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Diamessis, Peter J. and Jacobs, Gustaaf B.

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
School of Civil and Environmental Engineering, 220 Hollister Hall
Cornell University, Ithaca, NY 14853

Department of Aerospace Engineering and Engineering Mechanics
5500 Campanile Drive # 306, San Diego State University, San Diego, CA 92182

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14. ABSTRACT
The transition to fully turbulence under fully nonlinear internal solitary waves (NLIWs) has been investigated. Very well-resolved Large Eddy Simulations (LES) of the separated bottom boundary layer BBL under a NLIW of depression have been conducted. Exploratory and production runs involving typically 1.5 billion grid points have been executed on state-of-the-art DoD Facilities accessible via a Frontier contract. NLIWs propagating into quiescent waters and against oncoming barotropic currents with their own BBL have been studied. In the former set-up, a 3-D near-bed vortex wake forms only when volumetric forcing is included, whereas in the former a self-sustained near-bed turbulent wake occurs in the NLIW's lee through a complex spontaneous transition to turbulence. Integral measures and the energetics of the NLIW-driven BBL have been quantified. Mechanisms of particulate resuspension have been investigated through Lagrangian Coherent Structure (analysis) and the quantification of wave and wake-driven pressure signals at the bed.

15. SUBJECT TERMS
Nonlinear internal waves, continental shelf, turbulent bottom boundary layer, hydrodynamic instability, transition to turbulence, boundary layer separation, Lagrangian Coherent Structures, resuspension of bottom sediment.

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Cornell University
School of Civil and
Environmental Engineering

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Peter Diamessis
Associate Professor
Environmental Fluid Mechanics and Hydrology
School of Civil and Environmental Engineering
Cornell University
Ithaca, NY 14853
USA
Tel: 1-607-255-1719
e-mail: pjd38@cornell.edu
website: www.cee.cornell.edu/pjd38

Defense Technical Information Center
8725 John J. Kingman Road Ste 0944
Fort Belvoir, VA 22060-6218

To Whom It May Concern:

Please find attached my final report for the O.N.R.-Physical Oceanography-funded project titled "Near-Bottom Turbulence and Sediment Resuspension under Nonlinear Internal Waves" (Award Number: N00014-11-1-0511). I have also attached form SF298. I apologize for delay in sending this out but it has been an extremely semester for me compounded by a loss in my family. Please let me know if you would like any additional information from me.

Sincerely,

Peter Diamessis

FINAL REPORT (5/27/2015)

Near-Bottom Turbulence and Sediment Resuspension Induced by Nonlinear Internal Waves

Peter J. Diamessis
School of Civil and Environmental Engineering
220 Hollister Hall
Cornell University
Ithaca, NY 14853
phone: (607)-255-1719 fax: (607)-255-9004 email: pjd38@cornell.edu

Gustaaf B. Jacobs
Department of Aerospace Engineering and Engineering Mechanics
5500 Campanile Drive (Room 306)
San Diego State University
San Diego, CA 92182
phone: (619)-594-4046 fax: (619)-594-6005 email: gjacobs@mail.sdsu.edu

Award Number: N00014-11-1-0511
http://www.cee.cornell.edu/pjd38
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LONG-TERM GOALS

The long term goal of this work is to develop a fundamental understanding and predictive capability of the underlying physics of the interaction of nonlinear internal waves (NLIWs) with the continental shelf seafloor over a broad range of environmental conditions. We are particularly interested in how such interactions impact underwater optics and acoustics and shelf energetics and ecology by stimulating enhanced bottom boundary layer (BBL) turbulence and particulate resuspension leading to benthic nepheloid layer (BNL) formation.

OBJECTIVES

The specific objectives of this now-terminated project consisted of:

- Using Large Eddy Simulations (LES), to investigate the structural transition to turbulence within the separated BBL layer under a NLIW of depression and quantify the resulting NLIW energy losses.
- By means of Lagrangian coherent structure (LCS) theory, to identify mechanisms for the capturing of near-bed particles by the BBL-turbulence and their transport/deposition into BNLs.
- Analyze field observations from the New Jersey shelf to identify the applicability of hypothesized BBL physics and flesh out the underlying fluid mechanics from the field data.

Reproducing a turbulent BBL under a NLIW has involved a non-trivial effort, both conceptually and in terms of computational cost. Hence, we have focused on the first objective with consistent efforts recently initiated to address the second one. Any analysis of associated field data has been deferred to future efforts, particularly since any robust observations of the BBL induced by NLIWs of depression still remain to be obtained.

