A three-dimensional turbulence scheme for the gray zone in a convective boundary layer

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While a convective flow in a planetary boundary layer can be partly captured with the horizontal resolution less than 1 km, a turbulence scheme suitable for such the resolution is not sufficiently established. This issue is often called the gray zone problem for a boundary layer. Several schemes applicable to the gray zone has been proposed in recent years. Most of them are designed on the basis of a vertically one-dimensional (1D) scheme which is usually employed for a RANS model. On the other hand, Honnert and Masson (2014) indicated that the effect of the horizontal shear production, which cannot be taken into account in a 1D model, is not negligible in the gray zone.

Kitamura (2016) proposed a three-dimensional (3D) turbulence scheme based on the Deardorff (Deardorff 1980) model. While this model improves the representation of the resolved motion in the gray zone, it tends to underestimate the vertical gradient of the temperature in the surface layer and cannot reproduce a weak stable region seen in the upper part of the mixed layer for coarser model resolution. In the present study, we modify the three-dimensional (3D) scheme proposed by Kitamura (2016). First, the upper limit of the vertical length in the surface layer is given independently of the horizontal resolution, because the length scale should be determined by the height from the ground rather than the horizontal resolution. Second, the countergradient term by Troen and Mahrt (1986) is introduced to the vertical temperature flux.

We examined the numerical experiments for an unstable boundary layer using ASUCA which is an NWP model developed by Japan Meteorological Agency. In the experiments, the surface temperature is prescribed as an external forcing. The horizontal grid spacings of 125, 250, 500 and 1000 m are performed.

Figure 1 shows the ratio of the subgrid scale (SGS) components to the total turbulence kinetic energy (TKE) and vertical heat flux. Honnert et al. (2011) reported that the ratio could be well represented as a function of the horizontal resolution normalized by the boundary layer height and proposed the empirical functions for these SGS ratios. The ratio of the SGS component calculated by the present model is consistent with their empirical functions while that by the MYNN level 3 model (Nakanishi and Niino 2009) which is employed in the operational use is insensitive to the horizontal resolution and is overestimated in finer resolutions. Furthermore, The effect of the horizontal shear production in the new 3D scheme is analyzed. The ratio of the shear production to the total TKE production is displayed in Figure 2. The horizontal shear production is comparable to the vertical one and is not negligible in comparison with the buoyancy production in the gray zone. This result suggests that use of a 1D model induces underestimation of the SGS TKE because the effect of the horizontal shear production does not contribute to increasing the SGS TKE in the 1D model.

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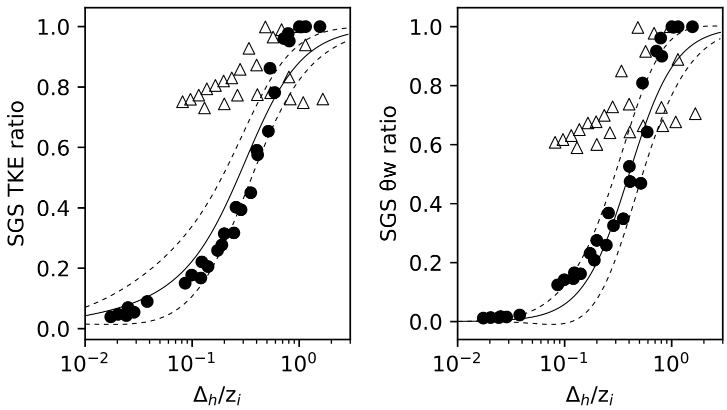

Figure 1: The ratio of the SGS components to the total TKE (left) and vertical heat flux (right). The abscissa indicates the horizontal grid size normalized by the height of the boundary layer. The open triangles and filled circles display the results for the MYNN level 3 model and the proposed model, respectively. The solid line shows the empirical function proposed by Honnert et al. (2011).

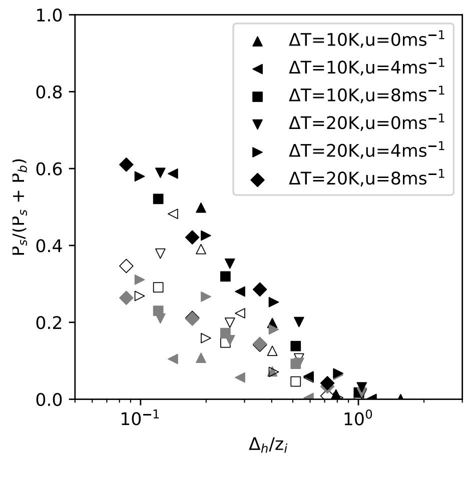

Figure 2: The ratio of the shear production to the total TKE production. The black, gray and open markers display the total shear production, the vertical and horizontal parts of the shear production.