Geophysical Research Abstracts, Vol. 7, 00323, 2005
SRef-ID: 1607-7962/gra/EGU05-A-00323

Scales and Aggregated Effects of the Most Energetic Turbulence Eddies in Planetary Boundary Layer

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1. Introduction

Classical turbulence theories as described in $e.g.$ Monin and Yaglom (1974) are based on Prandtl ideas. According to Prandtl, since the velocity shear is maximal in the surface proximity, the turbulence would be also produced at the beginning at the surface proximity and then evolve to larger eddies at higher levels. The Prandtl view gives the classical turbulence scaling, *kz*, in the surface layer, where k is the von Karman constant and z is the height above the surface. This scaling is actively used in design of semi-empirical theories of the turbulent exchange in the planetary boundary layer (PBL).

Being confirmed many times for low to moderate Re laboratory boundary layers, the Prandtl scaling has been recently challenged by very high Re turbulence in the PBL. Hunt and Morrison (2000), Zilitinkevich and Esau (2002) and Hogstroem et al. (2002) provided a theory and observational evidences on dominate role of non-local turbulence in the PBL. The principle difference to the Prandtl view is that the primarily acting agents of the non-local turbulence are large-scale eddies. Such large eddies occasionally would move down into the surface layer and burst the turbulence production due to related increase in the velocity shear. Understandably, the scaling of the non-local turbulence does not follow the Prandtl scaling. It would be rather defined by the integral turbulence scale, L^{int}, in the PBL. L^{int} is usually assumed to be the PBL depth, h_{PBL}.

In this study, the scaling of the non-local turbulence is investigated using a large eddy simulation (LES) modelling technique to generate high quality PBL data and a principle orthogonal decomposition (POD) technique to obtain the most energetic turbulence eddies in the PBL. Particularly, the study shows that the assumption $L^{int} = h_{PBL}$ is true only for shallow PBLs. In deeper PBLs, the non-local eddies reveal a natural limit in growth as it has been predicted by the linear theory of coherent structures (Bakas et al, 2001). Limits on the eddy size lead to the limits on the turbulent mixing rate with potentially important implications on climate and weather simulations.

2. Method

The principle orthogonal decomposition (POD) technique (Lamley, 1981) is an analogue of a widely used principal component analysis in the Fourier space. The mathematical theory behind it is a spectral theory of linear, compact, self-adjoint operators. Since the POD is essentially linear technique, it cannot analyse strongly non-linear evolution of individual turbulence eddies. However, the technique is able to reconstruct a spatial structure of the most energetic turbulence eddies (METE) with correct scale proportions. Obviously, the METE is the projection in the physical space of the first orthogonal function of velocity variations in the Fourier space.

3. Three-Dimensional Structure

The first step of the investigation is to reconstruct the METE from the 3D velocity fields obtained in LES. The LES code LESNIC has been developed by the author at the Nansen Environmental and Remote Sensing Centre. We focus the attention on the conventionally neutral PBL (Zilitinkevich and Esau, 2002) since h_{PBL} and so L^{int} in such PBLs can be controlled with a single governing parameter, namely, stratification of the free flow. It is clearly seen that $L^{int} = h_{PBL}$ is only in relatively shallow PBLs. These shallow PBLs are however the most common in the earth's atmosphere. The maximal METE size in the PBL seems to be about 600 m, while the maximal depth of the PBL can reach 2500 m.

The METE seems to be self-similar in its structure. Only the METE in the most shallow PBLs reveal signs of horizontal elongation. As the whole, the METE structure is similar to previous findings in the DNS and laboratory experiments (Finnigan and Shaw, 2000).

4. Effects on Turbulent Mixing

The very existence of the most energetic turbulence eddies demonstrates natural self-organization properties of the boundary layer turbulence. It is however more interesting to investigate the effects of the METE on the aggregated turbulent mixing in the PBL. The study reveals that the non-dimensional (external scaling) momentum flux is directly proportional to L^{int}. Saturation in L^{int} results in saturation in the momentum flux. The effect is easy to understand in terms of up-and downdraughts. The up- and downdraughts are clearly seen as streaks of positive and negative velocity anomalies in the PBL. The momentum flux is largely related to downdraughts. As it is seen, the downdraughts occupy progressively smaller area in shallow PBLs. So the aggregated effect is the overall decrease of the momentum flux. Another aggregated effect of the METE is sensitivity of turbulence properties of the surface layer to properties of the free atmosphere above the PBL. Zilitinkevich and Esau (2002; 2003) found functional dependence of h_{PBL} on the free-atmosphere stability. At the same time, the LES (Esau, 2004) and direct observations (Lange et al., 2004) reveal strong dependence of the momentum exchange coefficient at a standard height, C_D – a quantity heavily used in climate and weather models, on h_{PBL}. The reason is strong limitation of the log-law layer depth in the PBL as it cannot be deeper as about $^1/_2$ of the METE vertical scale.

5. Conclusions

The study's conclusions are:

- The turbulence dynamics of the high Re PBLs is dominated by energetic large eddies with origins in the PBL core
- These large eddies determine a distinct spatial structure of the up- and downdraughts with scales naturally limited by shear instability
- Stratification of the free atmosphere limits the vertical development of the large eddies causing their horizontal elongation
- Deformation of the large eddies results in proportional decrease of the turbulent momentum flux in the PBL

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