Benthic Turbulence and Mixing Induced by Nonlinear Internal Waves

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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 benthic turbulence and bottom particulate resuspension.

OBJECTIVES

The specific objectives of this project are directed towards:

- Characterizing the structure and energetics of the three-dimensional turbulence and mixing in the NLIW-induced time-dependent boundary layer as a function of wave-based Reynolds number and wave amplitude. In particular, we seek to elucidate the potential for the near-bed distribution of the NLIW-induced pressure field to establish a preferred location for benthic turbulence with respect to the wave trough/peak.

- Comparing results of implicit Large Eddy Simulation (LES) of NLIW-induced boundary layers with equivalent field observations to:
    - Flesh out the underlying fluid dynamics.
    - Provide consistency checks for the LES along with means for further refining future simulations.
    - Develop predictive tools for designing future deployments focused towards identifying signatures of energetic NLIW-induced benthic events.

APPROACH

Our approach uses implicit Large Eddy Simulation (LES) based on a spectral multidomain penalty method Navier-Stokes solver developed by the PI (Diamessis et al. 2005) for the simulation of high Reynolds number incompressible flows in vertically finite domains. The advantages of this computational tool lie in its high (spectral) accuracy, spatial adaptivity (straightforward resolution of the active regions of the flow, i.e. the bottom boundary layer and seasonal thermocline) and lack of the artificial dissipation inherent in commonly used low-order accuracy finite difference schemes which

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14. ABSTRACT

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 benthic turbulence and bottom particulate resuspension.

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can spuriously diffuse out critical boundary layer physics. To ensure numerical stability while preserving spectral accuracy at Reynolds number values as close as possible to oceanically relevant values, the numerical scheme is buttressed with explicit spectral filtering and a penalty method in the vertical direction.

Our problem geometry considers a wave fixed in a frame of reference moving with the phase speed of the NLIW through a waveguide of *uniform depth*. Thus, this temporally evolving simulation works in a Lagrangian reference frame. The wave field is introduced into the the Navier-Stokes equations in the form of forcing terms. The equations are then solved for the perturbation velocity/fields (Diamessis and Redekopp 2006) with a no-slip bottom boundary condition.

WORK COMPLETED

Funding of the project did not officially begin until mid-July 2007. In September 2007, a manuscript was submitted to the Journal of Physical Oceanography (Bogucki et al. 2008) discussing a comparison between results obtained from 2-D numerical simulations (recast in a Eulerian reference frame) and equivalent observations in limited portions of the near-bed measurements made as part of the ONR-funded Coastal Mixing and Optics 1996 (CMO 96) field experiment. Reviews of the manuscript emphasized the need for 3-D simulations for a reliable comparison with the data from the actual oceanic boundary layer. As originally proposed in this project, we are consistently working in generating 3-D results which will be incorporated in the revised manuscript but will also serve as the core of an additional paper focused on the 3-D evolution of the NLIW-induced boundary layer.

Based on the theoretical model of Sakai and Redekopp (2007) we have constructed *fully* nonlinear internal waves which can be readily incorporated in our Navier-Stokes solver. Fully nonlinear waves have been computed for values of the ratio of upper to lower layer thickness, h_1/h_2 within the range [1/10,1/3] (Figure 1). For a given value of h_1/h_2, wave amplitudes are bound by the conjugate state limit (Lamb and Wan 1998). Significant care has been taken for the wave velocity field to transition smoothly to the free-lsip condition at the top surface. The thermocline thickness is chosen to be a factor of two larger than that of the wave velocity shear layer to prevent the formation of any Kelvin-Helmholtz instabilities which can significantly alter the structure of the wave and the associated pressure field imprinted on the bed.

Our 3-D MPI-parallel Navier-Stokes solver was ported to the Army Research Lab's MJM & JVN Linux clusters. Note that this code had been running reliably for 3 years on both the University of Southern California and Cornell clusters and has been used to simulate high Reynolds number stratified wakes (Diamessis and Spedding 2007). During this summer, 6 weeks were spent to remedy a memory leak problem associated with the parallel data transposition routines used in the 2-D Fast Fourier Transforms (FFTs) and the processor interconnect technology (Infiniband) and software specific to ARL. With the help of the ARL consulting staff and Dr. Kraig Winters of Scripps I.O., we designed new parallel data transposition routines which, in early September 2008, were found to work well on the ARL cluster.

