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Interactions of Waves, Tidal Currents and Riverine Outflow and their Effects on Sediment Transport (RIVET II)

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LONG-TERM GOALS

Developing a robust coastal modeling system to study the dynamics of tidally-pulsed river plume and the resulting trapping, storage and resuspension of sediments in a wave-dominated environment. The model can be further used to interpret water column and seabed processes using the observed surface features through remote-sensing.

OBJECTIVES

- Studying how the interactions between stratified riverine outflow and bathymetry can cause different types of surface signature using the 3D non-hydrostatic model NHWAVE.
- Studying turbulent mixing and resuspension/delivery of various classes of sediment in the tidally-pulsed Columbia River plume nearfield.
- Enhancement of an existing non-hydrostatic coastal model NHWAVE with several key capabilities in order to carry out system-scale (O(10) km) simulation with high spatial resolution (O(1~10) m) in the plume nearfield.

SIGNIFICANCE

Studying hydrodynamics and sediment transport of inlets and river mouths is crucial to many scientific and engineering applications (e.g., Gelfenbaum & Kaminsky 2010; Hickey et al. 2010). For example, the interaction between the hydrodynamics and complex bathymetry can produce highly heterogeneous and locally intense flows. Consequently, morphological evolutions at many inlets and river mouths are very dynamic and cause concerns over navigation safety especially in areas where routine surveys are not possible. Moreover, the interaction between tidally-pulsed riverine outflows and complex bathymetry in the river mouth can cause highly stratified water column with large temporal and spatial variability (e.g., Spahn et al. 2009). Highly stratified flow structures also encourage the generation of turbulent coherent structures of various scales (e.g., Geyer et al 2010). These alterations in salinity, temperature and vortical flow field can also influence acoustic wave propagation in the water column.

Through modern remote-sensing technology, data on surface flow field (roughness), temperature field, and limited information on the bathymetry can be obtained. Recent studies in riverine environments suggest that observed surface signatures are indication of turbulent coherent structures generated due to the interaction of stratified plume and the bathymetry (Plant et al. 2009; Chickadel et al. 2009, 2011). To predict the generation and fate of turbulent coherent structures and their surface signature, a non-hydrostatic coastal modeling system is needed. In a river mouth, surface signatures become very complicated when both stratified flow and suspended particulate matters (SPM) in the water column co-exist. Moreover, the presence of surface waves (and white capping due to breaking) can further complicate the problem. Hence, the main challenges appear to be due to several key intra-wave, stratified turbulent flow and bottom boundary layer processes that are not directly resolved in conventional wave-averaged hydrostatic coastal modeling systems.

In this study, we carry out process-based numerical investigation focusing on the "critical interfaces", namely the mouth of Columbia River (MCR), which connects the estuary, inner shelf and adjacent beaches. A non-hydrostatic coastal modeling system NHWAVE (Ma et al. 2012) is adopted and extended to investigate two critical processes associated with tidally-pulsed Columbia River plume nearfield: (a) the stratified flow structures and the resulting 3D turbulent coherent structures and surface signatures. (b) turbulent mixing and sediment resuspension processes in an idealized MCR domain in order to generalize sediment delivery patterns in river mouths.

APPROACH

In this study, we carry out non-hydrostatic coastal modeling by extending the model NHWAVE (Ma et al. 2012). NHWAVE was originally developed to study the propagation of fully dispersive, fully nonlinear surface waves in complex 3D coastal environments and hence it solves the complete pressure field without the hydrostatic pressure assumption utilized by many coastal models (e.g., Warner et al. 2008). On the other hand, NHWAVE is also formulated in time-dependent, surface and terrain-following σ – coordinates, which is similar to typical coastal modeling systems. Due to large domain that needs to be covered in the Columbia River nearfield (Elias et al. 2012), NHWAVE is used here as a wave-averaged non-hydrostatic coastal model. The application of a non-hydrostatic model in a large domain can incur excessive computational cost due to the need to solve the resulting pressure Poisson equation over the full extent of the domain. The present structure of NHWAVE approaches this problem by partitioning pressure into hydrostatic and non-hydrostatic components, thus limiting the application of the Poisson solver to the non-hydrostatic correction. Recent studies using Poisson solver-based non-hydrostatic models have shown that an accurate prediction of wave dispersion does not require a large number of vertical layers if the dynamic pressure is properly discretized. We explored the possibility that the solution for the dynamic pressure field may, in general, be decimated to a resolution far coarser than used in representing velocities and other solute quantities, without sacrificing accuracy. We determine the dynamic pressure field by solving the Poisson equation on a coarser grid and then interpolate the pressure field onto the finer grid used for solving for the remaining dynamic variables. With the Pressure Decimation and Interpolation (PDI) method, computational efficiency is greatly improved (Shi et al., 2014).

