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Simulating Surfzone Bubbles

James T. Kirby and Fengyan Shi
Center for Applied Coastal Research
University of Delaware
Newark, DE 19716, USA
phone: (302) 831-2438 fax: (302) 831-1228 email: kirby@udel.edu
phone: (302) 831-2449 fax: (302) 831-1228 email: fyshi@udel.edu

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LONG TERM GOALS

Our long term goal is to develop a tested model of optical properties in the surf zone and adjacent nearshore ocean, including the influence of suspended sediment, bubble population and surface foam, to assess how optical properties are related to short term events such as individual breaking wave crests, and to determine how wave-driven surf zone circulation influences spatial distribution of optical properties just offshore of breaking through seaward transport of fine sediment, small persistent bubbles and surface foam.

OBJECTIVES

The ability to make optically-based observations in nearshore waters is strongly influenced by the presence of suspended sediment particles and of bubbles, both of which are present due to the action of breaking waves. Wave breaking is instrumental in injecting large volumes of air into the water column. This air volume subsequently evolves into a distribution of bubble sizes which interact with the fluid turbulence and are advected by the organized flow. Degassing of the water column can additionally generate a persistent foam layer which can prevent any optical penetration of the water column.

Our goal is to develop time-resolved models for these processes in order to make predictions of optical properties of the water column. To date, we have begun this process by incorporating a continuum description of bubble populations and associated dynamics in 2-D (Ripple) and 3-D (Truchas) Navier-Stokes solvers. In the continuation of this work, our objectives are to:

1) Implement a physics-based process model for bubble entrainment by small scale surface deformation processes, appropriate for applicaton to established surf zone bores.

2) Continue implementation of the multiphase model terms for bubble/bubble interactions.

3) Tackle the fluid mechanics problems associated with moving discretely resolved air volumes out of the model air phase and into the continuum bubble phases.

4) Develop a model for generation, transport and decay of a foam layer at the water surface.

APPROACH

Our initial approach to the problem is based around incorporating a comprehensive model of bubble physics within a Reynolds-averaged 2D hydrodynamic code. The physics is represented by a multiphase continuum model, using the formalism described by Drew and Passman (1999). In the present project, we are aiming to implement a model combining a water phase, a bubble phase with multiple bubble size (or, more accurately, mass) bins, and a non-cohesive sediment phase, also including multiple size or weight bins. A comprehensive version of the model physics would include full coupling between bubble size bins (fractionation and coalescence), interaction between sediment size classes (hindered settling and effect on turbulence), and interaction between sediment and bubble phases as well as between each of these and the water column. Carrica et al (1999) have provided a detailed model for the bubble/water component. The sediment component would be an elaboration of the two-phase model of Hsu et al (2003) to include multiple grain size bins. Finally, the framework for the bubble/sediment interaction needs development in the context of the present project. In order to get basic aspects of the transport problem implemented and tested first, we concentrated earlier in the project on running a version of the code with a simplified bubble phase description due to Buscaglia et al (2002), a simple advection-diffusion scheme for the sediment size bins, and no interphase interaction. Presently, we are concentrating more on the development of a 3-D code in an LES framework. The existing 3-D model Truchas has been extended to include the Carrica et al.'s mixture model and a turbulence closure model, and has been tested for several simplified cases including the bubble column experiments of Becker et al (1995). An application of solitary wave breaking is presently being carried out, for which a detailed experimental data set on flow field turbulence and coherent vortical structures exists (Ting, 2008). The effects of three-dimensional obliquely descending eddies (Nadaoka et al., 1989) and downburst (Kubo and Sunamura, 2001) on bubble transport are being investigated using the 3-D multiphase model.

Previous studies of foam dynamics are mostly restricted to modeling of foam microstructures and their evolutions which are determined by the interfacial forces occurring at the film level (Davini, 2010). Practical applications of such models in larger scale (surfzone scale) are rarely found in literature. Our approach to modeling foam coverage and transport inside the surfzone starts with a simple process-based transport model with incorporation of existing empirical formulations, parameterization of results from a bubble prediction model into calculations of source/sink terms in the model.

