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14. ABSTRACT
The goal of this project was to investigate numerical solution techniques to improve simulations of buoyant plumes in the coastal ocean. River plumes are difficult to simulate because both advection and mixing, traditionally troublesome aspects in numerical simulations of coastal flow, are important. Papers written as part of this study suggest methods for constructing robust numerical simulations of river plumes, and describe a framework for comparing these simulations to observations in salinity coordinates, a natural coordinate system for examining plume processes.

15. SUBJECT TERMS
River plumes, numerical simulations, buoyancy driven currents, coastal ocean flow

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Assessing the sensitivity of river plumes to the source region
Final report

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LONG-TERM GOALS

My long-term goal is to improve numerical simulations and predictions of buoyant flow in the coastal ocean.

OBJECTIVES

This project focuses on numerical simulations of wind-forced river plumes. In particular, it is hypothesized that the inclusion of wind forcing reduces the sensitivity of the numerical simulation to resolution and the choice of numerical advection scheme. More generally, this study sought to examine how wind forced mixing and other types of mixing affect plume structure.

APPROACH

The hypothesis is refined using idealized models, then tested by comparing realistic simulations to measurements. Idealized models used a grid-convergence method to ensure consistency within the idealized modeling.

WORK COMPLETED

A manuscript describing the idealized modeling has been published in the *Journal of Physical Oceanography*. Realistic models of the Mississippi River plume in the Gulf of Mexico, the Kennibec River plume in the Gulf of Maine, and the Po River plume in the Adriatic have also been developed. A paper describing the Kennibec River plume simulation is in press as part of an ECOHAB Gulf of Maine issue of Deep Sea Research II. I have published a paper explicitly discussing model event-based skill, based on a model/data comparison from Hetland and Signell. Finally, I have also submitted a paper examining plume structure very near the mouth of an estuary, the region where advective and mixing processes are strong.

RESULTS

The primary results are related to use the idealized model to track fresh water as it flows through the plume. This work is presented in Hetland (2005). This paper focuses on numerical requirements for simulating river plumes, and provides a framework for analysis of river plume simulations. The analysis framework defines properties of the plume in salinity coordinates – a coordinate system that follows the plume as it is translated by a combination of fresh water inputs and wind forcing. A basic form of this type of analysis was presented in Hetland and Signell (2005), who do a detailed model/data comparison of the buoyancy driven Maine Coastal Current based on fresh water flux.

The analysis method, similar to that used by MacCready et al. (2002), is based on an isohaline coordinate system, so that the plume may be followed as it changes position in response to wind forcing. Figure 1 shows fresh water distribution density as a function of salinity class using different wind forcing and mixing schemes. The results are from an idealized model, with very high resolution (grid sizes of a few hundred meters) in the estuary and near-field plume. Stronger wind forcing shifts the plume to higher salinity classes (a rightward shift peak values of fresh water distribution density). This shift in the fresh water density distribution is expected, since the wind increases mixing and causes the plume to become saltier, however, this method allows this shift to be quantified. Also, the entire structure of the plume has been mapped onto a single line, which allows for direct and simple comparison between one or more simulations.

The results in Figure 1 demonstrate how wind may reduce the sensitivity of plume structute to the source region. In the cases shown in Figure 1, in the absence of wind, mixing in the estuary and in the near field plume produce a plume with a median salinity of about 24 psu. Both of these regions are often unresolved by typical grid-scale resolution, as shown in Figure 2. If there were errors in calculating the mixing in either of these regions, the structure of the plume will not be correct.

