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Surfzone Bubbles: Model Development, Testing and Extension to Sedimentary/Chemical/Biological Processes

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LONG TERM GOAL

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 and small persistent bubbles.

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) Further develop the 3-D Navier Stokes framework to incorporate sediment particle phases as well as chemistry and biology phases with possible interactions

with bubble populations, and to incorporate a foam generation model during degassing processes at the water surface.

2) Further refine the NHWAVE framework to incorporate similar extensions, with a focus on surf zone scale (100 m to km) modeling of wave driven currents and bubble transport.

3) Perform tests of both frameworks against recent field data sets.

APPROACH

Our approach to the problem has followed along two tracks: (1) incorporation of a comprehensive model of bubble physics within a 3D LES hydrodynamic code., for application in detailed process studies and development of parameterizations for use at larger scale, and (2) development of a model with lower resolution but retaining a fully 3-D structure, for use in sur zone simulations at spatial scales on the order of a kilometer or so. The physics is represented by a multiphase continuum model, using the formalism described by Drew and Passman (1999), with the details of a formulation for an air and water mixture found in Carrica et al (1999). In the present project, we have implemented a model combining a water phase, a bubble phase with multiple bubble size (or, more accurately, mass) bins. The existing 3-D model Truchas has been extended to include Carrica et al.'s polydisperse multiphase model and an LES turbulence closure model, and has been tested against a number of detailed experimental data sets on flow field turbulence and coherent vortical structures (Ting, 2008; Ting and Nelson, 2011). 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.

A framework for performing simulations of bubble fields and surface foam distributions at kilometer length scales is being developed based on a fully 3-D nonhydrostatic wave resolving model. This model will be extended to incorporate bubble phases, and will be coupled to a model for foam generation, transport and decay on the water surface.

WORK COMPLETED

Following on work completed in FY11 and FY12 we have implemented a dynamic turbulence closure in the full 3-D VOF model for polydisperse multiphase flow and have carefully examined bubble entrainment and liquid-bubble interaction under an isolated breaking event. We have documented this work in a submitted manuscript (Derakhti and Kirby, 2013).

Turning to the problem of providing more useful wave-resolved model predictions at full surf zone scale, we first developed a robust shock-capturing scheme based on the finite volume TVD approach. Initially, we planned to base the model development on a Boussinesq-type, depth-integrated formulation in which the information about void fraction distribution would be incorporated in functional form with dependence on initial

conditions, vertical elevation and time since the initiation of breaking event. This approach let to the development of the Boussinesq code FUNWAVE-TVD (Shi et al, 2012a) which provides a robust model of a range of surfzone processes including breaking and runup without application of additional filtering steps. During this stage of the work, we decided, however, to concentrate our effort on a fully three-dimensional model which would eliminate the need to impose the vertical structure of void fraction. This led to the development of the code NHWAVE (Ma et al, 2012a), which is a shock capturing, fully nonhydrostatic, wave resolving model in surface and terrain following sigma coordinates. Extension of this model in the context of this project is described below.

A framework for performing simulations of bubble fields and surface foam distributions at kilometer length scales have been developed based on a fully 3-D nonhydrostatic wave resolving model NHWAVE (Ma et al. 2012a). The air bubble phase was implemented in NHWAVE following a multiphase description of polydisperse bubble population applied in a 3D VOF model by Ma et al. (2012b). The foam layer model is based on a shallow water formulation with a balance of drag forces due to wind and water column motion (Shi et al. 2012b). Foam mass conservation includes source and sink terms representing outgassing of the water column, direct foam generation due to surface agitation, and erosion due to bubble bursting. The coupled bubble and foam model has been tested at field-scale at FRF, Duck, NC.