WORK COMPLETED

To date, we have developed 2-D and 3-D multiphase bubble models for predicting quiescent phase of air bubbles including a 2DV model based on Buscaglia et al. (2002) (Shi et al., 2008, 2010a), 2DV model and 3D model based on Carrica et al. (2002) (Ma et al., 2010 a, b). Both 2DV models use the nonlinear k-e turbulence model which takes into account bubble effects. The 3-D multiphase model implements the LES model with an extra turbulent viscosity term due to bubble induced turbulence (Deen, 2001). All the multiphase bubble models use a prescribed air entrainment formulation which skips detailed modeling of the air entrainment process, making surfzone-scale modeling computationally affordable.

Following the initial air entrainment model by Shi et al. (2008, 2010a), a more theoretical adjustable model was derived based on the physical analysis of bubble creation processes. The bubble creation under breaking waves is determined by the turbulent dissipation rate with a linear relationship between the energy required for bubble creation and the dissipation rate. The initial bubble size spectrum is given by Deane and Stokes (2002). The new formulation does not contain a dimensional parameter as in the previous formulation in Shi et al. (2008, 2010a) and can be calibrated using data measured in laboratory experiments in different scales or field experiments.

Bubble breakup is an important component in the processes determining bubble size distributions after initial air entrainment. In Shi et al. (2010a), the bubble breakup model is based on the model of Luo and Svendsen (1996) who assumed that the breakup splits a bubble into two identical daughter bubbles. We have recently implemented the approach of Martínez-Bazán et al. (1999) in our 3-D multiphase model. Martínez-Bazán et al.'s model makes the bubble breakup process more realistic (Lasheras et al., 2002, Chen et al., 2005), which is confirmed by the results shown below.

The foam layer model is governed by the mass and momentum equations associated with foam thickness and foam transport velocity. The foam layer motion in the plane of the water surface arises due to a balance of drag forces due to wind and water column motion. Foam mass conservation includes source/sink terms representing outgassing of the water column, direct foam generation due to surface agitation, and erosion due to bubble bursting. The air volume from degassing can be parameterized by the two-fluid model. The foam layer model is being incorporated into the framework of a Boussinesq wave model which takes into account bubble effects. Model calibration and validation will be based on results collected during the Surf Zone Optics experiment at Duck, NC in September 2010. Initial effort(Kirby et al, 2010) is focussed on an examination of breaking wave patterns and persistent foam distributions, using ARGUS imagery.

RESULTS

The capabilities of the 2-D and 3-D models have been tested by comparing to experimental data in laboratory conditions. A simulation of air bubbles measured in the breaking wave experiment by Lamarre and Melville (1991) was carried out using the 2-D multiphase model (Shi et al., 2010a). Moments of the void fraction field defined in Lamarre and Melville (1991) were calculated based on numerical results of void fraction and compared to measurements. Figure 1 shows model/data comparisons of three moments: (a) the normalized total cross-sectional area A of the bubble plume above the void fraction threshold 0.3% (b) the normalized volume of air entrained per unit width, V and (c) the averaged void fraction, α. The model predicted a parabolic-like evolution of the void fraction area A, which has a similar trend as shown by the data fitted curve. The area A was over-predicted at the beginning of wave breaking, and a more moderate increase in A can be found in the early time in the wave period, compared with the data fitted line. The comparison of the normalized air volume shown in Figure 1 (b) indicates an under-prediction of air entrainment at the beginning of breaking, which is consistent with the absence of a large entrained pocket of air in the numerical simulation. An under-prediction of the average void fraction can also be found at the beginning of wave breaking as shown in Figure 1 (c). In general, the model predictions of the magnitude and evolutionary trend of the average void fraction are in reasonable agreement with the data. The under-prediction at the beginning of wave breaking was expected because the model does not account for large air pockets in the continuum phase.