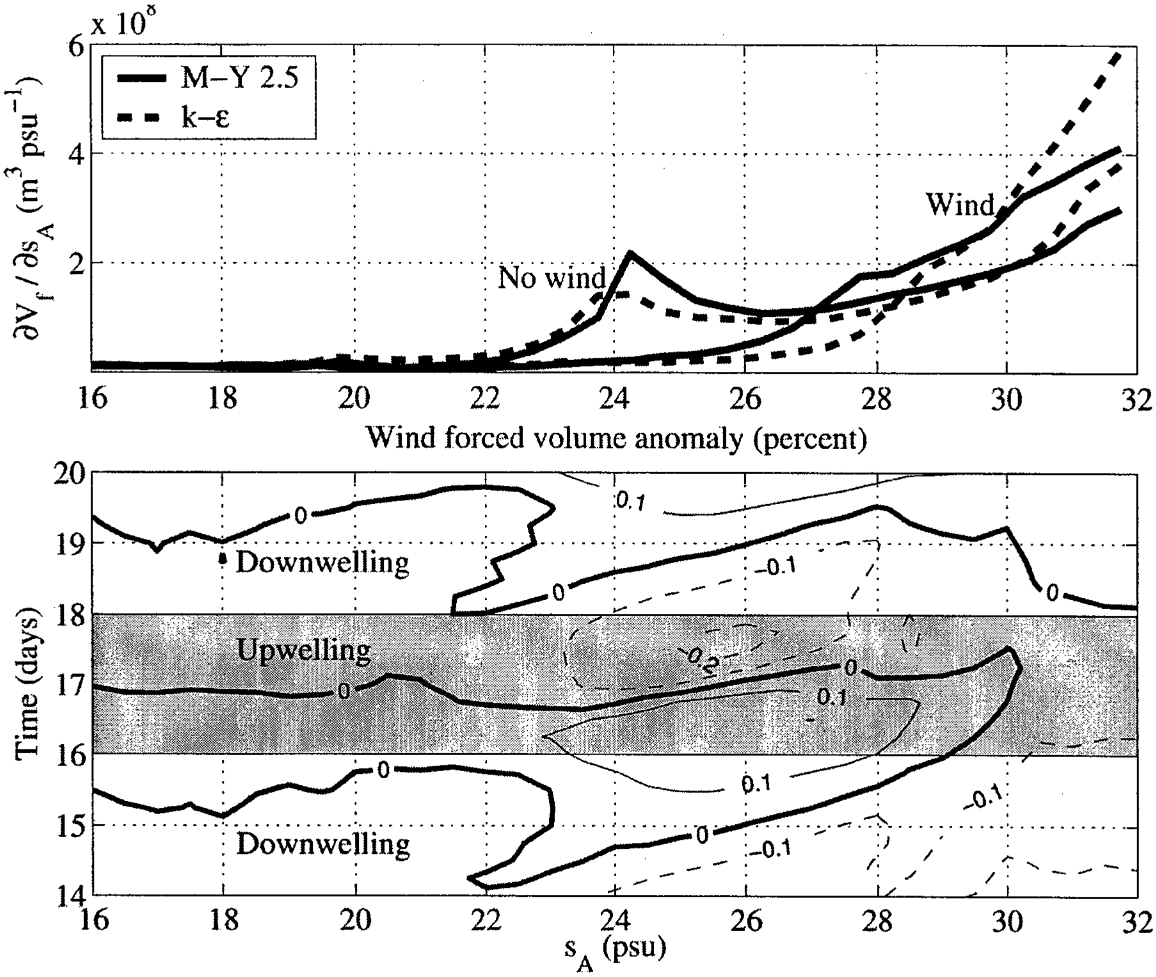

Figure 1: Upper panel, fresh water distrubution density as a function of salinity class for for two forcing cases (wind and no wind), and two turbulence mixing closure schemes (Mellor-Yamada and k-ε). Lower panel, time dependent motions of fresh water density for the wind-forced Mellor-Yamada case.

[Fresh water distribution density describes how much fresh water is contained between two isohaline surfaces within the plume, calculated by integrating the fresh water distribution density between two salinity values. The lower pane shows how fresh water is moved to higher salinity classes during upwelling winds.]

