

Wave-Current Interaction in Coastal Inlets and River Mouths

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LONG-TERM GOALS

The wave-driven dynamics of coastal areas are important for circulation, mixing and transport processes, and accessibility by vessels. The long-term goal of this study is to improve our understanding, observational capability, and model representation of wave-current interaction in complex coastal inlets, and determine the role of nonlinearity and inhomogeneity on wave statistics in such areas.

OBJECTIVES

The specific objectives of this study are to: 1) develop observational capability using wave- and current-resolving Lagrangian drifters to study wave-current interaction, and contribute to a comprehensive community data set of coastal inlet and river mouth processes, 2) better understand the role of current shear, wave inhomogeneity and nonlinearity in wave-current interaction through analysis of observations and modeling, and 3) develop predictive modeling capability of wave statistics in a complex coastal environment with two-dimensional bathymetry and currents.

APPROACH

To better understand interactions between waves, currents and topography in a coastal inlet, and improve predictive capabilities, we are conducting an integrated study that combines field observations acquired using newly developed wave-resolving drifters (WRD), with advances in theory and numerical modeling of wave-current interaction, random wave focusing, and wave dissipation.

WORK COMPLETED

Golden Gate Experiment

We conducted several large (15-35) drifter deployments in the Golden Gate during ebb tides. Our findings show that the WRDs can be successfully used in this challenging environment with heavy ship traffic, strong currents and large waves, to study the ebb current structure, and capture regional variations in the waves. Observations from April 27, 2012 shown in Figure 1 (left panel) reveal dramatic variations in wave conditions along the drifter tracks. Notably, a large increase in wave height is observed on the ebb tidal shoal followed by an abrupt decrease behind the shoal. A numerical simulation with the wave prediction model SWAN, one-way coupled with the flow model Delft3D, is in reasonable agreement with these observations, albeit the predicted wave amplification is somewhat less pronounced. Ray computations for the dominant 11 s period swell (Figure 1, left panel) confirm that the strong amplification is associated with the expected refractive focusing on the shoal. Interestingly, the abrupt decrease in wave height behind the shoal is not caused by bottom friction (turning bottom friction off in SWAN does not significantly change the prediction) but is the result of a divergence of the wave energy transport induced by refraction over the deeper shipping channel (note the bifurcation of rays in figure 1). Whereas the dominant swell is affected primarily by wave-bottom interactions over the ebb tidal shoal, higher-frequency waves are amplified further east in the channel where the opposing tidal ebb current exceeded 2 m/s. This secondary area of wave amplification, presumably the result of wave-current refraction and blocking, is not well reproduced in the SWAN prediction, possibly because the model does not account for vertical shear in the current field and the wave breaking dissipation source term only crudely represents the wave blocking effects