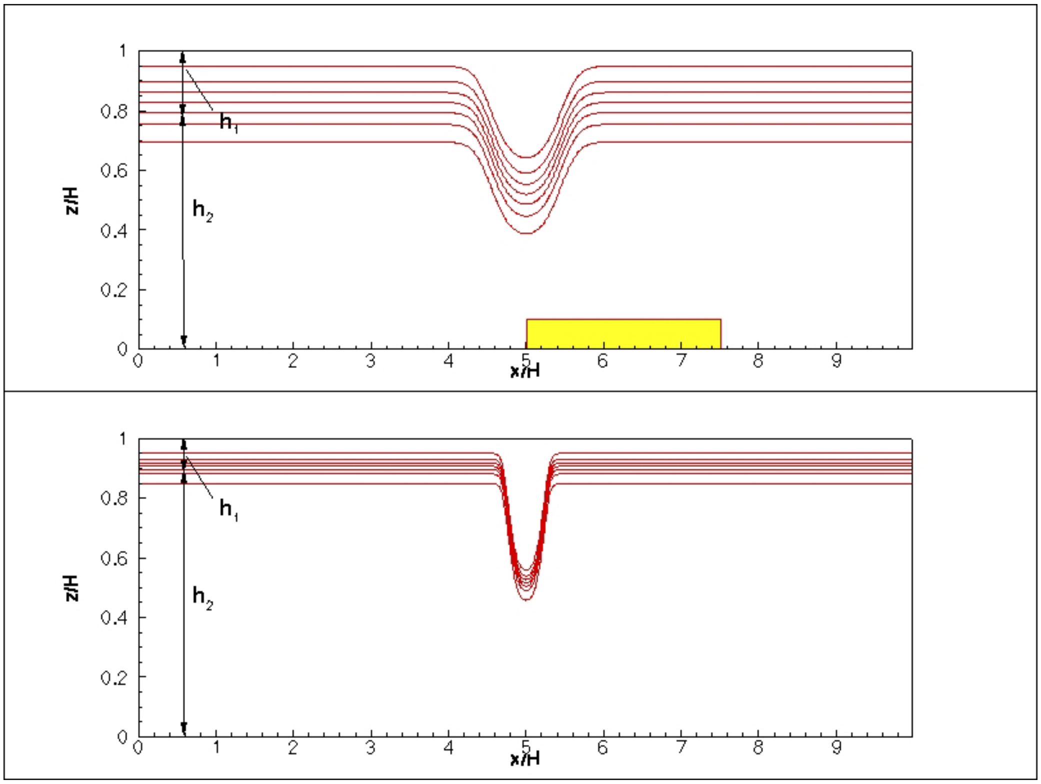

Figure 1: Isopycnal surfaces for the fully nonlinear internal waves used in our LES [Top Panel: Configuration with h_1/h_2=5 and wave amplitude of 0.33. Bottom Panel: Configuration with h_1/h_2=10 and wave amplitude of 0.39. Wave amplitude is defined as the maximum thermocline displacement normalized by water depth. The thermoclines are chosen intentionally thick to prevent the formation of Kelvin-Helmholtz instabilities as the simulation evolves. The highlighted box corresponds to the near-bed region examined in detail in figure 3.]

Discussions with Profs. Jim Moum and Jonathan Nash of the Oregon State Ocean Mixing group, initiated in the summer of 2007, continued at the March 2008 AGU Ocean Sciences meeting. These discussions have significantly helped focus the planned comparison of field observations with the soon-to-be-generated 3-D model results. In addition, Prof. Tim Stanton of N.P.S. visited Cornell in mid-September 2008 and has agreed with the P.I. to pursue an active comparison between 3-D LES results with data from the bottom boundary layer in Monterey Bay (see next section).

RESULTS

The strategy for our planned production runs was to initialize the 3-D runs with results from 2-D runs sampled upon the onset of instability in the separated region of the NLIW-induced boundary layer. At that point, we had expected the initial instability to be purely two-dimensional. However, our 2-D runs with fully nonlinear waves did not generate an instability in the separated flow under the wave for a broad range of values of h_1/h_2. Nevertheless, the recently published laboratory results of Carr et al. (2008) do reveal a visible vortex shedding pattern near the bed after the passage of a NLIW of depression (figure 2).

