

## **Turbulent Flow and Large Surface Wave Events in the Marine Boundary Layers**

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### **LONG-TERM GOALS**

The long term objective of our research for the “High Resolution Air-Sea Interaction” (HIRES) Departmental Research Initiative (DRI) is to identify the couplings between large wave events, winds, and currents in the surface layer of the marine boundary layers. Turbulence resolving large eddy simulations (LESs) and direct numerical simulations (DNSs) of the marine atmospheric boundary layer (MABL) in the presence of time and space varying wave fields will be the main tools used to elucidate wind-wave-current interactions. A suite of turbulence simulations over realistic seas using idealized and observed pressure gradients will be carried out to compliment the field observations collected in moderate to high winds. The database of simulations will be used to generate statistical moments, interrogated for coherent structures, and ultimately used to compare with HIRES observations.

### **OBJECTIVES**

Our near term goals are: 1) participate in the planning process for the HIRES field campaign; and 2) construct an LES code applicable to the HIRES high wind regime. In order to accomplish the latter goal we are improving the parallelization of our base LES code and developing an algorithm to allow simulations of turbulent winds over nearly arbitrary 3-D wave fields.

### **APPROACH**

We plan on investigating interactions between the MABL and the connecting air-sea interface using both LES and DNS. The waves will be externally imposed: (1) based on well established empirical wave spectra; or (2) ultimately provided by direct observations of the sea surface from field campaigns. The main technical advance is the development of a computational tool that

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allows for nearly arbitrary 3-D wave fields, *i.e.*, the sea surface elevation  $h = h(x, y, t)$  as a surface boundary condition. The computational method will allow time and space varying surface conditions over a range of wave scales  $\mathcal{O}(10)$ m or larger.

## WORK COMPLETED

**Meetings:** We attended PI meetings in La Jolla CA that focused on refining elements of the HIRES field campaign. The discussion concentrated on the atmospheric measurements to be collected from aircraft and from R/V FLIP with particular attention paid to the surface layer pressure measurements. We also spent several days at the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS), in Monterey CA, while the HIRES field campaign was underway in June 2010.

**Algorithmic Developments and Simulations:** During the past year we completed adapting our parallel LES code (Sullivan & Patton, 2008) to accommodate a general 3D time varying wavy surface. This was accomplished in the following stages: a) Develop the governing equations for an atmospheric PBL in curvilinear time-dependent surface-following coordinates; b) Build and test a module capable of generating a 3D wavy surface; and c) Implement and test a) and b) in our “flat bottom” parallel LES code for the atmospheric PBL. Extensive testing of the code is underway. A description of the code and first results are described in Sullivan *et al.* (2010a). We note that the formulation is general and also allows turbulence simulations over and around 3D stationary orography as described in Sullivan *et al.* (2010b) <sup>1</sup>.

Here we briefly highlight a process study that examines the influence of wave age on the dynamics of the marine atmospheric surface layer. In these simulations the geostrophic wind is varied from  $U_g = (5, 7.5, 10, 15, 20)$  m s<sup>-1</sup> for a neutrally-stratified marine PBL in a domain  $(X_L, Y_L, Z_L) = (1200, 1200, 800)$  m using  $(N_x, N_y, N_z) = (512, 512, 128)$  gridpoints. Thus the horizontal grid spacing  $\Delta x = \Delta y = 2.34$  m and the first vertical level is 1 m above the water. The synthetic surface wavefield is built to match a Pierson and Moskowitz (1964) wave spectrum with random phases. A directional spectrum is picked to emphasize long crested waves. An  $x - y$  view of the 3D surface wave field is given in figure 1 and an  $x - z$  slice of the computational mesh above this wavefield is given in figure 2. The initial temperature sounding  $\bar{\theta} = 300$  K up to the inversion height  $z_i = 400$  m, beyond this height  $\bar{\theta}$  increases linearly at  $3 \times 10^{-3}$  K m<sup>-1</sup>. The surface heating  $Q_* = 0$ , the surface roughness  $z_o = 0.0002$  m, and the Coriolis parameter  $f = 10^{-4}$  s<sup>-1</sup>. The wavefield is built based on the assumption of a surface wind speed of 15 m s<sup>-1</sup> and the phase speed of the peak in the spectrum  $C_p \sim 18$  m s<sup>-1</sup>. Thus the suite of simulations allows us to examine a wide variation of wave age from swell dominated to near wind-wave equilibrium. Table 1 lists bulk properties of the simulations, *viz.*, the geostrophic wind, wave age, and friction velocity  $u_*$ .  $U_{10}$  is the reference wind speed at a height of 10 m. The simulations are run for more than 50,000 timesteps using restart volumes with fully developed turbulence. The iteration count in the pressure Poisson solver is typically set to 30 and the calculations run on either 512 or 1024 computational cores.