WORK COMPLETED

In addition to completing several key technical developments of NHWAVE, we investigated the following science issues relevant to MCR:

1. NHWAVE is applied to simulate tidally-pulsed riverine outflow in the mouth of Columbia River in order to study the formation of an internal hydraulic jump and the resulting finger pattern observed in remote sensing imagery (see "Results" for more details).
2. NHWAVE is utilized to study the structure of a generic river plume, and the vertical mixing due to shear instabilities in an idealized domain similar to Connecticut River plume. The smaller domain required by the Connecticut River plume allows us to carry out rigorous large-eddy simulation (LES) with O(10) cm scale spatial resolution (see "Results" for more details). The primary goal relevant to this ONR project is to understand the surface signatures resulted from the simplest turbulent coherent structures, namely the Kelvin-Helmholtz (K-H) billow generated in stratified shear flow. This effort also leverages our ongoing support from NSF (see "Impact/application").
3. NHWAVE simulation of an idealized internal hydraulic jump is carried out to investigate the generation of K-H instabilities with the occurrence of an internal hydraulic jump. The idealized simulation with a higher grid resolution (1m) and simpler bathymetry than the realistic MCR simulation allows us to understand the controlling factors of the generation of K-H instabilities and evolution of turbulence coherent structures in an event of internal hydraulic jump.
4. To understand the dominant mechanisms controlling the delivery of sediment in the near field of river plumes, a numerical study is carried out using Regional Ocean Modeling System (ROMS) with an idealized river mouth domain. The domain is designed to be sufficiently simple such that it can be described by several nondimensional parameters but in the meantime, sufficiently representative of the key features of a given river mouth. Field observation by Drs. Geyer/Traykovski team (WHOI) as part of the RIVET II during the month of May 2013 shows interesting asymmetry of near bed turbidity with significantly higher turbidity during flood, which follows the landward migrating front. The idealized river mouth model predicts a significantly higher turbulence kinetic energy (TKE) following the landward-migrating front during flood, consistent with the location where high turbidity is observed. Preliminary analysis shows that the predicted high near bed TKE level is due to the stratified two-layer-like flow established during flood. The two-layer-like system establishes high flow shear at the density interface and enhances TKE in the lower layer. During ebb, flow is much less stratified and the flow field is consistent with the classic logarithmic law.

RESULTS

Realistic NHWAVE simulation of MCR during ebb: The realistic NHWAVE simultion of MCR is directly corresponding to the findings from the recent RIVET II field experiment. Airborne data measured during the field experiment has revealed that horizontally distributed thermal fingers regularly occur at MCR during strong ebb tidal conditions (C. Chickadel, G. Farquharson and G. McNeil, APL-UW). The finger pattern is associated with the occurrence of an internal hydraulic jump as the ebb buoyant outflow is approaching a constriction between the North Jetty and Cape Disappointment. Similar flow patter is also observed via radar image (M. Haller, OSU). NHWAVE was able to reproduce those features as the computational grid was refined to ~10 m. Figure 1 shows a snapshot of surface vorticity and velocity field predicted by NHWAVE at the maximum ebb tide, which highly correspend to the thermal figures and vorticity patterns oberserved in the airborne data and microASAR. Figure 2 shows the vertical profiles of salinity along the transects parallel to the North Jetty predicted by NHWAVE. The results indicate that large amplitude Kelvin-Helmholtz instabilities are generated in association with an internal hydraulic jump, which forms as the plume moves over bathymetric sills, and with location and orientation controlled by a lateral boundary (jetty) inclined to the plume front. Simulation results also indicate that as the fresh outflow is approaching the

inclined constriction, downwelling can occur that generate significant K-H billows with sufficiently large amplitudes to interrupt the water surface (see Profile 1), causing prominent features on the surface as indicated in thermal images and radar images (surface roughness). The current field in the interrupted region is modulated by the frontal structures, indicated by the vorticity field calculated from both the numerical model and data measured by the microASAR.

