three dimensional numerical model of the tidal currents in a typical Georgia coastal sound was used to describe these transport and mixing processes. The finite element gravity wave resolving simulation calculates the time evolution of the velocity field in ten second steps giving the full resolution of realistic tidal motions. To investigate mixing processes the model must carefully control numerical horizontal diffusion. Vertical and horizontal shear dispersion based on the model shear fields and Lagrangian dispersion based on particle tracking experiments can be calculated. Wassaw Sound Georgia was chosen as the modeling site because it exhibits the type of

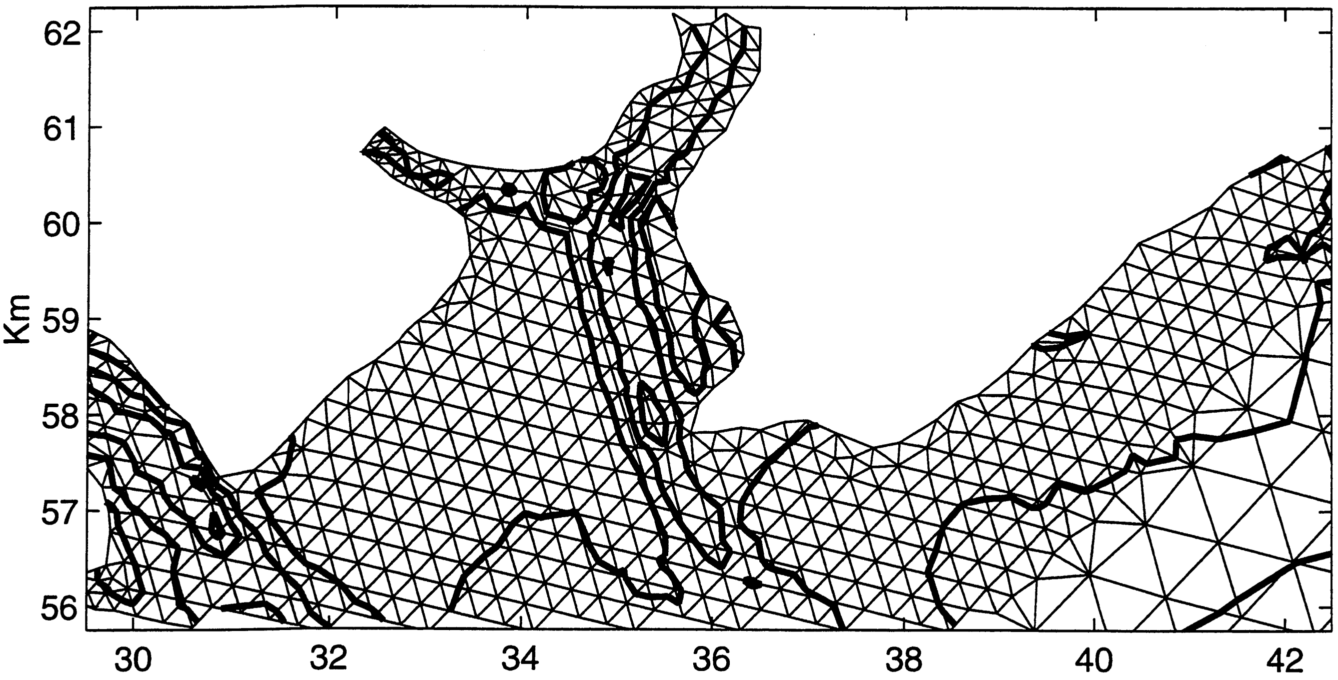

Figure 1: The finite element grid for the model. By using the Finite Element method with triangular elements an arbitrary coastline with variable resolution is easily accommodated. (Thick lines are 2 meter spaced isobaths.)

tidal geometry which leads to tidal shear diffusion and residual currents. Additionally it was the site of the 1996 Olympic Yachting events for which the tidal predictions were used to aid sailboat racing strategy (Gross 1996).