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<sup>1</sup>The meeting papers Sullivan *et al.*, (2010a,b) are available at <http://www.mmm.ucar.edu/people/sullivan/>.

**Table 1:** Simulation properties

Run	$U_g$ (m s <sup>-1</sup> )	$C_p/U_{10}$	$u_*$ (m s <sup>-1</sup> )
<i>A</i>	5	4.8	0.124
<i>B</i>	7.5	3.4	0.187
<i>C</i>	10	2.8	0.228
<i>D</i>	15	1.9	0.338
<i>E</i>	20	1.5	0.452

## RESULTS

Previous field observations, turbulence closure modeling, and our own idealized LES (see discussion in Sullivan *et al.*, 2008) all show that fast moving swell can induce marked changes in the atmospheric surface layer winds, *viz.*, an upward momentum flux from the ocean to the atmosphere, a low-level wind maximum, and departures from law-of-the-wall scaling. The preliminary LES computations performed here over a more realistic sea surface are in good qualitative agreement with the previous studies but suggest the impact of swell on the surface layer winds is sensitive to the content of the wave spectrum.

One of the surprising results from the present simulations is the significant impact of swell on the coherence and magnitude of the near-surface pressure fluctuations. This is illustrated in figure 3 where we compare  $p'/\rho$  for two levels of wind forcing  $U_g = (5, 20)$  m s<sup>-1</sup>, *i.e.*, a low-wind situation with swell and a high wind case approaching wind-wave equilibrium. The difference in the pressure signals is striking and even more remarkable in animations of the pressure field. In the low-wind swell case there is a very strong correlation between  $p'/\rho < 0$  and wave crests and similarly between  $p'/\rho > 0$  and wave troughs that extends over the depth of the surface layer. Inspection of the flow visualization and animations reveals that the strong correlation persists across the range of resolved waves, *i.e.*, both large and small scale waves appear to induce a similar pressure pattern. The coherence of the wave induced pressure field can extend to 20 m or more depending on the amplitude of the underlying wave. Also, the pressure signatures propagate at the speed of the wavefield, additional evidence that the signals are generated by surface waves and not atmospheric processes. These are clear signatures of “wave pumping” by the surface wavefield on the atmosphere. The amplitude of the wave spectrum (and hence the level of wave forcing) is held constant in our simulations but the magnitude of the turbulence, as measured by  $u_*$ , increases substantially with increasing wind speed. The structure of the near surface pressure field is a result of these two competing effects. At low winds coherent pressure signals are generated by the wave motions when the turbulence is weak but this coherence is destroyed by strong turbulence at higher winds.

Figure 4 shows that the impact of wave age also appears in the vertical velocity fields. In the low-wind swell regime we observe large-amplitude large-scale fluctuations in  $w'$ . At higher winds the spatial coherence of  $w'$  is destroyed by strong turbulence. Note each panel in figure 4 is sampled at the sample height above the wavefield. Also, the fields are made dimensionless by friction velocity  $u_*$  which further illustrates the strong impact of the wave motions on the winds in the surface layer.

In figure 5 we compare vertical profiles of the mean wind speed and turbulence variances for the different simulations. These statistics are computed by averaging in computational coordinates, *i.e.*, across horizontal planes at constant vertical height  $\zeta$ . Similar to our previous simulations we find that the wind speed and turbulence variances depend on wave age. At high winds as the simulations approach wind-wave equilibrium, the non-dimensional wind profile  $\langle U \rangle / u_*$  smoothly approaches the variation predicted by law-of-the-wall. Significant differences are observed for the cases dominated by swell: the surface layer winds are accelerated compared to rough wall scaling. As suggested by the flow visualization, the turbulence variances respond to the wave motion in dramatic ways. The horizontal and vertical variances are significantly enhanced by the motion of the wave surface in the low-wind cases. Even though the turbulence is relatively weak the turbulence variances are large near the wave surface due to wave pumping.

