IMPLICIT LARGE-EDDY SIMULATION OF THE STRATOCUMULUS-TOPPED BOUNDARY LAYER: A GRID SENSITIVITY STUDY

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Abstract A range of implicit large-eddy simulations of the stratocumulus-topped boundary layer is performed to study the influence of grid resolution on selected parameters including liquid water path and second and third moments of vertical velocity fluctuations. The simulations are based on two sets of aircraft measurements, which are also used to evaluate the results of the simulations. The specific case presented here indicates that simulations with a grid aspect ratio accounting for the anisotropic nature of the turbulence near the surface and at the top of the boundary layer lead to better agreement with measurements than simulations with an isotropic grid.

SIMULATIONS

Stratocumulus clouds cover approximately one fifth of the Earth's surface in the annual mean [7]. Thus, they play an important role in the radiative balance of the Earth and understanding of this type of cloud is essential for e.g. accurate climate prediction.

Large-eddy simulation (LES) is a widely used tool for stratocumulus studies, but how to best account for the influence of unresolved turbulence is still an open question. In the model intercomparison study of [6], simulations with no explicit subgrid-scale (SGS) term in the equations for the scalar variables showed – at least in some respects – better agreement with measurements than simulations employing an explicit SGS model. Here we continue along the lines of [6] and perform a range of implicit large-eddy simulations (ILESs) of the stratocumulus-topped boundary layer (STBL) to study the influence of grid resolution and aspect ratio on the temporal evolution and spatial structure of the simulated STBL. The performed simulations are based on two sets of aircraft measurements: research flight 1 of the second Dynamics and Chemistry of Marine Stratocumulus (DYCOMS-II) field study [5] and research flight 10 of the Physics of Stratocumulus Top (POST) experiment [1]. The measurements provide realistic initial conditions and forcing applied in the simulations, as well as means of evaluating the quality of the results.

We use an ILES code based on the EULAG model [3]. It solves the governing anelastic equations for liquid water and water vapour mixing ratios, momentum and potential temperature using finite differences and the MPDATA (Multidimensional Positive Definite Advection Transport Algorithm) advection scheme [4]. The longwave radiation scheme applied in the simulations is similar to the one used in [6]. As described by e.g. [2], the MPDATA scheme has the ability to implicitly account for the effect of the unresolved turbulence on the resolved flow through the truncation terms associated with the scheme. Thereby the need for an explicit subgrid-scale model is removed and hence the name "implicit LES".

RESULTS

Figure 1 shows the liquid water path (LWP) as a function of time from five simulations based on the DYCOMS-II measurements. We find this parameter to be very sensitive to changes in the vertical grid spacing; e.g. increasing Δz from 5 to 15 m leads to a decrease in the LWP from 80 to 25 $\mathrm{g\,m^{-2}}$ after six hours of simulation time. Increasing the horizontal grid spacing (Δx and Δy) on the other hand leads to an increase in the LWP. The shading of the lines in Fig. 1 indicates the grid aspect ratio ($\Delta x/\Delta z = \Delta y/\Delta z$) ranging from 7 (black) to 1 (light gray). The simulations with the highest aspect ratios are found to give the best agreement with the DYCOMS-II measurements which indicate a cloud layer of constant or perhaps even increasing thickness [6]. Hence, adding more grid points in the horizontal directions while keeping the vertical grid spacing constant does not necessarily improve the results.

The entrainment velocity estimated as the difference between the growth rate of the STBL and the applied large-scale subsidence shows no clear dependence on the grid spacing, and we come to the conclusion that the observed increase/decrease of the LWP in simulations with high/low grid aspect ratios must be related to the degree of coupling between the cloud layer and the sub-cloud layer. Figure 2 shows profiles of the second and third moments of the vertical velocity fluctuations ($\langle w'w'\rangle$ and $\langle w'w'w'\rangle$) from the same simulations as in Fig. 1 averaged over the period between 220 and 280 minutes of simulation time. The angle brackets denote horizontal averages across the computational domain. The markers represent measured data acquired from Fig. 5 in [6]. Also in comparison with these, we find the simulations with high grid aspect ratios to give the best agreement; in particular regarding the distinct maximum of $\langle w'w'\rangle$ at $z \sim 700$ m (near the middle of the observed cloud layer) and the change of sign of $\langle w'w'w'\rangle$ from positive below the cloud layer to negative within the cloud layer.

It can be argued, that in simulations of the STBL a computational grid of high aspect ratio is more representative of the anisotropic nature of the turbulence near the surface and at the cloud top then an isotropic grid, and thereby more suited for this type of simulation.