RESULTS

In addition to the application of the full 3-D VOF model for surf zone breaking waves during FY11 and FY12, we have carefully examined the model capabilities and accuracy to predict bubble-entrainment and transport as well as liquid-bubble interaction under an isolated breaking event. Figure 1 shows snapshots of the free surface evolution for a strong plunging breaker. The model captures overturning jet impact, splash-up process and formation of a bore-like region. Finger shape structures can be seen in the forward splash ($t^* = 0.05 \sim 0.3$) and, comparing to Lamarre and Melville (1991, figure 2a) the time and location $t^* = 0.25, x^* = 0.5$) at which the forward splash hits the undisturbed free surface is very accurately captured by the model. During cavity formation ($t^* = -0.15 \sim 0$) the model predicts void fraction up to 10% at the jet toe, consistent with the measurement of Blenkinsopp & Chaplin (2007, figure 4, a - c). The cavity entrapped by the jet entrains a considerable volume of air during $t^* = 0 \sim 0.25$. A backward splash is formed between $t^* = 0.2$ and $t^* = 0.35$ and entrains some volume of air. During $t^* = 0.25 \sim 0.5$ the entrained cavity collapses and big bubbles degas very quickly. The semicircular primary cloud initially advances approximately with the phase speed, but after $t^* = 0.5$ its horizontal centroid becomes constant and then moves backward slightly after $t^* = 1.1$. The secondary cloud is generated by the impact of the forward splash during $t^* = 0.25$ to $t^* = 0.65$ where at $t^* = 0.65$ we have the maximum entrainment by a jet like impact similar to the primary jet. The mean void fraction of the dispersed bubbles becomes more than 30% at $t^* = 0.65$ and then decreases gradually to 1% at $t^* = 1.7$. While the large bubbles outgas very quickly, small bubbles are preferentially entrained into the coherent vortices generated during breaking

and transported vertically by turbulent motions, and may remain in the water column for a very long time. Bubbles entrained by a plunging breaker can be divided into three different clouds. Figure 2 shows the 3D dispersed bubble plume evolution, in which the two semicircular clouds are related to the two downbursts of turbulent motion under the first impacting jet and forward splash, and the third cloud represents bubbles entrained by the bore which are transported by vortices behind the bore.

Liquid-bubble interaction, i.e. dispersed bubble effects on mean and turbulent motions, is still an open question. In LES, the transport equation for a resolved TKE can be obtained based on the resolved velocity field. SGS dissipation contains both shear- and bubble-induced dissipation and typically is much bigger than the viscous dissipation. In the case of a two phase flow with a dilute regime ($\alpha \approx 1$), common practice is to use the conventional single phase TKE transport equation with an additional term due to a correlation between fluctuating concentration and vertical turbulent velocity component, $-\rho g \alpha' \ w'$. High turbulent and dissipative regions are collocated with high void fraction regions. Due to large void fraction (> 10%) during active breaking period, the dilute assumption is not valid anymore, and concentration fluctuations cannot be ignored.

Figure 3 displays various integral properties of the breakier for the case of a strong plunging breaker. Figures 3a and b show the total production rate by mean shear and SGS dissipation for the simulation with and without consideration of the dispersed bubbles. Presence of the dispersed bubbles reduces turbulent mean shear production while enhances the turbulent dissipation. The total production by buoyancy is an order of magnitude smaller than the production by mean shear and the dispersed bubbles (not shown here). Figure 3c shows the dispersed bubbles damped TKE about 20% to 30%. Exception is in $0.1 < t^* < 0.5$, where TKE has not been damped and even is enhanced in the large plunging case. This can be explained through the work done by the dispersed bubbles on the turbulent motions. Figure 3d shows total viscous (ϵ^r) and SGS dissipation (ϵ^{sgs}) per unit crest width in the breaking region. In all breaker types, most of the energy is dissipated during the first period after breaking, at which bubble-induced dissipation is about 50% bigger than the shear-induced dissipation. Corresponding simulations without the inclusion of dispersed bubbles predict smaller ϵ^{sgs}, about 35%, which is surprisingly invariant with respect to the different breaker types and intensity. Lamarre and Melville (1991) approximated the total dissipation by estimating the total energy flux difference between upstream and downstream of the breaking region. Table 1 summarizes the dissipation contributions predicted by the model and the estimation from Lamarre and Melville (1991). Comparing to the experimental estimations, we can conclude that inclusion of bubble-induced dissipation improves the model results and that simulations without inclusion of dispersed bubbles underpredict the total dissipation by about 40% both in plunging and spilling breaking.