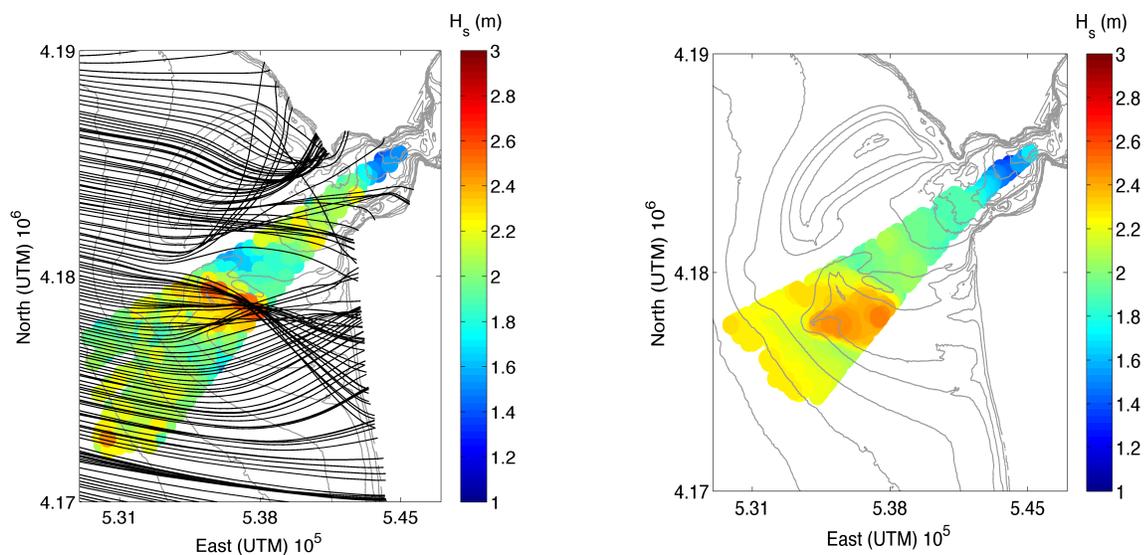


Figure 1. Spatial variability of significant wave height in the entrance to San Francisco Bay observed on April 27, 2012, with 30 Wave-Resolving Drifters (WRD) (left panel) and predicted with the model SWAN (right panel). Ray trajectories for the dominant 11 s period swell, superimposed on the observed wave heights, show that the large increase in wave height on the ebb tidal shoal and the subsequent abrupt decrease can be explained by refractive focusing on the shoal areas and a divergence of the energy transport in the deeper channel (from Pearman et al., 2014, in press).

RESULTS

Model development

In areas of strong wave-current interaction, and in the presence of focusing, reflection, and blocking of waves, inhomogeneous and non-Gaussian effects are important. To improve modeling capability of such dynamics we have started development of a stochastic model that incorporates inhomogeneous effects in random waves, and can represent wave dynamics in focal zones (Smit & Janssen, 2013). The model is a natural extension of quasi-homogeneous theory (the radiative transfer equation used in third-generation wave prediction models) and can deal with inhomogeneities in wave fields of arbitrary spectral shape.

This so-called quasi-coherent (QC) approximation resolves coherent interference contributions that are important in wave focal zones. The omission of such terms, such as implied in quasi-homogeneous theory, will result in dramatically different statistics in areas of strong inhomogeneity such as produced by interaction with current jets and coastal bathymetry

We used the new QC model to investigate the effects of a submarine canyon on wave statistics using measurements from the Nearshore Canyon Experiment (NCEX) conducted in 2003 at Scripps Canyon on the Southern California coast (Figure 2). In this experiment, 7 Datawell Directional Waverider buoys, 17 bottom pressure recorders and 12 pressure-velocity sensors were deployed to capture the transformation of ocean swell over the steep canyon topography. Observed wave height variations for a long period swell arriving from the Southern Hemisphere are compared to predictions of the radiative transfer equation (RTE, used in WAM, WavewatchIII and SWAN) and the new QC model. Both the RTE and QC models generally capture the extreme wave height variations induced by refraction over the canyon (Figure 2, lower panels). However in the shallower areas, and in the vicinity of the canyon head, the abrupt wave height variations are accurately reproduced by the QC model, whereas the RTE model tends to smooth out the variations. These large gradients are the result of the coherent interference of waves traveling along different ray paths (Figure 2, upper right panel), which is not accounted for in the RTE approximation.