Large-eddy simulation of an idealized river plume using NHWAVE: High resolution 3D large-eddy simulation approach is used with the aim to resolve turbulent coherent structures in the simplest buoyant plume setting to order to understand how the most generic type of K-H instabilities can leave surface signature. The computational domain is of length 500 m (x-direction), depth 10 m (z-direction) and width 30 m (y-direction) and is initially quiescent containing saltwater of salinity 26 psu. Freshwater plume is sent from the left boundary with a range of internal Froude number. Simulation results demonstrates that the model is able to predict the generation and evolution of shear instabilities although the effects of secondary instability at high Reynolds number need to be parameterized by a subgrid closure model (the standard Smagorinsky closure is used here). The characteristic length scale of the shear instabilities is around 10 m, which is consistent with field observation of Connecticut River plume using a 4-channel broadband echo sounder (Geyer et al. 2010). The model also provides the information on fine structure of surface variations, which enables us to correlate the surface signature with the turbulent billow underneath. Currently, we found that there is a good correlation between surface elevation change, surface velocity divergence (linear strain rate in two horizontal directions) and the K-H billow underneath (see Figure 3). Particularly, surface velocity divernence may represents surface roughness which can be directly related to the backscatter signal captured by radar images (Plant et al. 2010). Simulation results reveal that some of the K-H billows are sufficiently intense (see the snapshot at t=280 sec shown Figure 4) to leave a range of surface signatures, which are presented in terms of demeaned surface elevation change and divergence of surface velocities. Figure 4a shows the enlarged view between x=150 m and 200 m with turbulence coherent structures visualized by Q-criterion (Hunt et al. 1988). In Figure 14b, the mean location of the fresh and saltwater interface is visualized via iso-surface of salinity equals to 13 psu. The coherent structures indicated by two black arrows shown in Figure 4a are responsible for the surface signatures located at around x=160 m and x=190 m (see Figure 3a,b).

IMPACT/APPLICATIONS

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 successs of the NSF project. This NSF project further allows us to expand the scientific findings to other river plume systems.