The numerical codes FUNWAVE-TVD (Shi et al, 2012a) and NHWAVE (Ma et al, 2012a) have been published and are available as open source code for community use. FUNWAVE-TVD has not been extended yet for multi-phase effects, as it was decided to concentrate this effort on the 3-D model NHWAVE. Ma et al (2012a) describe basic testing of NHWAVE as a surf zone model. The model has also been extended to

incorporate the multiphase bubble model. At present, we are performing more extensive tests of the model's ability to predict circulation and bubble void fraction over complex topography. The NHWAVE model is has also been coupled to a model for foam distribution and transport on the water surface (Shi et al, 2012b).

Field-scale model testing is based on an extensive history of imagery obtained at the USACE FRF at Duck, NC, including ARGUS imagery in the visible band and IR band imagery collected during the 2010 Surf Zone Optics Experiment (SZO). To incorporate AGGUS measurements into the model tests, we applied wave conditions measured in several selected ARGUS recording periods. Figure 4 shows predictions of void fraction (left panel) predicted by the NHWAVE bubble model and foam coverage (middle panel) predicted by the foam layer model. IR-based PIV surface velocity map shown in the right panel reveals a significant rip current between 850-900 m which is also predicted by the numerical model.

Figure 5 shows the time stack of foam thickness from the model (left) compared with the time stack of nearshore water surface in infrared band from IR imagery (right). IR imagery is likely to separate active breaking from passive foam in terms of more rapidly cooling on passive foam. The predicted foam thickness looks consistent with foam signals in IR imagery, although further work needs to be done to establish a quantitative correspondence.

IMPACT/APPLICATIONS

The work proposed here would provide a general framework for modeling the combined effects of bubble distribution, sediment load and foam coverage on optical properties 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

Development of the multiphase aspects of the NHWAVE model code continues with additional support from NSF-PO through the project "The interaction of waves, tidal currents and river outflows and their effects on the delivery and resuspension of sediments in the near field.

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(A number of papers have benefitted in a significant way from project support in relation to the development of the new FUNWAVE-TVD and NHWAVE codes. Ma et al (2013b) provides the model extension to calculation of suspended sediment load which will feed back into the present project.)

Grilli, S. T., Harris, J. C., Tajalibakhsh, T., Masterlark, T. L., Kyriakopoulus, C., Kirby, J. T. and Shi, F., 2013, “Numerical simulation of the 2011 Tohoku tsunami based on a new transient FEM co-seismic source: Comparison to far- and nearfield observations”, *Pure and Applied Geophysics*, **170**, 1333-1359.

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Derakhti, M. and Kirby, J. T., 2013, "Turbulent bubbly flow under unsteady breaking

