16th US National Congress of Theoretical and Applied Mechanics
June 27 - July 2, 2010, State College, Pennsylvania, USA

USNCTAM2010-636

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF STABLY STATIFIED ATMOSPHERIC FLOWS

Elie Bou-Zeid
Civil and Environmental Engrg., Princeton University
Princeton, New Jersey, USA
ebouzeid@princeton.edu

Stimit Shah
Civil & Environmental Engrg.
Princeton University
Princeton, New Jersey, USA

Marc Parlange
Swiss Federal Institute of
Technology-Lausanne
Lausanne, Switzerland

Lex Smits
Mechanical & Aerospace Engrg.
Princeton University
Princeton, New Jersey, USA

Chad Higgins
Swiss Federal Institute of
Technology-Lausanne
Lausanne, Switzerland

Hendrik Huwald
Swiss Federal Institute of
Technology-Lausanne
Lausanne, Switzerland

Charles Meneveau
Mechanical Engrg.
Johns Hopkins University
Baltimore, Maryland, USA

ABSTRACT

Statically stable atmospheric flows are characterized by weak and highly anisotropic turbulence, gravity waves, instabilities, and meandering motions that are not observed in neutral or unstable flows. These features complicate both modeling and measurements in stable boundary layers. Nevertheless, these flows remain of considerable importance for a variety of problems including nighttime flow and transport and polar boundary layers and climates. This paper presents experimental and numerical studies of turbulence under stable conditions in the atmospheric boundary layer.

INTRODUCTION

Using experimental measurements over a glacier and numerical experiments using the Large Eddy Simulation (LES) technique, we seek to study the effects of varying stability on high Reynolds number flows in the atmospheric boundary layer (ABL). We focus on statically stable flows (Richardson number > 0) which are considerably complicated by numerous flow dynamics that are negligible or not present in unstable flows.

The experimental results are from the Snow Horizontal Array Turbulence Study (SnoHATS) field experimental campaign which was performed over an extensive glacier in Switzerland from February to April 2006. The snow cover provided stable stratification of the flow over long periods. We perform a-priori analysis of the dynamics of small-scale turbulence and test the skills of existing subgrid scale models used in numerical simulation tools to represent the role of these scales.

The numerical results are from ongoing large eddy simulation studies we are conducting to examine the impact of stability on the TKE budget in a stable ABL under a range of Richardson numbers. Some of the simulations are designed to reproduce the experimental conditions of wind tunnel Particle Image Velocimetry measurements to facilitate the validation of the simulation results and to cover a wider range of turbulent scales and Reynolds numbers.

The aim is to study the effect of stability on turbulence structure and dynamics in the ABL. The experimental studies focus on small turbulent scales that cannot be resolved in large eddy simulations of high Reynolds number flows. These so-called subgrid scales play an important role and their proper parameterization is critical for adequate numerical modeling of stable ABL flows.

SUMMARY OF RESEARCH

The experimental studies use an array of 3D sonic anemometers measuring wind speed and temperature at 20 Hz to obtain turbulence measurements that resolve scales down into the inertial subrange. These measurements are subsequently filtered to separate the large scales, that would be resolved in LES, from the subgrid scales (SGS). The role and modeling of the subgrid scales and their interaction with the resolved can then be studied (for previous applications of this a-priori testing approach, see [1; 2; 3]). The data were analyzed in periods of 30 minutes to ensure the convergence of turbulent statistics and the relative steadiness of the flow conditions (linear detrending was still applied to the data). We observed that the unresolved fraction of the fluxes of momentum and heat (SGS/Reynolds fluxes) is highest in the vertical direction, reaching up to 45% (FIGURE 1), while for horizontal directions, it is less than 20% (results averaged over all stability conditions during the experiment). Surprisingly, stability was not found to be important in determining the fraction of SGS fluxes and the stress-strain alignment in the flow, plotting these parameters versus stability parameters such as the Obukhov or Ozmidov scales showed no significant trend.