APPROACH

Our approach has relied on implicit 3-D Large Eddy Simulation (LES) based on spectral multidomain solver developed by P.I. Diamessis (Diamessis et al. 2005), with the extrinsically prescribed dissipation of the spectral filter serving as a subgrid scale model surrogate. This code has been successfully applied to a number of computational stratified flow process studies in 2-D and 3-D (Abdilghanie and Diamessis 2013, Diamessis et al. 2014), including the study of the primary instability of the NLIW-induced BBL (Diamessis and Redekopp 2006). It employs a uniform periodic (Fourier-based) grid in the along-wave direction and a multidomain Legendre-polynomial-based discretization, equipped with a penalty scheme, in the vertical. Its parallel implementation is based on a hybrid MPI/Open-MP approach.

Note that during the first 4 months of this project we sought to use a more recently developed code in the PI's group, one relying on two-dimensional Legendre subdomains in the along-wave and vertical direction (Escobar-Vargas et al. 2014). The particular discretization enabled a more flexible positioning of grid-points in the separated BBL under the NLIW. Nevertheless, issues with slow-convergence iterative solver for the pressure in this code, due to the presence of high-aspect ratio subdomains naturally resulting I the problem at hand, forced us to return to our original code. A significantly improved version of the two-dimensional subdomain code, where a custom-designed hybrid direct-iterative pressure solver is used, is now available (Joshi et al. 2015) and can be used in future endeavors.

Our problem geometry considers a mode-1 wave of *depression* fixed in a frame of reference moving with the NLIW's phase speed through a uniform-depth waveguide (figure 1). The background stratification across the full water column consists of a two uniform density layers separated by a finite-thickness pycnocline (figure 1). If required, the wave propagates against an oncoming barotropic background current which has, at the bed, its own idealized Blasius-like boundary layer. As the wave is kept fixed in time, we solve for the perturbation to this wavefield that develops through the mismatch between the non-zero wave velocity field and no-slip condition at the bed (Diamessis and Redekopp 2006). To maximize resolution of the 3-D turbulence in the NLIW-induced BBL, our computational domain is a truncated in the vertical direction. A detailed view of the computational domain with the appropriate boundary conditions is shown in Figure 1.

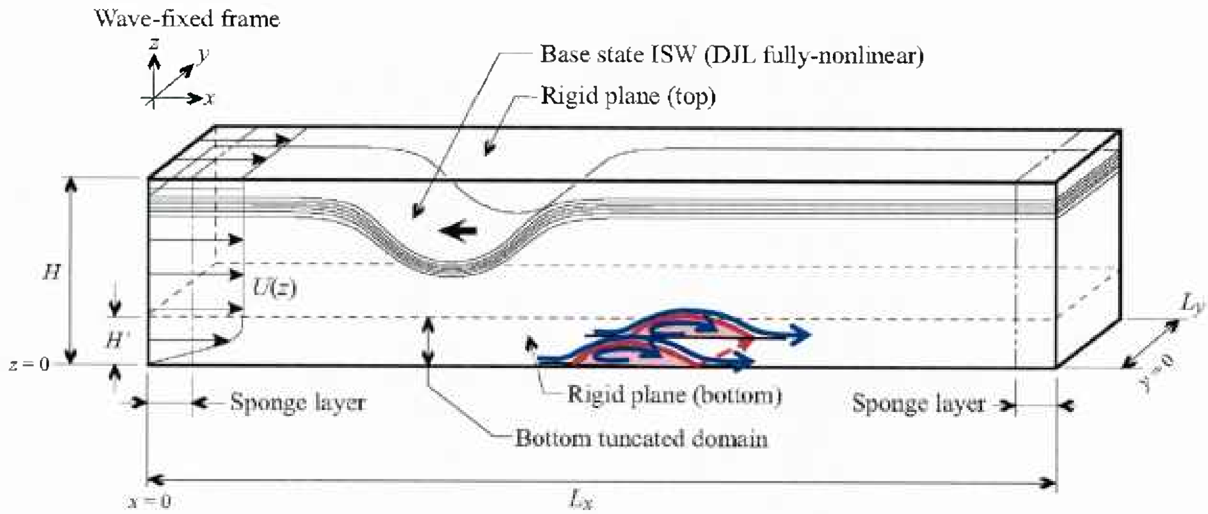

Figure 1: Schematic of flow configuration used in Large Eddy Simulations. The separation bubble (near-bed recirculation zone) is highlighted.

Our particle-tracking tools revolve around libraries built by co-P.I. Jacobs based on a higher-order accuracy Eulerian-Lagrangian (EL) approach (Jacobs and Hesthaven 2006, Jacobs and Don 2009). These tools have been used by the co-P.I. to determine particle-laden flow with relevance to liquid-fuel combustors and have been enriched with the necessary LCS analysis techniques. Most recently, they have been adapted to any type of grid used by a discontinuous element-based higher-order method (discontinuous Galerkin of spectral multidomain penalty).