## IMPACT/APPLICATIONS

The computational tools developed and the database of numerical solutions generated will aid in the interpretation of the observations gathered during the past HIRES field campaign. In addition idealized process studies performed with the simulations have the potential to improve parameterizations of surface drag under high wind conditions in large scale models. Also future computations will utilize wave fields measured from a conventional marine X-Band radar, *i.e.*, WAMOS see <http://www.oceanwaves.org>.

## TRANSITIONS & RELATED PROJECTS

The current work is a collaborative effort between NCAR, numerous university investigators and international research laboratories. Also the present work has links to the ONR DRI on the impact of typhoons in the Western Pacific Ocean (ITOP).

## REFERENCES

Pierson, W. J. & L. Moskowitz, 1964: A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii. *Journal of Geophysical Research*, **69**, 5181-5190.

Sullivan, P. P., J. B. Edson, T. Hristov, & J. C. McWilliams, 2008: Large eddy simulations and observations of atmospheric marine boundary layers above non-equilibrium surface waves. *Journal of the Atmospheric Sciences*, **65**, 1225-1245.

Sullivan, P. P. & E. G. Patton, 2008: A highly parallel algorithm for turbulence simulations in planetary boundary layers: Results with meshes up to  $1024^3$ . *18th Conference on Boundary Layer and Turbulence*, Stockholm, Sweden.

Sullivan, P.P., 2010a: Large eddy simulation of high wind marine boundary layers above a spectrum of resolved moving waves. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

Sullivan, P.P., E. G. Patton & K. W. Ayotte, 2010b: Turbulent flow over and around sinusoidal bumps, hills, gaps and craters derived from large eddy simulations. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

Thomas, P.D. & C. K. Lombard, 1979: Geometric conservation law and its application to flow computations on moving grids. *AIAA Journal*, **17**, 1030-1037.

## PUBLICATIONS

Liang, J-H., J. C. McWilliams, P. P. Sullivan & B. Baschek, 2010: Modeling bubbles and dissolved gases in the ocean. *Journal of Geophysical Research - Oceans*, [submitted].

Moeng, C.-H. Moeng, P. P. Sullivan, M. F. Khairoutdinov, & D. A. Randall, 2010: A mixed scheme for subgrid-scale fluxes in cloud-resolving models. *Journal of the Atmospheric Sciences*, [accepted].

Suzuki, N., T. Hara, & P. P. Sullivan, 2010: Turbulent airflow at young sea states with frequent wave breaking events: Large eddy simulation. *Journal of the Atmospheric Sciences*, [submitted].

Patton, E. T. Horst, P. Sullivan, D. Lenschow, S. Oncley, W. Brown, S. Burns, A. Guenther, A. Held, T. Karl, S. Mayor, L. Rizzo, S. Spuler, J. Sun, A. Turnipseed, E. Allwine, S. Edburg, B. Lamb, R. Avissar, R. Calhoun, J. Kleissl, W. Massman, K. Paw-U, & J. Weil, 2010: The canopy horizontal array turbulence study (CHATS). *Bulletin of the American Meteorological Society*, [submitted].

Kukulka, T., A. J. Plueddemann, J. H. Trowbridge, & P. P. Sullivan, 2010: Rapid mixed layer deepening by the combination of Langmuir and shear instabilities- a case study. *Journal of Physical Oceanography*, [in press].

Hanley, K. E., S. E. Belcher & P. P. Sullivan, 2010: A global climatology of wind-wave interaction. *Journal of Physical Oceanography*, **40**, 1263-1282.

Kelly, M., J. C. Wyngaard & P. P. Sullivan, 2009: Application of a subfilter scale flux model over the ocean using OHATS field data. *Journal of the Atmospheric Sciences*, **66**, 3217-3225.

Nilsson, E., A. Rutgersson, & P. P. Sullivan, 2009: Flux attenuation due to sensor displacement over sea. *Journal of Atmospheric and Oceanic Technology*, [in press].

