J. Adv. Model. Earth Syst., **Vol. 1**, No. 6, 1–6

One-Way Nested Large-Eddy Simulation over the Askervein Hill

Jean-Christophe Golaz[1], James D. Doyle[2] and Shouping Wang[2]

[1] NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA
[2] Naval Research Laboratory, Monterey, California, USA

Manuscript submitted 5 February 2009; in final form 4 May 2009

Large-eddy simulation (LES) models have been used extensively to study atmospheric boundary layer turbulence over flat surfaces; however, LES applications over topography are less common. We evaluate the ability of an existing model – COAMPS®-LES – to simulate flow over terrain using data from the Askervein Hill Project. A new approach is suggested for the treatment of the lateral boundaries using one-way grid nesting. LES wind profile and speed-up are compared with observations at various locations around the hill. The COAMPS-LES model performs generally well. This case could serve as a useful benchmark for evaluating LES models for applications over topography.

DOI:10.3894/JAMES.2009.1.6

1. Introduction

The Askervein Hill Project was a field measurement program conducted during the months of September and October in 1982 and 1983 on the island of South Uist in the Outer Hebrides of Scotland. The Askervein Hill is 116 m high – its top is 126 m above sea level – and located on the west side of South Uist. Its shape is nearly elliptical with a 2 km major axis and 1 km minor axis (see Fig. 1).

Taylor and Teunissen (1987) present a general overview of the Askervein Hill Project and Mickle et al. (1988) describe some measurements of wind and turbulence. Additional data are also available in two technical reports (available at www.yorku.ca/pat/research/Askervein). A retrospective of the experiment and summary of its impact is reported in Walmsley and Taylor (1996).

During the experiment, more than 50 towers for wind measurements were deployed on the hill. These towers were arranged in three linear arrays, one parallel and two perpendicular to the hill's major axis (A, AA, and B in Fig. 1). Together, they provide a detailed description of the near surface wind field. A large number of modeling studies have been conducted using data collected during the Askervein Hill Project (e.g. Beljaars et al. 1987; Kim and Patel 2000; Castro et al. 2003; Undheim et al. 2006; Lopes et al. 2007; Chow and Street 2009).

We select the Askervein Hill to evaluate the ability of COAMPS®-LES to perform large-eddy simulations (LES) of flow over topography. The small size of the hill and the availability of observational data make this experiment an ideal application for LES models. One unique aspect of our

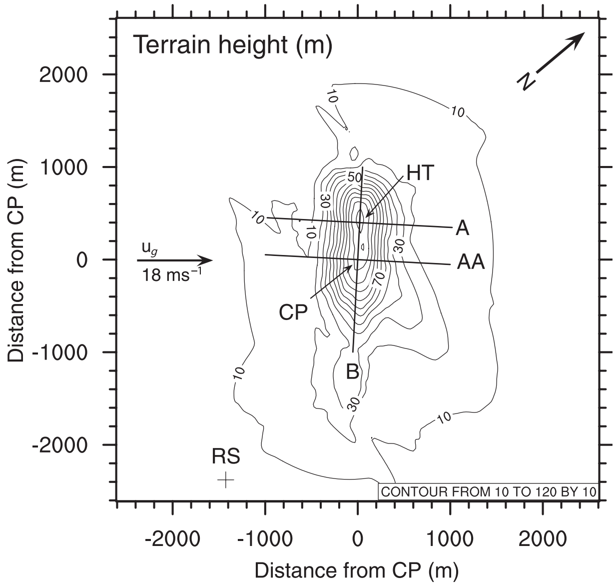

Figure 1. Nested grid topography. RS indicates the reference site for undisturbed measurements, CP the center point, and HT the hill top. The three linear arrays of instruments are denoted by A, AA, and B.

To whom correspondence should be addressed.
Jean-Christophe Golaz, NOAA Geophysical Fluid Dynamics Laboratory, P.O. Box 308, Princeton, NJ 08542, USA
Chris.Golaz@noaa.gov

study is the use of a one-way nesting technique for the treatment of the lateral boundary conditions.