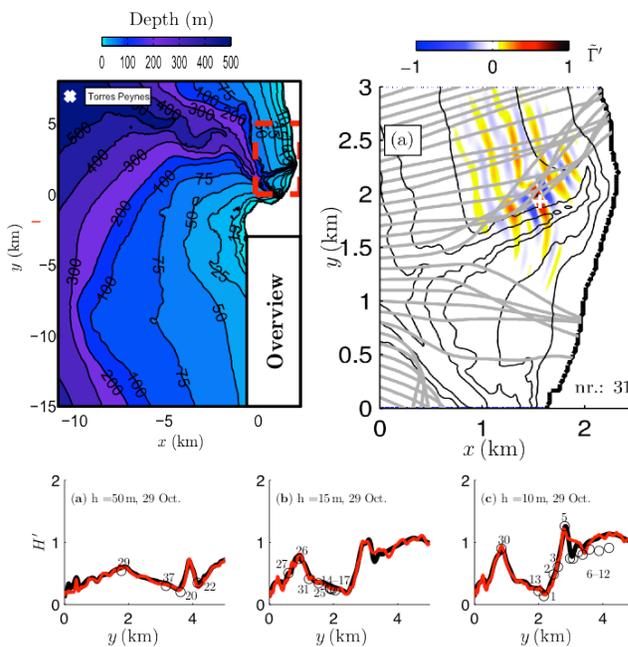


Figure 2. Comparison of Radiative Transfer Equation (RTE) and Quasi-Coherent (QC) model prediction of wave evolution over a submarine canyon with observations from the Nearshore Canyon Experiment (NCEX). Upper left panel: bathymetry (in color). Most of the instruments were concentrated around the head of Scripps Canyon (red box), a narrow, deep canyon that has a profound effect on the nearshore wave climate. Upper right panel: spatial covariance function predicted by the QC model, using the location of instrument 31 on the north side of the canyon (white cross) as a reference point. The covariance function shows the expected coherent variation in the dominant swell direction associated with the oscillatory swell motion, but also lateral variations with a distinct nodal structure, caused by the coherent interference of waves travelling along different ray paths (grey lines). Lower panels: Observed (circles) and predicted (red curves: RTE, black curves: QC) wave height variations along (from left to right) the 50 m, 15 m and 10 m depth contours. The significant wave heights are normalized by the offshore wave height (from Smit et al., 2014, submitted).

Mouth of the Columbia River (MCR) Experiment

The main focus of our research this past year was the analysis of observations collected in the Mouth of the Columbia River Experiment (MCR), which took place in May/June 2013. Our primary objective was to observe wave-current interactions in the river mouth where large Pacific Ocean swells oppose unusually strong ebb tidal currents, coupled with significant river run-off in the spring season. The use of Lagrangian drifters is particularly well suited to this extreme environment, and therefore we concentrated our effort on deploying a massive number of drifters (figure 3) with a limited number of fixed instruments (a moored waverider buoy, three bottom pressure recorders, and a bottom-mounted ADCP) to provide some Eulerian observations.

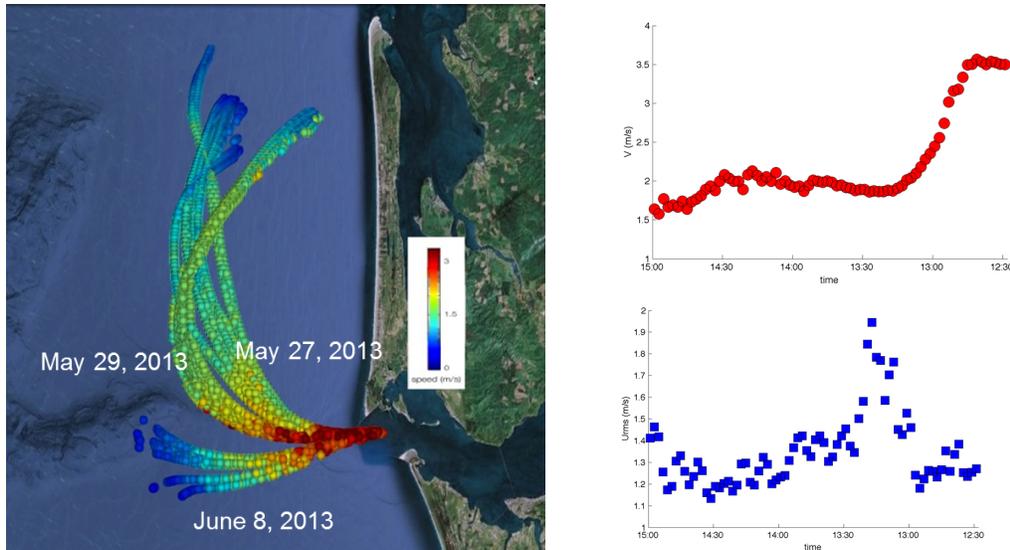


Figure 3 Drifter tracks from the three large ebb deployments. The right panels show a record of 2-min-mean currents and the associated rms fluctuation measured by one of the drifters on June 8.