Sullivan, P.P., 2010: Large eddy simulation of high wind marine boundary layers above a spectrum of resolved moving waves. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

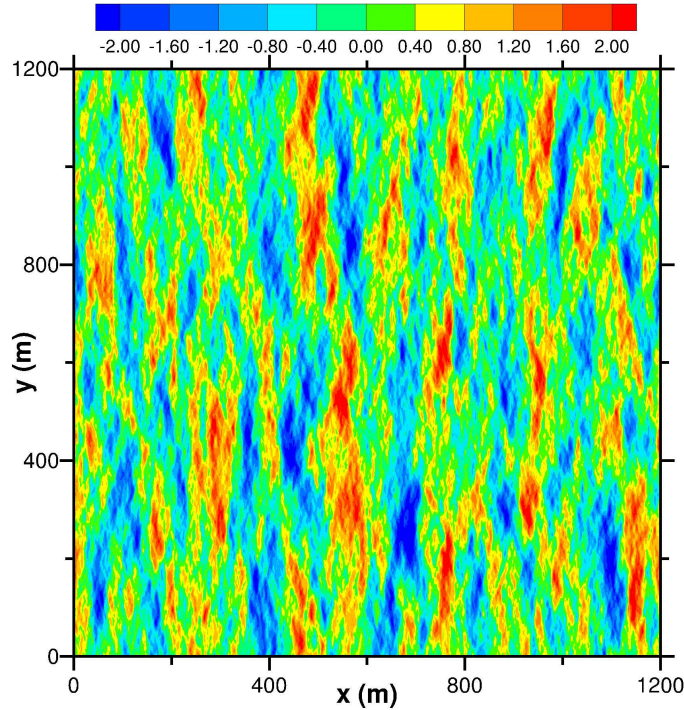
Sullivan, P.P., E. G. Patton & K. W. Ayotte, 2010: Turbulent flow over and around sinusoidal bumps, hills, gaps and craters derived from large eddy simulations. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

Mironov, D. V. & P. P. Sullivan, 2010: Effect of horizontal surface temperature heterogeneity on turbulence mixing in the stably stratified atmospheric boundary layer. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

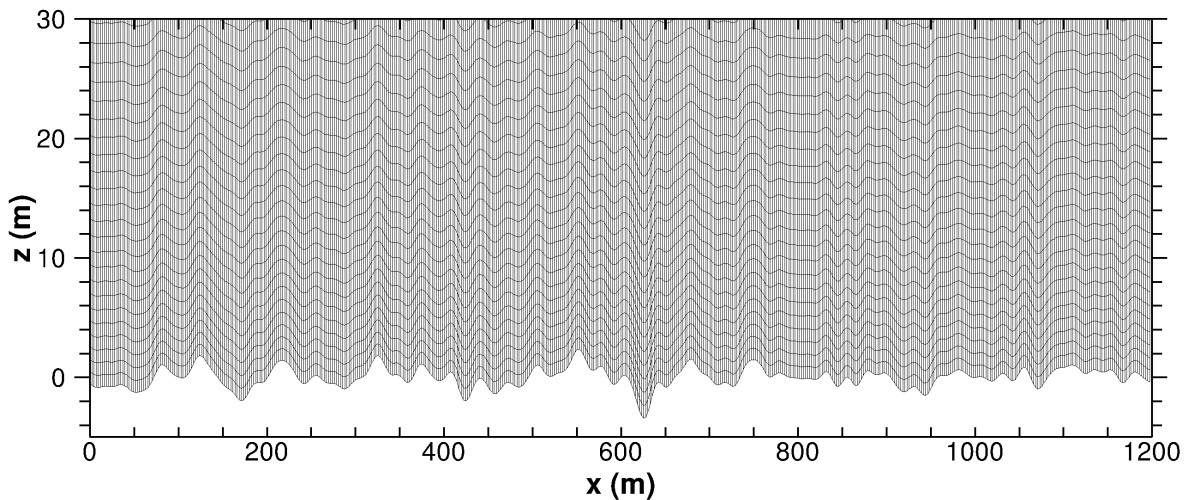
Jonker, H. J. J., P. P. Sullivan, E. G. Patton & M. van Reeuwijk, 2010: Direct numerical simulation of entrainment in dry convective boundary layers. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

Nilsson, E., A. Rutgersson & P. P. Sullivan, 2010: Similarities between atmospheric boundary layers influenced by free convection and surface waves. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.