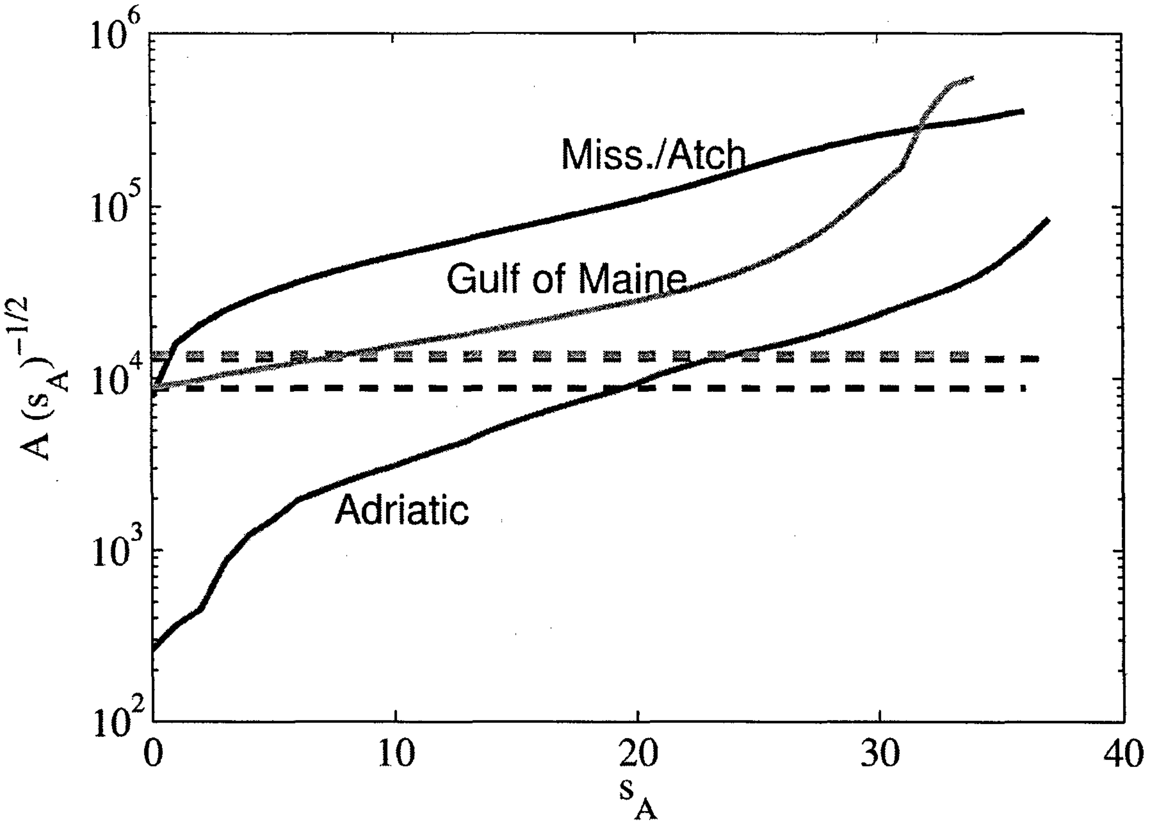

Figure 2: Average root of the area enclosed as a function of salinity.
[The characteristic length scale, the square root of the area, of a plume is calculated as the area enclosed by a surface salinity contour, s_A, for different salinities. Three realistic simulations are shown; plumes with more fresh water discharge have a larger area. The dashed lines show the approximate model resolution for each simulation.]

However, wind forcing may mix the plume to a specific salinity class, regardless of previous mixing history. It was found that there is a critical plume thickness beyond which wind mixing is suppressed [based on results of Fong and Geyer (2001)]. The critical thickness is dependent on the local fresh water thickness (the vertical integral of the salinity anomaly, $(s-s_0)/s_0$, where s_0 is the reference salinity) and the magnitude of the local wind stress. Agreement with theory is good, but not perfect. It seems that shear in the upper layer may be caused by geostrophic currents in addition to wind stress.

Salinity coordinates may be used diagnostically, to describe changes in plume structure in a coordinate system that moves with the plume as it is blown on- and offshore by the wind forcing. However, salinity coordinates may also be used to obtain an estimate of the salt flux. An example showing salt flux within the plume at various salinity classes (a proxy for different dynamical regions within the plume) is shown in Figure 3. Salt flux is calculated using the salinity structure of the plume (i.e., hydrographic measurements of the plume) and direct estimates of the using the results from the turbulence closure models shows that the salt flux may be accurately estimated.