The bubble breakup model of Martínez-Bazán et al. (1999a,b) was examined by a numerical experiment which shows the bubble size distribution resulted from breakup of large bubbles with an initial uniform size. Figure 2 shows the simulated bubble size distributions at different vertical locations at $(t-t_b)/T= 0.1$, where t_b is the time of wave breaking. The model can reproduce the -10/3 dependence for bubbles larger than 1 mm at z=1.5 cm where is close to the air-water interface.

Nevertheless, the -3/2 low for bubbles smaller than 1 mm are not predicted by the model, which supports the theory of Deane and Stokes (2002) who suggested that bubbles larger than about 1 mm are mainly created by the breakup of air cavities. Our result also suggests that it is necessary to use a prescribed polydisperse bubble entrainment model in simulations.

We carried out a 3D modeling of an oscillatory bubble plume measured in an experimental vessel by Becker et al. (1994). The numerical results indicated that the 3D model predicted well the flow pattern, bubble plume-induced liquid velocity and oscillation period of the bubble plume measured in the laboratory experiment. The model was also applied to predicting breaking wave-induced bubbly flows measured by Cox and Shin (2003). The model/data comparisons of time series of void fraction at different measurement points in the water column are encouraging (Ma et al., 2010b). The effects of three-dimensional obliquely descending eddies (Nadaoka et al., 1989) and downburst (Kubo and Sunamura, 2001) on bubble transport were investigated using the 3-D multiphase model. We used the vortex core representation technique (Jeong and Hussain, 1995) to examine the occurrence of coherent vortical structures and to quantify the primary direction of the vortices. The obliquely descending eddies behind breaking wave crest can be recognized as shown in Figure 3. After wave breaking, spanwise vortices are dominant near the water surface, while obliquely descending eddies become dominant inside the water column with angles tilting toward the x-axis to be around 25 and 205 degrees. Numerical results suggest that vortex turning and stretching play an important role in the evolution processes from spanwise to obliquely descending eddies. The vertical transport of bubbles is greatly enhanced by the presence of coherent vortices.

The foam layer model has been implemented with a wetting-drying scheme. Figure 3 shows a preliminary test in which the foam layer model was coupled with the NearCoM model (Shi et al., 2005). Monochromatic waves were applied on an idealized barred beach bathymetry with rip channels. The left panel of Figure 4 shows wave crests predicted by the REF/DIF-1 wave model. The right panel shows the foam pattern (color) predicted by the foam layer model and the nearshore circulation predicted by the nearshore circulation model SHORECIRC (Svendsen et al., 2004, Shi et al., 2003). Foam patches are driven by waves and nearshore currents, exhibiting onshore/offshore flow patterns including the onshore movement driven by waves and offshore transport convected by rip currents. The foam generation and bursting rates were artificially set up in the test and their formulations need to be further investigated.

IMPACT/APPLICATIONS

The work proposed here would provide a general framework for modeling bubble distribution and foam coverage in the surf zone. The model framework for bubble population is intended to be general in nature and will be applied at a later date in more computationally intensive studies of processes in individual breaking wave crests in a wide range of water depths.

RELATED PROJECTS

Kirby is a co-PI in MURI effort entitled “Impact of oceanographic variability on acoustic communications”. This effort involves the development of a model for spatial and temporal distribution of bubble population under a sea surface with whitecap coverage, for use in water depths in the 50 to 100m range. Models developed in the present study are being used in support of efforts to parameterize bubble distributions under individual whitecap events.

A joint effort with Tobias Kukulka (UD) to examine the influence of breaking wave-induced bubbles on air-sea gas transfer effects in the mixed layer is presently proposed (NSF). This work would utilize the present wave resolving models in conjunction with an extension of the LES mixed layer model (Sullivan et al, 2007) to include bubble phases in order to simulate the spatial evolution of bubble populations in the ocean mixed layer.