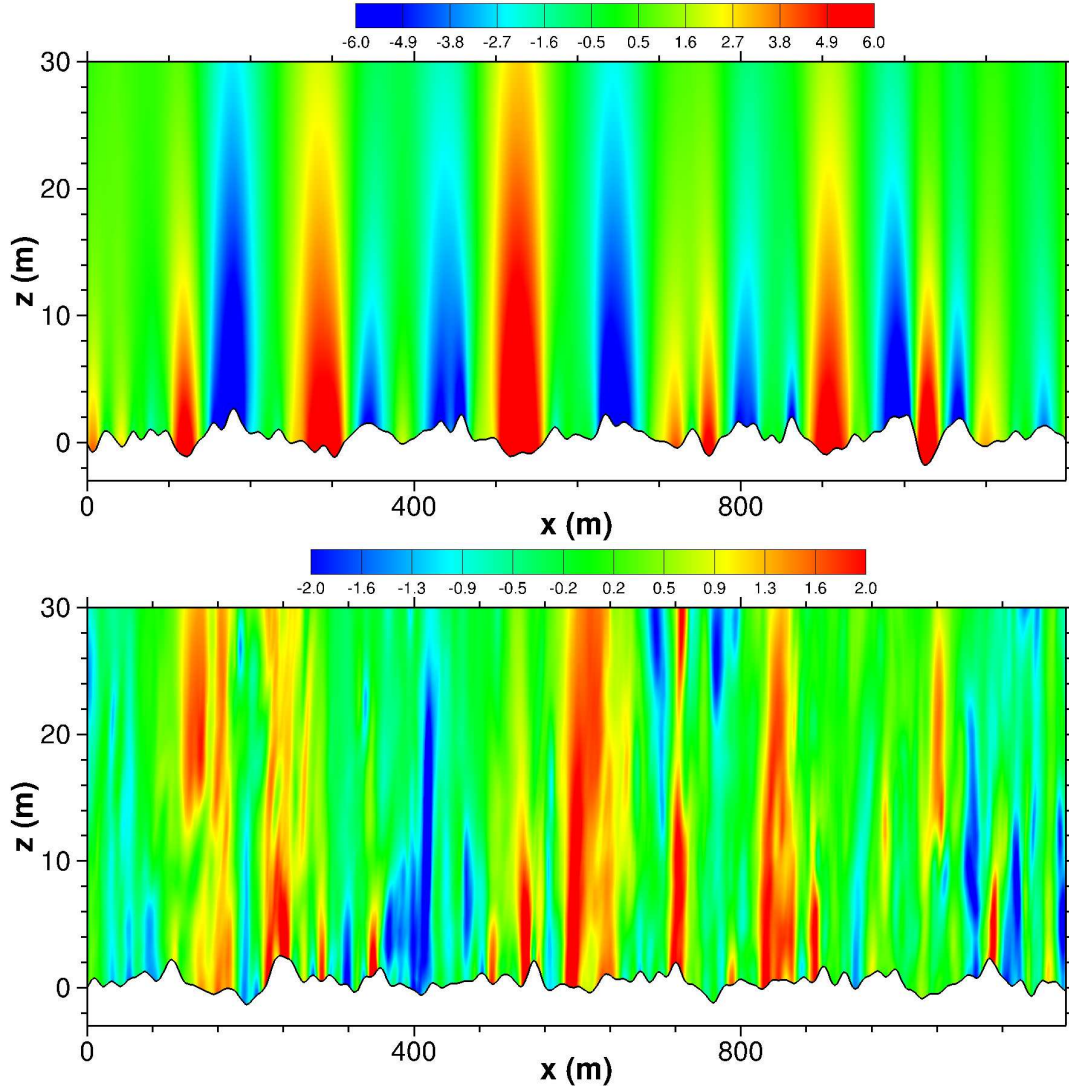
- Weil, J. C., E. G. Patton & P. P. Sullivan, 2010: Line-source diffusion in a walnut orchard canopy during CHATS. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.
- Patton, E. G., J. C. Weil & P. P. Sullivan, 2010: Impact of a coupled canopy-soil model on canopy-resolving turbulence simulation. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.
- Nguyen, K. X. S. P. Oncley, T. W. Horst, P. P. Sullivan & C. Tong, 2010: Investigation of subgrid-scale turbulence in the atmospheric surface layer using AHATS field data. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.
- Kang, S-L., D. Lenschow, P. Sullivan & P. Mininni, 2010: Significance of mesoscale surface heterogeneity in wind speed forecasting. *19th Symposium on Boundary Layers and Turbulence*, Keystone, CO.
- Ayotte, K., P. P. Sullivan & E. G. Patton, 2010: LES and wind tunnel modelling over hills of varying steepness and roughness. *5th International symposium on computational wind engineering*, Chapel Hill, NC.
- Lothon, M., D. H. Lenschow, G. Canut, S. D. Mayor & P. P. Sullivan, 2010: Measurements of higher-order turbulence statistics in the daytime convective boundary layer from a ground-based Doppler lidar. *International Symposium for the Advancement of Boundary Layer Remote Sensing*, Paris.
- Sullivan, P. P., J. C. McWilliams, W. K. Melville, 2010: Ocean boundary layers driven by high winds and wave effects. *Ocean Sciences Meeting*, Portland, OR.
- Liang, J., J. C. McWilliams, P. P. Sullivan, 2010: Modeling the gas bubbles in the oceanic boundary layer. *Ocean Sciences Meeting*, Portland, OR.
- Kukulka, T., A. J. Plueddemann, J. J. Trowbridge, P. P. Sullivan, 2010: The role of Langmuir turbulence during a rapid mixed-layer deepening event. *Ocean Sciences Meeting*, Portland, OR.
- Suzuki, N., T. Hara, & P. P. Sullivan, 2010: Turbulent airflow at young sea states with frequent wave breaking events: Large eddy simulation. *Ocean Sciences Meeting*, Portland, OR.



