DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Wave-Current Interaction in Coastal Inlets and River Mouths

Tim T. Janssen
Department of Geosciences, San Francisco State University
San Francisco, California 94132
t: 415 338 1209; f: 415 338 7705; e: tjanssen@sfsu.edu

Thomas H. C. Herbers
Department of Oceanography, Code OC/He, Naval Postgraduate School
Monterey, California 93943
t: 831 6562917; f: 831 656 2712; e: thherber@nps.edu

Award Numbers: N000141010411, N000141110248, N0001411WX20873

LONG-TERM GOALS

The wave-driven dynamics of coastal areas are important for circulation and mixing, 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 and 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 propose an integrated study that combines field observations acquired using newly developed drifter buoys, with advances in theory and numerical modeling of wave-current interaction, random wave focusing and wave dissipation. The modeling effort will include the development of a spectral model [e.g. Janssen & Herbers, 2009] that is suitable for nonlinear waves in a variable medium.

WORK COMPLETED

We have continued the development of Lagrangian drifter buoys that can resolve both surface currents and waves. To augment the GPS observations, which sample at 1Hz (Nyquist is 0.5Hz) and do not resolve the vertical motions as accurate as they do the horizontal, the drifter buoys are equipped with

off-the-shelf accelerometer packages. These sensors are capable of resolving higher frequencies (10 Hz sampling rate) that are of interest to characterize the wind-wave spectrum, and provide the resolution of the vertical motions that is lacking in the GPS sensor observations.

Figure 1 Breaking waves as seen from R/V Questuary over the sill in Raccoon Strait (San Francisco Bay) opposing a developing flood tide.

We conducted two pilot experiments in Raccoon Strait located in San Francisco Bay (May and July 2011) to test the new instruments, and collect a first dataset of wave-current interaction in this area. These pilot experiments where single or two-day experiments during which we experimented with deployment and retrieval strategies, made observations during different phases of the tidal cycle, and collected preliminary data (currents, stratification, and waves) to better understand the current and wave regimes in the area.

Preliminary analysis shows that the GPS-accelerometer prototype instruments agree well with observations made with conventional instruments (Datawell buoy for waves, ADCP for currents). The observations also reveal a complex wave-current interaction regime in the vicinity of the sill near the west-end of Angel Island (Figure 2), where topography and stratification effects in the fluid play an important role.

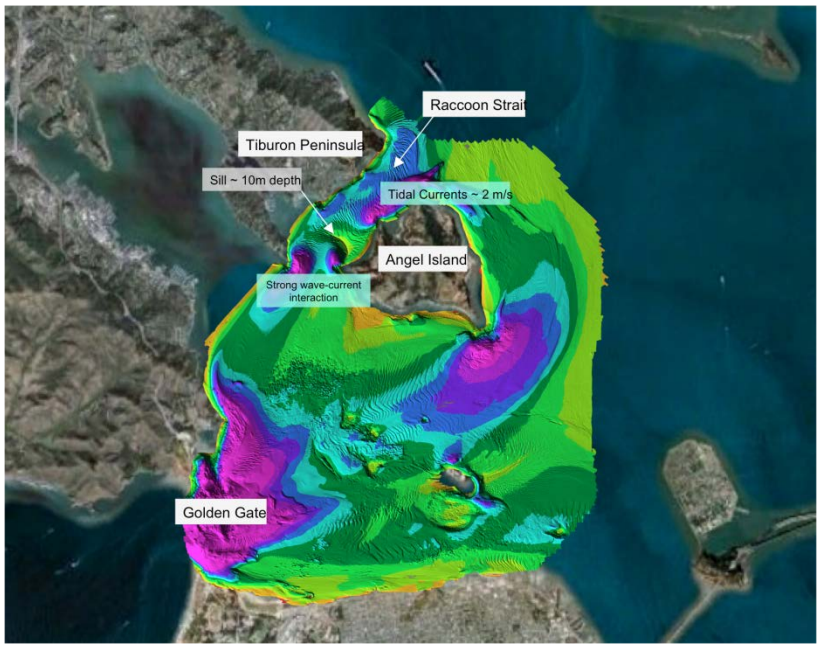

Figure 2. Raccoon Strait, San Francisco Bay. Strong tidal currents through the Strait result in wave-current interaction (and blocking) near the western tip of Angel Island. The proximity to the Romberg Tiburon Center makes the site easily accessible by small vessels. Several pilot experiments at this site have been conducted to test and develop prototype instruments and collect wave-current data in the Strait. Bathymetry data courtesy of the Seafloor Mapping Lab of California State University Monterey Bay.