REFERENCES

Becker, S., Sokolichin, A. and Eigenberger, G., 1995, Gas-liquid flow in bubble columns and loop reactors. Part II. Comparison of detailed experiments and flow simulations, *Chem Engng. Sci.,* **49**, 5747

Buscaglia G. C., Bombardelli F. A., and Garcia M H., 2002, Numerical modeling of large-scale bubble plumes accounting for mass transfer effects, International Journal of Multiphase Flow, **28**, 1763-1785

Buckingham M.J., 1997, Sound speed and void fraction profiles in the sea surface bubble layer, *Applied Acoustics*, **51**,225-250

Carrica P. M., Bonetto F., Drew D. A., Lahey R. T. Jr, 1998, The interaction of background ocean air bubbles with a surface ship, Int. J. Numer. Meth. Fluids, **28**, 571-600.

Carrica, P. M., Drew, D., Bonetto, F., and Lahey Jr, R. T., 1999, A polydisperse model for bubbly two-phase flow around a surface ship, Int. J. Multiphase Flow, **25**, 257-305.

Chen, P., Sanyal, J., and Duduković, M. P., 2005, Numerical simulation of bubble column flows: effect of different breakup and coalescence closures, *Chemical Engineering Science*, **60**, 1085-1101.

Cox D. and Shin S., 2003, Laboratory measurements of void fraction and turbulence in the bore region of surf zonewaves, *J. Eng. Mech.*, **129**, 1197-1205

Davini C., 2010, A continuum model for fluid foams, *Journal of Elasticity*, **101**, 77-99.

Deane G.B. and Stokes M.D., 1999, Air entrainment processes and bubble size distributions in the surf zone, *J. Phys. Oceanogr*., **29**, 1393–1403

Deane G.B. and Stokes M.D., 2002, Scale dependence of bubble creation mechanisms in breaking waves, *Nature*, **418**, 839-844

Deen N.G., Solberg T. and Hjertager B.H., 2001, Large eddy simulation of the gas-liquid flow in a square cross-sectioned bubble column, *Chem. Engng Sci.,* **56**, 6341-6349

Drew, D. A. and Passman, S. L., 1999, Theory of Multicomponent Fluids, Springer, 308pp.

Garrett C., Li M., and Farmer D., 2000, The connection between bubble size spectra and energy dissipation rates in the upper ocean, Journal of Physical Oceanography, **30**, 2163-2171.

Hsu, T.-J., Jenkins, J. T. and Liu, P. L.-F., 2003, ``On two phase sediment transport: dilute flow'', J. Geophys. Res., **108**, C3, 3057, doi:10.1029/2001JC001276.

Jeong J. and Hussain F. ,1995, On the identification of a vortex, J. Fluid Mech., **285**, 69-94

Kirby, J. T., Shi, F. and Holman, R. A., 2010, Models and observations of foam coverage and bubble content in the surf zone, AGU Fall Meeting, Abstract OS43C-06.

Kubo H. and Sunamura T., 2001, Large-scale turbulence to facilitate sediment motion under spilling breakers, *Proceedings of the 4th Conference on Coastal Dynamics*, Lund, Sweden, 212-221

Lamarre, E. and Melville, W. K., 1991, Air entrainment and dissipation in breaking waves, *Nature*, **351**, 469-472.

Lasheras, J. C., Eastwood, C., Martínez-Bazán, and Montañes, J. L., 2002, A review of statistical models for the break-up of an immiscible fluid immersed into a fully developed turbulent flow, *International Journal of Multiphase Flow*, 28, 247-278.

Lin, P. and Liu, P. L.-F., 1998, Turbulence transport, vorticity dynamics, and solute mixing under plunging breaking waves in surf zone, J. Geophys. Res., **103**, 15677 -15694.

Liu, D. and Lin, P., 2008, A numerical study of three-dimensional liquid sloshing in tanks, *J. Comp. Phys.*, **227**, 3921-3939.

Luo, H. and Svendsen, H. F., 1996, Theoretical model for drop and bubble breakup in turbulent dispersions, *AIChE J.*, **42**, 1225-1233.

