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ROLL VORTICES IN THE ATMOSPHERIC BOUNDARY LAYER

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Summary Numerical simulations on the formation of organized structures (roll-vortices) in the atmospheric boundary layer are presented and compared to field observations and related features in laboratory Ekman layers.

Despite being quite turbulent, the atmospheric boundary layer shows forms of organized vortices with horizontal axis orientated in the mean flow direction. The secondary circulations (lateral and vertical) can be identified by clouds organizing themselves as parallel lines in the updraft regions between pairs of counter-rotating roll vortices, as shown e.g. in Figure 1. From the Lagrangian point of view, air parcels exhibit a swirling motion along the mean wind direction due to the combined effect of axial, radial and tangential velocity components of the vortices. Those kind of horizontal roll vortices are well known from laminar boundary layers over rotating disks or Ekman layers in rotating fluids [1].

In the atmospheric boundary layer, the origin of roll vortices is attributed to classical Ekman layer instability for unstratified flow and to buoyancy – induced instability in unstably stratified cases [2]. Both mechanisms are known for laminar flows from linear theory and laboratory experiments. But as the atmospheric boundary layer is always turbulent, one might wonder, how large scale structures can still form. To investigate this problem, we have conducted numerical simulations with a parallelized large-eddy simulation (LES) model. The model is described [3] and has been applied e.g. to small scale vortex structures [4]. Here we present a case of the unstably stratified boundary layer, which resembles the spatial development of the air flow of an cold-air-outbreak over warm ocean water.

The three-dimensional model domain covered an area of about 200 x 6 x 4 km with a grid size of about 50m in all directions. Results of the simulations are displayed for a horizontal (x, y) slice of the vertical velocity at about mid-boundary layer and as vertical cross-section (x, z) at some downstream-distance (Figure 2). One can recognize quasi lineal structures in upward and downward motion which are attributed to quasi two-dimensional roll vortices. The cross section in Figure 2 gives some impression of these roll vortices, which exhibit a cross-wind wavelength of about 2km equivalent two times of the boundary layer depth. Further downstream this roll organization is somewhat broken up (not shown here), but some vortex features are still be seen. Concerning the physical mechanism of roll formation we suggest a combination of thermal convection and boundary layer wind shear.

Vertical transport of momentum by these vortices leads to the formation of stripes of enhanced and reduced surface wind stress oriented in the direction of the roll axis. These features can be compared to observations of the sea surface by Synthetic Aperture Radar (SAR) from satellites, where similar structures have been identified on numerous occasions [5].

References

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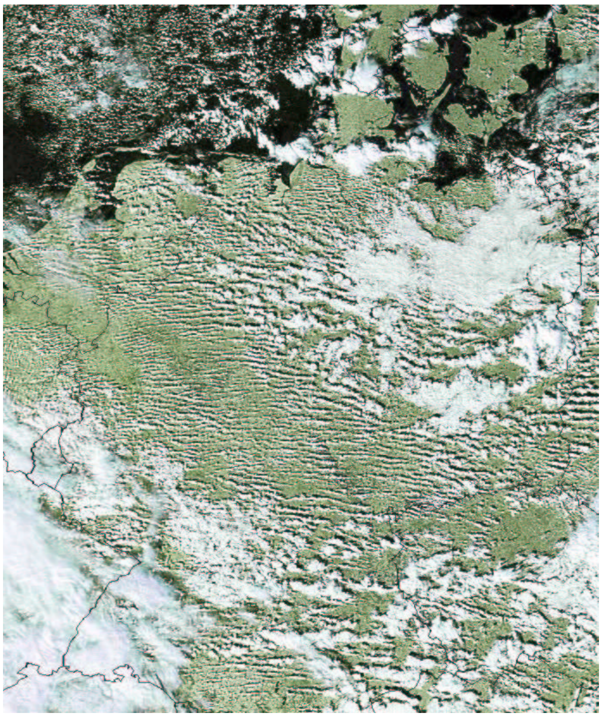

Figure 1: Clouds organized into rows due to roll-vortices in the atmospheric boundary layer.

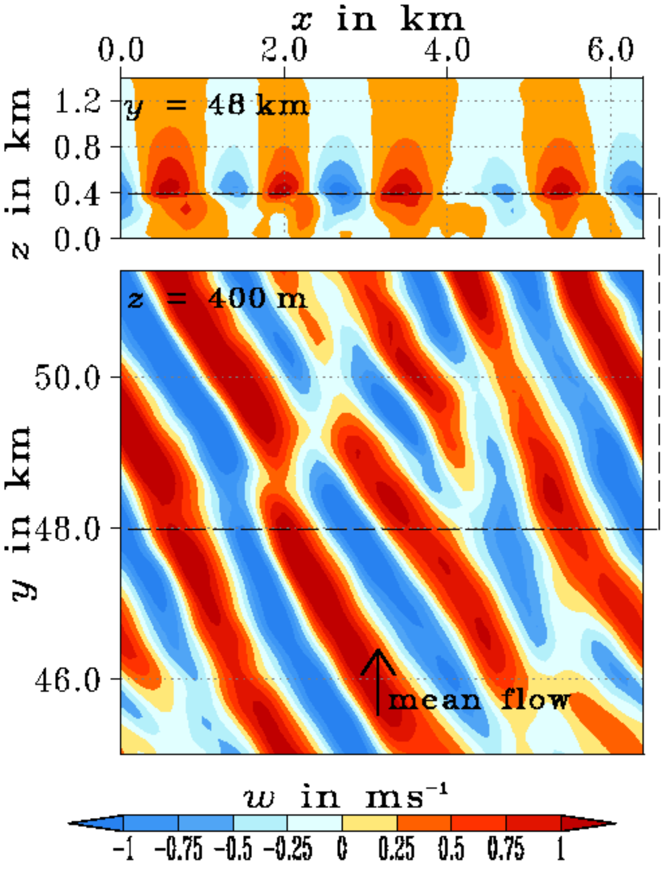

Figure 2: Model simulations of vertical velocity in the atmospheric boundary layer.
Bottom: horizontal cross section; top: vertical cross section. Red = upward motion, blue = downward motion.