RESULTS

Thus far we have completed two pilot experiments in Raccoon Strait (see figure 2), which is the waterway between the Tiburon Peninsula and Angel Island. The area is characterized by a very strong tidal current regime, in particular over the shallow sill near the western tip of Angel Island (see figure 2) where the current intensity is magnified due to the flow area contraction.

The objectives of the pilot experiment where to

- Test and develop the Lagrangian drifter wave-current buoys
- Collect a first comprehensive dataset capturing the internal and surface dynamics in the Strait

Thereto we have conducted short experiments in May 2011 (two days) and July 2011 (one day) deploying a number of experimental drifter buoys, conventional Datawell buoys, ship-board ADCP and a CTD. These experiments were conducted from the R/V Questuary and R/V Salty Dog, both operated by the Romberg Tiburon Center for Envrionmental Studies.

Instrument validation

One of the new developments tested during the pilot experiments was the use of off-the-shelf accelerometers to complement the GPS sensors on the prototype buoys. In some ways these instrument packages are complementary in that the GPS sensors are most accurate for horizontal motions at lower frequencies (< 0.5 Hz), whereas the accelerometers can accurately resolve the vertical motions and at much higher frequencies (10 Hz sampling rate).

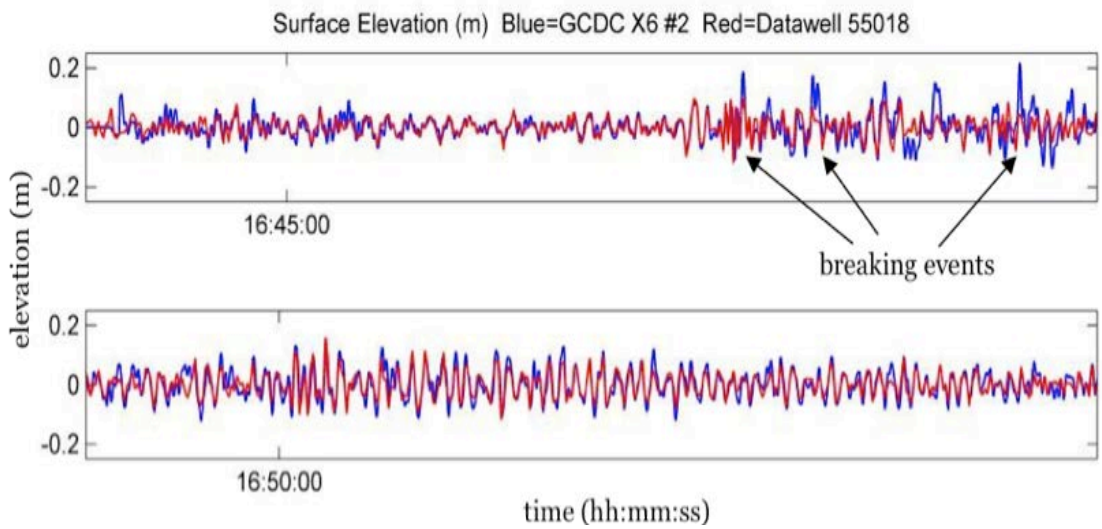

Figure 3. Comparison between time series of surface elevations from a GPS-based Datawell buoy (red lines) and an accelerometer package that was attached to the same buoy (blue line). The agreement between these independent instruments is mostly excellent, apart from a few minutes time period when the buoy traversed the current maximum on the sill (see right of top panel). These steeper waves are presumably breaking which registers in the accelerometer observations (large accelerations, shown in blue) but is not resolved in the GPS (in red) data.