Ma, G., Shi, F. and Kirby, J. T., 2010a, A polydisperse two-fluid model for bubble plumes under breaking waves, *Proc. 7th Int. Conf. Multiphase Flow*, ICMF 2010, Tampa, FL, May 30-June 4.

Ma, G., Shi, F., and Kirby, J. T., 2010b, A polydisperse two-fluid model for surfzone bubble simulation, submitted to *J. Geophys. Res.*

Martínez-Bazán, C., Montañes, J.L., Lasheras, J.C., 1999, On the break-up of an air bubble injected into a fully developed turbulent flow. Part I: Break-up frequency, J. Fluid Mech. **401**, 157-182.

Nadaoka, K., Hino, M., Koyano, Y., 1989. Structure of turbulent flow field under breaking waves in the surf zone. *J. Fluid Mech*. 204, 359–387.

Shi, F., Svendsen, I. A., Kirby, J. T., and Smith, J. M., 2003, A curvilinear version of a quasi-3D nearshore circulation model, *Coastal Engineering*, **49**, 99-124.

Shi, F., Zhao, Q., Kirby, J. T., Lee, D. S. and Seo, S. N., 2004, Modeling wave interactions with complex coastal structures using an enhanced VOF model, Proc. 29th Int. Conf. Coastal Engrng., Lisbon, September, 581-593.

Shi, F., Kirby, J. T., Newberger, T. A., and Haas, K., 2005, NearCoM master program, version 2005.4, User's manual and module integration, Research Report 2005-10, Center for Appl. Coastal Res., Univ. of Del., Newark.

Shi, F., Kirby, J. T., Haller, M. C. and Catalan, P., 2008, Modeling of surfzone bubbles using a multiphase VOF model, *Proc. 31st Int. Conf. Coastal Engrng*., Hamburg, 157-169.

Shi, F., Kirby, J. T., and Ma, G., 2010a, Modeling quiescent phase transport of air bubbles induced by breaking waves, *Ocean Modelling* , **35**, 105-117.

Shi, F., Ma, G., and Kirby, J. T., 2010b, Numerical modeling of optical properties inside the surfzone, *Proc. 32nd Int. Conf. Coastal Engineering*, Shanghai, July, in press.

Sullivan, P. P., McWilliams, J. C. and Melville, W. K., 2007, Surface gravity wave effects in the oceanic boundary layer: large-eddy simulation with vortex force and stochastic breakers, *J. Fluid Mech.,* **593**, 405-452.

Svendsen, I. A., Haas, K., and Zhao, Q., 2004, Quasi-3D Nearshore Circulation Model SHORECIRC: Version 2.0, Research Report, Center for Applied Coastal Research, University of Delaware.

Terrill E. J., Melville W. K., and Stramski D., 2001, Bubble entrainment by breaking waves and their influence on optical scattering in the upper ocean, J. Geophys. Res., **106**, C8, 16,815-16,823.

Ting, F. C. K., 2008, Large-scale turbulence under a solitary wave: Part 2 forms and evolution of coherent structures, *Coastal Engineering,* **55**, 522-536.

PUBLICATIONS

Ma, G., Shi, F. and Kirby, J. T., 2010a, A polydisperse two-fluid model for bubble plumes under breaking waves", *Proc. 7th Int. Conf. Multiphase Flow*, ICMF 2010, Tampa, FL, May 30-June 4.

Ma, G., Shi, F., and Kirby, J. T., 2010b, A polydisperse two-fluid model for surfzone bubble simulation, submitted to *J. Geophys. Res.*

Shi, F., Kirby, J. T., and Ma, G., 2010a, Modeling quiescent phase transport of air bubbles induced by breaking waves, *Ocean Modelling* , 35, 105-117.

Shi, F., Ma, G., and Kirby, J. T., 2010b, Numerical modeling of optical properties inside the surfzone, *Proc. 32nd Int. Conf. Coastal Engineering*, Shanghai, July, in press.

