Component testing of the COSMO model's turbulent diffusion scheme

Balázs Szintai and Oliver Fuhrer

MeteoSwiss, Krähbühlstrasse 58, 8044 Zürich, Switzerland

1 Introduction

In the framework of the COSMO Priority Project UTCS (Towards Unified Turbulence-Shallow Convection Scheme) the current one-equation turbulence scheme of the COSMO model was further evaluated. The aim of this evaluation was to better understand and eventually improve the current scheme. The work was focused on the component testing of the one-equation scheme. The budget terms of the TKE equation were analysed one-by-one. During the component testing, the results of COSMO simulations were compared to Large Eddy Simulation (LES) data and turbulence measurements. In the present paper the results of the evaluation of an ideal convective case will be presented.

2 Method

For the parameterization of atmospheric turbulence the COSMO model uses a one-equation scheme, which corresponds to level 2.5 in the Mellor and Yamada notation (Mellor and Yamada, 1974 and 1982). This closure type carries a one-dimensional prognostic equation for turbulent kinetic energy (TKE), which can be written using the conventional notation as:

$$\frac{\partial e}{\partial t} = -\beta g \overline{w'\theta_v'} - \overline{u'w'}\frac{\partial U}{\partial z} - \overline{v'w'}\frac{\partial V}{\partial z} - \frac{\partial \left[\overline{w'(\frac{1}{2}u_i'^2 + (p'/\rho))}\right]}{\partial z} - \epsilon,$$

where $e = \frac{1}{2}\overline{u_i'^2}$ is defined as TKE per mass unit. The term on the left hand side of the equation is the local tendency of the TKE. Terms on the right hand side refer to the buoyancy and shear production/destruction, the turbulent and pressure transport of TKE and the dissipation of TKE. In the COSMO model's scheme the turbulent transport of TKE (due to velocity-velocity triple correlation) and the pressure transport of TKE (due to velocity-pressure correlation) are parameterised together through the down-gradient formulation. For the parameterization of dissipation the Kolmogorov hypothesis is used. In the turbulence closure applied, equations for all second-order moments (fluxes and variances) except for the TKE are reduced to algebraic relations where the fluxes of momentum and scalar quantities are approximated with the down-gradient approach.

During the component testing of the turbulence scheme most of the above terms were analysed separately. It is important to note that in the current configuration all the terms are discretized using an implicit scheme, except for the turbulent transport term, which is discretized using an explicit scheme.

3 Results - Ideal case

The ideal convective case which was investigated for this study is described in Mironov et al. (2000). The setting for this simulation was a horizontally homogeneous and flat terrain with constant heating rate at the bottom. In the simulation no phase changes were considered (dry case) and wind shear was neglected. For this case the LES dataset was available from Dmitrii Mironov (DWD), containing all the TKE budget terms, which were important for the evaluation. Figure 1 shows the scaled profiles of TKE and the TKE budget terms after the steady state was achieved.

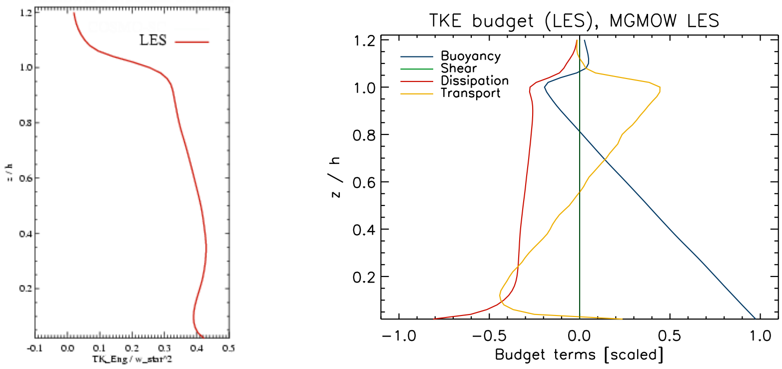

Figure 1: Scaled profiles of TKE (left) and the TKE budget terms (right) from the Large Eddy Simulation of the ideal convective case.

The above described case was simulated with the single column version of the COSMO model (Raschendorfer, 2007). In the first step, the settings of COSMO-2 were used. COSMO-2 is run operationally at MeteoSwiss at a horizontal resolution of 2.2 km. In the single column simulation 60 vertical levels were used with the first level at 10 m height, and the timestep for the integration was 72 s. The results (Fig. 2) show that the turbulent transport of TKE is too weak in the COSMO model, compared to the LES results. Consequently, TKE values at the top of the planetary boundary layer (PBL) are low and the negative bouyancy flux in the entrainment zone is nearly completely missing.

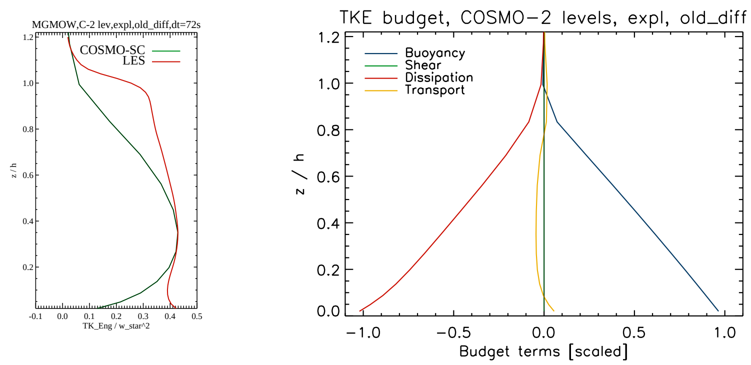

Figure 2: Scaled profiles of TKE (left) and the TKE budget terms (right) from the COSMO simulation with the operational level distribution and dt=72 s.