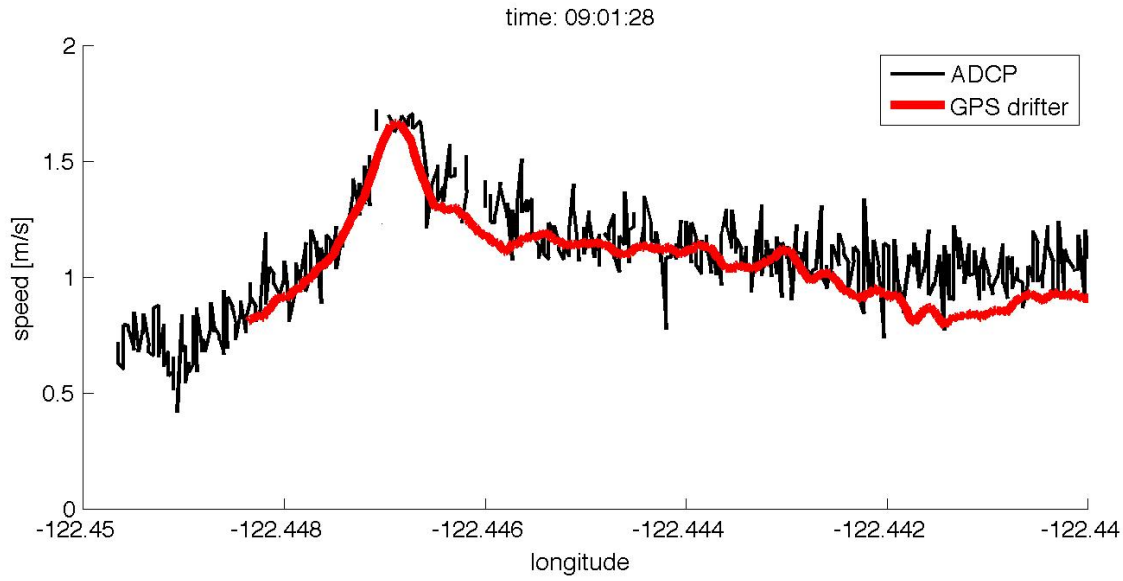

Figure 4. Comparison of surface currents observed with ship ADCP (black line) and GPS drifter (red line). In this comparison the top bin (nearest the surface) of the down-looking ADCP is used.

We tested the accelerometers by mounting them inside Datawell buoysand comparing the vertical elevation records with the GPS-based Datawell measurements. The agreement is mostly excellent (figure 3), apart from some discrepancies when the buoys traversethe blocking zone and encounter very steep, and presumably breaking, waves (as observed visually, see also figure 1). The accelerometer appears to pick up these large accelerations associated with these events, suggesting that breaking events can possibly be identified in the wave height records. This would allow us to estimate dissipation from the time series directly. We will test this further in the upcoming experiment (October 2011) in Raccoon Strait using buoy-mounted video cameras to obtain simultaneous visual observations of breaking events.

Apart from wave motion, the GPS data collected by the new drifter buoys can also be processed (averaging out the waves) to estimate mean currents near the surface. Current velocities estimated from the drifter data compare well with the observations made by the ship-board ADCP (see figure 4). Further validation tests of drifter-derived currents will be conducted in a follow-up experiment.

Observations of wave-current dynamics

To characterize the current and wave dynamics, we analyzed observations of surface drifters (surface currents and waves), ship-board ADCP (vertical structure of the flow field), and several CTD casts (stratification). These combined observations reveal strong internal hydraulics in the lee of the sill that may play an important role in the surface wave dynamics.