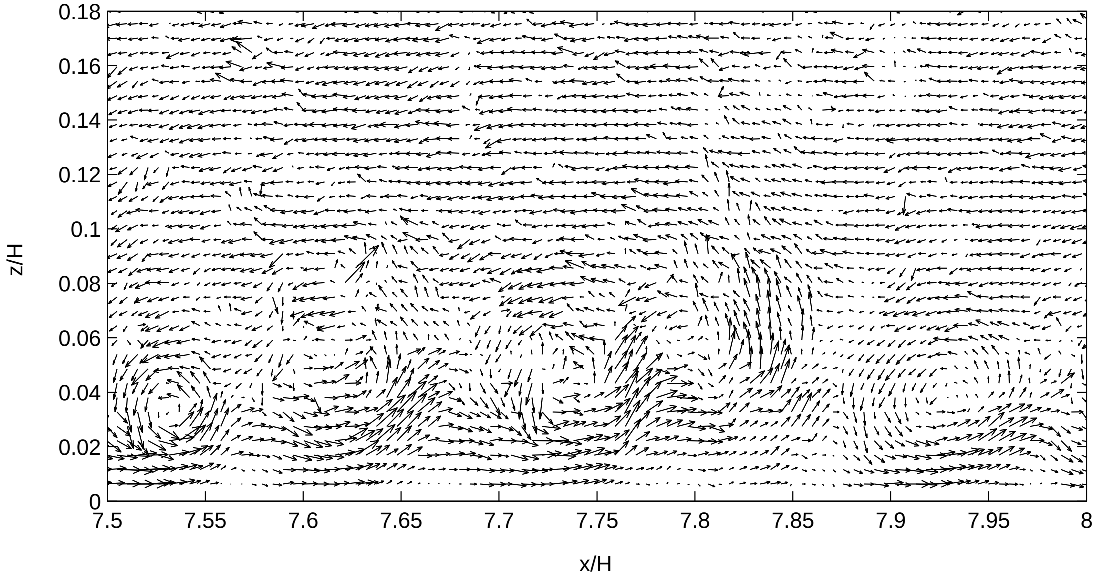

Figure 2: Velocity vectors in the lee of a NLIW of depressionf in the laboratory experiments of Carr et al. (2008) (courtesy of Dr. Magda Carr).
[The wave is propagating from left to right and its trough is centered at x/H = 13. The lab-generated vortices do not ascend as high as in previous 2-D simulations (Diamessis and Redekopp 2006) due to 3-D effects. The specific experiment has been performed in a two-layer system with $h_1/h_2=5$ and a Reynolds number, $Re=CH/\nu=10^5$ (C and H are the NLIW phase speed and H the waveguide depth, respectively). The wave amplitude is 0.28.]

For a fully nonlinear wave, we had originally anticipated that, at a given wave Reynolds number (based on wave phase speed and water depth), a near-bed instability would be triggered at even lower wave amplitudes than those required for weakly non-linear waves (Diamessis and Redekopp 2006) ; The steeper fully nonlinear waves induce a sharper near-bed adverse pressure gradient (APG) and presumably stronger boundary layer separation. Closer examination of results from 2-D runs with fully nonlinear waves (figure 3) show that, upstream of the distinct reversals in the near-bedNLIW-induced horizontal velocity, a near-wall jet structure is observed. As a result, the boundary layer does note reattach and no separation bubble forms. We attribute this behavior to the narrower waveform of fully nonlinear waves. The broader wave profiles of weakly nonlinear waves provide for a larger streamwise extent of the separation region.

We began exploring possible strategies for achieving the reattachment of the separated boundary layer runder fully nonlinear waves. To this end, the introduction of an oncoming background current (a model for an idealized tidally-driven boundary layer) was found to be an efficient solution. The only condition is that the background current reach its free stream value at a distance above the bed larger than the vertical lengthscale of the flow reversal region. In that case, an inflection point does indeed develop in the horizontal velocity profile and a distinct separation bubble is established (figure 3).