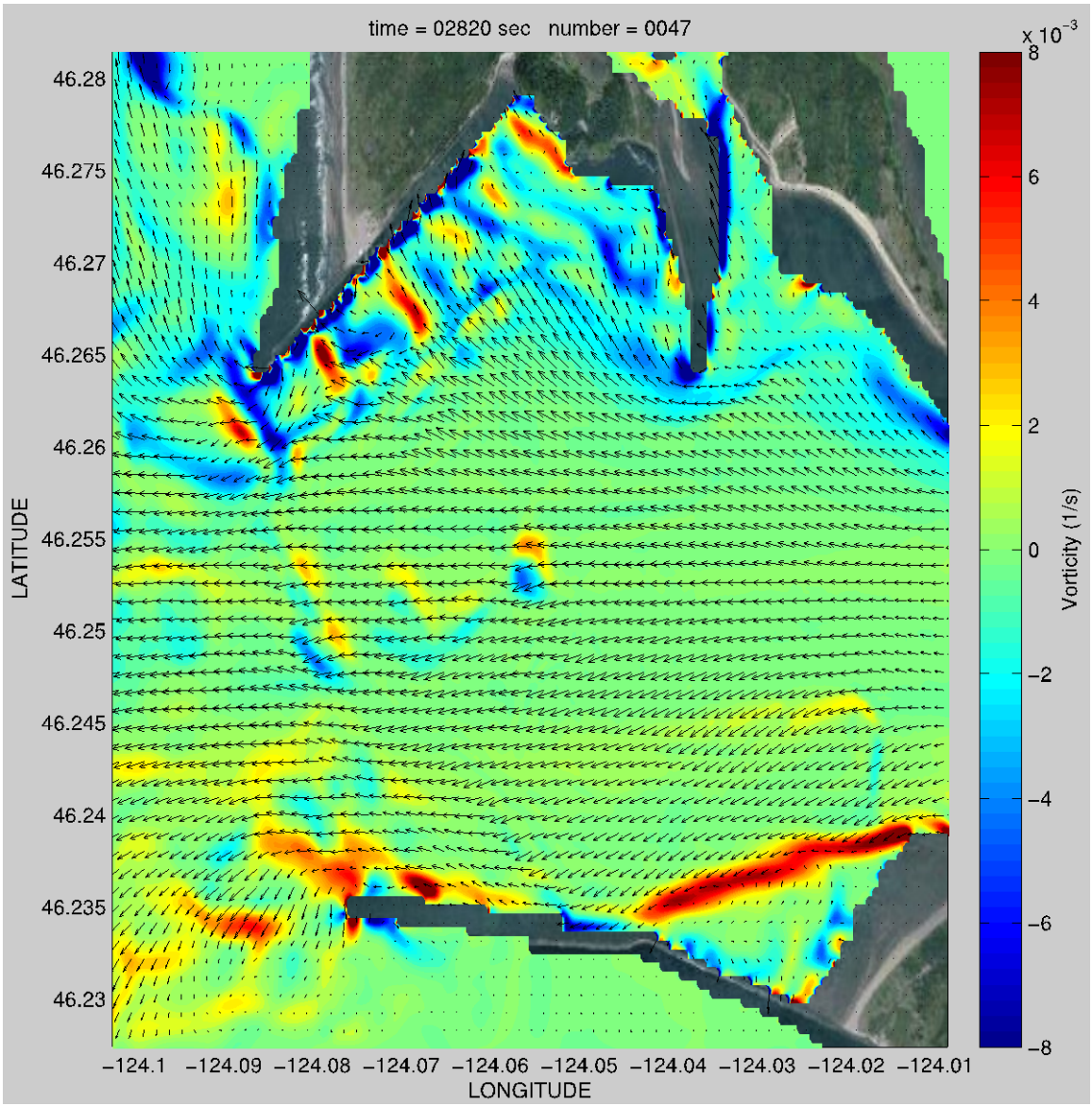

Figure 1: Surface vorticiry (color) and velocity (arrows) field predicted by NWAVE at the maximum ebb tide. The calculated vorticity patterns near the North Jetty highly correspond to the thermal fingers and vorticity field observed in the airborne data and microASAR.