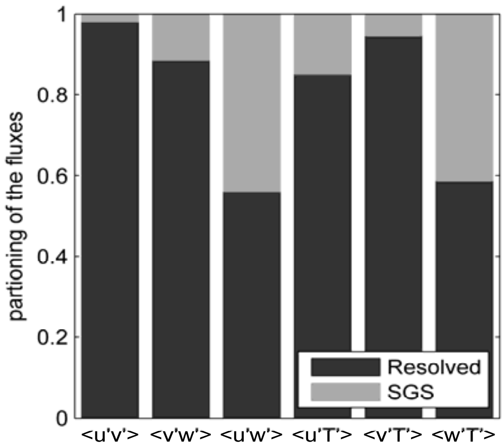

FIGURE 1. PARTITIONING OF THE FLUXES INTO THE RESOLVED AND SUBGRID SCALES

On the other hand, stability did impact the SGS model coefficients as reported in previous studies [2]; the Smagorinsky coefficient ([4]; see [5] for model details) decreases with increasing stability and the collapse of the coefficient values is best when the stability is estimated using the Ozmidov scale (FIGURE 2). On the other hand, the SGS Prandtl number (Pr_{SGS}) increases with increasing stability and the trend seems to fit well with the variation of $\mathrm{Pr}_{\mathrm{SGS}}$ under statically unstable conditions. When the results from the stable conditions studied here and the unstable condition studied over a lake [3] are considered together, a continuous increase in $\mathrm{Pr}_{\mathrm{SGS}}$ is observed (FIGURE 3)

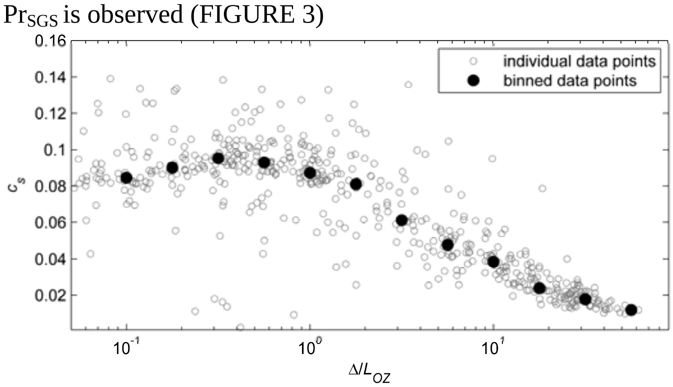

FIGURE 2. VARIATION OF THE SMAGORINSKY COEFFICIENT WITH STABILITY

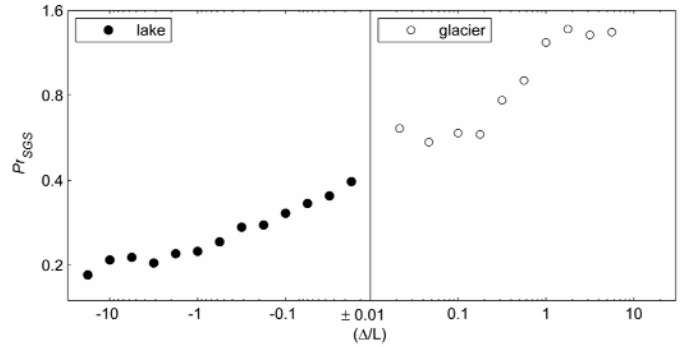

FIGURE 3. VARIATION OF Pr_{SGS} WITH STABILITY

Results from the LES studies are forthcoming. We are improving and testing the LES code for better performance under the challenging stable conditions; for example, we are including the radiative divergence term in the heat equation, implementing grid-stretching in the vertical direction, and improving the wall-models to compare with finite Reynolds number PIV studies.

CONCLUSIONS

Experimental and (ongoing) numerical investigations of the statically stable turbulent flow in the atmospheric boundary layer are performed. A-priori testing of SGS model suggests that they do not pose a particular problem under stable conditions; their role and dynamics are similar to statically neutral or unstable conditions. As such, a unified approach for SGS modeling is possible. These results motivate further investigations of the stable ABL, using LES with a new-generation scale-dependent dynamic model [6], to further study the structure and dynamics of turbulence under stable conditions.

REFERENCES

[1] Porte-Agel F., Pahlow M., Meneveau C. and Parlange M. B. (2001) Atmospheric stability effect on subgrid-scale physics for large-eddy simulation. Advances in Water Resources, 24(9-10), 1085-1102.

[2] Kleissl J., Parlange M. B. and Meneveau C. (2004) Field experimental study of dynamic Smagorinsky models in the atmospheric surface layer. Journal of the Atmospheric Sciences, 61(18), 2296-2307.

[3] Vercauteren N., Bou-Zeid E., Parlange M. B., Lemmin U., Huwald H., Selker J. and Meneveau C. (2008) Subgrid-scale dynamics of water vapour, heat, and momentum over a lake. Boundary-layer Meteorology, 128(2), 205-228.

[4] Smagorinsky J. (1963) General circulation experiments with the primitive equations: i. the basic experiment. Monthly Weather Review, 91, 99-164.

[5] Meneveau C. and Katz J. (2000) Scale-invariance and turbulence models for large-eddy simulation. Annual Review of Fluid Mechanics, 32, 1-32.

[6] Bou-Zeid E., Meneveau C. and Parlange M. B. (2005) A scale-dependent Lagrangian dynamic model for large eddy simulation of complex turbulent flows. Physics of Fluids, 17(2), 025105.