2. Model description and configuration

The LES model is based on the Naval Research Laboratory COAMPS mesoscale model (Hodur 1997) with suitable modifications for LES scales (Golaz et al. 2005). As a LES model, COAMPS has only been employed for horizontally homogeneous simulations over flat surfaces. As a mesoscale model, COAMPS has been employed to perform nested simulations over complex terrain (e.g. Doyle and Durran 2007; Doyle and Jiang 2006; Jiang and Doyle 2005; Doyle et al. 2005). Because of the shrinking gap between grid increments of regional nested simulations and those of LESs, there is a natural interest in investigating the feasibility of using COAMPS-LES over topography.

LESs of the atmospheric boundary layer are typically performed using periodic boundary conditions in the horizontal directions. Such boundary conditions are well suited for applications over uniform surfaces (see for example Moeng and Sullivan (2003) for a review). Periodic boundary conditions can also be used when surface conditions are inhomogeneous but remain periodic. These includes periodically varying surface heating (e.g. Hadfield et al. 1991) or topography (e.g. Walko et al. 1992; Dörnbrack and Schumann 1993). However, periodic boundary conditions cannot be used for flow over more complex terrain or inhomogeneous surface conditions.

One alternative for inhomogeneous surface conditions is the so-called ‘‘perturbation recycling method’’ (Mayor et al. 2002): mean conditions are imposed at the inflow boundary and turbulent perturbations are added. These perturbations are ‘‘recycled’’ from a region downstream of the inflow boundary where the turbulence is resolved. Mayor et al. (2002) used this technique to perform a LES of a cold-air outbreak.

Lopes et al. (2007) and Chow and Street (2009) followed a second approach. They simulated flow over the Askervein Hill by imposing a fully turbulent inflow boundary condition at each model time step. The imposed inflow boundary condition is derived from a separate LES with homogeneous conditions and flat terrain.

Here, we propose a third alternative that employs a one-way grid nesting capability already present in many numerical models. A total of two grids are used. The parent grid has a flat terrain and uses periodic boundary conditions in the horizontal directions. The nested grid contains the terrain to be simulated and is forced at its boundaries by the parent grid. Because the nesting is restricted to one-way interaction, the parent grid is not affected by terrain induced perturbations from the nested grid. The parent grid therefore continuously provides a turbulent inflow to the nested grid. This approach is simple to implement in any model with a one-way nesting capability. Furthermore and unlike other alternatives, it is independent of the inflow direction.

Two-way nesting has also been employed in the context of LES over flat surface with outer periodic boundary conditions. Sullivan et al. (1996) developed a vertical nesting approach to refine a slice of the horizontal domain. Moeng et al. (2007) designed two-way horizontally nested LES-within-LES experiments using the Weather Research and Forecasting (WRF) model. They successfully simulated dry convective and shear driven neutral layers.

Although attractive for many applications, two-way nesting is not a viable option for our application of LES over the Askervein Hill since we require an inflow field that is turbulent but undisturbed by the topography.

Model configuration and initial conditions are described in details in Appendix A. The boundary layer is nearly neutral and forced by a geostrophic wind. The model grids are rotated to align the geostrophic wind with the x axis. Horizontal grids consist of 135×135 points with 90 m spacing and 175×175 points with 30 m spacing for the parent and nested grids, respectively. Both grids share the same 97 levels with spacing of 6.66 m in the lowest 100 m and stretching above. Figure 1 shows the topography of the nested grid along with reference points.

Our grids are larger but with slightly coarser spacing that the ones Moeng et al. (2007) employed for their shear driven layer (100×100 at 60 m and 121×121 at 20 m). The grid spacing in this study is within the range of other LESs of neutral layers (e.g. Andren et al. 1994; Moeng and Sullivan 1994).

One-way interaction between the coarse and nested grid operates as follows. The fine grid lateral boundaries are updated every coarse grid time step. The inner time step is 1/3 of the outer grid. Tendencies are added in at the boundaries to account for the smaller time step. The outer most points on the inner grid are not predicted and are identical to their coincident coarse grid points. Data is then interpolated in a blend zone of 7 grid points wide with weights following Davies (1976).

Flow over the Askervein Hill is simulated for a total of six hours: four hours with the parent grid only, followed by two with both grids. Data from the last hour of the simulations are used for the analysis.