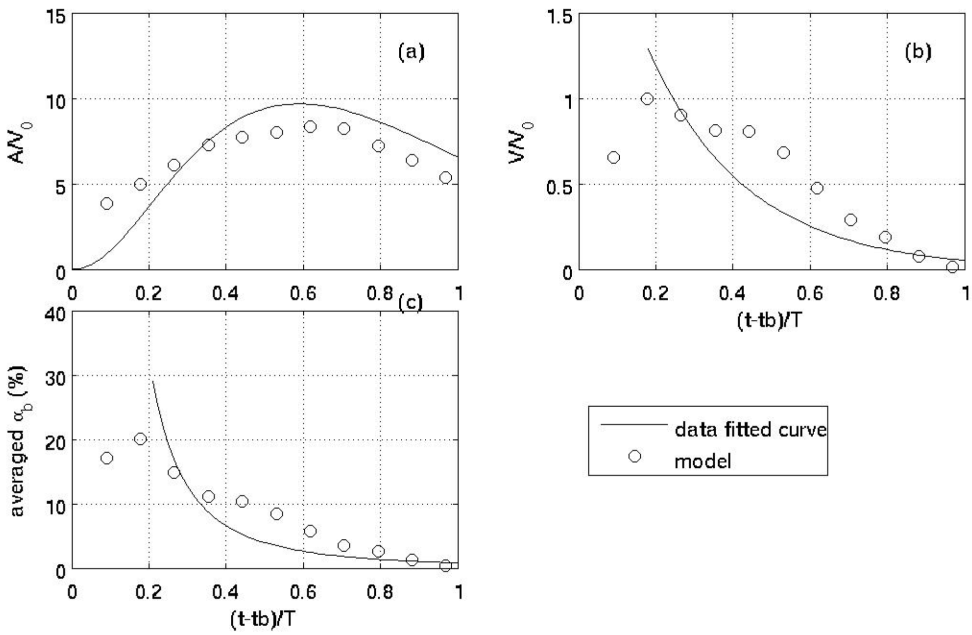

Figure 1. Moments calculated using the void fraction threshold of 0.3%, (a) Cross-sectional area A of bubble plume normalized by V0; (b) Air volume V normalized by V0; (c) Mean void fraction α. Case: fc = 0.88 Hz, kc = 0.38, and Δf/fc = 0.73. Solid curves are functional fits to laboratory data from Lamarre and Melville (1991). Model results shown as open circles.

