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Organised structures, non-local transports and turbulence closure for atmospheric convective boundary layer (CBL)

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The heart of the traditional concept of turbulence closure is the idea that higher-order statistical moments are expressed through lower-order moments. In this context self-organised structures typical of turbulent convection are not distinguished from large turbulent eddies. Such approach faces principal difficulties in reproducing convective heat and mass transfer at the surface and vertical transports in the interior of atmospheric (or oceanic) convective boundary layer (CBL) [e.g., Zilitinkevich et al. (1999, 2006), Elperin et al. (2002, 2006), Käpylä et al. (2012), Pergaud et al. (2009), Hellsen and Zilitinkevich (2013)]. In recent years it has become clear that paradoxical "shear-convection regime" typical of the atmospheric surface layer (Zilitinkevich, 1973; Kader and Yaglom, 1990) exhibits totally unusual turbulence, in which small-scale buoyancy-driven vertical plumes merge to form larger plumes, instead of breaking down and feeding horizontal velocity fluctuations, as it should be in the case of the forward energy cascade. We follow these works in an effort to develop unconventional, non-local theory of atmospheric CBL, distinguishing between the three sub-layers of essentially different nature.

- The *surface layer* is responsible for the flow-surface interaction. It is unstably stratified and dominated by small-scale turbulence. The latter is generated by the buoyancy forces and the velocity shears inherent in both mean flow and organised structures.
- The *CBL core* is responsible for the vertical transport, mixing and dispersion across the CBL. It is dominated by large-scale organised structures, which entail very efficient mixing and hence almost neutral stratification. Here, there are two basic sources of small-scale turbulence: its local generation by the velocity shears inherent in organised structures, and vertical advection of the surface-layer turbulence by ascending branches of organised structures. The latter represent narrow plumes surrounded by wider but weaker downdraughts, which draw into CBL the weaker turbulent air from above (Zilitinkevich, Kleeorin and Rogachevskii, 2013b).
- The *turbulent entrainment layer* (TEL) is responsible for the CBL-free flow interaction. The free flow is strongly stably stratified and therefore only weakly turbulent. TEL is also stably stratified but essentially turbulent due to local generation of turbulence by the structural velocity shears and deliver of the remaining surface-layer turbulence by ascending plumes. The impact of plumes on the TEL-free flow interface excites internal gravity waves in the free flow and hence removal of kinetic and potential energy from CBL (Zilitinkevich, 1991, 2012; Zilitinkevich et al., 2012).

These issues are discussed in the three talks summarising the following recent developments.

Part 1: **Modern vision of the surface layer, CBL core and TEL:** turbulent, organised-structure and internal-wave mechanisms.

Part 2: **Analytical theory of typical convective structures:** axisymmetric Benard-type cells in shear-free CBLs and two-dimensional rolls in essentially sheared CBLs (often visualised in the atmosphere as cloud cells and cloud streets, respectively).

Part 3: **Three-fold decomposition turbulence closure theory for the CBL core:** generalisation of the EFB turbulence closure theory (Zilitinkevich et al., 2013a) to the CBL system (mean flow + organised structures + turbulence) accounting for advection and generation of turbulence by organised structures.