Two simulations are performed. Both employ a LES Smagorinsky-type subgrid-scale scheme, but differ by the choice of the subgrid scale mixing lengths. The first one (hereafter S50-50) uses a mixing length of 50 m for both grids, whereas the second one (S50-30) has a mixing length of 50 m for the parent grid, and 30 m for the nested grid. These two simulations provide an estimate of the sensitivity of the results to details of the LES subgrid-scale mixing.

3. Results

Undisturbed wind from the LES closely follows a logarithmic profile and compares well with RS observations (Figure A1 in Appendix A). Comparison of the wind flow around the Askervein Hill is performed in terms of the fractional

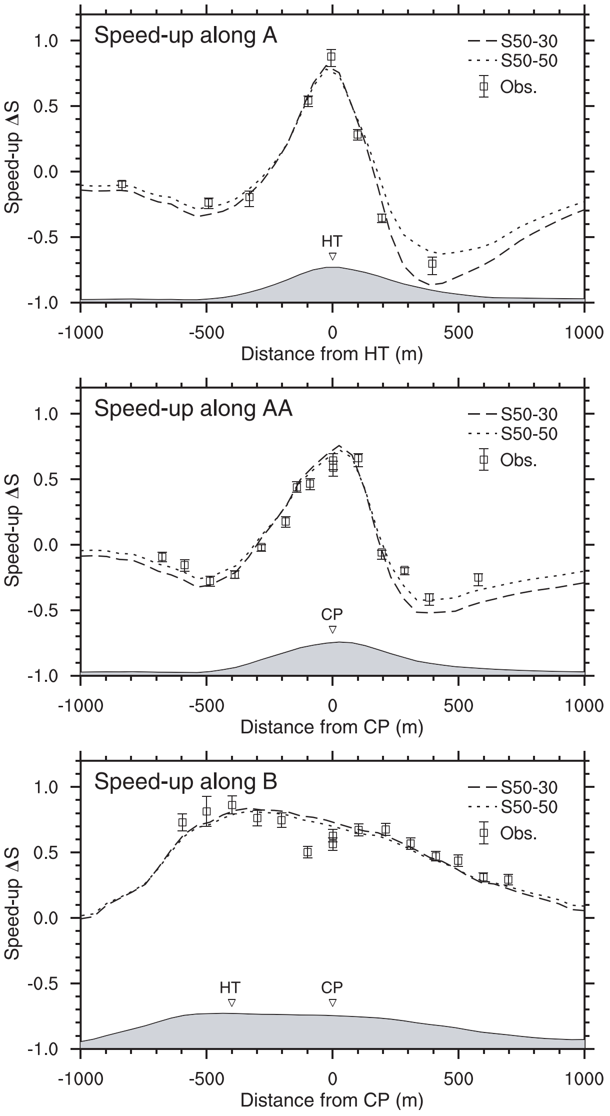

Figure 2. Comparison of the 10-m fractional wind speed-up along sections A, AA, and B with observations. Experiments S50-30 and S50-50 correspond to simulations with differing subgrid-scale mixing lengths (see text for details).

speed-up ratio, ΔS, defined as:

$$\Delta S = \frac{U(\Delta z) - U_{RS}(\Delta z)}{U_{RS}(\Delta z)}, \tag{1}$$

where Δz is the height above the local terrain, and U, U_{RS} the wind velocities at the point of interest and at RS, respectively. ΔS provides a direct measure of the impact of the terrain on the wind field compared to the undisturbed flow.

The 10-m fractional wind speed-up along sections A, AA, and B is depicted in Figure 2. Along A and AA, the speed-up is largest near the top of the hill. COAMPS-LES slightly underestimates the maximum speed-up at HT. Minimum values occur in the lee of the hill. This is where the two simulations diverge the most. S50-30 tends to overestimate the slowdown. Along B, results indicate a good agreement except between HT and CP, where both simulations fail to predict the relative slowdown shown by the observations.