MODELING THE TIDAL CIRCULATION

Wassaw Sound on the Georgia coast is a macrotidal estuary. It has ±1.5 m tides, peak currents on the order of 1 m/s, and depths of 2–15 meters. The entrance channel of Wassaw is not dredged and the "typical" ebb tide delta is present. Wassaw Sound has little direct fresh water input; the Wilmington and Bull "rivers" which flow into it drain large saltmarsh areas and are not continental fresh water rivers. The landward reaches of the rivers are influenced by surface fresh water runoff and tidal channel connections to the Savannah River fresh water creating a horizontal salinity gradient. Even though the density gradient is well mixed vertically, the horizontal baroclinic pressure gradient can force vertical shear, requiring the use of 3-D modeling techniques.

The offshore (seaward) extent of our domain will be within the coastal front. The coastal front, the seaward boundary of a 20-30 km wide band of low salinity water adjacent to the coast, is dynamic and known to be controlled by fresh water discharge, and mixing within the coastal zone (*e.g.*, Blanton, 1981 and 1986; Werner *et al.* 1993). As the coastal front is several tidal excursion lengths offshore from the sound it has no dynamic influence on tidal circulation within one excursion length of the sound. The model will, however, resolve the riverine plume-front (e.g., O'Donnell, 1990) which is entirely within our modeling domain and landward of the coastal front. The definition of the landward boundary of our domain is complicated as Wassaw Sound connects through rivers and channels to a network of distributary channels that flood and drain "backwater" salt marshes – a feature which is common to the many shelf-sound-marsh systems. An appreciable amount of mixing occurs within the dendritic channels of the marsh which discharge into the main channels. For this reason the details of particular pathways, where and for how long materials reside within the sounds is particularly important. These details provide the physical basis behind estimates of "residence times".

The 3-D (QUODDY) model resolving $\mathcal{O}$(1 km) length scales, *i.e.*, $\mathcal{O}$(100 m) grid spacing, has been used by Kapolnai *et al.* (1996) to trace and delin-

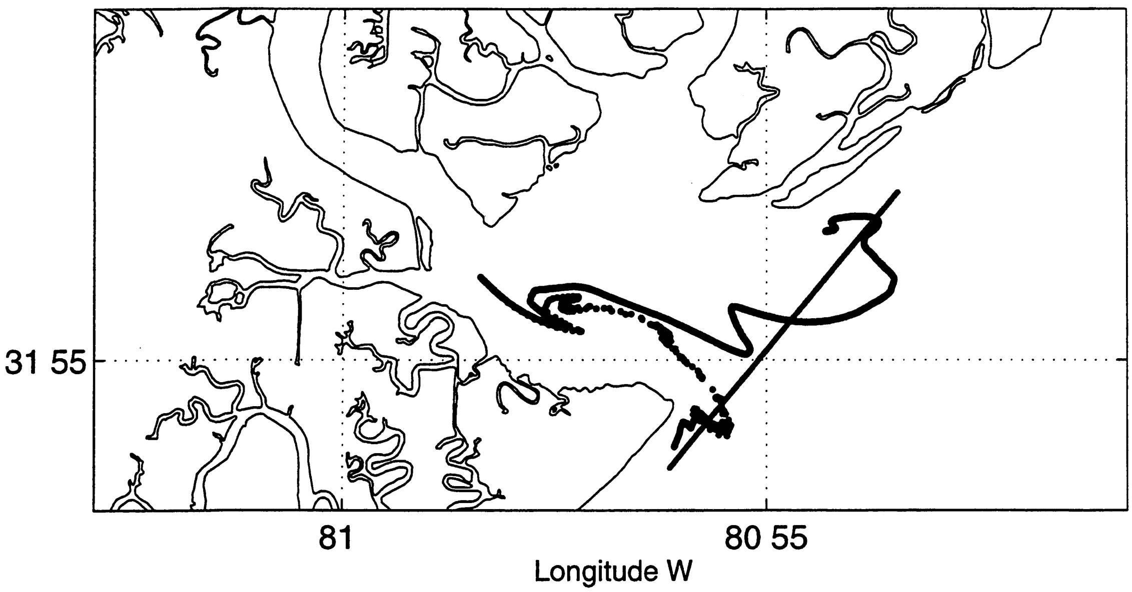

Figure 2: Tidal shear dispersion is demonstrated by releasing Numerical drogues from positions in a line across the mouth of the sound which move in and out of sound until after three tidal cycles they arrive at the second curved line of positions.