WORK COMPLETED

The computational reproduction of the transition to turbulence in the separated BBL under a NLIW turned out to be a non-trivial effort. At the onset of this project, we had anticipated that replicating such a transition would be straightforward, much in analogy to what is observed in the computational literature of stratified shear layer simulations (Smyth and Moum 2000): the self-sustained primary instability (global instability in the case of the NLIW-driven BBL) will first break-down into a secondary spanwise instability and high-order instabilities, ultimately giving rise to a self-sustained near-bed turbulent wake in the rear of the NLIW. Following a circuitous path of almost 2.5 years, involving significant numerical experimentation and cost of 10 million CPU hours, we have discovered that our original hypothesis is indeed correct.

In an attempt to capture the above classical transition to turbulence, we resorted to well-resolved implicit LES, thereby avoiding any spurious physical effects due to wall-modeling or eddy-viscosity-based subgrid scale models. Specifically, we use a wall-normal resolution of 0.1 wall-unit with streamwise and spanwise resolutions ranging between 10 and 12 such units. Such relatively stringent resolution requirements restricted us to examining values of the wave-based Reynolds number, $Re_W=Hc/\nu=1.6\times10^5$ (here H and c are the wave-guide depth and NLIW phase speed, respectively) that were slightly above those examined in the laboratory (Carr et al. 2008). As a result, our simulations use **12288×256×480 grid points on 1536 cores** and relied on state-of-the-art DoD-HPC systems. We emphasize that the computational domain is particularly long to accommodate the full length of the NLIW and also a sufficiently long region in the rear of the wave for the BBL to transition to fully developed turbulence. Hence, the very large number of grid points in the along-wave direction.

At the above value of Re_W, and for a specific two-layer stratification where the upper layer is 7 times thinner than the lower one, we have examined three cases of background barotropic current strength: no barotropic current (U_0/c=0) and background currents 20% and 40% the value of the NLIW phase speed in the no current case (U_0/c=0.2 and 0.4). Given that the no-current case was unable to produce a spontaneous 2-D instability in the separated BBL (see Results section), we focused most of our efforts in replicating the transition to turbulence in the U_0/c=0.4 case.

Significant computational tests, spanning from September 2012 to July 2014, were performed towards reproducing the above transition. At first, we followed the approach used in simulation of turbulent separating boundary layers in Mechanical Engineering application (backward facing step, curved diffuser) where synthetic turbulence is inserted in the separation region. This approach produced what was more like a temporally evolving shear layer which quickly transitioned to turbulent motion. Unfortunately, due to the convectively unstable nature of this shear layer, the turbulence advected out of the domain, i.e., there was no self-sustained turbulent wake.

After 4 months of testing, an alternative approach was adopted from the aerodynamics community (Jones et al. 2008): Localized volumetric forcing was inserted in the rear of the separation bubble. This forcing had a random spectral content biased towards the most unstable secondary transverse instability mode of the vortices shed by the separation bubble. Identifying this most unstable transverse wavelength involved extensive and costly experimentation in runs with 16 points in the spanwise direction. The aim was to replicate Jones et al. (2008) in the sense that a forced turbulent BBL would first develop. Upon reaching a steady state, the forcing would be turned off and the leading shed vortices would remain three-dimensional destabilizing the vortices trailing them: a self-sustained turbulent BBL would thus be established. As we reported at the 2014 AGU Ocean Sciences meeting, the forced case did indeed produce a near-bed turbulent BBL in the lee of the NLIW, whose characteristics we systematically have characterized (see next section). Unfortunately, as soon as the forcing was turned-off we were still unable to attain a self-sustained near-bed turbulent wake. The no-current case was also simulated using the above volumetric forcing.

The postdoc employed by this grant, now a lecturer at USC, returned to Cornell for 2 months in summer 2014, to analyze the existing data. Towards the end of this stay, we came to realized that we had committed a very fundamental mistake in our formulation: In the configuration with a reference frame moving with NLIW phase speed, we had not adjusted the above phase speed to account for its reduction by the presence of an oncoming current. In October 2014, we initiated a new set of runs with oncoming current at U_0/c=0.2 and 0.4 (where c is the NLIW phase speed of the no-current case). Computational time was offered on the new DoD-HPC Armstrong cluster, through a Frontier grant led by Prof. Steve de Bruyn Kops of U. Mass. Amherst where Diamessis is a co-PI. The unusually fast speed of this system enabled us to obtain some first results by late November: much to our satisfaction, the transition to turbulence is indeed happening ! We are now in the process of fine-tuning the design of the computational domain (width and resolution) to complete these two remaining production runs and analyze all results by Fall 2015. We will write a manuscript for the Journal of Fluid Mechanics immediately after that. Clearly, there has been a delay in producing a manuscript on the primary objective of this grant but we are confident we will deliver an unprecedented set of results with a first robust set of insights on the physics of NLIW-driven boundary layers.