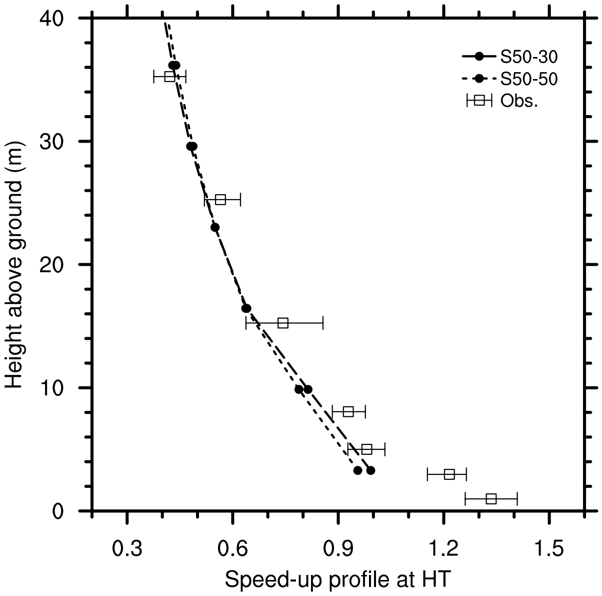

Figure 3. Comparisons of modeled and observed vertical profile of fractional wind speed-up at the hill top (HT).

Vertical profiles of the low level speed-up at HT are shown in Figure 3. The model vertical resolution is too coarse to capture the large gradient in the lowest 5 m above ground. However, the agreement with measurements improves above 5 m, with model results falling within observational errors at most measurement heights.

Finally, Figure 4 compares turbulence intensity. Subgrid turbulence contributes to approximately half of the total. LES results show a qualitative agreement with observations, but the magnitude is overestimated upstream of HT and underestimated downstream. The largest difference between S50-50 and S50-30 appears in the lee and is consistent with the wind speed-up difference observed in Fig. 2. Stronger subgrid turbulence generates more mixing and therefore increases wind speed by mixing momentum downwards.

Compared to Chow and Street (2009) who used a more sophisticated subgrid-scale model, COAMPS-LES results are encouraging. They indicate that a simple subgrid model can capture many features of the flow over the Askervein Hill with reasonably good accuracy.

4. Summary and conclusions

Simulations of the flow over the Askervein Hill are performed using COAMPS-LES. A new treatment of the lateral boundary conditions that makes use of the one-way nesting capability in COAMPS is employed. The parent grid, which has no topography, generates undisturbed turbulent flow that is fed as a boundary condition to the nested grid. This boundary

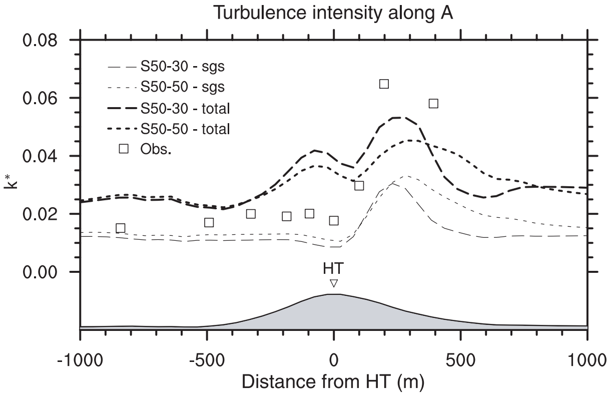

Figure 4. Comparison of the 10-m turbulence intensity along section A with observations. Turbulence intensity is defined as the turbulence kinetic energy (TKE) normalized by the wind speed at RS. Both subgrid (sgs) and total intensity are shown.

treatment offers the advantages of being easy to implement in any model that possesses a one-way grid nesting capability, and of being independent of the inflow direction.

Evaluation of COAMPS-LES results against observations from the Askervein Hill generally reveals good agreement between the model and observations. Sensitivity to the choice of mixing length is small, except in the lee of the hill where the LES with the smaller mixing length tends to accentuate the deceleration.

The availability of observations and topographic data makes this case a useful benchmark for LES models. To facilitate future model comparisons, Dataset S1 [data.tar.gz] provides data and scripts needed regenerate figures presented here.

Acknowledgments: COAMPS is a registered trademark of the Naval Research Laboratory. Peter Taylor and Wensong Weng are acknowledged for graciously providing electronic versions of the Askervein Hill Project technical reports and datasets. J. D. Doyle and S. Wang acknowledge support through the Office of Naval Research's Program Element 0601153N. Computational resources were supported in part by a grant of HPC time from the Department of Defense Major Shared Resource Center, Wright Patterson Air Force Base, OH.