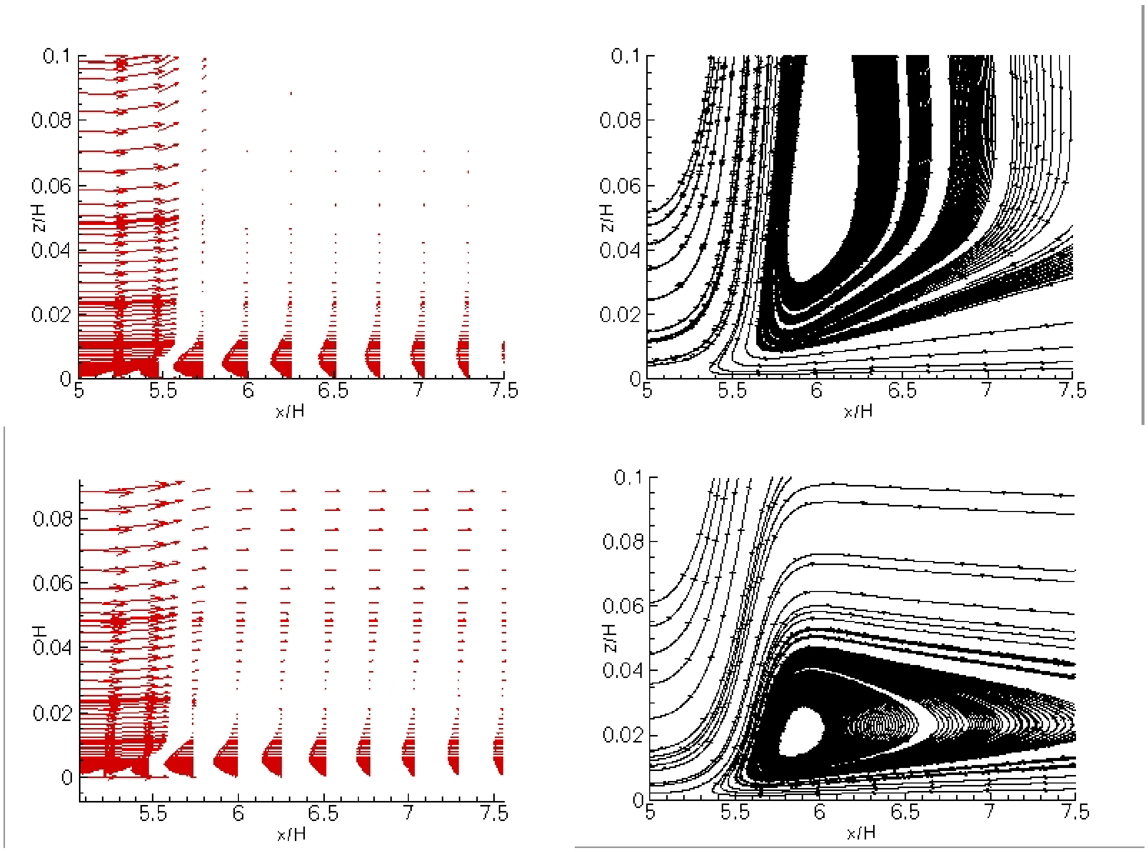

Figure 3: Near-bed velocity fields from 2-D simulations of the boundary layer induced by a NLIW of depression
[Simulations are performed in a two-layer system with $h_1/h_2=5$ in waveguide of depth H. The Reynold number is equal to $Re=CH/\nu=10^5$. The wave is centered at x/H=5, propagates from right to left with a phase speed C and has an amplitude of 0.33. The left column shows velocity vector profiles sampled every 20 streamwise grid points and the right column shows the corresponding instantaneous streamlines. The data are sampled after the wave has propagated a distance of 25H. In the top row, the NLIW propagates against no oncoming current and the near-bed streamlines in the rear of the wave trough are open up to z/H=0.6. The boundary layer is unable to reattach and no separation bubble is observed. In the bottom row, an idealized oncoming barotropic tidal current has been introduced which reaches its maximum value of 0.4|C| at a height z/H=0.25. A zero-crossing point is now present in the velocity profile which enables the formation of a robust separation bubble.]

Nevertheless, despite having added an oncoming current, we were unable to destabilize any 2-D NLIW-induced boundary layers. Now, for a value of $h_1/h_2=5$, the vortex shedding observed in the experiments of Carr et al. occurred for waves with amplitudes of lower than those considered in our 2-D simulations. We thus concluded that the instability is inevitably 3-D in nature.

Specifically, our proposed mechanism of benthic excitation under a NLIW is driven by a large-scale APG established in a manner analogous to that occurring over an airfoil at incidence. Jones et al.

(2008) have found that the separation region on an inclined airfoil is susceptible to a three-dimensional instability once the appropriate oscillatory forcing is introduced. This 3-D instability occurs for much weaker levels of boundary layer separation than those required for the corresponding 2-D instability. Furthermore, because this is an absolute instability, the vortex shedding and wake-like structure persist well after the forcing is turned off. Finally, as shown in figure 4, vortical structures with considerable spanwise coherence are ejected out of the APG region after the excitation is shut off.