Note that the soon-to-be completed datasets will serve as platforms for comparison with more operationally-based, lower-resolution, LES simulations. In this regard, we have begun discussing with

Prof. Andrzej Domaradzki, a turbulence modeling specialist at U.S.C., possible avenues of collaboration where we can perform reliable coarser LES at 1% of the resolution of the runs presented here. Such coarser runs will ultimately allow us to explore a broader parameter space of NLIW-seafloor interaction. Examples of coarser LES of engineering-focused separated turbulent bottom boundary layers may be found in Cadieaux et al. (2015).

A senior Ph.D. student supervised by the co-P.I. visited the Cornell campus in July. Beyond instructing the P.I.'s group on LCS theory, he worked with a Cornell Ph.D. student on applying the co-P.I.'s particle tracking tools and associated LCS analysis techniques to results from 2-D NLIW-driven BBL simulations. Results were presented at the A.P.S.-D.F.D. meeting in November. Ongoing analysis is expected to completed by summer's end and a collaborative paper will be written soon after that.

Finally, the P.I. and his Ph.D. student funded by this grant have initiated an ongoing discussion with Prof. Jim Jenkins at Cornell and visiting Professor Diego Berzi (from Politecnica de Milano) both specialists in sediment transport. The collaboration is aimed towards assessing the tendency of the bed towards failure due to the pressure/bottom shear-stress field exerted under the NLIW trough and exploring the potential for resuspension due to the corresponding fields in the near-bed wake in the lee of the NLIW. This pilot study is conducted for the 2-D problem for different materials (sand vs. mud) and for select waves in specific two-layer stratifications (different ratios of layer thickness).

RESULTS

Significant analysis of existing 3-D results has focused on elucidating the coherent flow structures linked to the transition to turbulence, integral measures of the BBL, estimates of bottom drag and investigation of departure from the standard law of the wall. The structure of the bottom shear stress field, turbulence spectra and spanwise autocorrelations have also been examined (not shown here). The same exact analysis will be applied to our currently generated datasets where the NLIW has the correct value of phase speed.

The bottom shear stress field, quantified by the corresponding non-dimensional coefficients, is shown in Fig. 2 for both its streamwise and spanwise components. Streaky structures typical of turbulent boundary layers are immediately evident, with the streamwise component dominated by positive values with occasional islands of negative ones.

Integral measures of the BBL are given in Figure 3, focusing on the forced regime of the oncoming current case. The elevated shape factor confirms the presence of a separated turbulent boundary layer. The presence of a momentum-thickness Reynolds number exceeding 500 in the turbulent region of the BBL suggests the presence of well-developed turbulence with sufficient scale separation. A bottom friction coefficient within the range [0.004,0.006] is computed, whereas the levels of the turbulent kinetic energy in the BBL are within 25% of U_2^2 where U_2 is the NLIW-induced along-wave velocity in the lower layer (not shown).

The bottom drag, as resulting from both the laminar leading edge of the NLIW and also the turbulent near-bed wake in the rear of the wave, are shown in the left panel of Figure 4. The latter turbulent contribution is supplement by the viscous dissipation inside the wake itself. We have found that 1.2% of the NLIW energy is lost during propagation over one wavelength. Consequently, bottom friction linked to this near-bed wake can induce non-negligible wave energy losses over typical NLIW propagation paths of $O(10)$ wavelengths over continental shelves of slowly varying depth.