Appendix A: Model configuration

To perform simulations over the Askervein Hill, COAMPS-LES is configured using two grids with one-way interaction between parent and nested grids. The parent grid is composed of 135 points in the x and y directions with a horizontal grid spacing of 90 m. The nested grid consists of 175 points in each horizontal direction and a grid spacing of 30 m.

Both grids share the same 97 vertical levels. The vertical grid spacing is a constant 6.66 m in the lowest 100 m, followed by a stretching factor of 1.05 per level up to a grid spacing of 50 m and a height of 2000 m. No turbulence is expected at and above this height, but terrain induced waves may be present. Therefore, to damp upward propagating waves, we add some coarse model layers above 2000 m. Their grid spacing is stretched by a factor 1.2 per level until it reaches a value of 1000 m. The grid spacing is then held fixed above that. The domain top is located just above 10000 m. A Rayleigh damping layer is imposed to these upper 17 model layers, between 2100 m and 10000 m.

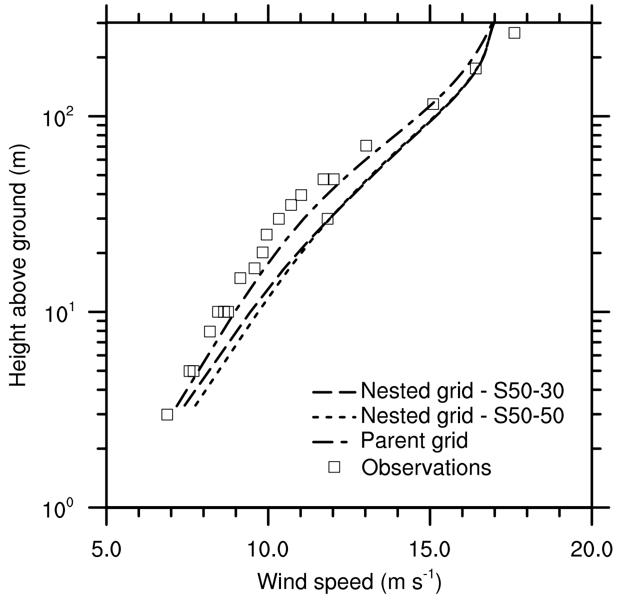

Figure A1. Comparison of wind profiles at the reference site (RS) and on the parent grid.

Initial conditions for the parent grid are idealized from observations taken on 3 October 1983 at 1302 LST (Taylor and Teunissen 1985, Fig. 2.5, p. 172). The atmosphere is assumed to be neutral with $\theta = 290$ K from the surface up to 1200 m, capped by a stable layer with a lapse rate of 6.25×10^{-3} K m^{-1}. Initial random temperature are applied in order to allow turbulence to develop. Surface pressure is 1003 hPa according to observations (Taylor and Teunissen 1985, Fig 2.4, p. 164). The estimated surface geostrophic wind for that day was reported to be 22 m s^{-1} with a direction of 220° (Taylor and Teunissen 1985, Table 2.2, p. 112). We first attempted to use this value for the geostrophic wind in a one grid simulation with flat terrain, but it led to an overestimation of the 10 m wind speed on the parent grid compared to observations at the reference site. A geostrophic value of 18 m s^{-1} was used instead in order to better match the parent grid wind profile with reference site observations. Smaller wind values have also been used by other modelers as inflow boundary conditions. For example, domain-top wind speed was 17 m s^{-1} at 2000 m in Undheim et al. (2006). The initial wind profile is logarithmic. The model grids are rotated 50° counter-clockwise to align the x axis with the geostrophic wind.

Two topographical datasets are available from the Askervein Hill project (Walmsley and Taylor 1996). The first one (Map A) contains the Askervein hill as well as downstream neighboring hills. The second one (Map B) only contains the Askervein hill. We select Map B for the terrain in our nested grid because it blends naturally with the flat terrain used in the parent grid. Furthermore, modeling studies have generally found that neighboring hills only modestly impact the wind field over the Askervein hill.

Figure 1 in the text shows the topography of the nested grid along with the cross sections and reference points. Measurements of undisturbed wind flow were taken at the reference site (RS). Measurements perpendicular to the hill's major axis were taken along lines A (crossing the hill top HT) and AA (crossing the center point CP). Line B represents the measurement along the major axis. CP is placed at the center of the nested grid in our simulations.