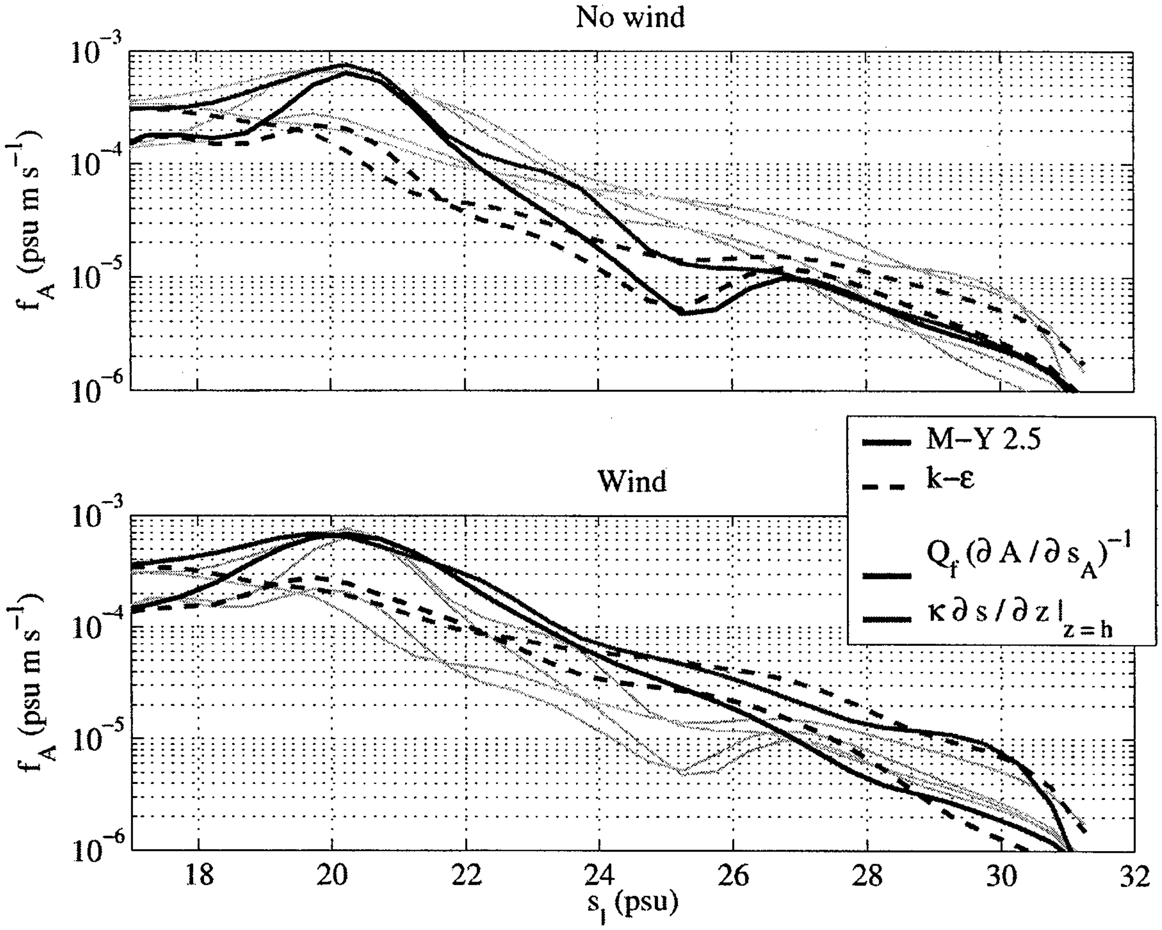

Figure 3: Salt flux in the plume as a function of salinity class
[The salt flux is calculated as a function of plume area at different salinity classes (blue lines), and is calculated directly from the turbulent closure scheme in the model. Very good agreement between these two calculations shows the utility of estimating salt flux using hydrographic measurements.]