Extrapolating from the inclined airfoil to the NLIW-induced boundary layer, 3-D instabilities are likely to occur for much weaker wave amplitudes than those required for a 2-D instability and can persist in the form of a self-sustained near-bed wake structure over a long time during the wave evolution.

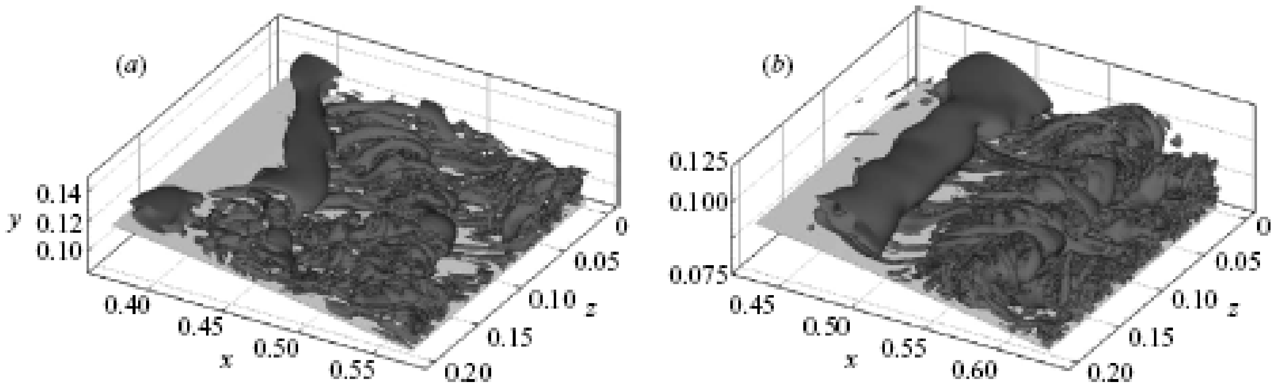

Figure 4. Isosurfaces of high values the second invariant, Q of the velocity gradient tensor from simulations of boundary separation of an airfoil at incidence at high Reynolds number (Jones et al., 2008)
[Q is an indicator of coherent vortical structure in a flow field. An inclined airfoil in a free stream produces boundary layer instability and turbulence that is very analogous to that under a NLIW, on account of the presence of a large-scale adverse pressure gradient. Left Panel: Flow structure in the separation region when high frequency periodic forcing is turned on. Right Panel: Flow structure in the same region after the forcing has been shut off. In the latter case, vortex structures with significant spanwise coherence are ejected into the ambient.]

Our ongoing efforts in configuring 3-D NLIW-induced bottom boundary layer LES are focused towards identifying the appropriate forcing functions for the Navier-Stokes equations that will trigger instability and transition to turbulence in the separated flow region. Following the necessary stability analysis, the appropriate location and frequency of these forcing functions have been determined. We have just begun (in late September 2008) running preliminary 3-D simulations. We are confident that our full 3-D production runs will be completed by early January.

Analysis of 3-D simulation results will focus on examining the degree of spanwise coherence in the NLIW-induced boundary layer and its impact on near-bed vertical velocity fields and the distribution of the bottom shear stress. The spatially and temporally integrated bottom shear stress fields will enable a reliable estimate of the NLIW energy dissipation due to wave-seafloor interactions and its impact on along-path energy transport by NLIWs (Moum et al. 2007). Finally, Prof. Stanton has obtained a wealth of (unpublished) data in 15 m deep waters and 1km offshore as part of the Monterey Inner Shelf Observatory (MISO). Such data includes unprecedented detail on 3-D velocity profiles over 1m range above the bed measured by a 1cm resolution bistatic coherent Doppler profiler (BCDVSP). The corresponding ADCP data reveals NLIW of depression (amplitude 5 to 6m) riding on internal bores. Both bores & embedded NLIWs remain surprisingly intact for such a close distance to the shore. We have agreed with Prof. Stanton to isolate a number of NLIW events recorded by his data and to focus on the bottom shear stress fields recorded by the BCDVSP upon passage of the wave. A comparison with the shear stress fields reproduced by the LES will provide further insight on the role of the wave-induced near-bed APG in generating enhanced benthic turbulence.

