Surface Gravity Waves and Coupled Marine Boundary Layers

Peter P. Sullivan
National Center for Atmospheric Research
Boulder, CO 80307-3000
Phone:(303) 497-8953 fax:(303) 497-8171 email: pps@ncar.ucar.edu

James C. McWilliams
Department of Atmospheric Sciences and
Institute of Geophysics and Planetary Physics, UCLA
Los Angeles, CA 90095-1565
Phone:(310) 206-2829 fax:(310) 206-5219 email: jcm@atmos.ucla.edu

Chin-Hoh Moeng
National Center for Atmospheric Research
Boulder, CO 80307-3000
Phone:(303) 497-8911 fax:(303) 497-8171 email: moeng@ncar.ucar.edu

Award #: N00014-00-C-0180
http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html

LONG-TERM GOALS

The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean. These mechanisms will be considered for a variety of surface wave states. Finally, we intend to make an effort to connect our simulation results with the proposed Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns.

OBJECTIVES

Our recent research objectives have focused on understanding the interaction between an imposed surface gravity wave and stratified turbulence in the ABL and OBL, and developing a stochastic wave breaking model for the OBL.

APPROACH

We are investigating interactions among the ABL, OBL, and the connecting air-sea interface using both LES and DNS. The premise behind this approach is that the fundamental processes that lead to air-sea coupling will manifest themselves in three-dimensional, time-dependent simulations. The capabilities of the LES code used here are documented in Moeng (1984), Sullivan *et al.*(1994), Sullivan *et al.*(1996), and McWilliams *et al.*(1997). A companion DNS code that accommodates a

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Surface Gravity Waves and Coupled Marine Boundary Layers**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Center for Atmospheric Research,,Boulder,,CO, 80307**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean. These mechanisms will be considered for a variety of surface wave states. Finally, we intend to make an effort to connect our simulation results with the proposed Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

temporal and spatial varying lower boundary utilizing a collocated grid architecture is described in Sullivan *et al.*(2000) and Sullivan & McWilliams (2002).

Our most recent research emphasis concentrates on developing and implementing a simplified stochastic wave breaking model in our simulation codes for the OBL. Turbulence resolving simulations of the OBL typically impose a mean (constant) surface wind stress τ_o at the water surface despite the known spatial and temporal variations in stress. This assumption neglects intermittent processes that occur at the sea surface and in particular wave breaking which is believed to be an important, but poorly understood, mechanism for transferring momentum and energy from waves to the underlying ocean currents (Melville, 1996). Our wave breaking model for LES of the OBL neglects the considerable complexity of a full air-water microphysical interface and instead focuses on what we believe are the important bulk processes, *viz.,* intermittent momentum and energy transmission from breaking waves to the underlying OBL. In this effort we have collaborated extensively with Professor W.K. Melville (Scripps Institute of Oceanography). The analytic formulation, numerical implementation, and testing of this model cannot be fully described in this progress report and we ask interested researchers to contact us directly for further details.

WORK COMPLETED

As a first model of breakers we introduce a random 3D body force $a_b(\mathbf{x}, t)$ into the resolved-scale u momentum equation in our LES and DNS codes, and in the case of LES we also include a random work density $W_b(\mathbf{x}, t)$ for the subgrid-scale turbulent kinetic energy equation. The stochastic forcing a_b takes the form

$$a_b = k_b \frac{c}{T} \mathcal{T}(\alpha) f(\beta) h(\gamma) g(\delta), \tag{1}$$