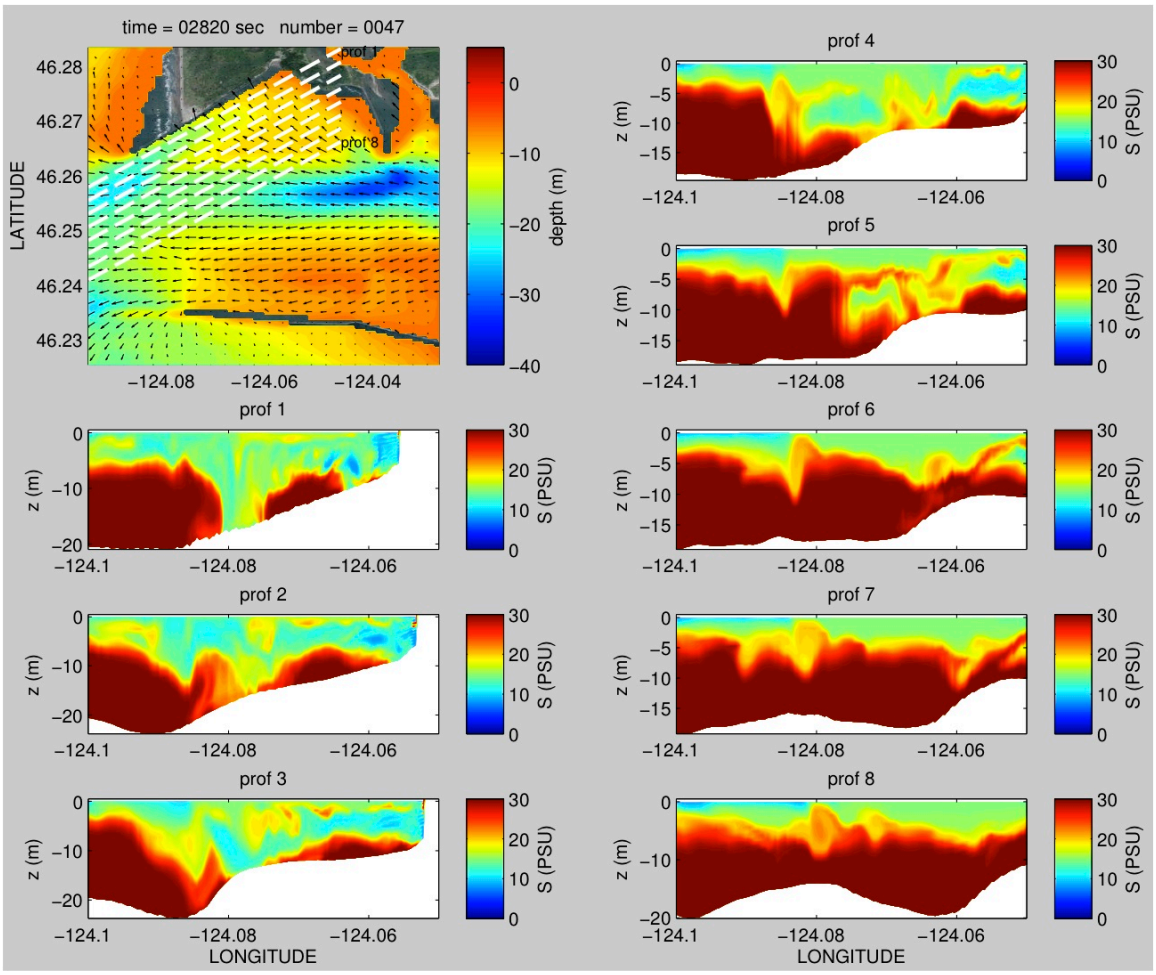

Figure 2: Salinity profiles along the vertical transects parallel to the North Jetty (Prof 1-8 in the top-left panel). Large amplitude Kelven-Helmholtz instabilities occur in association with internal hydraulic jumps at the lateral boundary (jetty) inclined to the plume front.