Due to the stretched vertical level distribution of COSMO-2, the model layers are relatively thick (around 100 m) near the top of the PBL. In the next step it was investigated, whether an increased resolution in the PBL would result in a better description of the transport term. To achieve this, a 10 m equidistant level distribution was tried with the same integration timestep (72 s). The result of this simulation (Fig. 3) is astonishing at first sight, because the transport term completely vanishes, causing a sharp decrease of TKE at the PBL top. The cause for this strange behaviour is a numerical limiter in the explicit scheme of the transport term. This numertical limiter is active, if the selected timestep is too large for the given vertical level distribution.

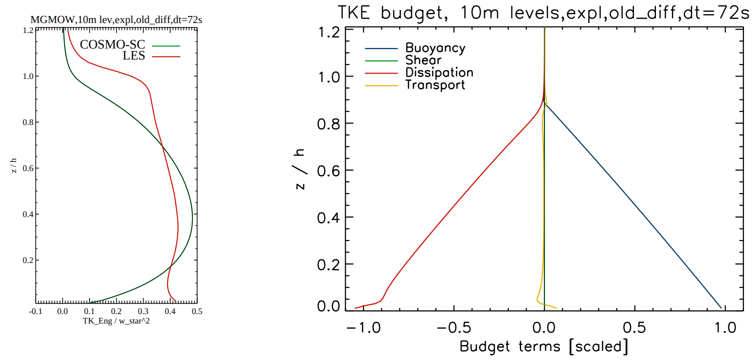

Figure 3: Scaled profiles of TKE (left) and the TKE budget terms (right) from the COSMO simulation with 10 m equidistant level distribution and dt=72 s.

To achieve a physically consistent solution without any numerical limitations, first, the numerical limiter in the transport term should be deactivated. This was realized in two different ways. First, an appropriately small timestep was chosen, and secondly, a semi-implicit formulation of the transport term was implemented. Figure 4 shows the result of the first approach. To achieve a stable integration without the numerical limiter, a significantly smaller timestep of 3.6 s had to be used for 10 m equidistant levels. It has to be noted, that the solution was independent of the vertical resolution, if the correct timestep was used in each case (eg. dt=7.2 s for 20 m equidistant levels).

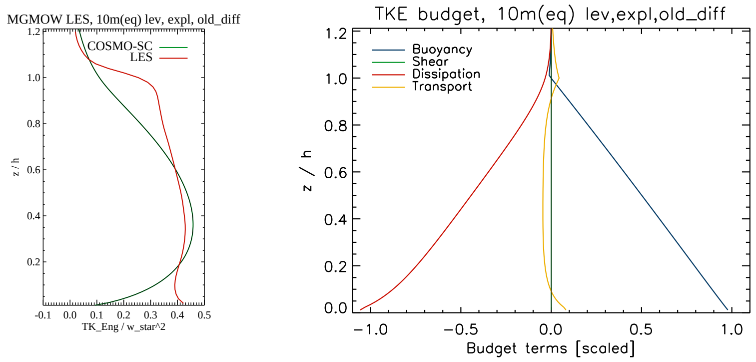

Figure 4: Scaled profiles of TKE (left) and the TKE budget terms (right) from the COSMO simulation with 10 m equidistant level distribution and dt=3.6 s.

In the case of the second approach a semi-implicit formulation was implemented for the transport term, which allowed the use of large timesteps even for very high (even 1 m) vertical resolution. Due to the semi-implicit approach the solution was independent of the vertical resolution and timestep (Fig. 5).

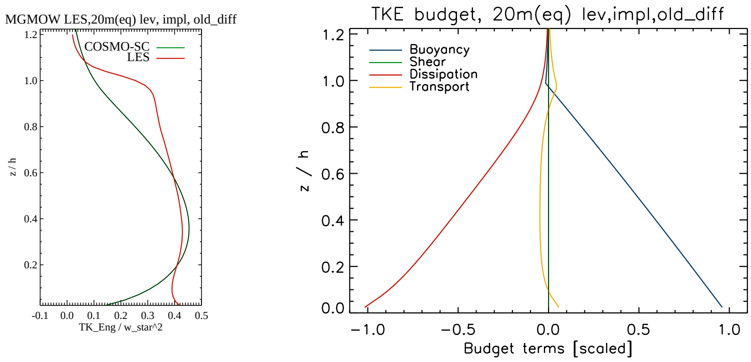

Figure 5: Scaled profiles of TKE (left) and the TKE budget terms (right) from the COSMO simulation with semi-implicit formulation for the transport term (20 m equidistant level distribution with dt=72 s).

4 Conclusion and Outlook

In the experiments described above a COSMO model solution of the ideal convective boundary layer was achieved which is independent of the vertical resolution and the timestep, consequently, representing the physical capabilities of the current turbulence scheme in such a situation. Compared to the LES results the turbulent transport of TKE is too weak in the COSMO model, and as a consequence TKE values near the PBL top are too low. This results in an insufficient negative bouyancy flux in the entrainment zone. If we compare the diagnosed horizontal velocity variances (not shown) with the LES results, it turns out that the anisotropy of turbulence is badly described in the COSMO model, i.e. the horizontal variances are too low in the upper and lower part of the PBL. The experiments have also shown the drawbacks of the explicit handling of the transport term. Consequently, in future developments a semi-implicit approach should be considered.

As a next contribution to the UTCS Project, a real-world convective case will be simulated with the COSMO model. For this experiment the LITFASS-2003 campaign (Beyrich and Mengelkamp, 2006) was chosen. To analyze the behaviour of the turbulence scheme in a real situation, COSMO results (both single column and three dimensional) will be compared to LES data and turbulence measurements.

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