Surface momentum fluxes are computed assuming a uniform roughness height of $z_0 = 0.03$ m as suggested by Taylor and Teunissen (1987). Surface heat flux is set to zero, reflecting the near neutral conditions observed on 3 October 1983 (Taylor and Teunissen 1987). Buoyancy effects are included in our LES model, but following most other modeling studies, we neglect the effects of moisture on the simulations.

LES simulations are performed for a total of six hours. The first four hours consist of a single grid to allow for the turbulence to develop on the parent grid. After four hours, the wind profile on the parent mesh is consistent with a neutral boundary layer and the resolved scale turbulence is well established. The nested mesh is then spawned at hour 5 and the model run for an additional two hours. Data from the last hour of the simulations are used for the analysis.

To validate the model configuration, we compare the wind profile to the RS observations from Taylor and Teunissen (1985, Fig 3.7d, p. 240) in Fig. A1. Three lines are shown along with the reported measurements: the domain averaged wind profile from the parent grid (identical for both simulations), and the RS profiles extracted from the nested grids of the two simulations S50-50 and S50-30. All model results are time averaged over the last hour of the simulations. The parent grid results follow the observations very closely. This provides assurances that the parent grid feeds a wind profile to the nested grid that is in good agreement with observations. The wind velocities tend to be slightly larger at low levels on the nested grids compared to the parent grid. Differences between S50-50 and S50-30 are small and only apparent in the lowest 30 m.

References

Andren, A., A. R. Brown, J. Graf, P. J. Mason, C.-H. Moeng, F.T.M. Nieuwstadt, and U. Schumann, 1994: Large-eddy simulation of a neutrally stratified boundary layer: A comparison of four computer codes. *Quart. J. Roy. Meteor. Soc.*, **120**, 1457–1484, doi: 10.1002/qj.49712052003

Beljaars, A. C. M., J. L. Walmsley, and P. A. Taylor, 1987: A mixed spectral finite-difference model for neutrally stratified boundary-layer flow over roughness changes and topography. *Bound.-Layer Meteor.*, **38**, 273–303, doi: 10.1007/BF00122448

Castro, F. A., J. M. L. M. Palma, and A. Silva Lopes, 2003: Simulation of the Askervein flow. Part 1: Reynolds averaged Navier-Stokes equations ($k - \varepsilon$ turbulence model). *Bound.-Layer Meteor.*, **107**, 501–530, doi: 10.1023/A:1022818327584

Chow, F. K. and R. L. Street, 2009: Evaluation of turbulence closure models for large-eddy simulation over complex terrain: flow over Askervein Hill. *J. Appl. Meteor. Climatol.*, **48**, 1050–1065, doi: 10.1175/2008JAMC1862.1

Davies, H. C., 1976: A lateral boundary formulation for multi-level prediction models. *Quart. J. Roy. Meteor. Soc.*, **102**, 405–418, doi: 10.1002/qj.49710243210

Dörnbrack, A. and U. Schumann, 1993: Numerical simulation of turbulent convective flow over wavy terrain. *Bound.-Layer Meteor.*, **65**, 323–355, doi: 10.1007/BF00707032

Doyle, J. D. and D. R. Durran, 2007: Rotor and subrotor dynamics in the lee of three-dimensional terrain. *J. Atmos. Sci.*, **64**, 4202–4221, doi: 10.1175/2007JAS2352.1

Doyle, J. D. and Q. Jiang, 2006: Observations and numerical simulations of mountain waves in the presence of directional wind shear. *Quart. J. Roy. Meteor. Soc.*, **132**, 1877–1905, doi: 10.1256/qj.05.140

Doyle, J. D., M. A. Shapiro, Q. Jiang, and D. L. Bartels, 2005: Large-amplitude mountain wave breaking over Greenland. *J. Atmos. Sci.*, **62**, 3106–3126, doi: 10.1175/JAS3528.1

Golaz, J.-C., S. Wang, J. D. Doyle, and J. M. Schmidt, 2005: COAMPS®-LES: Model evaluation and analysis of second- and third-moment vertical velocity budgets. *Bound.-Layer Meteor.*, **116**, 487–517, doi: 10.1007/s10546-004-7300-5

