Vertical resolution dependency of boundary layer schemes

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1 Introduction

The performance of physical processes in numerical weather prediction (NWP) model is significantly affected by vertical resolution because physical processes in the current NWP models are vertical one dimensional models.

In the atmospheric boundary layer, turbulence transports momentum, heat and moisture. The turbulence is mainly driven by surface flux, i.e. exchange of momentum, heat and moisture between the atmosphere and the surface. In addition, at the top of stratocumulus, which is often generated at the top of the mixed layer, longwave radiation cooling also drives turbulence inside stratocumulus. One of the main roles of boundary layer (or turbulent) schemes in the NWP models is to represent the transport by turbulence.

Boundary layer schemes should also be sensitive to vertical resolution, especially in stratocumulus at the top of which sharp discontinuity and considerably large subsidence can be seen. Lenderink and Holtslag (2000) pointed out that boundary layer schemes based on prognostic or diagnostic turbulent kinetic energy (TKE) can give artificial mixing, which they call "numerical entrainment", due to insufficient vertical resolution.

On the basis of that, with the aim of increasing the vertical resolution of the operational NWP models, the sensitivity of the improved Mellor-Yamada level 3 model (MYNN3) (Nakanishi and Niino 2009) employed in JMA's operational mesoscale model (Saito et al. 2007) was examined using a single column model (SCM) in the Unified Model (UM) of the UK Met Office[1] for typical boundary layer situations. The configurations used in GABLS2[2] for diurnal changes of cloud-free boundary layer and EUROCS (Duynkerke et al. 2004) for diurnal changes of stratocumulus-capped boundary layer were adopted as test cases.

2 Configurations of the experiments

2.1 Boundary layer scheme

The MYNN3 assessed in the experiments predicts four covariances of turbulent fluctuation: TKE, self-covariance of liquid water potential temperature ($\overline{\theta_l'^2}$), water content ($\overline{q_w'^2}$), and their covariance ($\overline{\theta_l' q_w'}$). Buoyancy flux appearing in the production term of TKE is evaluated using the bi-normal probability distribution function (PDF) to incorporate the effect of subgrid condensation (Sommeria and Deardorff 1977). The width of the bi-normal PDF is determined from the prognostic covariances in the MYNN3. Flux plays an important role in generating turbulence inside clouds.

2.2 Vertical resolution

In order to examine the dependency on vertical resolution, three sets of vertical layer assignments were prepared. The grid spacings are regulated by an arithmetic sequence written as

$$\Delta z_n = \Delta z_1 + a(n-1), \qquad (1)$$

with the common difference a and the first grid spacing increment Δz_1. The height of the n-th layer z_n is determined as $z_{n+1} = z_n + \Delta z_n$.

In Table 1, the parameters necessary to establish the vertical layer assignments (z_1, Δz_1, a) in the three configurations and the number of layers up to some typical height are shown.

2.3 Test cases

1) GABLS2 (diurnal change of cloud-free boundary layer)

The simulation starts with a fully developed mixed layer at midday. The diurnal change is realized through forced ground temperature. The maximum and minimum ground temperatures are about 292 K and 272 K, respectively. During the daytime, the ground temperature changes in a form of a sine curve, while its decrease during the night is represented by a linear function.

2) EUROCS (stratocumulus-capped boundary layer)

The initial condition displays a sharp inversion at a height of around 600m above the surface. The average jump across the inversion is given by $\Delta\theta_l = 12$ K and $\Delta q_w = -3.0$ g kg^{-1}. The long radiative upward flux is imposed as a function of the total water path, and a simple shortwave radiation scheme is employed. The forced horizontal divergence in the original configuration is instructed as 1×10^{-5} s^{-1}, which leads to the subsidence rate $w = -1 \times 10^{-5} z$ m s^{-1} with the height above the surface z. The forced surface fluxes of heat and moisture are also given.

3 Results

3.1 GABLS2

Fig. 1 shows vertical profiles of potential temperatures in the GABLS2 experiments with a number of vertical layer assignments. In the case of the fully developed mixed layer shown in Fig. 1 (left), while grid configuration (A) generates a mixed layer that is a little too shallow

Table. 1: Specification of vertical layer assignments prepared for the experiments (#: number)

Grid configuration	(A)	(B)	(C)
Height of the lowest layer z_1[m]	20	5	
First grid spacing increment Δz_1 [m]	60	16.6	11
common difference a[m]	40	6.6	1
# of layers up to 1,000 m	8	17	37
# of layers up to 2,000 m	10	23	55
# of layers up to 3,000 m	13	30	69

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[1]The author implemented the MYNN3 into the UM during a spell as a visiting scientist in the UK Met Office.