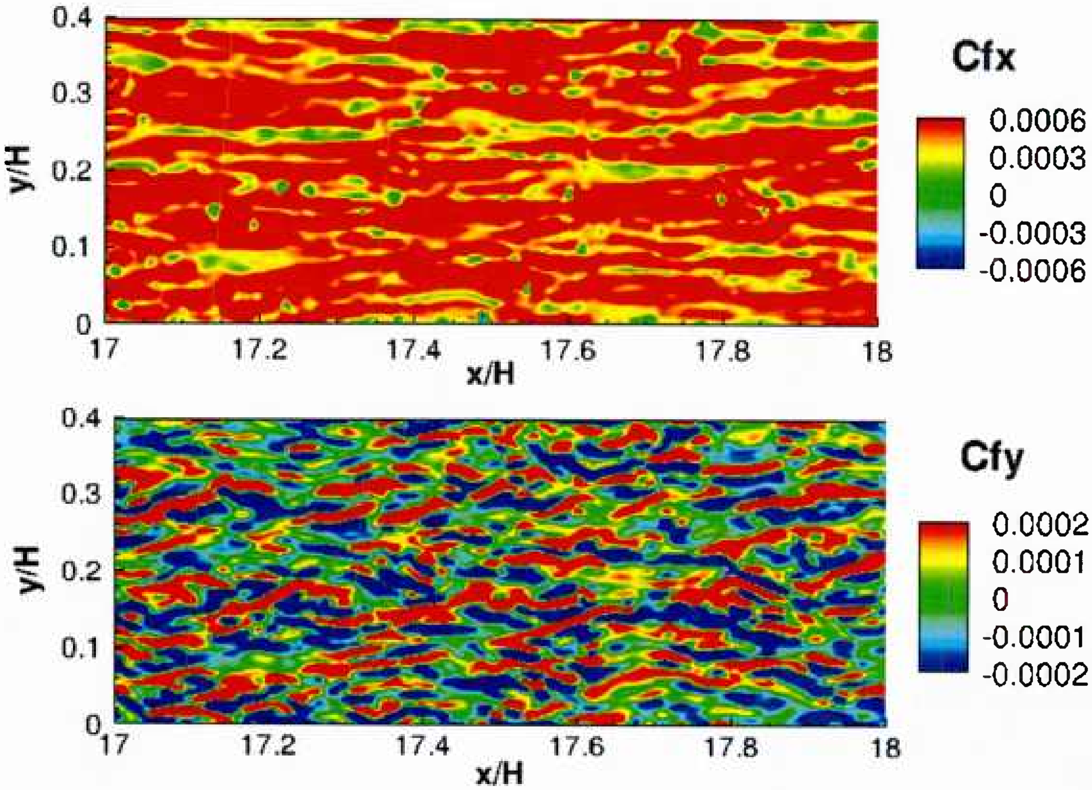

Figure 2: Snapshots of the bottom shear stress coefficients (component of shear stress field normalized by $\rho_0 c/2$, where ρ_0 is the reference density of water) corresponding to the nearly developed turbulent region of the BBL driven by a NLIW propagating against a barotropic current of strength U_0/c =0.4. Top: along-wave stress field ; Bottom: transverse stress coefficient. The turbulence in the NLIW-induced BBL corresponds to a persistently forced separation region. The phase speed has (erroneously) been chosen to be equal to the no-current case.

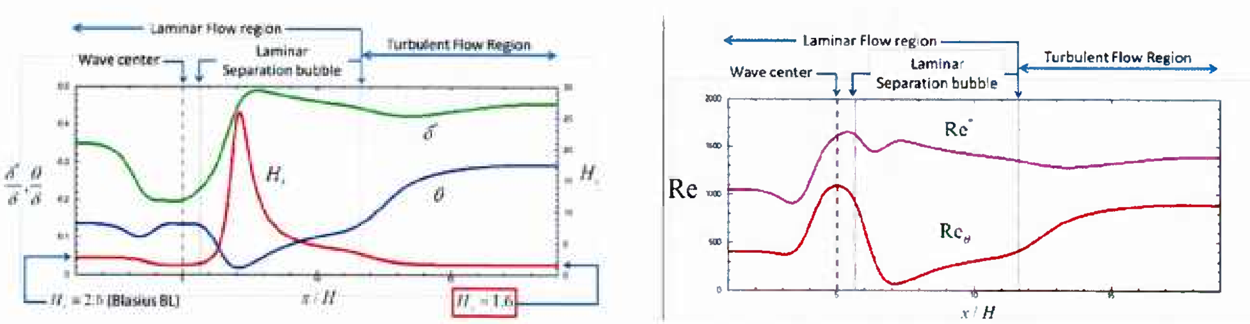

Figure 3: Left panel: Integral measures of NLIW-driven BBL, including displacement thickness δ^*, momentum thickness θ and shape factor H_s, for the same case as in Fig. 2. The thickness of the Blasius BL associated with the model oncoming current is denoted by δ. Right-panel: BBL Reynolds numbers based on δ^* and *θ*, denoted by *Re* and *Re^*, respectively.*

The spanwise-averaged vertical profile of the streamwise velocity is shown in the right panel of Fig. 4 at three different locations along the bed in the near-bed turbulent wake. Although the theoretically prescribed profile of the viscous sublayer is tracked very closely, when transitioning into the buffer layer and log-law region a significant departure is observed from the canonical logarithmic profile. All profiles are sampled outside of the NLIW-induced adverse pressure gradient (APG). Nevertheless, the above departure from the log-law suggests a "memory" of the APG bearing implications for parameterizing NLIW-seafloor interaction in the field.

