Frontal Structures in the Columbia River Plume
Nearfield – A Nonhydrostatic Coastal Modeling Study

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LONG-TERM GOALS

Developing a robust non-hydrostatic coastal modeling system to predict and to study frontal structures, mixing and turbidity of tide-modulated river outflows for a wide range of stratification and wave-dominance.

OBJECTIVES

• To study frontal structure and the resulting surface signature at the mouth of Columbia River (MCR) using the 3D non-hydrostatic model NHWAVE.

• To carry out more comprehensive model validation and analysis for frontal structures using existing remote-sensing and in-situ data resulted from RIVET II and DARLA MURI projects and field data to be obtained in newly planned field campaigns in 2015 and 2016.

• Investigate the performance and sensitivity of different sub-grid closure schemes in NHWAVE to effectively resolve various flow structures in the frontal zone. Enhancement and refinement of NHWAVE to be a robust open-source non-hydrostatic coastal modeling system.

SIGNIFICANCE

In coastal zones where fresh riverine water meets salty seawater, such as in a river mouth, flow structures can be highly complex and unpredictable due to density stratification and shear instabilities. For riverine outflow that is also modulated by tides, the frontal zone, defined here as the sharp transition between freshwater and seawater (salt wedge), is highly dynamics both spatially and temporally (Geyer & MacCready 2014). Various flow structures are generated which manifest the sharp transition of flow properties (e.g., salinity) at different scales, such as internal hydraulic jumps, internal waves and shear instabilities (e.g., Honegger et al. 2015; Nash et al. 2009; Geyer et al. 2010). These flow structures can alter acoustic wave propagation (e.g., Reeder 2014). Moreover, the enhanced mixing and turbidity can scatter light and affect water clarity. Some of these flow structures are sufficiently intense to impact navigation safety but in the meantime, they can leave unique surface
signatures which can be detected by remote sensing imagery. Hence, studying frontal dynamics is of high naval relevance as well as of civilian interest.

There are several challenges in studying frontal dynamics. From the physical perspective, in-situ measurement is central as it is the only means to acquire real data on flow structures. Remote sensing imagery can provide large spatial coverage of two-dimensional-horizontal (2DH) near-surface features. However, the relationship between the 2DH near-surface signatures and vertical water column processes is poorly understood and remains a subject of continuing research (e.g., Plant et al. 2009; Chickadel et al. 2009; Talke et al. 2010). In this case, a 3D non-hydrostatic numerical model that is able to resolve various flow structures in the frontal zone and their surface signatures becomes the critical linkage (Giddings et al. 2012). However, non-hydrostatic numerical simulations for various scales of frontal structures in a realistic setting are still at preliminary stage. Rigorous evaluation and validation of the simulation results in terms of their accuracy and feasibility still rely highly on in-situ and remote-sensing data. Therefore, studying frontal dynamics in river mouths is a fascinating problem from both the perspectives of scientific research and practical applications.

MCR is the “critical interface” that connects the estuary, inner shelf and adjacent beaches. Motivated by recent ONR-supported RIVET II, the outstanding issues that we like to investigate at MCR are frontal dynamics and the corresponding surface signatures using a three-dimensional high-resolution non-hydrostatic coastal model, NHWAVE (Ma et al. 2012, 2013). Such numerical simulations typically require spatial grid size less than O(10) meter, and hence practically they can only be applied a computation domain of spatial scale less than O(10) km and temporal scale of no more than a few hours. On the other hand, regional-scale modeling can cover O(100) km domain of Columbia River estuary-shelf system and provide accurate inter-tidal flow field associated with tide-modulated riverine outflow in MCR (e.g., Baptista et al. 2005; Elias et al. 2012). To study flow structures and their surface signatures in a realistic setting, both modeling approach may need to be adopted effectively. The present study focuses on O(10) km scale non-hydrostatic modeling with the primary goal to resolve various shear instabilities, however, the effective coupling methodology with regional scale models will also be addressed.

**APPROACH**

We carry out non-hydrostatic coastal modeling by extending the numerical model NHWAVE (Ma et al. 2012, 2013). NHWAVE was originally developed to study the propagation of fully dispersive nonlinear surface waves in 3D coastal environments, and hence NHWAVE solves the complete pressure field without the hydrostatic pressure assumption. Moreover, NHWAVE is also formulated in time-dependent, surface and terrain-following σ – coordinates, which is similar to typical hydrostatic coastal modeling systems (e.g., Warner et al. 2008; Elias et al. 2012). In this study, NHWAVE is applied as a wave-averaged non-hydrostatic coastal model. Exploiting the non-hydrostatic capability in NHWAVE, we focus on resolving frontal features, instabilities and the resulting surface signatures.

**WORK COMPLETED**

This year, we focused on the following model development and scientific investigations:

1. NHWAVE is used to study the formation of internal hydraulic jump and associated finger pattern at the MCR captured by remote sensing imagery. We refined the numerical simulations and carried out more thorough analysis on the generation mechanisms of the internal hydraulic jump and the
finger patterns. Highlights of our findings are summarized in "Results and planning" section. A manuscript has been submitted (see Publications).

(2) NHWAVE is also used simulate shear instabilities in an idealized river plume with spatial length scale and flow condition similar to that observed in Connecticut River estuary. Using 20 million grid points, the grid resolution is sufficiently fine and the grid size is near the estimated Ozdimov scale. Such high spatial resolution allow us to carry out more rigorous turbulence-resolving simulation with relatively simple subgrid closure. Hence, a more rigorous turbulence-resolving simulation can be carried out. A manuscript has been submitted (see Publications).

