Numerical Modelling of Small-Scale Turbulence in clouds

Mirosław Andrejczuk[*], Szymon P. Malinowski[*]
Wojciech W. Grabowski[**] and Piotr K. Smolarkiewicz[**]
Warsaw University, Institute of Geophysics, Pasteura 7, 02-093 Warszawa, Poland.
**National Center for Atmospheric Research, Boulder, CO, USA*

Summary. High-resolution modelling of small-scale turbulent mixing of clouds and clear air was performed. A substantial production of TKE by negative buoyancy resulting from evaporation of cloud water occured at centimeter scale. Anisotropy of turbulence due to buoyancy effects appeared to be an important feature of the simulations, even when TKE produced by evaporation was small in comparision to TKE cascading down from larger scales.

Introduction.

Despite recent progress in cloud physics, the understanding of key issues such as spatial distribution of cloud particles, turbulent mixing of clouds with the environment, or interaction of turbulence and microphysics, is still far from being complete. These issues are important - beyond fundamental understanding - in applications such as radiative transfer through clouds, initiation of precipitation in warm (i.e. ice-free) clouds, and parameterization of small-scale and microscale processes in models resolving larger scales.

This paper discusses results from a series of idealized numerical simulations of moist 3D turbulence accompanying the small-scale cloud/clear-air mixing. In the moist case, kinetic energy of small-scale motions comes not only from the classical downscale energy cascade, but it can also be generated internally due to the evaporation of cloud droplets.

We simulate directly the interfacial mixing, in order to study the impact of the evaporative cooling and cloud droplets' sedimentation on the generation of the turbulent kinetic energy (TKE). Our numerical model is set up to simulate the crux of the laboratory experiment described in [1]. Insofar as the initial and boundary conditions are concerned, we do not strive to mirror the laboratory case - the latter would be both computationally demanding and mathematically complex - but tend rather to capture key physical features of the problem at hand. This is in the spirit of DNS turbulence studies which assume heavily idealized initial and boundary conditions, while focusing on an accurate representation of the evolving flow.

Numerical model setup.

The analytic equations of motion (in anelastic approximation), thermodynamic energy equation, water substance conservation equation and equations for the cloud water parameterizations (bulk and detailed, accounting for droplet sedimentation) are solved by means of finite-difference approximations using the semi-Lagrangian/Eulerian nonhydrostatic anelastic model EULAG, broadly documented in the literature ([2-6] and references therein).

Taking into account all physical and numerical limitations of the approach, we compromised on using a relatively coarse grid length 0.01 m and modest computational grid 64^3, for all simulations reported here. In effect, the simulations reported fall into the gray area between poorly resolved DNS and well resolved LES.

The initial velocity field has the same spatial distribution for three series of experiments corresponding to high, moderate and low TKE level in clouds. The initial air temperature is set to 293K everywhere and the water vapor mixing ratio outside the cloud is 9.9g/kg ; this corresponds to the relative humidity of 65%). The initial cloud water is specified to form filaments, with the same temperature as in the environment, 100% relative humidity, and the cloud water mixing ratio around 3.2g/kg defined such that cloudy filaments are neutrally buoyant.

In all detailed microphysics simulations, 16 classes of cloud droplets are used with the droplet sizes linearly distributed in the range from 0.78 μm to 24 μm.

Results and conclusions.

Our simulations suggest that, at high initial values of the large-scale TKE, moist processes have minor impact on the small-scale dynamics of mixing and homogenization. In particular, the evolutions of TKE and dissipation rate (proportional to enstrophy) differ between moist and dry simulations only at the final stage of mixing, when most of the TKE has already been dissipated.

There are, however, significant differences related to the small-scale anisotropy. Moist turbulence is anisotropic even for high values of the TKE input, with turbulent filaments elongated in the vertical, consistent with the laboratory experiment [7].