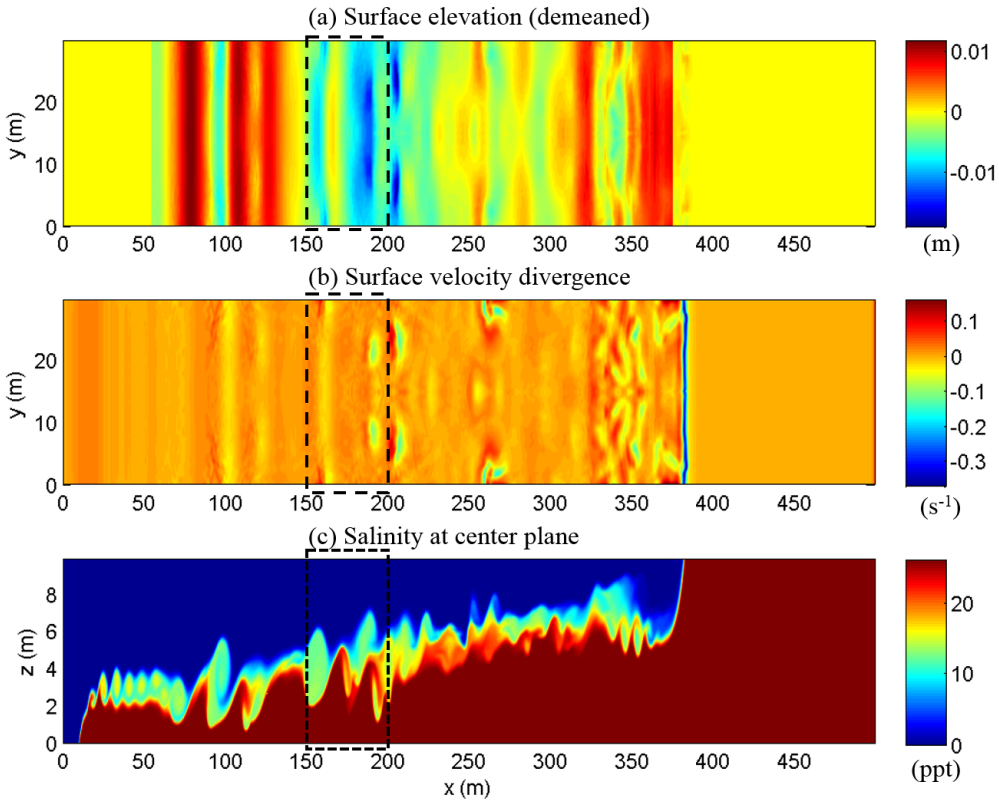

Figure 3: 3D Large-eddy simulation of Kelvin-Helmholtz billows in a buoyant plume. A snapshot at t=280 sec for (a) 2D horizontal (xy-plane) view of surface elevation, (b) 2D horizontal view of surface velocity divergence, and (d) 2D vertical (x-y plane) view of salinity. There is clearly a correlation between the surface signatures and K-H billow underneath. The black box represent the location where detailed 3D coherent structures are shown in Figure 4.

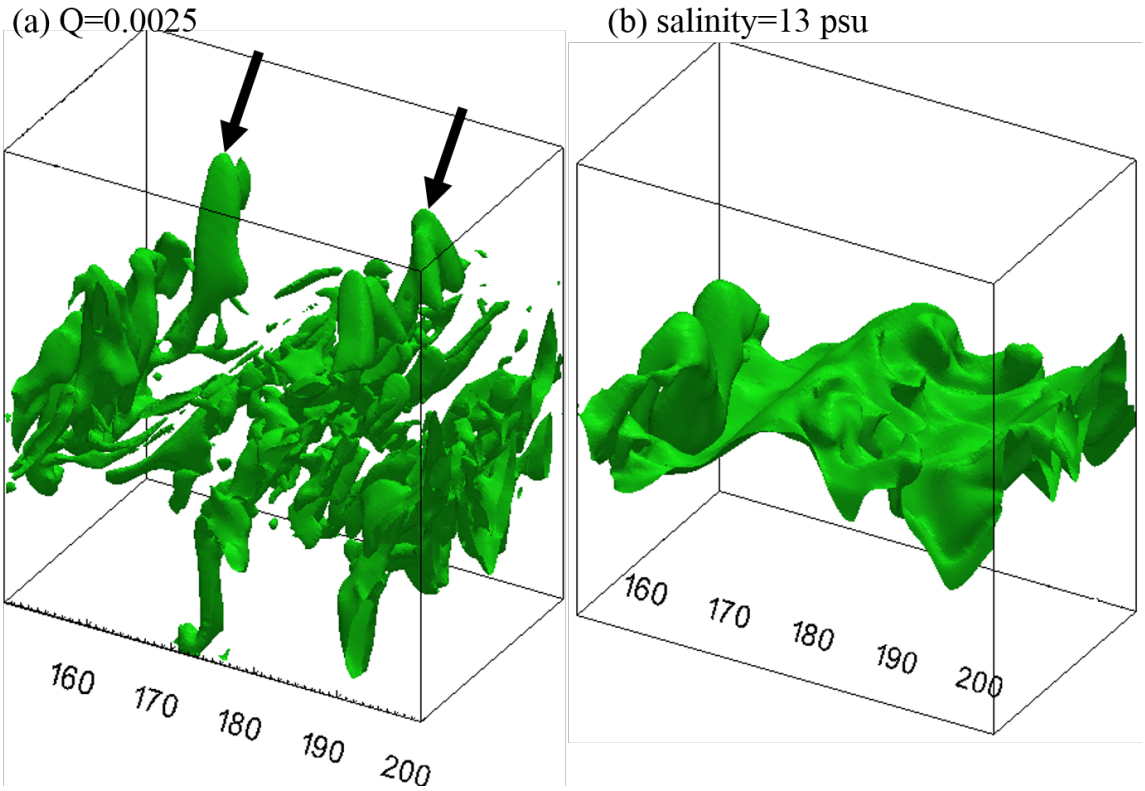

Figure 4: Enlarged 3D view between x=150 m to 200 m (see Figure 3 for the entire fow flow field). (a) coherent structures visualized with Q-method. The iso-surface of Q=0.0025 is shown. (b) the corresponding iso-surface of salinity of 13 psu. Two arrows shown in panel (a) indicate those K-H billows that leave clear surface signatures.

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PUBLICATIONS

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2. Shi, J., Shi, F., Kirby, J. T., Ma, G., and Wu, G., 2014, Pressure decimation and interpolation (PDI) method for a baroclinic non-hydrostatic model, *Ocean Modelling*. [SUBMITTED]