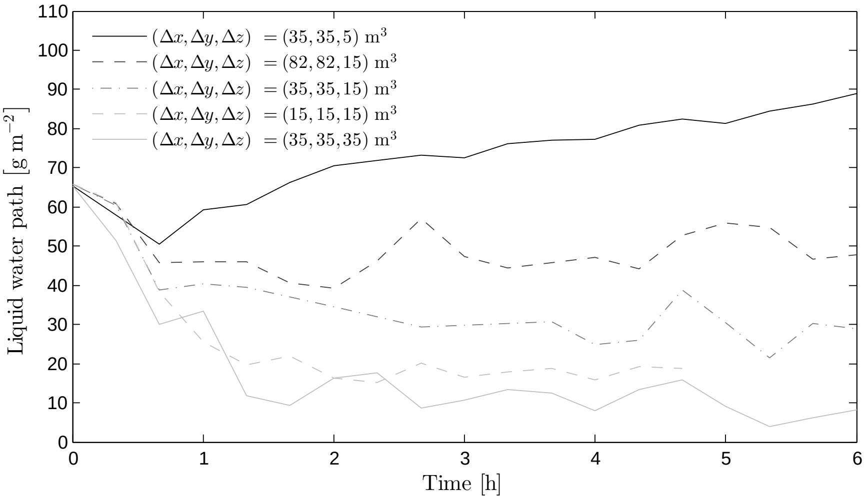

Figure 1. Liquid water path as a function of time from five simulations based on the DYCOMS-II measurements. The shading of the lines indicates the grid aspect ratio ranging from 7 (black) to 1 (light gray).

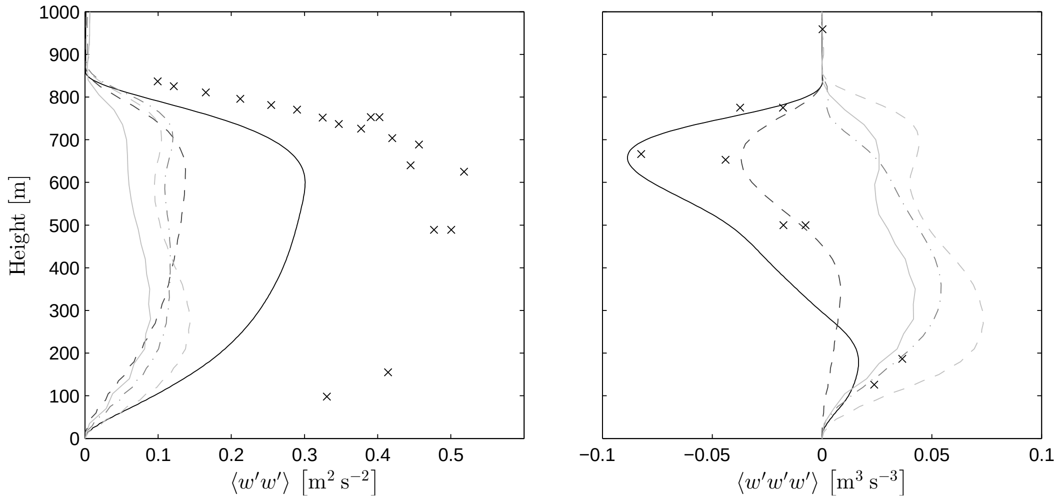

Figure 2. Profiles of (left) the second moment and (right) third moment of vertical velocity fluctuations from the same simulations as in Fig. 1. The markers represent measured data acquired from Fig. 5 in [6].

References

[1] S. P. Malinowski, H. Gerber, I. J.-L. Plante, M. K. Kopec, W. Kumala, K. Nurowska, P. Y. Chuang, D. Khelif, and K. E. Haman. Physics of Stratocumulus Top (POST): turbulent mixing across capping inversion. *Atmos. Chem. Phys.*, **13**:12171–12186, 2013.

[2] L. G. Margolin and W. J. Rider. A rationale for implicit turbulence modelling. *Int. J. Numer. Meth. Fluids*, **39**:821–841, 2002.

[3] J. M. Prusa, P. K. Smolarkiewicz, and A. A. Wyszogrodzki. EULAG, a computational model for multiscale flows. *Computers & Fluids*, **37**:1193–1207, 2008.

[4] P. K. Smolarkiewicz. Multidimensional positive definite advection transport algorithm: An overview. *Int. J. Numer. Meth. Fluids*, **50**:1123–1144, 2006.

[5] B. Stevens, D. H. Lenschow, G. Vali, H. Gerber, A. Bandy, B. Blomquist, J.-L. Brenguier, C. S. Bretherton, F. Burnet, T. Campos, S. Chai, I. Faloona, D. Friesen, S. Haimov, K. Laursen, D. K. Lilly, S. M. Loehrer, S. P. Malinowski, B. Morley, M. D. Petters, D. C. Rogers, L. Russell, V. Savic-Jovcic, J. R. Snider, D. Straub, M. J. Szumowski, H. Takagi, D. C. Thornton, M. Tschudi, C. Twohy, M. Wetzel, and M. C. van Zanten. Dynamics and Chemistry of Marine Stratocumulus-DYCOMS-II. *Bull. Amer. Meteor. Soc.*, **84**:579–593, 2003.

[6] B. Stevens, C.-H. Moeng, A. S. Ackerman, C. S. Bretherton, A. Chlond, S. de Roode, J. Edwards, J.-C. Golaz, H. Jiang, M. Khairoutdinov, M. P. Kirkpatrick, D. C. Lewellen, A. Lock, F. Müller, D. E. Stevens, E. Whelan, and P. Zhu. Evaluation of Large-Eddy Simulations via Observations of Nocturnal Marine Stratocumulus. *Mon. Wea. Rev.*, **133**:1443–1462, 2005.

[7] R. Wood. Stratocumulus Clouds. *Mon. Wea. Rev.*, **140**:2373–2423, 2012.