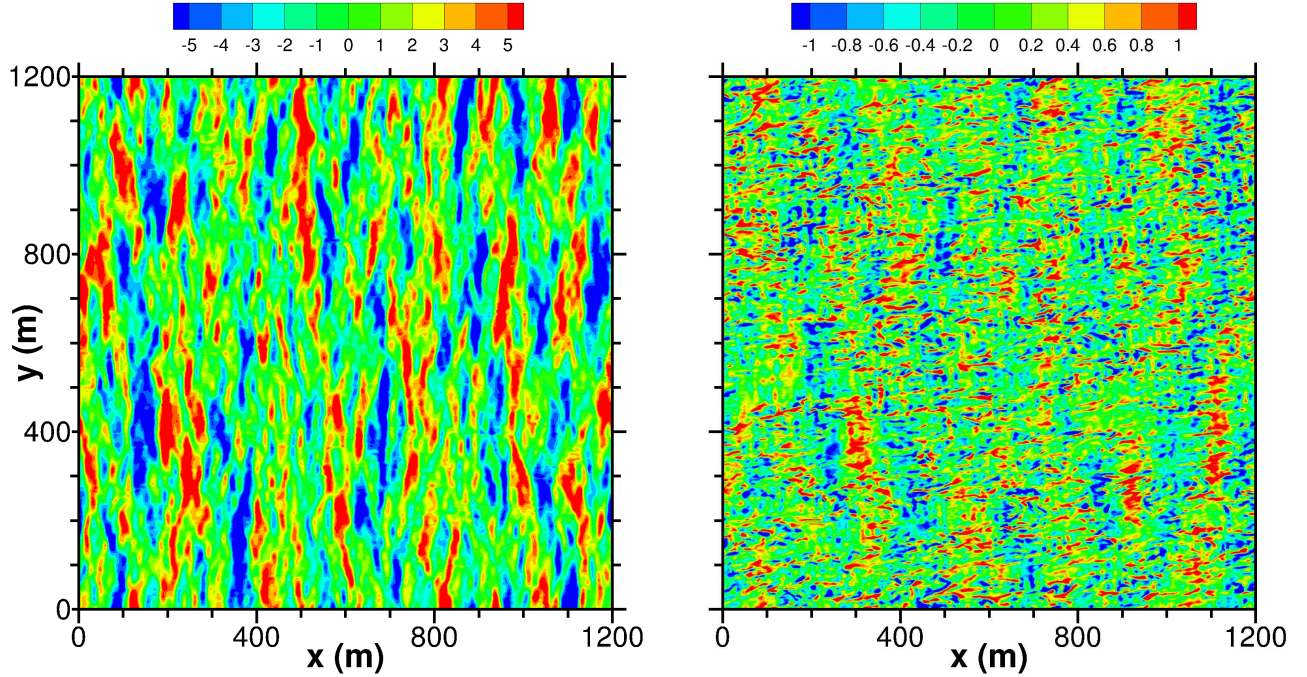
**Figure 1:** A snapshot of the wavefield height  $h(x, y, t)$  that is imposed at the bottom of the LES code.  $h$  is built from a sum of linear plane waves, and waves propagate left to right according to the dispersion relationship. The horizontal grid spacing matches the LES, *i.e.*,  $\Delta x = \Delta y = 2.34$  m. The color bar is in units of meters.