IMPACT/APPLICATIONS

The benthic dissipation and mixing induced by NLIWs are linked to the terminal stage of an energetic cascade process which decides the fate of the large-scale energy input into the ocean and tides. Accurate parameterization of these mechanisms of NLIW energy is of paramount importance for the reliable performance of operational coastal ocean models. The unstable/turbulent boundary layer in the footprint of a NLIW can drive significant resuspension of biogeochemical constituents which impacts directly ocean optics and acoustics and the functionality of near-bed instrumentation. The current work will provide further insight into the physical mechanisms of the above dissipative and resuspension processes, their signatures in field observations and their implications for operational forecast modeling and remote sensing.

RELATED PROJECTS

A graduate student, Jorge Escobar-Vargas, supported by internal funds and supervised by the PI is currently developing a spectral *quadrilateral* multidomain penalty method solver for high Reynolds incompressible flows in doubly non-periodic domains. The full Navier-Stokes solver (the key remaining code development task is the implementation of an efficient Poisson equation solver) is anticipated for spring 2009 and further funding has been applied for by the PI through the NSF-OCE CAREER Award. Availability of such a solver will enable the investigation of the shoaling of NLIWs over gentle slopes (i.e. propagation over *variable depth*), with a focus on wave-scale interactions and their effect on benthic excitation mechanisms and the formation of trapped recirculation cores. Drs. Ren-Chieh Lien of A.P.L., U. Wash. and Ben Reeder of N.P.S. have shown an active interest in comparing their data from the South China Sea with results from this new solver. In collaboration with Prof. Todd Cowen (Civil & Env. Eng., Cornell), we have obtained a wealth of data from thermistor chains deployed in Cayuga Lake, as part of an effort to characterize the nonlinear internal wave weather in this prototypical lake. Deployment data continues to be analyzed with Prof. Leon Boegman (Civil & Env. Eng., Queens Univ., Canada) serving as a technical consultant. The P.I. is co-advising a graduate student of Prof. Boegman's in using MIT-G.C.M. to perform fully non-hydrostatic field scale simulatoins of the internal wave field in Cayuga Lake. Later stages of this collaboration will involve using the quadrilateral multidomain code under development to investigate the breaking of NLIWs on steep slopes. Finally, the P.I. is serving as a co-P.I. with Prof. Phil Liu (Civil and Env. Eng., Cornell) in a recently-funded N.S.F.-CBET project which uses the P.I.'s spectral multidomain code to examine the unstable boundary layer under different types of surface waves.

REFERENCES

Carr, M., Davies, P.A. and Shivaran, P. 2007 Experimental evidence of internal solitary wave-induced global instability in shallow water benthic boundary layers, ***Phys. Fluids***, 20, Art No. 0666031

Diamessis, P. J., Domaradzki, J. A. and Hesthaven, J. S. 2005 A spectral multidomain penalty method model for the simulation of high Reynolds number localized stratified turbulence. ***J. Comp. Phys.***, 202:298–322.

Diamessis, P. J. and Redekopp, L.G. 2006 Numerical investigation of solitary internal wave-induced global instability in shallow water benthic boundary layers. ***J. Phys. Oceanogr.***, 36(5):784–812.

Diamessis, P.J. and Spedding, G.R. 2006 Scaling and Structure of Stratified Turbulent Wakes at High Reynolds Number (*Proceedings of 6th Intnl. Conf. on Stratified Flows, Perth, Australia*).

Jones, L.E., Sandberg, R.D. and Sandham, N.D. 2008 Direct numerical simulations of forced and unforced separation bubbles on an airfoil at incidence. ***J. Fluid Mech.***, 602:175–207.

Lamb, K. G. and B. Wan, B. 1998 Conjugate flows and flat solitary waves for a continuously stratified fluid. ***Phys. Fluids***, 10:2061–2079.

Moum, J., J. Klymak, J. Nash, A. Perlin, and W. Smyth, 2006 Energy Transport by Nonlinear Internal Waves. ***J. Phys. Oceanogr.,*** 37, DOI: 10.1175/JPO3094.1

Sakai, T. and Redekopp, L.G. 2007 Models for strongly-nonlinear evolution of long internal waves in a two-layer stratification 2007 ***Nonlinear Processes in Geophysics,*** 14 (1): 31-47

PUBLICATIONS

Diamessis, P.J., Lin, Y.C. and Domaradzki, J.A. 2008: Effective numerical viscosity in spectral multidomain penalty method-based simulations of localized turbulence. ***J. Comp. Phys.,*** 227, 8145-8164.

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