where the breaker shape functions $\mathcal{T}, f, h, g$ describe the evolution of an individual breaking event in space and time. In this model, all breakers are assumed to be similar in the dimensionless time and space coordinates $\alpha = (t-t_o)/T, \beta = (x-x_o)/c(t-t_o), \gamma = z/\chi c(t-t_o), \delta = (y-y_o)/cT$ where $(t_o, x_o, y_o, z_o = 0)$ is the initial time and position and (c, λ, T) are the phase speed, wavelength, and period of the chosen breaker. The latter are related to each other through a linear dispersion relation $c^2 = g\lambda/2\pi$ and hence $T = \lambda/c$. The constant $0 < \chi < 1$ controls the depth penetration of the breaker forcing and the constant k_b is initially used to scale the breaker forcing relative to the imposed stress τ_o. The breaker shape functions $\mathcal{T}, f, h, g$ are chosen to be smooth functions with continuous first derivatives and are consistently determined from field and laboratory observations of breaking waves (Rapp & Melville, 1990; Melville & Matusov, 2002; Melville *et al.* , 2002). The work density $W_b(\mathbf{x}, t)$ is assumed to have a similar functional form as a_b. Inclusion of the breaker model requires special attention in our simulation codes. As a simulation progresses, breakers of constant phase speed c are introduced at random (Gaussian) positions (x_o, y_o) at the top of the water and tracking routines monitor the birth, growth, and death of all breakers. Meanwhile, an exclusion principle is applied so that as new breakers are added they do not overlap existing breaking events. We found an effective means of controlling the white cap coverage (*i.e.,* the total amount of surface water that is covered by all breaking waves) is to introduce breakers at a uniform rate throughout the course of the simulations.

For our initial tests, we included the 3D body force a_b in our DNS code and performed a series of idealized (Couette flow) OBL simulations. We note that companion high-Re LES with this breaker model are under construction. The DNS use $200 \times 200 \times 96$ gridpoints in a domain of size $(x, y, z)/h = (5, 3, 1)$ where h is the box height at a bulk Reynolds number $Re = 8000$ with neutral stratification. This Re is adequate to sustain turbulence and is equal to that used in our prior DNS studies of flow over water waves (Sullivan, *et al.*, 2000; Sullivan & McWilliams, 2002). All simulations are homogeneous in the lateral (x, y) directions (*i.e.,* periodic boundary

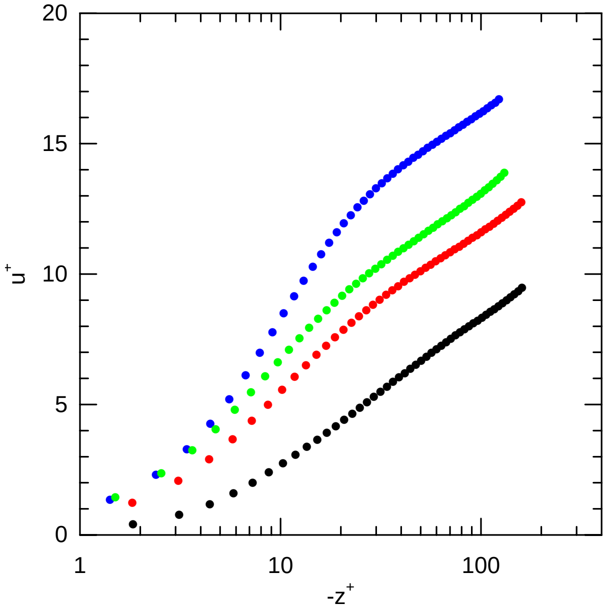

Figure 1: Average current profiles $\mathbf{u^+ = \langle u_o - u\rangle / u_*}$ with varying depth in the water column $\mathbf{z^+ = z u_*/\nu}$ (ν is the viscosity). Results are for DNS of an upper ocean boundary layer driven by a constant surface current $\mathbf{u_o}$ (blue dots), a constant surface stress $\tau_\mathbf{o}$ (green dots), constant stress plus weak wave breaking (red dots), and constant stress plus strong wave breaking (black dots).