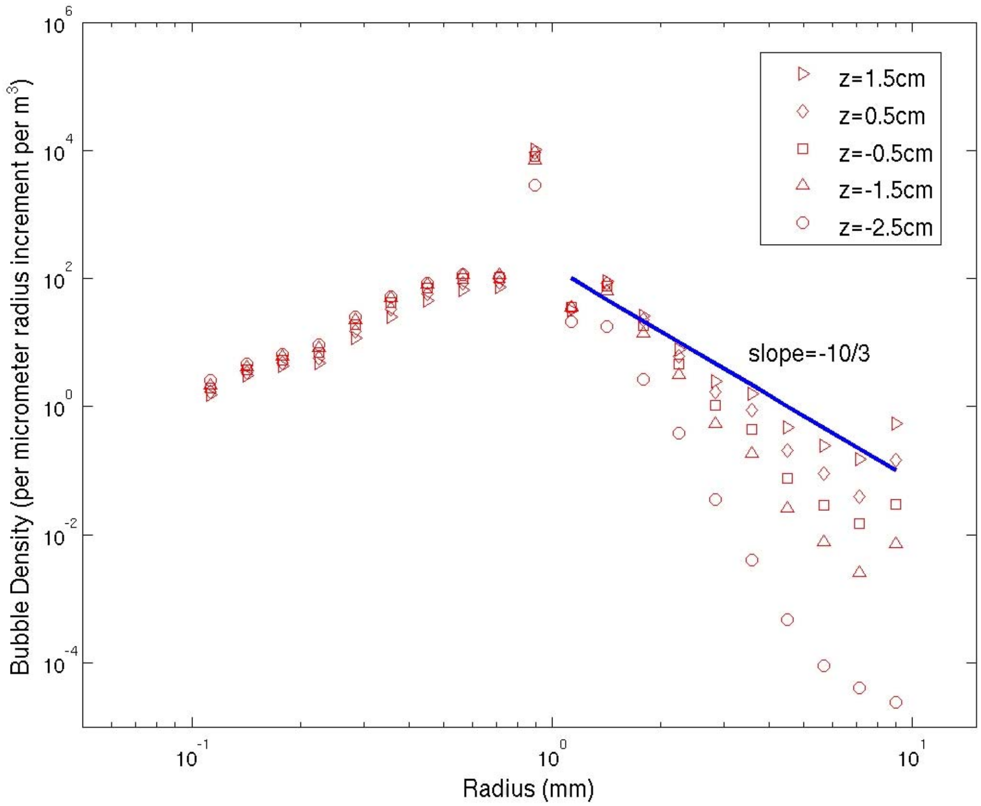

Figure 2. Vertical evolution of bubble size distribution resulting from bubble breakup at $x - x_b$=0.74 m.