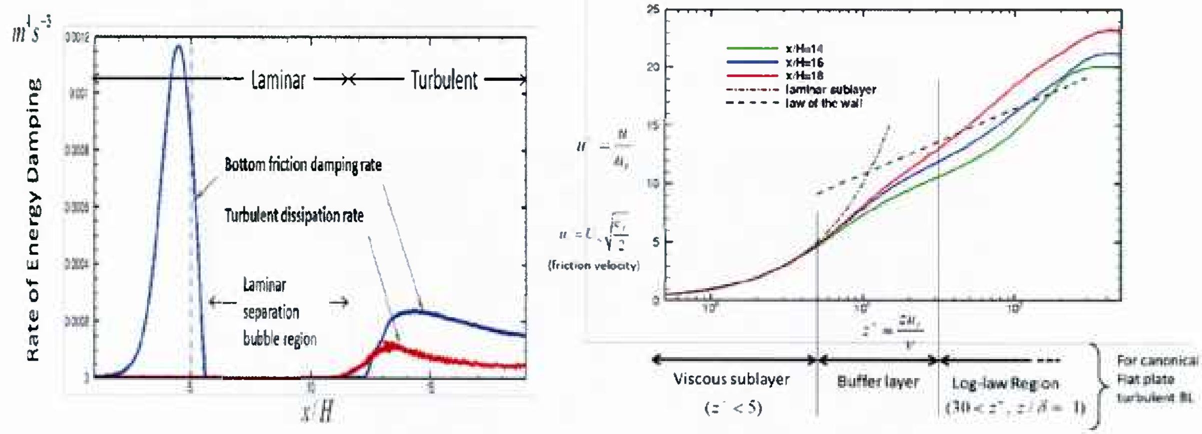

Figure 4: Left panel: Rate of NLIW energy loss (integrated in spanwise direction) per time of one NLIW wavelength propagation time as a function of along wave position in wave-fixed reference frame. The model wave has a wavelength of 100m and propagates with a phase of speed of 0.89 m/s in a model domain that is 10m-deep and 1m wide. Right panel: Spanwise-averaged along-wave velocity profiles at different streamwise locations as compared to classical theoretical estimates, including the log-law.

The case with no-oncoming current generates a transitional near-bed 3-D structure in the lee of the wave which is indicative of a higher-order instability, though not fully developed turbulence (a further confirmed by the structure (Figure 5, right panel). Any 3-D motion immediately advects out of the domain upon turning off of the forcing. Curiously, recent unpublished experimental data (Aghsaee and Boegman 2015) shows a persistent near-bed vortex wake under a NLIW in a similar configuration. We conjecture that this difference is in the inevitable non-negligible roughness of the laboratory flume bed (which provides persistent excitation) and the non-symmetric wave that is generated in the flume which differs significantly from the theoretical fully nonlinear waves examined in our study.

Figure 6 shows some very recent results from the case with an oncoming current case with U_0/c=0.4 where the NLIW phase speed is correctly prescribed. In the left panel, the development of a transverse instability (left panel) and three-dimensionalization (right panel) of the 2-D vortices shed by the global instability of the separated BBL under the NLIW is evident. Note that this 3-D instability occurs spontaneously, as no noise or volumetric forcing are introduced. In our previous runs with an oncoming current, using the phase of the no-current case apparently forced any perturbations within the shed vortices to advect too rapidly outside the computational domain. The 3-D spanwise instability appears to be intimately connected to an elliptic instability, the result of the interaction of two co-rotating vortices in close proximity to each other. Further downstream, the shed vortices have transformed into turbulent "blobs" of fluid advecting away from the wave. Full analysis of the wave-induced BBL, along the lines of what is shown in figures 2 through 4, upon termination of the planned production runs. Beyond analyzing energetically-relevant quantities and producing metrics of interest to field observations, we will also explore the feedback between the downstream-advecting turbulent blobs with the separated flow immediately under the wave.

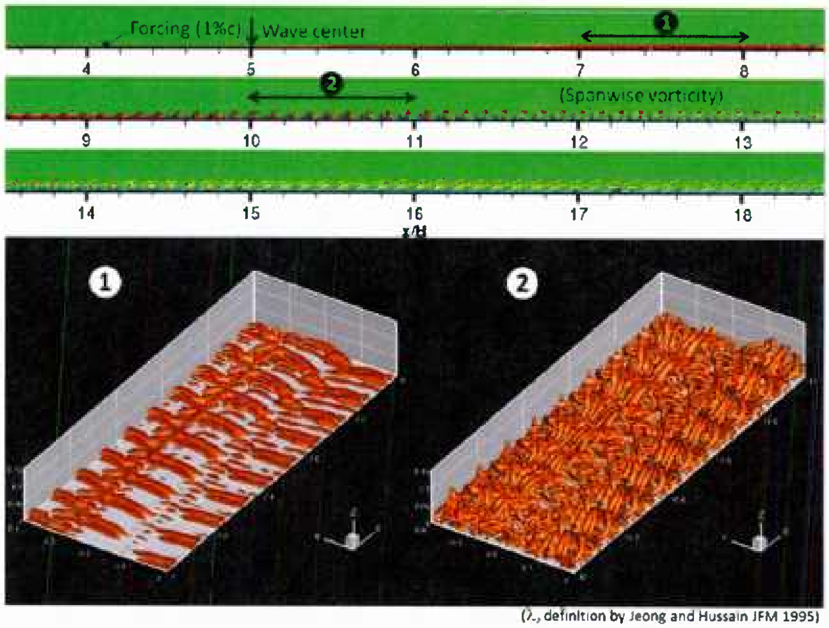

Figure 5: 3-D coherent structures in the near-bed wake in the NLIW-induced BBL in the case with no oncoming barotropic with a persistent volumetric forcing. The contour plots on the top show stream-depth contours of spanwise vorticity at two different downstream locations where the 3-D visualizations are sampled. Despite non-negligible three-dimensionalization, these complex structures never transition to fully-developed turbulence along the bed.