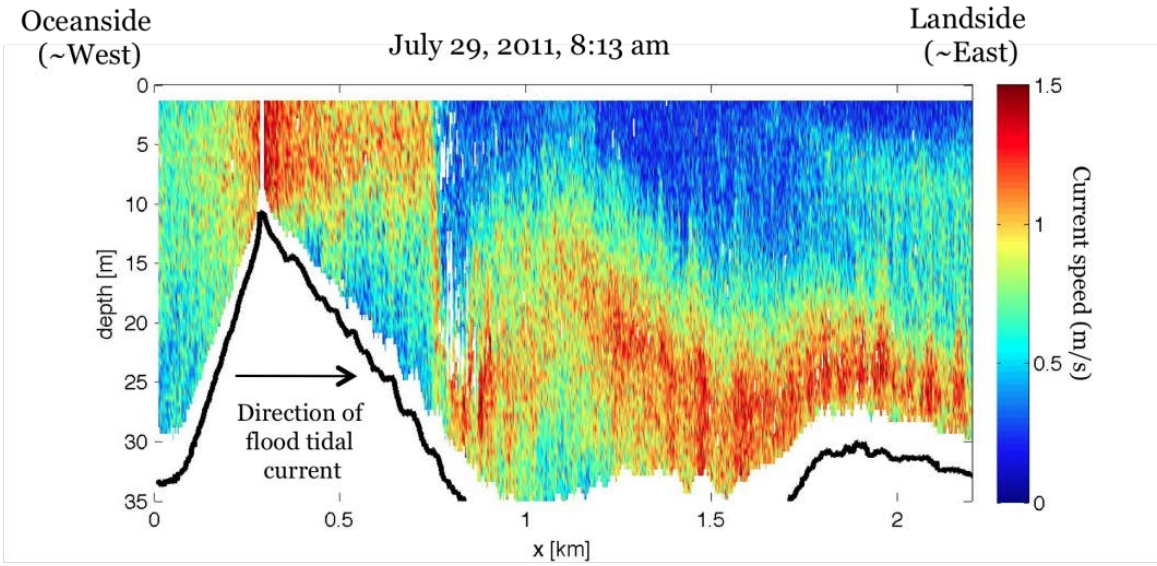

Figure 5. Flow velocities observed using ship-board ADCP with the ship track in along-strait direction. The incoming flood tide is accelerated over the sill and plunges underneath the lighter bay water about 700m after the sill.

During the flood tide, surface waves may get trapped between the sill (maximum current velocity) and an outcropping front developing between the incoming ocean water and fresher surface waters in the lee of the sill (see figure 1 for photograph of surface waves and figure 5 for internal flow structure). As the flood develops, the denser ocean water plunges underneath the fresher bay water, and the flood current develops what appears an internal lee-wave behind the sill (see figure 5).

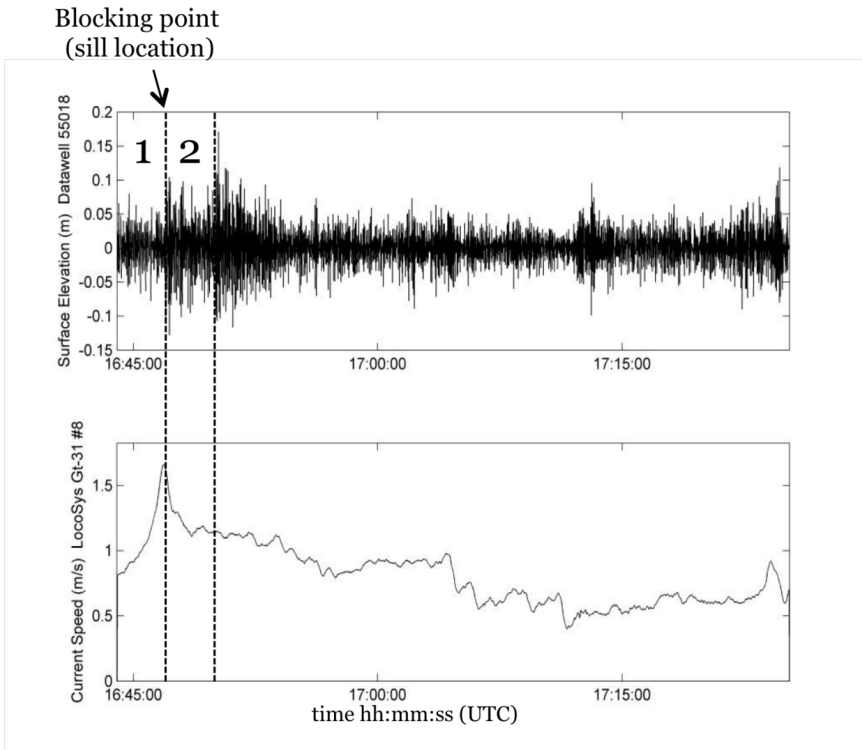

Figure 6. Top panel: time series of surface wave elevation observed with Datawell buoy. Bottom panel: currents observed with GPS receiver attached to the same buoy. The time intervals marked 1 & 2 in the top panel indicate two short time series (separated bydashed lines), approximately corresponding to just outside (1) and just inside (2) the blocking zone; results ofdirectional analysis for these time series in shown in figure 7.