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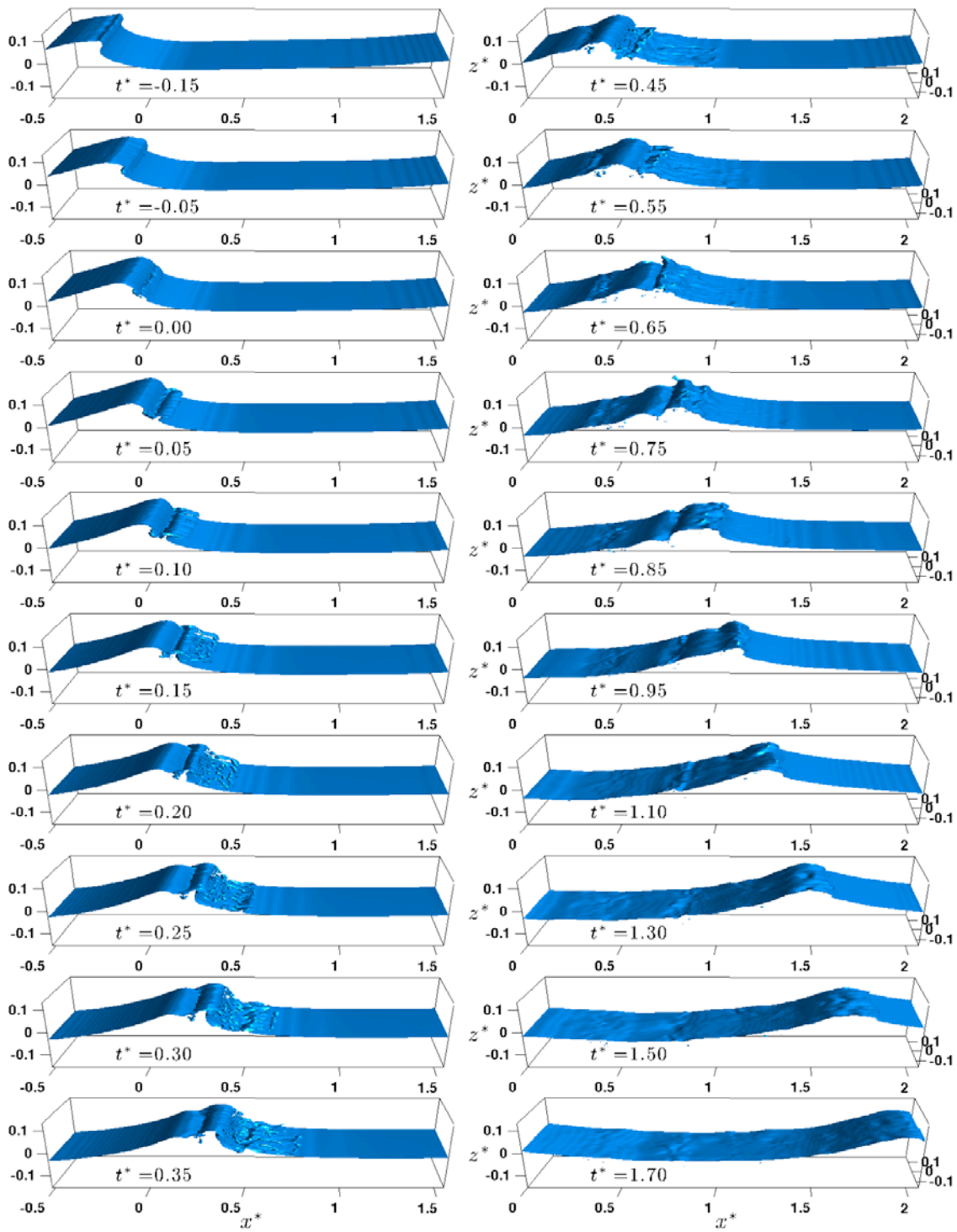


Figure 1: Snapshots of the time sequences of free surface evolution in the breaking region for a strong plunging breaker.

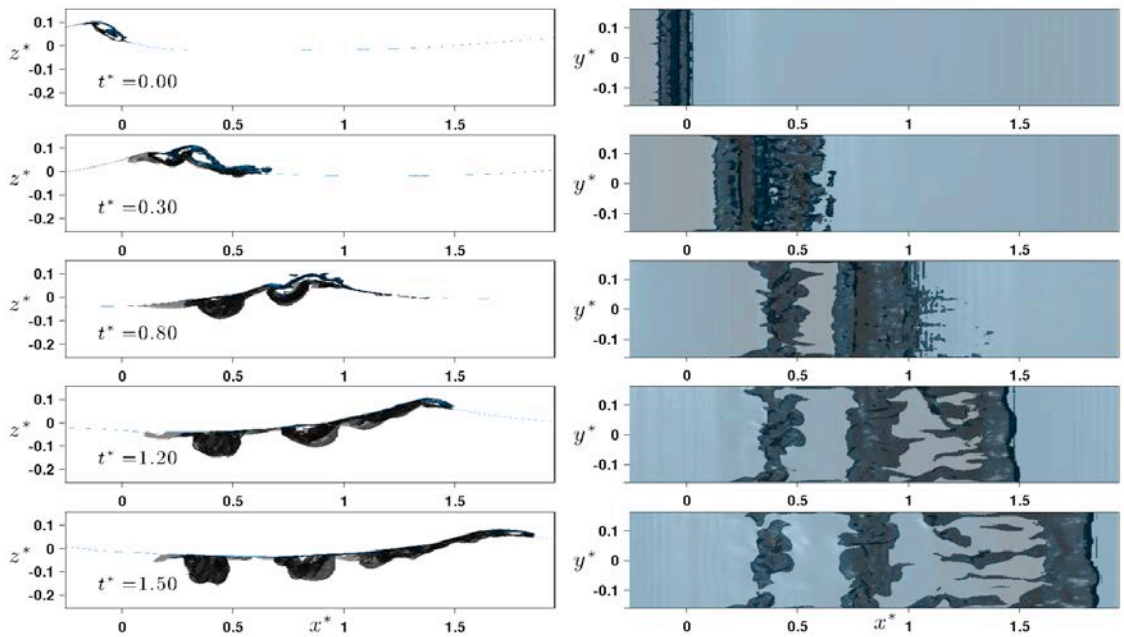
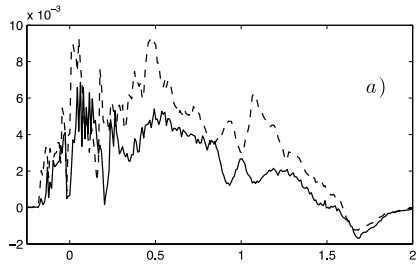