We deployed drifters almost every day of the three-week-long experiment to study wave-current interaction and to support observations by other teams. The observations include three intensified drifter deployments at the peak of the ebb cycle on May 27 (27 drifters), May 29 (49 drifters), and June 8 (30 drifters). During these intensified ebb deployments, drifters were released at short (10-20 s) intervals near the time of maximum ebb current with the vessel maintaining its position.

During the May 27 and 29 deployments (see Figure 3), the drifters took a distinct northerly course after exiting the inlet and crossing the bar. During the June 8 deployment, the drifters split up in two groups, with a small cluster of drifters (the first in the water) taking a slightly more northerly route; all drifters continued approximately due west on this day after crossing the Columbia bar (in contrast to the more northerly tracks seen in the earlier deployments). The degree of dispersion also shows significant differences with almost no dispersion on May 29 when all 49 drifters were recovered within a few km of each other about 27 km north of the river mouth.

To illustrate the observed spatial variability of currents and waves, a record of two-minute mean current speeds and root-mean-square (rms) current fluctuations is shown in figure 3 (as measured by one of the drifters deployed on June 8). The mean current, dominated by the tidal ebb flow, shows a rapid decrease from about 3.5 m/s in the channel to 2 m/s just offshore of the mouth. The rms fluctuations, dominated by the wave orbital motion, are strongly amplified over the bar reaching a maximum value of about 2 m/s. These unusually large fluctuations, associated with the strong wave amplification on the bar, on top of the

tidal current, produce instantaneous velocities measured by the drifters that often exceed 5 m/s and thus momentarily change the direction of the flow!

To our knowledge these are the first detailed in situ wave and current observations in such an extreme environment, and we believe the data set will provide a unique opportunity to develop a better understanding of wave-current interactions. In particular, preliminary analysis results of the drifter observations suggest that nonlinear effects are important in wave focal zones (see Figure 4), consistent with the numerical results from Janssen & Herbers (2009).

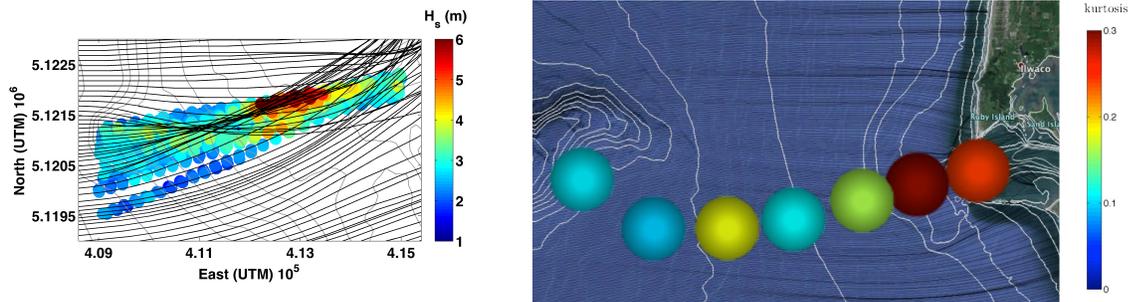


Figure 4 Left panel: Significant wave height estimates from drifter observations in the mouth of the Columbia river, overlaid with ray computations. The waves arrive from 275 degrees, and have a 14s period. Extremely large waves occur down-stream of the focal point, consistent with the numerical results from Janssen & Herbers (2009). Right panel: averaged kurtosis values are largest in the focal region over the bar, indicative of nonlinear effects on the wave statistics in this region.