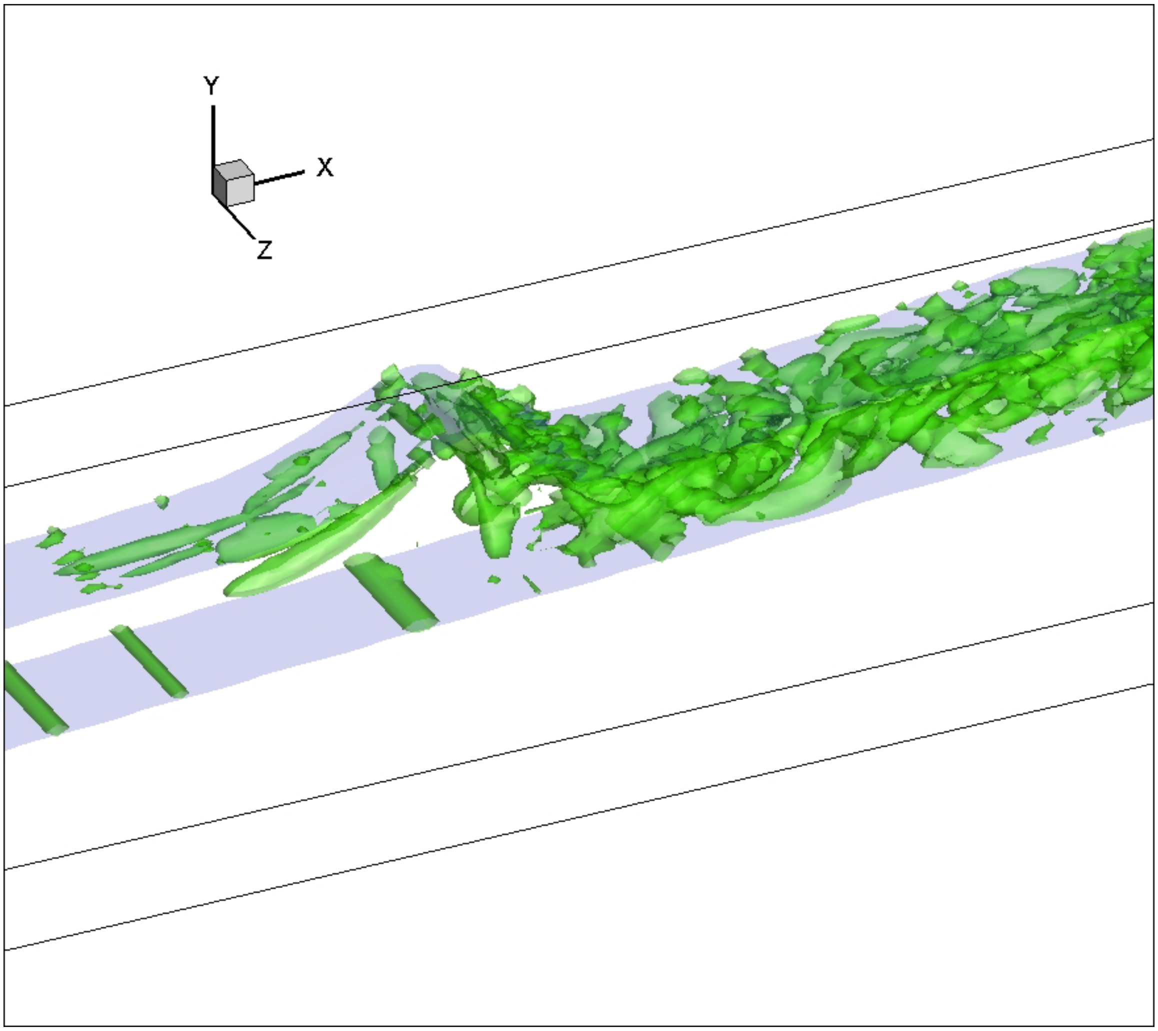

Figure 3. Coherent vortical structures in a breaking wave crest. Snapshot taken 0.3 wave periods after breaking of dominant wave crest in middle of frame.

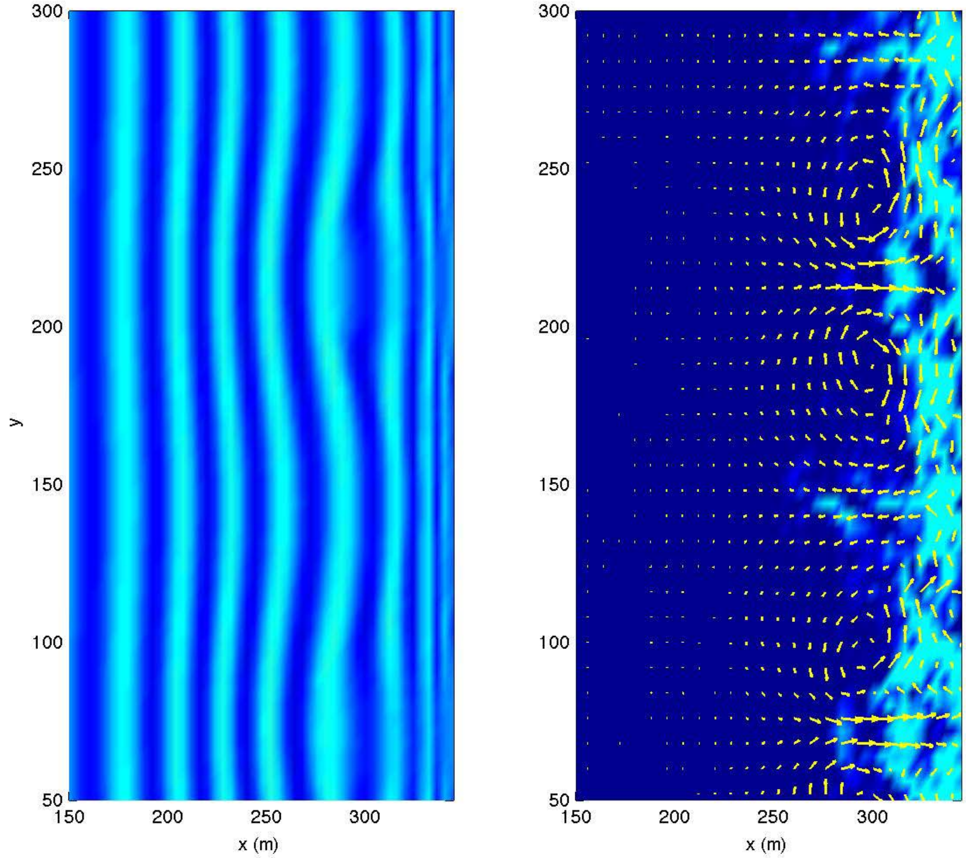

Figure 4. (Left) wave crests predicted by REFDIF-1;
(right) foam pattern and wave-induced nearshore circulation (vectors).