Figure 2: Snapshots of 3D bubble plume (Isosurface of $\alpha = 0.05\%$) evolution in the breaking region for a strong plunging breaker. (left): side view of the 3d results; (right): top view of the 3d results.



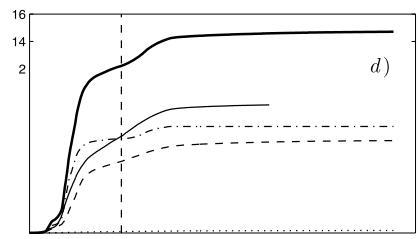


Figure 3: Integral results for a strong plunging breaker case. a) The two phase total production rate by mean shear (solid line) simulations with the inclusion of the dispersed bubbles and (dotted line) simulations without dispersed bubbles. The reference value is $\rho L_c^2 C_c^2 T_c^{-1}$, where Lc, Cc and Tc are the wavelength, phase speed and period of the center frequency of the wave packet. b) The two phase total SGS dissipation rate by mean shear from (solid line) simulations with the inclusion of the dispersed bubbles and (dotted line) simulations without dispersed bubbles. The reference value is $\rho L_c^2 C_c^2 T_c^{-1}$. c) Normalized total resolved TKE in the breaking region, (solid line) simulations with the inclusion of dispersed bubbles and (dashed line) simulations without dispersed bubbles. The reference value is $L_c^2 C_c^2 S^{4.5}$, where S is the wave packet steepness. d) Total dissipation per unit crest width in the breaking region (J/m). (Thick solid line) Total dissipation in the breaking region, ϵ_{total}^{b}; (solid line) total dissipation from the simulations without the inclusion of dispersed bubbles, ϵ_{total}^{nb} . (dashed-dotted line) bubble-induced dissipation ϵ_{sgs}^{BI} (dashed line) shear-induced dissipation ϵ_{sgs}^{SI}

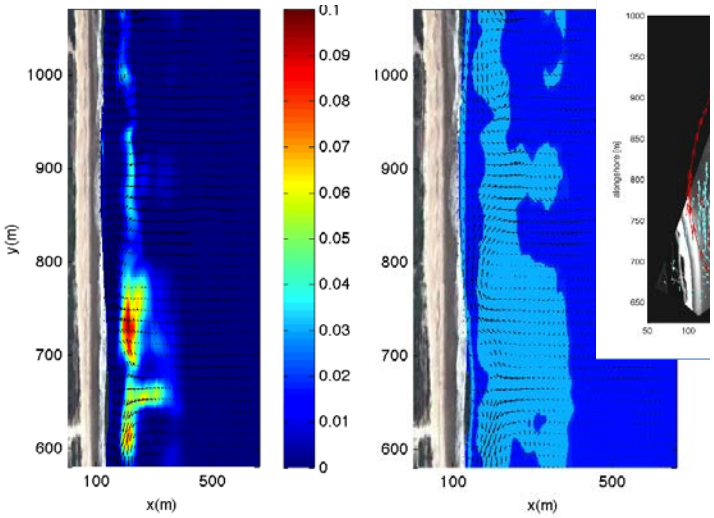


Figure 4: Air void fraction (left) and foam coverage (middle) predicted by the coupled bubble-foam model. IR-based PIV surface velocity map (right panel, courtesy of Andy Jessup, Chris Chickadel) reveals a significant rip current between 850-900 m which is also predicted by the numerical model.