To study the representation of the wave-focusing dynamics in operational wave models, we have conducted a hindcast study of the MCR observations with a preliminary SWAN model implementation (see Figure 5). The SWAN model was initialized with observations from the Astoria Canyon buoy operated by the Coastal Data Information Program (CDIP, buoy # 46248). Three-dimensional current fields and bathymetry were provided by the Center for Coastal Margin Observations & Prediction (CMOP).

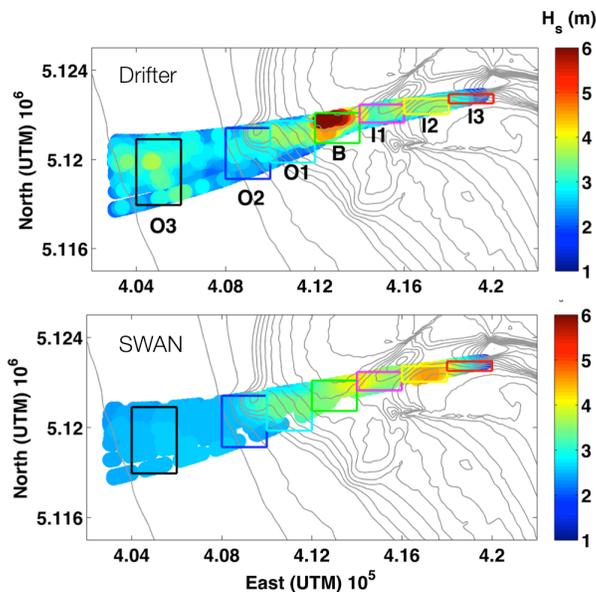


Figure 5 Comparison between drifter observations (top panel) and predicted wave heights (SWAN, bottom panel) in the Mouth of the Columbia River for June 8 2013. The observed and predicted wave focusing near the Columbia river bar show considerable differences. The SWAN model uses observations from CDIP buoy # 46248 as boundary condition; three-dimensional current data and bathymetry is provided by the Center for Coastal Margin Observation and Prediction (CMOP).

The SWAN model shows an area of wave focusing due to bottom and current refraction near the river mouth (see Figure 5). Although qualitatively consistent with the observed focusing, the observations indicate that wave heights in the focal zone are much larger than predicted and that the wave height variability is much more abrupt. In other words, the model predicts focusing in a larger area, but underestimates the strongest amplification effects considerably. Although these results are preliminary, they indicate that there are still large improvements to be made in the representation of wave focusing in coastal inlets by operational wave models. By providing a spatial snapshot of the wave evolution, the drifter data provides a new and unique opportunity to test and improve wave models.

Reconstruction of surface dynamics from drifter arrays

Arrays of drifters can be used to capture snapshots of the surface elevation, which can be an aid to study the spatial characteristics of the wave field, or create an intuitive visualization of the free surface in an area. We have used the observations at MCR to develop and test an algorithm for ocean surface reconstruction and visualization (see Figure 6). The algorithm is based on a least squares optimization of the free surface utilizing an array of simultaneous drifter observations. The model uses only the available observations and does not require calibration and/or tuning. Comparison between a drifter time series (excluded from the analysis) and the reconstruction time series shows good agreement (see left bottom panel of Figure 6).