These results are summarized in a conceptual model of mixing within the plume, shown in Figure 4 below. This figure shows different regions where different processes act to mix the plume. It was calculated, for the idealized models, that approximately half of the mixing occurred within the estuary and near-filed plume, the other half was due to wind mixing in the far-field plume. Thus, approximately half of the water mass modification occurs in portions of the plume that are unresolved by conventional coastal models. This highlights the need to better understand how small-scale processes effect the larger scale coastal circulation. In particular, small-scale processes may influence the far-field plume in periods of low wind stress, and might be ignored when wind forcing is strong.

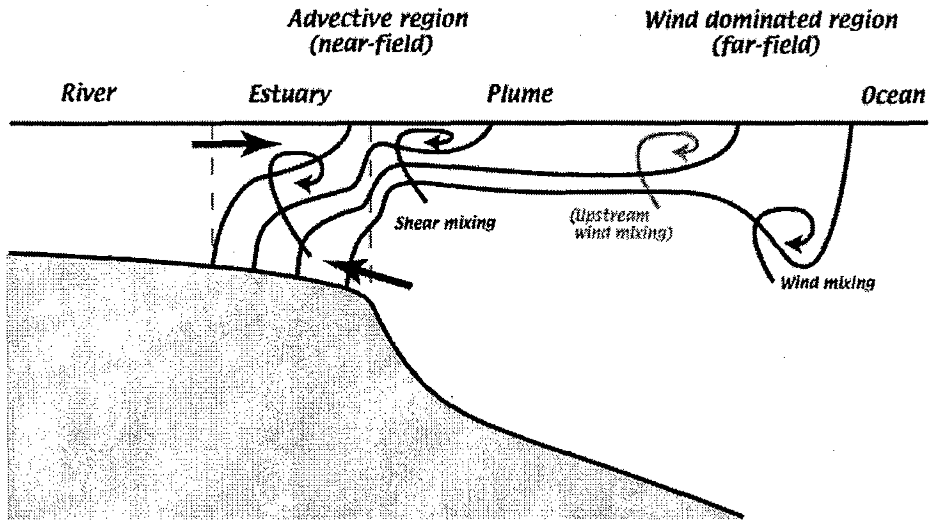

Figure 4: A conceptual model of mixing in a narrow estuary/river plume system.

IMPACT/APPLICATIONS

The primary application for this research is to define the resolution requirements for simulations of river plumes. Resolution requirements are obviously dependent on the scales over which accurate simulations are desired, but also depend on the forcing conditions. For example, a plume that is forced with very strong fresh water forcing and little wind (e.g., the Mississippi River plume in summer) will require resolution of the near field plume more than a simulation of the Kennebec River plume in spring, where wind forcing is stronger.

This study also hints at the importance of the supercritical flow region just outside the estuary mouth in determining the ultimate salinity when winds are weak or buoyancy forcing is strong. The idea of hydraulic control at the estuary mouth dates back to Stommel and Farmer (1953), is examined from the point of view of estuarine circulation in Hetland and Geyer (2005), and is the topic of a paper I have recently submitted to the Journal of Physical Oceanography.

The methods developed to examine the plume in salinity space may also be used to obtain bulk estimates of mixing in the plume from simple hydrographic measurements. This has an advantage over direct measurements of turbulence, because it integrates mixing across the plume, and is therefore less suseptable catching or missing isolated, strong mixing events.

The ultimate goal is to use this analysis framework in model/data comparisons. Presently it is difficult to compare river plume simulations to observations because motions of the plume cause different portions of the plume to be measured at different times. For example, a mooring may measure either the core or edge of the plume at different times, if it is present at all.

RELATED PROJECTS

The realistic modeling done within this project is related to other observational programs and modeling efforts: A new NOAA funded project to examine mechanisms controlling Hypoxia on the Louisiana shelf, the ECOHAB Gulf of Maine program (http://www.whoi.edu/ecohab/), and a variety of projects in the Adriatic Sea (http://gsvaresa07.er.usgs.gov/adria23).

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IX. Disputes

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