Surface wave energy is enhanced in the blocking zone (see figure 6) where the waves are relatively steep and breaking occurs. From a directional analysis based on observations of horizontal and vertical motions it is seen that the higher-frequency waves (> 0.3 Hz) propagate in opposite direction on either side of the blocking point (see figure 7).

These initial observations show a complicated interaction between tidal currents, stratification, topography and surface waves, the details of which are not yet fully understood. In the following series of experiments in this area we will focus on the origin of the surface wave energy and its directional properties, and the implication of the internal hydraulics on the surface dynamics.

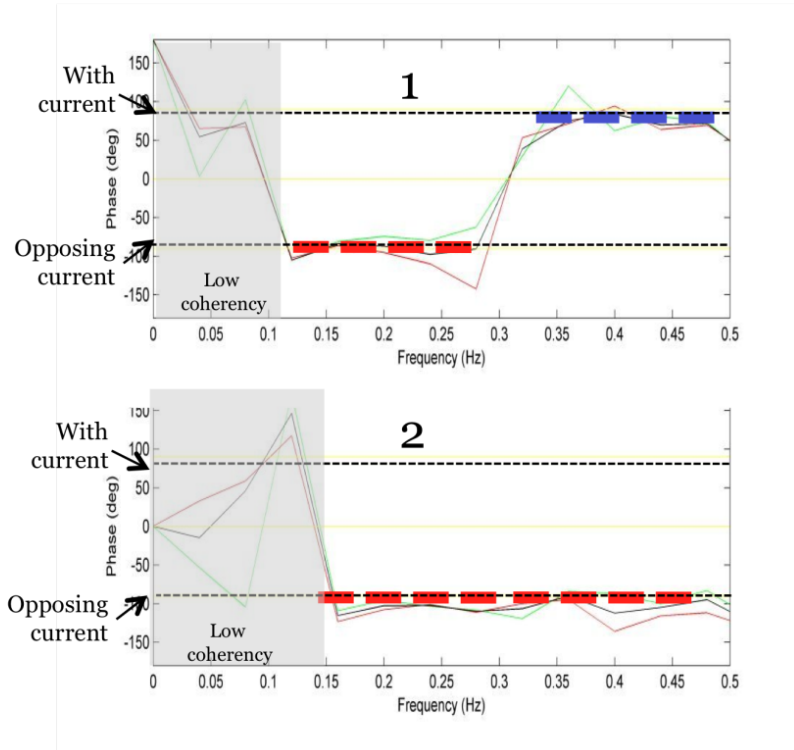

Figure 7. Wave directions as derived from observations of horizontal and vertical buoy motions. Directions are defined such that +90° and -90° indicate waves propagating with and against the flood current respectively. Just outside the blocking zone (top panel) waves with frequencies > 0.3 Hz propagate with the current (into Raccoon Strait from the Central Bay); inside the blocking zone, these waves propagate in the opposite direction, and thus oppose the flood current.

Model development

In areas of strong wave-current interaction, and in the presence of focusing, reflection, and blocking of waves, the wave field is likely to develop inhomogeneous and non-Gaussian statistics. 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, 2011). The model is a natural extension of quasi-homogeneous theory (the radiative transfer equation) and can deal with inhomogeneities in wave fields of arbitrary spectral shape.

This quasi-coherent 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 (see figure 8 for an example of the evolution of wave variance associated with the propagation of three coherent wave packets in the vicinity of the focal point).

.