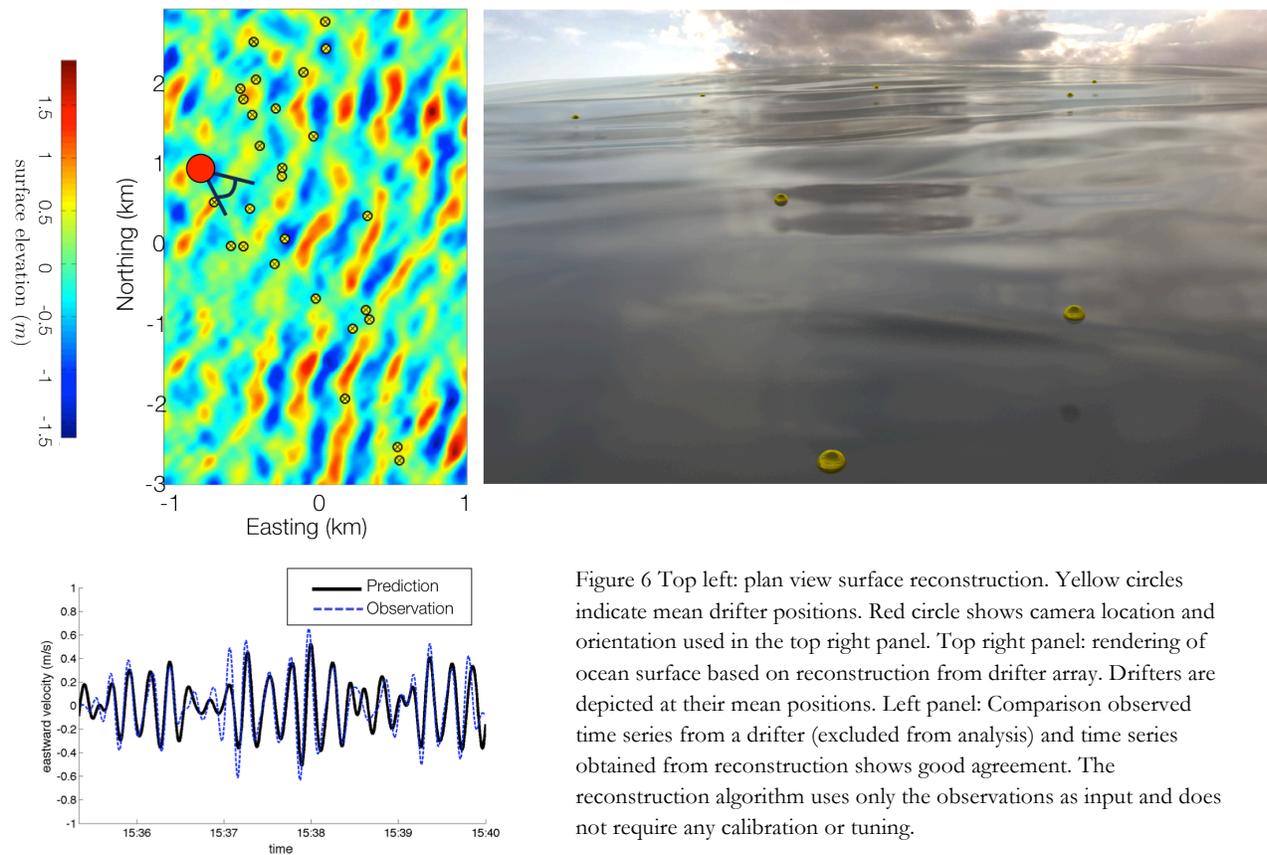
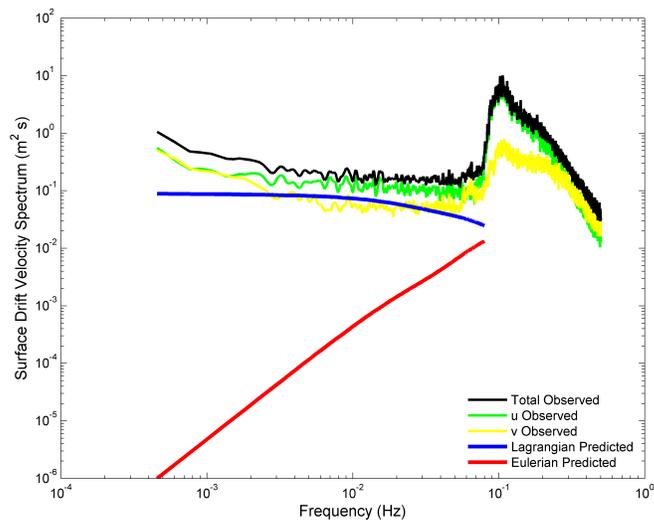
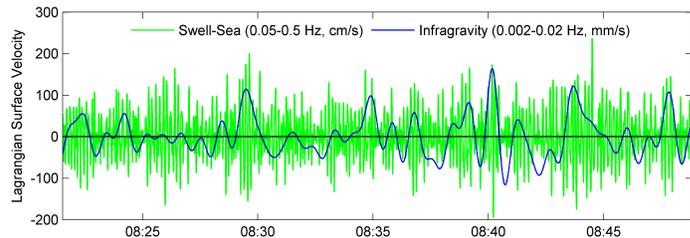