(3) To better resolve flow near complex bathymetry in high (O(1) m) spatial resolution and to carry out more extensive estuarine applications, the immersed boundary method (Mittal & Iaccarino 2005) is incorporated in NHWAVE through collaboration with Dr. G. Ma at Old Dominion University (see related project). Currently, we are carrying out extensive testing of this newly incorporated capability for eddy-resolving simulation.

RESULTS AND PLANNING

The airborne data measured during the recent RIVET II field experiment has revealed that the horizontally distributed thermal fingers regularly occur at the MCR during the strong ebb. The high-resolution, non-hydrostatic coastal model, NHWAVE, is used to simulate ebb processes at MCR with an aim to resolve the frontal zone and coherent structures as the ebb flow approaches the north jetty and gets diverted. The NHWAVE domain covers the mouth region and high spatial resolution of ~15 m mesh size and 40 vertical layers are used (Fig. 1). Model is able to predict the salinity anomaly on the water surface, which is believed to be associated with the thermal fingers (Fig. 2). It is noted that at early ebb when the plume front approaches the north jetty, no finger pattern is observed (see Fig. 2(a)). Finger pattern starts to appear after the plume impinges to the north jetty and hence it is likely that these salinity anomaly patches are entrained from the bottom saltier layer. The current field in the interrupted region is modulated by the frontal structures, indicated by the vorticity field calculated from both the numerical model (see Fig. 3) and data measured by an interferometric synthetic aperture radar (not shown).

The model results indicated that large amplitude shear instabilities are generated due to internal hydraulic jumps (see Fig. 4, left panels) as the plume moves over bathymetric sills and a lateral boundary inclined to the plume front. In this case, simulation results indicate that the Kelvin-Helmholtz billows have sufficiently large amplitudes to interrupt the water surface, causing the prominent features of stripes on the surface (see Fig. 4, notice the yellow color near the surface in the right panels).

In summary, the model results revealed that an internal hydraulic jump occurs after the plume reaches North Jetty during the maximum ebb tide, consistent with field observation (e.g., Honegger et al. 2015). Large amplitude shear instabilities are generated downstream from the hydraulic jump front, which leads to the entrainment of pockets of saltier water approaching the surface. The surface expression of these instabilities and the entrained pockets of saltier water may be responsible for the O(100)m-scale finger pattern observed between the front and the jetty by the airborne radar. The modeled vorticity field shows the finger pattern consistent with the vorticity field derived from the ATI-SAR data. Vertical profiles from the model revealed strong vertical motions, suggesting significant non-hydrostatic effects. The vertical advection not only causes thermal/salinity divergence but also local convergence/divergence of flow velocity and hence can be detected by IR and Radar imagery.
Looking forward, we plan to extend the numerical simulation to flood condition at MCR. We will focus on resolving the landward migrating bottom-hopping salt front (W. R. Geyer (WHOI), personal communication) and the corresponding surface signature (M. Haller and R. Holman (OSU), personal communication). The coupling of SWAN with NHWAVE based on new wave-current interaction theory extended from Dong and Kirby (2012) has been completed. We plan to revisit the ebb flow condition with wave effects included. We also plan to work closely with Dr. Geyer and his colleagues on model validation using their new data at MCR (to be obtained in 2015 and 2016), including in-situ measurement. Finally, to evaluate NHWAVE’s capability in resolving coherent structures at the front of the density current (e.g., lobes and cleft structures), we plan to carry out idealized simulation with internal Froude number and domain geometry similar to that observed by A. Horner-Devine and C. Chickadel (U. Washington/APL) at the front of the Merrimack River plume.

**IMPACT/APPLICATIONS**

This study focuses on using a non-hydrostatic surface and terrain-following $\sigma$ – coordinates coastal model to better resolve frontal structures. Our research efforts can eventually provide a reliable numerical tool to relate surface signatures captured by the remote sensing imagery with water column processes.

**RELATED PROJECTS**

Lead by Dr. Kirby, we are also supported by a NSF project (OCE-1334325; Collaborative Research: The interaction of waves, tidal currents and river outflows and their effects on the delivery and resuspension of sediments in the near field; collaborative with Dr. Gangfang Ma of ODU) to study river plume processes in the nearfield. The ongoing ONR project provides valuable field data and scientific input from the Columbia River system that are important to the success of the NSF project. This NSF project further provides us with more resource to extend the model capabilities and expand the scientific findings to other estuarine systems.
Figure 1: The Columbia River is located in the Pacific Northwest coast of the United States. NHWAVE is set up in the marked rectangular domain covering North Jetty and South Jetty in the south-north direction, and extending from the 20 m offshore contour to the southern end of Sand Island. Dashed lines: bathymetry contours in meters.
Figure 2: Modeled surface salinity distributions at time = 2760, 3180, 4620 and 5520 sec. Gray color range is set as 12-23 psu for the best illustration on the salinity anomaly on the water surface. Fresh water moves towards offshore with pretty homogeneous salinity on the plume surface before the plume reaches the North Jetty. The salinity anomaly starts to develop on the surface 25 min after the plume reaches the jetty (time = 4620 sec). Significant salinity anomalies remain persistently at later time (time = 5520 sec).
Figure 3: Modeled surface vorticity field (color) and flow field (arrows) at time = 4320, 4500 and 4680 sec, respectively. Finger pattern can be clearly seen via surface vorticity contour.
Figure 4: Left panels (a1)~(a5): vertical profiles of salinity (color) and flow field (arrows) along the transect perpendicular to the north jetty (black dashed line in Figure 3(a)). Right panels (b1)~(b5): vertical profiles of salinity (color) and flow field (arrows) along the transect parallel with the jetty (while dashed line in Figure 3(a)). The jet location is marked by red arrow in (a1) and (b1). Note that the vertical velocity component is over-scaled.
REFERENCES


**PUBLICATIONS**