For moderate and low initial values of TKE, the influence of moist processes on small-scale mixing and homogenization is substantial. Especially, for low initial TKE, the energy/enstrophy evolutions are dominated by moist processes, and the impact of cloud droplet sedimentation is the largest. Relative differences between simulations with the bulk and detailed microphysics appear not big even for low TKE input. However, coarse spatial resolution afforded in this study tends to overestimate the role of the temperature and moisture diffusion compared to the cloud droplet sedimentation, across the cloud/clear-air interface. More detailed numerical experimentation at higher resolutions (e.g., 128^3, 256^3, etc.), whatever possible is necessary
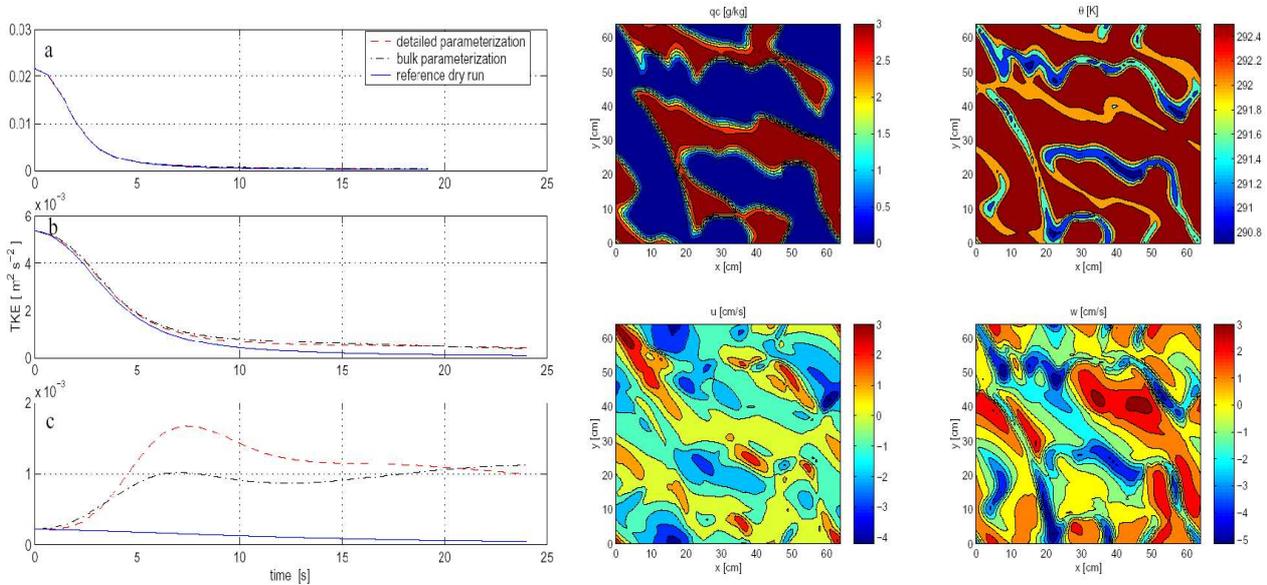
Fig.1. On the left: temporal evolution of TKE for three initial values: (a) – high, (b) moderate, (c) low. On the right: vertical cross section through the computational domain after 3.6 seconds of simulations with low initial TKE and detailed microphysics. Clockwise from the upper left panel: cloud water, potential temperature (visible cooling due to evaporation of sedimenting droplets), horizontal (u) and vertical (w) velocity components.
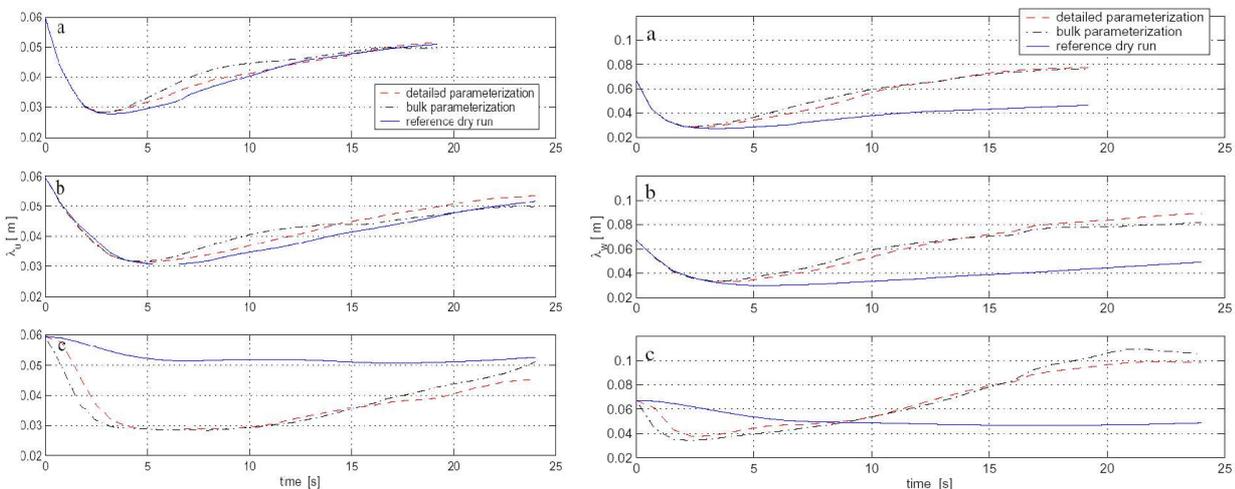

Fig.2. Temporal evolution of horizontal (left) and vertical (right) Taylor microscale Reynolds number, showing anisotropy in smallest scales of resolved motions.

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