Figure 7 shows representative findings from our application of LCS analysis to results from 2-D simulations of NLIW-induced boundary layers. Backward and forward-time finite Lyapunov exponents (FTLE ; Haller 2001) are indicators of transport attractors and barriers, respectively, in the flow induced by the vortices shed by the separating NLIW-driven BBL. Transport barriers are identified as local maxima in the FTLE field and define the boundaries within which fluid is entrained. Particles cannot move through such barriers. At the time depicted, the primary vortices shed of the BBL have completely engulfed intermediate vortices that originated in-between the primary vortices. Fluid above and leading the primary vortices is entrained, contributing to the growth of the vortices. Attractors in the flow are identified by local maxima in the FTLE field determined backward in time. Attractors responsible for the upwelling and re-suspension of particles follow each primary vortex. A superposition of particles on the forward-time FTLE field shows the exact trajectory of resuspended near-bed particles and enables key insight into the physical mechanism underlying resuspension.

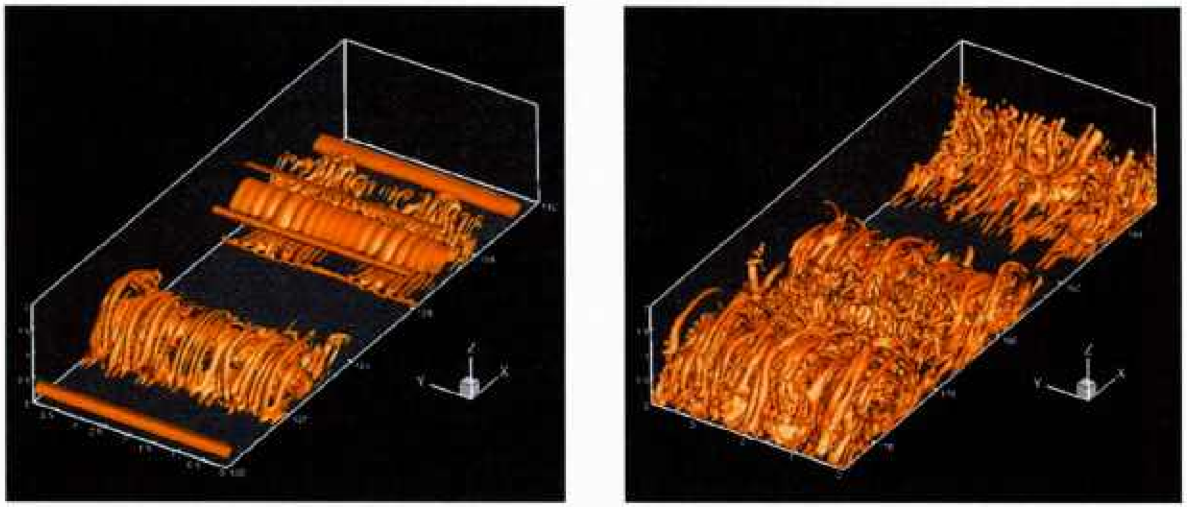

Figure 6: 3-D coherent structures in the self-sustained turbulent near-bed wake in the NLIW-induced BBL in the case with an oncoming barotropic current of strength U_0/c=0.4. These are results from the most recent and ongoing simulations where the correct phase speed of the NLIW is used (accounting for the oncoming current). No volumetric forcing or noise is applied. Left panel: the 2-D vortices shed by the global instability of the separated BBL spontaneously develop a transverse instability. Right panel: Further downstream, each shed vortex has developed a fully turbulent burst that propagates away from the NLIW.

Finally, preliminary results from our computations of NLIW-induced seafloor pressure into a model porous medium (in this case, sand) are shown in Figure 8 for the same wave considered above. For now, we have only examined the bottom pressure field generated by the wave itself and the associated potential of the bed for failure. We are currently exploring the role of the near-bed vortex wake in this regard. The NLIW-induced pressure and the corresponding vertical gradient show adequate penetration into the sand at a depth of 5% of the total water column depth. More analysis is needed to determine the likelihood of bed failure.