Hadfield, M. G., W. R. Cotton, and R. A. Pielke, 1991: Large-eddy simulations of thermally forced circulation in the convective boundary layer. Part I: A small-scale circulation with zero wind. *Bound.-Layer Meteor.*, **57**, 79–114, doi: 10.1007/BF00119714

Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev.*, **125**, 1414–1430, doi: 10.1175/1520-0493(1997)125<1414:TNRLSC>2.0.CO;2

Jiang, Q. and J. D. Doyle, 2005: Wave breaking induced surface wakes and jets observed during a bora event. Geophys. *Res. Lett.*, **32**, L17807, doi: 10.1029/2005GL022398

Kim, H. G. and V. C. Patel, 2000: Test of turbulence models for wind flow over terrain with separation and recirculation. *Bound.-Layer Meteor.*, **94**, 5–21, doi: 10.1023/A:1002450414410

Lopes, A. S., J. M. L. M. Palma, and F. A. Castro, 2007: Simulation of the Askervein flow. Part 2: Large-eddy simulations. *Bound.-Layer Meteor.*, **125**, 85–108, doi: 10.1007/s10546-007-9195-4

Mayor, S. D., P. R. Spalart, and G. J. Tripoli, 2002: Application of a perturbation recycling method in the large-eddy simulation of a mesoscale convective internal boundary layer. *J. Atmos. Sci.*, **59**, 2385–2395, doi: 10.1175/1520-0469(2002)059<2385:AOAPRM>2.0.CO;2

Mickle, R. E., N. J. Cook, A. M. Hoff, N. O. Jensen, J. R. Salmon, P. A. Taylor, G. Tetzlaff, and H. W. Teunissen, 1988: The Askervein Hill Project: Vertical profiles of wind and turbulence. *Bound.-Layer Meteor.*, **43**, 143–169, doi: 10.1007/BF00153977

Moeng, C.-H. and P. P. Sullivan, 1994: A comparison of shear- and buoyancy-driven planetary boundary layer flows. *J. Atmos. Sci.*, **51**, 999–1022, doi: 10.1175/1520-0469(1994)051<0999:ACOSAB>2.0.CO;2

Moeng, C.-H. and P. P. Sullivan, 2003: Large eddy simulation. *Encyclopedia of Atmospheric Sciences*, J. R. Holton, J. A. Curry, and J. A. Pyle, Eds., Elsvier Science, 1140–1150.

Moeng, C.-H., J. Dudhia, J. Klemp, and P. Sullivan, 2007: Examining two-way grid nesting for large eddy simulation of the PBL using the WRF model. *Mon. Wea. Rev.*, **135**, 2295–2311, doi: 10.1175/MWR3406.1

Sullivan, P. P., J. C. McWilliams, and C.-H. Moeng, 1996: A grid nesting method for large-eddy simulation of planetary boundary-layer flows. *Bound.-Layer Meteor.*, **80**, 167–202, doi: 10.1007/BF00119016

Taylor, P. A. and H. W. Teunissen, 1985: The Askervein Hill Project: Report on the September/October 1983 main field experiment. Technical report, Internal Report MSRB-84-6, Atmos. Environ. Service, Downsview, Ont., Canada (ASK83). Available from www.yorku.ca/pat/research/Askervein/ASK83.pdf.

Taylor, P. A. and H. W. Teunissen, 1987: The Askervein Hill project: overview and background data. *Bound.-Layer Meteor.*, **39**, 15–39, doi: 10.1007/BF00121863

Undheim, O., H. I. Andersson, and E. Berge, 2006: Nonlinear, microscale modelling of the flow over Askervein Hill. *Bound.-Layer Meteor.*, **120**, 477–495, doi: 10.1007/s10546-006-9065-5

Walko, R. L., W. R. Cotton, and R. A. Pielke, 1992: Large-eddy simulations of the effects of hilly terrain on the convective boundary layer. *Bound.-Layer Meteor.*, **58**, 133–150, doi: 10.1007/BF00120755

Walmsley, J. L. and P. A. Taylor, 1996: Boundary-layer flow over topography: impacts of the Askervein study. *Bound.-Layer Meteor.*, **78**, 291–320, doi: 10.1007/BF00120939