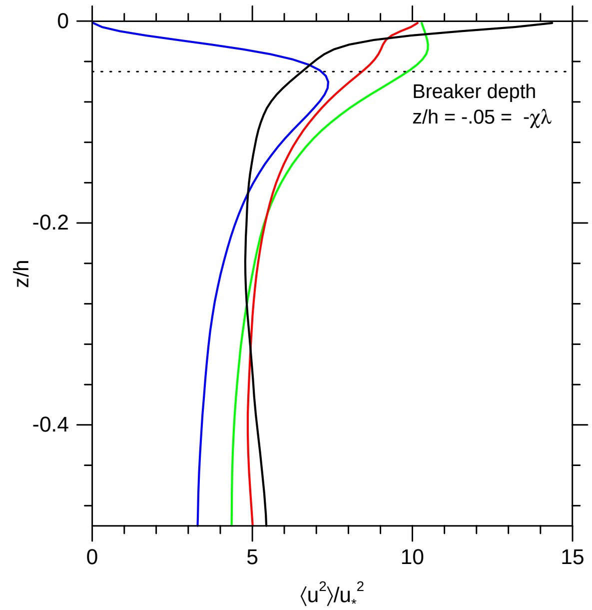

Figure 2: Vertical profile of average horizontal current variance $\langle \mathbf{u^2}\rangle$ normalized by friction velocity $\mathbf{u_*^2}$ near the water surface for ocean boundary layers with and without wave breaking. The vertical coordinate z is normalized by the height h of the simulation domain. Colored lines correspond to the simulations in Figure 1.

conditions) with no-slip (sticky) lower boundary conditions for all three velocity components and are run for more than 50,000 time steps (or more than 400 large scale turnover times) to gather adequate statistics. Results from four simulations with varying amounts of wave breaking and different surface boundary conditions are shown, *viz.,* OBLs driven by; (1) constant current u_o and no breakers, (2) constant surface stress τ_o and no breakers, (3) constant stress and weak wave breaking, and (4) constant stress and strong wave breaking. In the latter two cases, the breaker penetration constant $\chi = 0.2$ and k_b in equation (1) is adjusted so that the wave breaking is 25% and more than 80% of the total surface stress, respectively. The total stress in the breaker cases is however equal to the value used for the no breaker simulations. In future LES the amount of breaking and its contribution to the total stress at the top of the water will not be an independent parameter but will be correlated to a reference wind speed. In the simulations with breaking the imposed $(c/u_*, \lambda/h) = (60, 0.25)$ and breakers are added at a rate of about 70 breakers per unit of dimensionless simulation time. Ensemble statistics, indicated by $\langle\ \rangle$, are obtained by a combination of spatial $x - y$ and temporal averaging. The average friction velocity u_* computed from the stress at the lower boundary of the computational domain is used to normalize the current mean, variances, and momentum fluxes.

RESULTS

The upper surface boundary condition and the amount of wave breaking significantly impact the