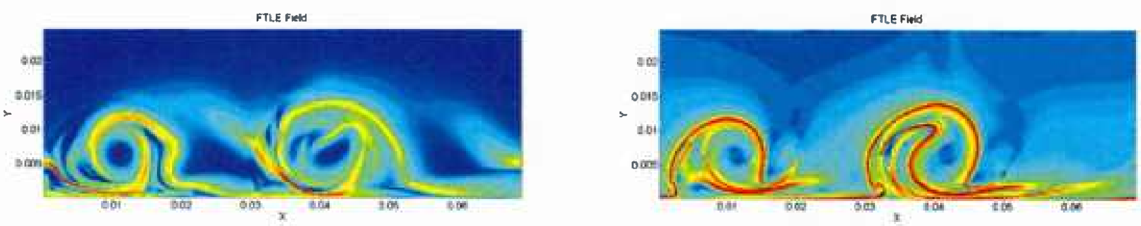

Figure 7: Finite-time Lyapunov exponents (FTLEs) computed via Lagrangian Coherent Structure (LCS) analysis for two shed vortices in the separated NLIW-induced BBL, as generated through 2-D simulations. Left and right panels show forward and backward-time FTLEs which show transport barriers and attractors, respectively, linked to the two particular vortices. Any particles originating from the bed in the right panel will faithfully follow the red contour lines. Ongoing studies are examining the role of this Langragian transport in benthic nepheloid layer formation.

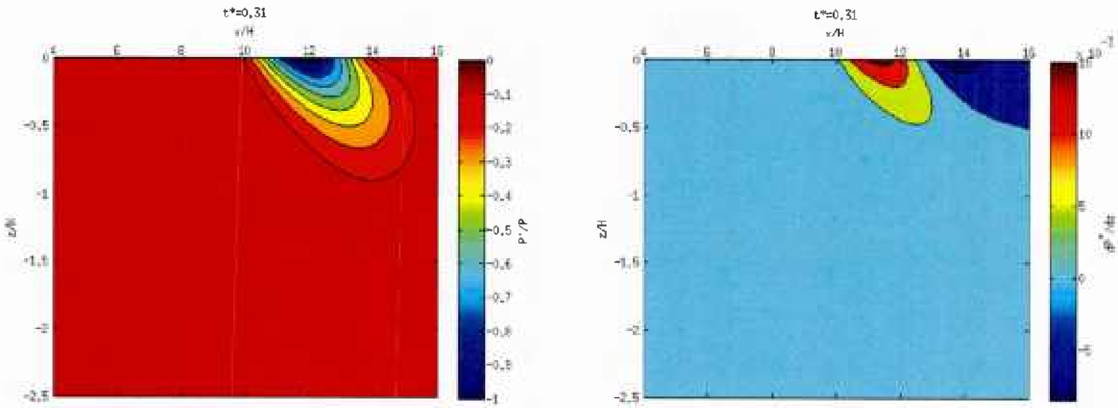

Figure 8: Penetration of NLIW-induced pressure (left) and its vertical pressure gradient (right) into a model sand porous medium underlying a water column of depth H. The wave trough initially (as shown in the snapshots) sits at x/H=12 and moves from right-to-left as the pressure signal in the bed follows along under the wave.

IMPACT/APPLICATIONS

The accurate representation of the structure and magnitude of shear stress field field in the NLIW footprint and accurate estimation of the NLIW energy losses due to bottom interactions will allow the formulation of improved subgrid-scale parameterizations of energy dissipation and bottom boundary conditions for larger-scale operational forecasting models used to simulate environments with high NLIW activity. An enhanced understanding of the underlying physics of the NLIW-driven BBL also provides critical insight on how the bottom shear stress and pressure fields conspire to generate high-amplitude sandwaves, such as those observed in the South China Sea, which can pose significant challenges in efforts of acoustic bathymetry mapping. Finally, the generated resuspended particle distributions under NLIWs, a reliable proxy of BNLs, can be used to quantify the transmission or backscatter of optical/acoustic signals of importance to remote sensing efforts and near-bed SONAR operation.

RELATED PROJECTS

Funded by an NSF-CAREER award in Physical Oceanography and a NDSEG fellowship, a Ph.D. student in the P.I.'s group has completed the design of a high-performance hybrid MPI/open-MPI quadrilateral SMPM code that accounts for variable bathymetry (Escobar-Vargas et al. 2014 and Joshi et al. submitted). This new code will be used to study the shoaling of NLIWs in domains with bathymetry replicating the South China Sea (SCS). In collaboration with Dr. Scott Wunsch, the P.I. recently published an article on the nonlinear generation of harmonics during the impact of an internal wave beam (IWB) on a model sharp oceanic pycnocline and the associated interfacial wave generation (Diamessis et al. 2014). Supported by internal funds, a Ph.D. student in the P.I.'s group is studying the energetics of IWB-pycnocline interaction. Parallel efforts, funded by O.N.R. code 33, have investigated Lagrangian mean flows associated with the reflection of an IWB off a free-slip surface (Zhou and Diamessis submitted --- (a)) and the surface signature of the internal waves radiated by a stratified turbulent wake (Zhou and Diamessis submitted --- (b)) . In collaboration with Prof. Luis Parras at the U. of Malaga, Spain, the P.I. and a Ph.D. student are investigating numerically and theoretically the 2-D and 3-D instability analysis of the BBL under long surface solitary waves (Sadek et al. 2015).

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