eate sub-tidal time scale mixing and dispersion processes in an idealized domain. The QUODDY model developed by Lynch and Werner (1991) and Lynch *et al.* (1996) is a state-of-the-art, free-surface, 3-D, nonlinear finite element model. It incorporates advanced turbulence closure, operates in tidal time, and computes the evolution of tracer and density (baroclinic) fields prognostically. Variable horizontal and vertical resolution are facilitated by the use of unstructured meshes. The model has the ability to resolve the details of tidal shear dispersion by directly including the shear length scales and a turbulent bottom boundary layer closure. Attention has been given during the model development to explicitly control numerical horizontal diffusion, isolating the horizontal spread to the interaction of vertical turbulent diffusion with horizontal advection. The transport of passive (and active) tracers and their advection outside the sound has been successfully modeled (*e.g.*, Lynch *et al.* 1996; Werner *et al.* 1996), and boundary conditions describing the volume of water exchanging within the shallow marsh areas have been incorporated into the model (Gross and Werner, 1994).

The semi-diurnal tides in the SAB shelf propagate as Poincaré waves, with phase lines parallel to shore and resulting tidal ellipses' principal axes perpendicular to the isobaths (Wang *et al.* 1984). Over 80% of the tidal signal is contained in the semi-diurnal band and over 80% of that signal is due to the M_2 tide. The seaward tidal boundary conditions were derived from past studies (*e.g.*, Werner *et al.* 1993 and Westerink *et al.* 1994). For the Olympic simulations six tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1) were specified on the outer boundary.

Within the sounds there is an almost infinite hierarchy of drainage channels which communicate with the marsh system. These were modeled by specifying the area or volume of water drained by the primary channels. The currents and total tidal excursion are expected to depend not only on the changes in sea level height, but on the tidal prism as well. Although the main body of the sound and tidal rivers can contain a large part of the tidal prism, a significant volume is drained out of the distributary channels which finger through the large marsh areas between the barrier islands and land.

The parametrization of the flooding and draining of the backwater marshes will be related to the sea level height along the distributary channel open boundary, the flow across that boundary and the area behind the channel (*i.e.*, into which, or from which the flooding and draining takes place). We use a boundary condition that models the flooding (and

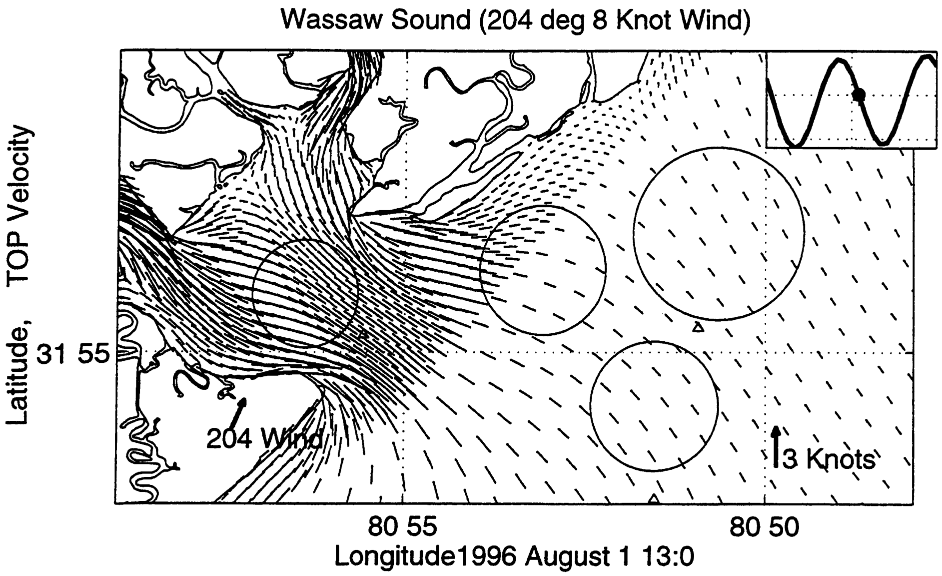

Figure 3: Surface currents for the Olympic Yachting venue. The velocity vectors are indicated by lines moving away from a dot indicating the node where the velocity was calculated.