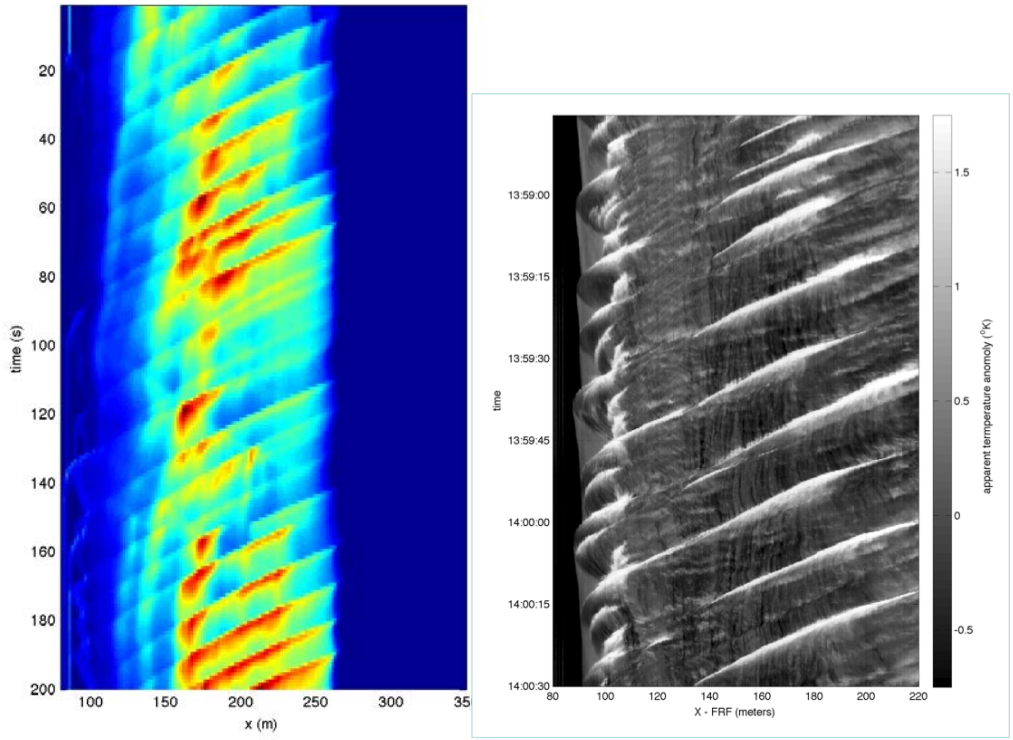


Figure 5: Time stack of foam thickness from the model (left) compared with time stack of nearshore water surface in infrared band from IR imagery (right, courtesy of Andy Jessup, Chris Chickadel).

Case no.	**LM** (J/m)	$\hat{\epsilon}_{total}(J/m)$	$\hat{\epsilon}^{nb}_{total}/\hat{\epsilon}_{total}$ (%)	$\hat{\epsilon}^{SI}_{sgs}/\hat{\epsilon}_{total}$ (%)	$\hat{\epsilon}^{BI}_{sgs}/\hat{\epsilon}_{total}$ (%)
P1	17.8	14.7	63.7	45.9	52.9
P2	8.6	7.7	64.8	45.4	53.0
SP1	4.3	2.6	65.9	43.2	53.7

Table 1: Total dissipation in the breaking region, ϵ^{b}_{total}. ϵ^{SI}_{sgs} *and* ϵ^{BI}_{sgs} represent the shear- and bubble-induced dissipation, respectively. ϵ^{nb}_{total} is the total dissipation from the simulations without the inclusion of dispersed bubbles.