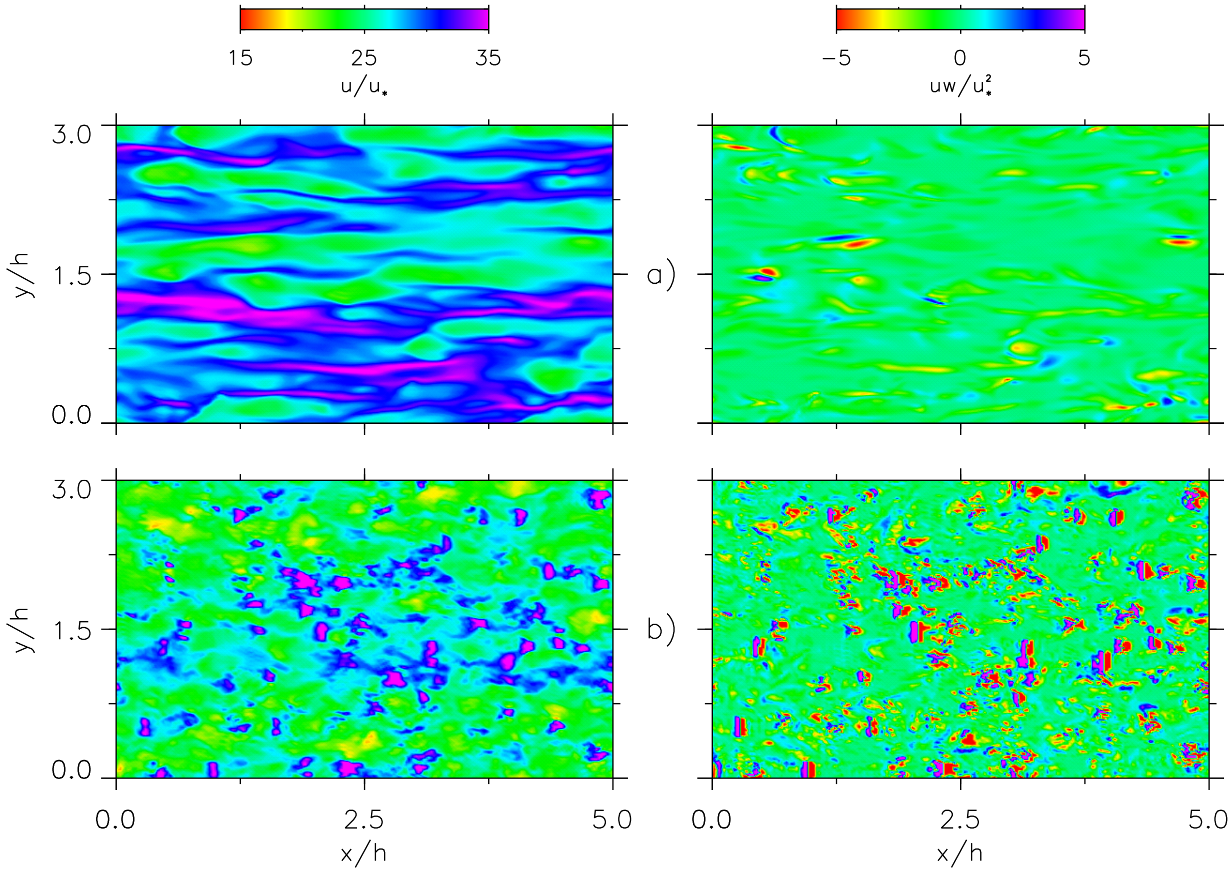

Figure 3: Visualization of the horizontal current field u, panels left and right of a), and vertical momentum flux uw, panels left and right of b), at z/h = -0.014 below the water surface. Snapshots in the upper panels are for an OBL driven by a constant surface stress τ_o while the flow fields in the lower panels contain strong breaker forcing. The presence of breaking disrupts the streak formation and enhances the vertical momentum flux.

mean and turbulent fields, especially so near the water surface. This is illustrated in Figures 1 and 2 where vertical profiles of the horizontal current mean and variance are depicted. Several noteworthy features are present in Figure 1. First, we observe that the type of upper surface boundary has an important influence on the overall mean current profile even in the absence of wave breaking. In the dimensionless variables (u^+, z^+), the current profile for the case with constant imposed τ_o (and no breakers) is shifted noticeably downward compared to its counterpart with an imposed constant current u_o. From the perspective of a classic wall-bounded shear flow this downward shift in current profile corresponds to an *increase* in surface roughness z_o (*e.g.,* Cebeci & Bradshaw, 1988, p. 167). We attribute this increase in effective surface roughness to higher turbulence levels near the water surface. A boundary condition with constant u_o requires that all horizontal current fluctuations be zero at the upper boundary while a constant τ_o boundary condition maintains a finite level of horizontal fluctuations very near the water surface (see Figure 2). Compared to the case with a u_o boundary condition the horizontal variances increase continuously as the water surface is neared and are a factor of two greater for the simulation driven by constant τ_o. A significant change in effective surface roughness with different boundary conditions was not expected prior to these simulations and highlights that the turbulence level in the OBL surface layer is higher than its atmospheric counterpart. We note that the prevailing perception is that the turbulence statistics of the OBL and ABL, properly non-dimensionalized, are the same. Note that under a Galilean shift of the horizontal current, the simulation with a constant u_o essentially imposes boundary conditions comparable to those of an atmospheric simulation.