[2]http://people.su.se/~gsven/gabls/

at a glance as it does not have sufficient grid spacing to resolve the mixed layer adequately, the heights of the mixed layers for the grid configuration (B) and (C) are mostly identical. A similar feature can also be seen in the stable boundary layer as presented in Fig. 1 (right). These results imply that the vertical layer assignment with 30 layers below a height of 3,000m is enough to represent mixed and stable layers with no clouds.

3.2 EUROCS

While no significant differences are seen between grid configurations (B) and (C) in GABLS2, the test case of a boundary layer capped by stratocumulus reveals another dependency on vertical resolution. Vertical profiles of potential temperature with the three vertical layer assignments, including an LES result obtained from the project web site[3], are displayed in Fig. 2, which shows that coarser vertical resolution result in higher inversion. This is not just a problem in terms of the height of the inversion; the higher inversion height implies that too much air is entrained across the inversion layer. Since this test case imposes subsidence, as mentioned above (and it is often true in layers with stratocumulus), the inversion would be simply be lowered by the subsidence. However, the artificial vertical gradients of potential temperature that appear due to coarse resolution generate numerical, i.e. not genuine vertical mixing. Lenderink and Holtslag (2000) call this “numerical entrainment”. In order to reduce the numerical entrainment, higher vertical resolution is necessary as shown in Fig. 2.

4 Conclusion and Discussion

The GABLS2 experiments confirmed that extremely high vertical resolution is not necessary to properly represent generation of mixed and stable boundary layers in diurnal changes. However, the model run with EUROCS, the case with stratocumulus, revealed that higher vertical resolution is desirable to reduce the false entrainment when TKE-based closure is adopted.

Since the computational resources available in operational NWP systems are fairly limited, it is impossible to secure as many vertical layers as needed even though the experiments showed that higher resolution is desirable. However, the results of the experiments provide an important guide in determining the assignment of vertical layers. They suggest that grid configuration (B) is enough for cloud-free boundary layer, and that it behaves better than a coarser one even in cloudy layers.

JMA plans to enhance vertical resolution in the global and mesoscale models. In addition to assisting with the examination of how vertical layers should be placed, single column models are expected to be useful in determining the performance of physical processes with enhanced vertical resolution.

Acknowledgment

This work was conducted while the author was at the UK Met Office as a visiting scientist. The author sincerely appreciates the supports received there.

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[3]http://www.phys.uu.nl/~wwwimau/research/atm_dyn/EUROCS_PART_I/eurocs.html

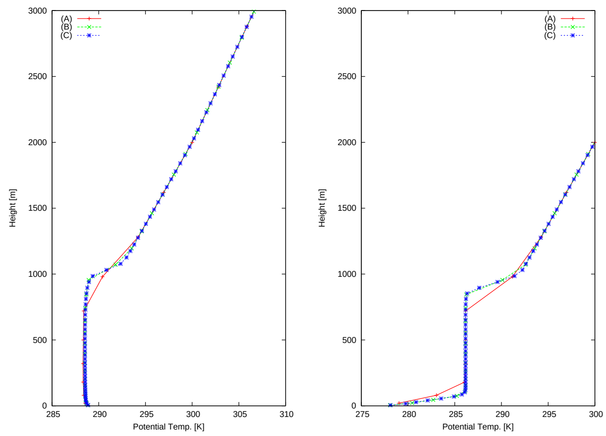

Fig. 1: Vertical profiles of potential temperature in the GABLS2 experiments. Left: when the mixed layer is fully developed; right: when the stable layer is evolved. Each line corresponds to grid configurations (A), (B) and (C) shown in Table 1.

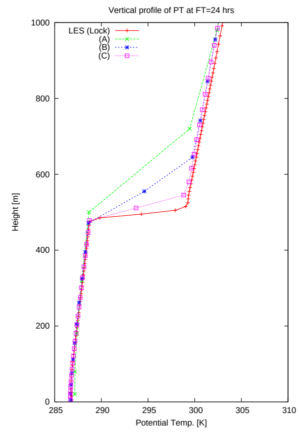

Fig. 2: Vertical profiles of potential temperature in the EUROCS experiments (24 hours after the initial time). Each line corresponds to LES (by A. Lock, obtained from the project web site), the single column model with grid configurations (A), (B) and (C) shown in Table 1.