draining) of an area behind a main channel where a cross-shore flow is allowed (Gross and Werner, 1994). The boundary condition states that flow through the open boundary will be resisted by the rise of sea level beyond the open boundary and is related to the backwater tidal prism. Sea level will rise in proportion to the area flooded and the flow through the open boundary's cross-section. An advantage of this method which specifies flooded area per depth (the hypsometric basin curve) is that exceptional storm surge or fresh water runoff events can be accurately modeled and predicted. The otherwise difficult to estimate current/height phase specification of the incoming tidal wave is avoided. For shelf circulation, only the major sounds and rivers need be specified. For nearshore flows the tidal creeks must be added, with mud flats and the distributary creeks becoming important to circulation within the sound.

The backwater area and volume must be empirically provided. A graphical method was used based upon NOAA charts. A better technique would be to use GIS information on marsh extent and channel depths, but such a data base is just now being developed. Another method uses current and tidal height measurements at the mouths of the distributary channels. The backwater area drained by a channel can be empirically determined by measuring the volume flux (velocity) and the time-varying sea level change at the mouth of the root creek. The relation of the rate of change of tidal height to velocity provides a hypsometric curve for the area behind the channel mouth. There are about ten primary creeks which open into Wassaw Sound, the Wilmington and Bull Rivers, which drain a total of area of about 40 km^2. Only four rivers/channels were specified for the Olympic runs.

RESULTS AND CONCLUSIONS

Figure 2 is a demonstration of the spread of numerical drifters placed in the current field calculated by the model. Using the modeled tidal current results a row of numerical particles were initialized across the entrance to Wassaw Sound just after low slack, before the flood currents. It is important to realize that drifter experiments, such as this, are critically dependent upon the phase of the tide at the moment of initial release. The initial spread of a group of points can be quite different if released at slack before flood verses slack before ebb. Identifying the "Eulerian" location of a "Lagrangian" measure of dispersion is a controversial topic (*e.g.* Salomon *et al.* 1996). After exactly three tidal cycles the line has been drawn out to the curved shape. The drifters move great distances each tidal cycle, but only spread apart when adjacent drifters experience differential shear during their motions. The shear is greatest across the channel where the largest amount of dispersion can be seen. The average tidal dispersion is obtained from the rate of dispersal of originally adjacent drifters. The paths of water parcels may be followed for several tidal cycles to ascertain the actual residence time, without using a tidally averaged diffusion coefficient.

In addition to its use as a research tool the model of Wassaw Sound was used to forecast daily tidal currents for use by the Olympic yachting competitors during the summer 1996 games held in and just outside Wassaw Sound. Figure 3 is a typical hourly summary chart provided to the race teams at the morning race briefings. Winds were simply modeled using the previous days measured wind time history and specified in the model as a spatially uniform field. The effects of the winds on the currents inside Wassaw Sound were hardly noticeable in the face of the large currents, but outside, the keel boats could pick up a quarter knot speed difference across the race area. Thus the charts were used by most competitors, although most sailors took the advice with some well placed skepticism.

SUMMARY

Three dimensional modeling of tidal flows is now practical and should be considered as a basic tool when working in coastal and estuarine waterways. The most difficult aspect of the modeling task is the construction of the numerical grid describing the geometry, bathymetry and boundary conditions of the particular area of interest. For the Wassaw Sound model updated bathymetry surveys conducted by NOAA in support of the 1996 Olympic sailboat races solved the geometry and bathymetry acquisition problem. Techniques which incorporate accurate GIS numerical products with mesh generation tools will help to solve the geometry problems. However, a clear scientific approach to boundary conditions will always determine the reliability of the final product. In the case of Wassaw Sound, and probably most Georgia sounds, the backwater condition of flooding marsh and tidal rivers proved to be of first order importance and became a distinguishing attribute of the model.

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