In the presence of breaking waves, the current profile is shifted even further downward compared to the u_o-driven simulation, and in the simulation with the strong breaker forcing, the horizontal current variance attains a maximum at the water surface that is twice as large as the maximum in the u_o-driven simulation. The observed change in current profile is similar to that observed by Cheung & Street (1988) in a wind-wave tank under high wind conditions, presumably where breaking waves are present. If we fit a log-linear velocity profile $u^+ = \langle u_o - u \rangle / u_* = \frac{1}{\kappa}\ln(-z^+) + b$ (with $\kappa = 0.41$ and z decreasing into the water) to the data we estimate the effective surface roughness $z_o^+ = z_o u_* / \nu = e^{-\kappa b}$ (Sullivan *et al.*, 2000) to vary from $(0.13, 0.46, 0.82, 3.26)$ for the four simulations. Thus with strong wave breaking the effective roughness can be a factor of 25 times larger than for the case with a constant u_o boundary condition. The transition to a log-linear variation occurs at smaller values of z^+ in the situation with strong wave breaking, which is also an indicator of an increase in z_o^+. The white cap coverage for the weak and strong wave breaking cases averages about 1.6%, a realistic value for the open ocean (Melville & Matusov, 2002).

The presence of breaking waves impacts the instantaneous flow structures and momentum transport near the water surface as illustrated in Figure 3. At $z/h = -0.014$, breaking is observed to greatly disrupt the elongated near-wall streaky structures associated with wall-bounded shear flows. Intense impulses from the breaking waves impart strong vertical momentum flux, both positively and negatively signed, to the water column. We also observe that the energy, momentum, and spanwise vorticity imparted from an individual breaking event is felt for considerable time after the particular event forcing is extinguished, *i.e.,* the temporal impact of a breaking wave is much longer than the breaker lifetime $T = \lambda / c$. As a result, even though the observed white cap coverage of the breakers at the surface is very intermittent (less than 2%) the presence of breaking eventually stirs the entire surface layer of the OBL.

IMPACT/APPLICATIONS

We have developed a stochastic model for breaking waves that can be used in turbulence simulations of the ocean boundary layer. From direct numerical simulations (DNS), we found that a small intermittent level of breaking can greatly alter the flow patterns and turbulence statistics in the surface layer of the OBL. These results are being extended to large-eddy simulations and can further be used to help interpret field measurements taken during the ONR CBLAST initiative. Changing the surface boundary conditions in OBL simulations from an imposed constant current u_o to constant stress τ_o leads to an effective increase in surface roughness which can be readily observed in the current profiles in the OBL. This effect is enhanced by breaking waves.

TRANSITIONS & RELATED PROJECTS

In related efforts, we have performed an extensive analysis of the subgrid velocity and momentum fields deduced from surface layer observations collected during the Horizontal Turbulence Study (HATS), fall 2000 (see http://www.atd.ucar.edu/sssf/projects/hats/). A journal article describing this analysis was recently submitted (Sullivan, *et al.*, 2002) and an oral presentation was given at the NCAR Geophysical Turbulence Program workshop "*New Developments in Sub-Filter-Scale Closures*" held August 2002 in Boulder, CO. A similar field observational study is being proposed as part of the CBLAST low-wind field campaign, summer 2003. This effort would provide new insights into flow over moving waves and provide a database for improving subgrid scale models in LES of atmospheric marine boundary layers.

REFERENCES

Cebeci, T. & P. Bradshaw, 1988: *Physical and Computational Aspects of Convective Heat Transfer*, Springer-Verlag, 487 pp.

Cheung, T. K. & R.L. Street, 1988: The turbulent layer in the water at an air-water interface. *J. Fluid Mechanics*, **194**, 133-151.

McWilliams, J.C., P.P. Sullivan, & C-H. Moeng, 1997: Langmuir turbulence in the ocean. *J. Fluid Mechanics*, **334**, 1–30.

Melville, W.K., 1996: The role of wave breaking in air-sea interaction, *Annual Review of Fluid Mechanics*, **28**, 279-321.