Figure 6 Top left: plan view surface reconstruction. Yellow circles indicate mean drifter positions. Red circle shows camera location and orientation used in the top right panel. Top right panel: rendering of ocean surface based on reconstruction from drifter array. Drifters are depicted at their mean positions. Left panel: Comparison observed time series from a drifter (excluded from analysis) and time series obtained from reconstruction shows good agreement. The reconstruction algorithm uses only the observations as input and does not require any calibration or tuning.

Drifter observations of infragravity Stokes drift modulations

The Lagrangian nature of drifter observations has the important advantage of providing direct measurements of Stokes drift which plays an important role in upper ocean transport and mixing. In a random wave field Stokes drift is not a steady drift but exhibits large fluctuations at infragravity time scales. Using second-order wave theory we show that these infragravity motions observed by a Lagrangian instrument are much larger and of opposite phase relative to the well-studied Eulerian infragravity motions. Comparisons of the Lagrangian theory predictions to observations (see Figure 7) show that 1) the Lagrangian nonlinear model is in good agreement with the observations and 2) Lagrangian infragravity energy levels are indeed several orders of magnitude larger than those seen by an Eulerian instrument (see Figure 7, bottom panel). These large infragravity modulations of the Stokes drift may have important implications for horizontal diffusion at the sea surface.

Figure 7 Drifter observations in deep water collected during field testing in preparation for the MCR. Top panel: Time series of the measured velocity component in the dominant wave direction. Band-passed infragravity drift fluctuations (blue) show a positive correlation with the wind wave groups (green) as predicted by Lagrangian theory. Bottom panel: Observed velocity spectra are compared with predicted spectra of infragravity drift fluctuations (blue curve). The observed spectral levels are comparable to the levels predicted by the Lagrangian theory (blue curve) and several orders of magnitude higher than the spectral levels of Eulerian bound wave contributions (red curve).



IMPACT/IMPLICATIONS

The development of inexpensive drifter buoys equipped with GPS sensors and accelerometer packages that resolve both surface waves and surface currents, has extended observational capability to areas where it is difficult to deploy and maintain moorings (such as in strong currents and/or energetic waves).

The observations of wave-current interaction in the presence of variable (tidal) currents, topography, and stratification, will contribute a comprehensive new data set that will improve our understanding of wave variability in coastal inlets and river mouths. These observations can be used to test theories and models, either existing, or those developed within the scope of this study.

Improved understanding of nonlinear wave dynamics in Lagrangian records will provide a framework to apply free-drifting instruments to the study of e.g. effects of infragravity modulations of upper ocean circulation and other processes affected by nonlinear effects in surface waves.

The development of a stochastic wave model that resolves inhomogeneous effects in random waves, is an important and critical step to develop statistical modeling capability of wave dynamics in complex coastal environments.

RELATED PROJECTS

The development of the GPS-tracked drifter buoys was started as part of the ONR HiRes DRI to enable deployment of a greater numbers of instruments to capture the spatial variability of waves and currents. The instrument development and deployment strategies planned in the present project build on our findings during the HiRes DRI. The development of a transport model for non-Gaussian and inhomogeneous wave fields also contributes to, and benefits from, progress in the ongoing Wave Modeling NOPP. The data collected in this project will also be of use in validation of new model parameterizations developed in the NOPP project.

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