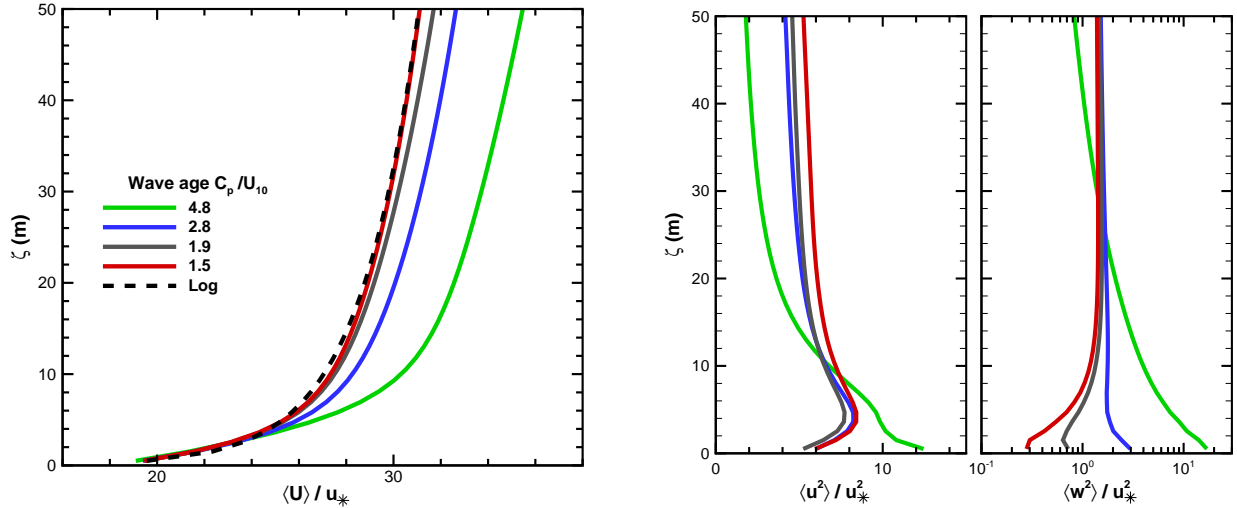
**Figure 2:** An instantaneous  $x$ - $z$  slice of the 3D time varying computational mesh in the lowest portion of the PBL. The horizontal gridlines become level surfaces at about 100 m above the water. Only a fraction of the grid is displayed.



**Figure 3:** Snapshot of static pressure fluctuations  $p'/\rho$  in an  $x$ - $z$  plane near the water surface. The upper panel is a swell dominated regime with wave age  $\sim 4.8$  while the lower panel is a case near wind-wave equilibrium with wave age  $\sim 1.4$ . The wave spectrum is a Pierson-Moskowitz spectrum. Notice the coherence between the wave field and the pressure fluctuations in the case with swell. The color bar is in units of  $\text{m s}^{-2}$  and the range is different between the two cases.



**Figure 4:** Snapshot of resolved vertical velocity fluctuations  $w'/u_*$  in a wave following  $x$ - $y$  plane near the water surface  $\zeta = 2.5$  m. The left panel is a swell dominated regime with wave age  $\sim 4.8$  while the right panel is a case near wind-wave equilibrium with wave age  $\sim 1.4$ . The wave spectrum at the bottom of the PBLs is the same. Notice the range of the color bar is different between the two cases. The (normalized) fluctuations in the wind-wave equilibrium case are smaller.



**Figure 5:** Vertical profiles of wind speed (left panel) and turbulence variances (right panels) for different values of wave age  $C_p/U_{10}$ . Friction velocity  $u_*$  is used for normalization. The dashed black line is the rough wall formula  $U/u_* = \ln(z/z_o)/\kappa$ , where  $\kappa = 0.4$ . Temporal and spatial averaging is used to make the statistics. The spatial averaging is over horizontal planes in computational space, *i.e.*, at constant  $\zeta$ .