Melville, W.K., & P. Matusov, 2002: Measurements of the distribution of breaking waves at the ocean surface. *Nature*, **417**, 58-63.

Melville, W.K., F. Veron, & C.J. White, 2002: The velocity field under breaking waves: coherent structures and turbulence. *J. Fluid Mech.*, **454**, 203-232.

Moeng, C.-H., 1984: A large-eddy-simulation model for the study of planetary boundary-layer turbulence. *J. Atmos. Sci.*, **41**, 2052–2062.

Rapp, R.J., & W.K. Melville, 1990: Laboratory measurements of deep-water breaking waves. *Phil. Trans. R. Soc. London A* **331**, 735-800.

Sullivan, P.P & J.C. McWilliams, 2002: Turbulent flow over water waves in the presence of stratification. *Physics of Fluids*, **14**. 1182–1195.

Sullivan, P.P., J.C. McWilliams, & C-H. Moeng, 2000: Simulation of turbulent flow over idealized water waves. *Journal of Fluid Mechanics*, **404**, 47-85.

Sullivan, P. P., J. C. McWilliams, & C.-H. Moeng, 1996: A grid nesting method for large-eddy simulation of planetary boundary layer flows. *Boundary-Layer Meteorology*, **80**, 167-202.

Sullivan, P. P., J. C. McWilliams, & C.-H. Moeng, 1994: A subgrid-scale model for large-eddy simulation of planetary boundary-layer flows. *Boundary-Layer Meteorology*, **71**, 247-276.

PUBLICATIONS

Sullivan, P.P, T.W. Horst, D.H. Lenschow, C-H. Moeng, & J.C. Weil, 2002: Structure of subfilter-scale fluxes in the atmospheric surface layer with application to les modeling. *J. Fluid Mech.*, submitted.

Weng, W., P.A. Taylor, & P.P. Sullivan, 2002: On turbulent and mean flow reynolds stress above sinusoidal waves. to be submitted.

Sullivan, P.P & J.C. McWilliams, 2002: Turbulent flow over water waves in the presence of stratification. *Physics of Fluids*, **14**, 1182-1195.

Moeng, C-H. & P.P. Sullivan, 2002: Large Eddy Simulation. In: *Encyclopedia of Atmospheric Sciences*, in press.

Dubrulle, B., J-P. Laval, P.P. Sullivan, & J. Werne, 2002a: A new dynamical subgrid model for the planetary surface layer. I. The model and *a priori* tests. *Journal of the Atmospheric Sciences*, **59**, 861-876.

Dubrulle, B., J-P. Laval, & P.P. Sullivan, 2002b: A new dynamical subgrid model for the planetary surface layer. II. Analytical computation of fluxes, mean profiles, and variances. *Journal of the Atmospheric Sciences*, **59**, 877-891.

Patton, E.G, P.P. Sullivan, & K.J. Davis, 2002: The influence of a forest canopy on top-down and bottom-up diffusion in the planetary boundary layer. *Q.J. Royal Meteor. Society*, in press.

Sullivan, P.P, T.W. Horst, D.H. Lenschow, C-H. Moeng, & J.C. Weil, 2002: Analysis of subfilter-scale fluxes in the atmospheric surface layer. *15th Symposium on Boundary Layers and Turbulence*, U. Wageningen, The Netherlands, 440–443.

Horst, T.W., J. Kleissl, D.H. Lenschow, C. Meneveau, C-H. Moeng, M.B. Parlange, P.P. Sullivan, J.C. Weil, 2002: Field measurements of spatially-filtered turbulence in the atmospheric surface layer. *15th Symposium on Boundary Layers and Turbulence*, U. Wageningen, The Netherlands, 436–439.

Patton, E.G., P.P. Sullivan, C-H. Moeng, 2002: The influence of large-scale soil moisture heterogeneity on wetting and drying planetary boundary layers. *15th Symposium on Boundary Layers and Turbulence*, U. Wageningen, The Netherlands, 676–679.