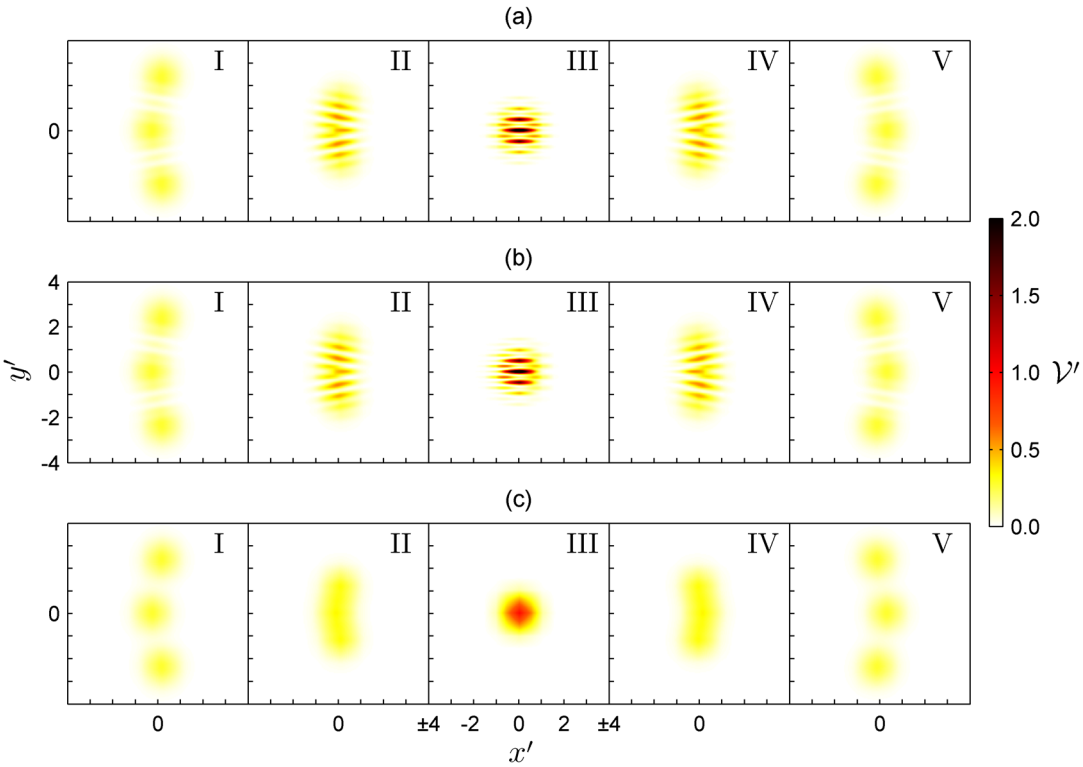

Figure 8. Snapshots of normalized wave variance of a three-packet interference example (see Smit & Janssen, 2011). The wave variance is shown at discrete times $t_{I\text{-}V}$, starting at t_I (left panels) and increasing in time (from left to right). Top panel (a) exact model prediction; middle panel (b) quasi-coherent approximation (the present model); bottom panel (c) quasi-homogeneous theory. Quasi-homogeneous theory does not resolve the coherent interference of the packets (cross-phase information is not available), whereas quasi-coherent theory (middle panels) is in excellent agreement with the exact solution. In general, the theory is a very good approximation to the exact result as long as the angles between coherent wave components are moderate.

IMPACT/APPLICATIONS

The development of inexpensive drifter buoys equipped with GPS sensors and accelerometer packages that resolve both surface waves and surface currents, will extend 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.

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.

REFERENCES

Janssen, T. T. & T. H. C. Herbers (2009) Nonlinear wave statistics in a focal zone, *J. Phys. Ocean.*, **39**, 1948-1964.
Smit P. & T. T. Janssen (2011) Coherent structures in random waves *J. Fluid Mech.*, submitted

PUBLICATIONS

Herbers, T.H.C., P. F. Jessen, T.T. Janssen, .D. B. Colbert, J. H. MacMahan (2011) Observing ocean surface waves with GPS-tracked buoys *J. Atmos. Oceanic Tech.*, [submitted, refereed]
Smit P. & T. T. Janssen (2011) Coherent structures in random waves *J. Fluid Mech.*, [submitted, refereed]