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Formation of Vortices in Rotating Thermal Convection

Abstract

We have investigated the problem of thermal convection subject to background rotation by means of a three-dimensional, non-hydrostatic numerical model. In accordance with the set up of laboratory experiments, a fluid layer in solid rotation is heated by applying a constant heat flux at the lower boundary. In the non-rotating case, more or less random convection cells develop after the heated layer has reached a certain critical height. If background rotation is applied, these cells are replaced by vortices with vertical axis, whose strength and dimensions depend on the applied heat flux and on the background rotation rate.

Introduction

Turbulent thermal convection is manifested in many geophysical flow systems. Examples are the mixed layer in the ocean or the convective boundary layer (CBL) in the atmosphere. The convective atmospheric boundary layer has been treated extensively through field experiments and numerical simulations during the last decade.

Although atmospheric and oceanic convective boundary layers are developing on a rotating Earth, only little attention has been given to the influence of background rotation on turbulent convection. This may stem from the observational fact that the typical time-scale in the atmospheric CBL of about 30 minutes is much shorter than the inertial time scale of about 15 hours for mid latitudes. Nevertheless, recent laboratory experiments on rotating turbulent convection (e.g. Boubnov and Golitsyn, 1990; Fernando *et al.*, 1991; Maxworthy and Narimousa, 1991) have been performed with respect to geophysical applications. In addition to this work, results of numerical simulations on the rotating convection problem will be presented here.

Rotating turbulent convection

In order to compare field observations, laboratory experiments and numerical simulations it is necessary to define characteristic values for the convective

boundary layer. In the case of vanishing mean wind the CBL can be fully described by the surface kinematic heat flux $\overline{w'\theta'_0}$ and the inversion height h. With $\overline{w'\theta'_0}$ and h, a characteristic velocity w_* can be defined by:

$$w_* = \left(\frac{g}{\bar{\theta}}\overline{w'\theta'_0}h\right)^{1/3} \tag{1}$$

where g is the acceleration due to gravity and $\bar{\theta}$ a mean temperature of the CBL.

In a rotating CBL we need the angular frequency Ω of the rotation as an additional scaling factor. It is usual to use the Coriolis parameter $f = 2\Omega$ for this purpose. For application to oceanic or atmospheric problems $f = 2\Omega \sin \varphi$, where φ is geographic latitude and Ω the Earth's angular frequency, as usual. A characteristic non-dimensional number may now be formed from the governing parameters h, w_* and f by

$$Ro_c = \frac{w_*}{fh} \tag{2}$$

which we may call a "convective" Rossby number. We will use Ro_c for evaluation of our numerical simulations of rotating turbulent convection.

The influence of background rotation on the CBL has been investigated with a three-dimensional LES model, similar to the approach used e.g. by Moeng (1984). The model equation and the numerical techniques are described in detail in Raasch and Etling (1991) and will therefore not be repeated here. The principle setup of the experiments is as follows.

All runs start with an atmosphere at rest. The initial temperature stratification is neutral up to a height of 800 m with a stable layer of 1 K/100 m aloft, in order to allow a rapid growth of the CBL in the beginning of the simulation. The boundary layer is heated by imposing a constant uniform surface heat flux of 0.1 K ms^{-1} (about 125 Wm^{-2}). At the start of the simulation, convection is enforced by a vertical velocity perturbation applied in the lower part of the neutral layer.

Model results

From model runs, no difference in the CBL structure has been found for non rotating case and cases with coriolis parameter typical for the earth ($f = 10^{-4}\ s^{-1}$). Therefore f was increased artificially ("fast rotating planet") and the simulations were repeated for fixed surface hear flux but different rotation rates.

Numerical simulations have been performed for a non-rotating case ($f = 0$) and three fast rotating cases ($f = 0.01$, 0.03, 0.05 s^{-1}). The related values of the convective Rossby number are $Ro_c = \infty$, 0.16, 0.053, 0.03 respectively. Without

going into further details, the model results might be summarized as follows concerning vertical profiles of horizontally-averaged quantities:

- mean temperature gradient increases with increasing rotation rate. No well mixed CBL like in the non-rotating case is found.
- Vertical heat flux due to resolved scale motions is decreased for increasing rotation, subgrid-scale heat flux is increased at the same time.
- Variances of vertical and horizontal velocity components are decreased with increasing rotations. The ratio of vertical to horizontal variance is also decreasing to near isotropic conditions.

Marked changes in the flow structure can be also observed when the background rotation is increased. This is illustrated in figures 1 and 2, where streaklines of the horizontal flow patterns are displayed. For the non-rotating case (Fig. 1), convergence lines, marking the boundaries of convective cells, exhibit little rotation. If background rotation is applied, these cells are modified by vortices with vertical axis as can be seen in Fig. 2. Strength and dimensions of these vortices depend on the applied heat flux and on the background rotation rate. The scale of convective cells (updrafts and downdrafts) is decreased for increasing rotation.

These type of vortices have also been observed in laboratory experiments on rotating convection by Boubnov and Golitsyn (1990), Fernando *et al.* (1991) and Maxworthy and Narimousa (1991).

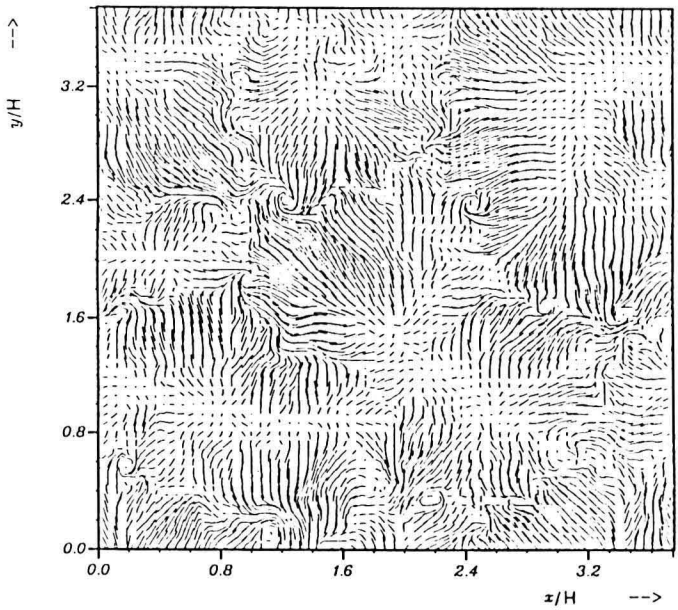

Fig. 1. Streaklines of horizontal motions in a non-rotating CBL. Horizontal cross section at $z = 0.05$ h.

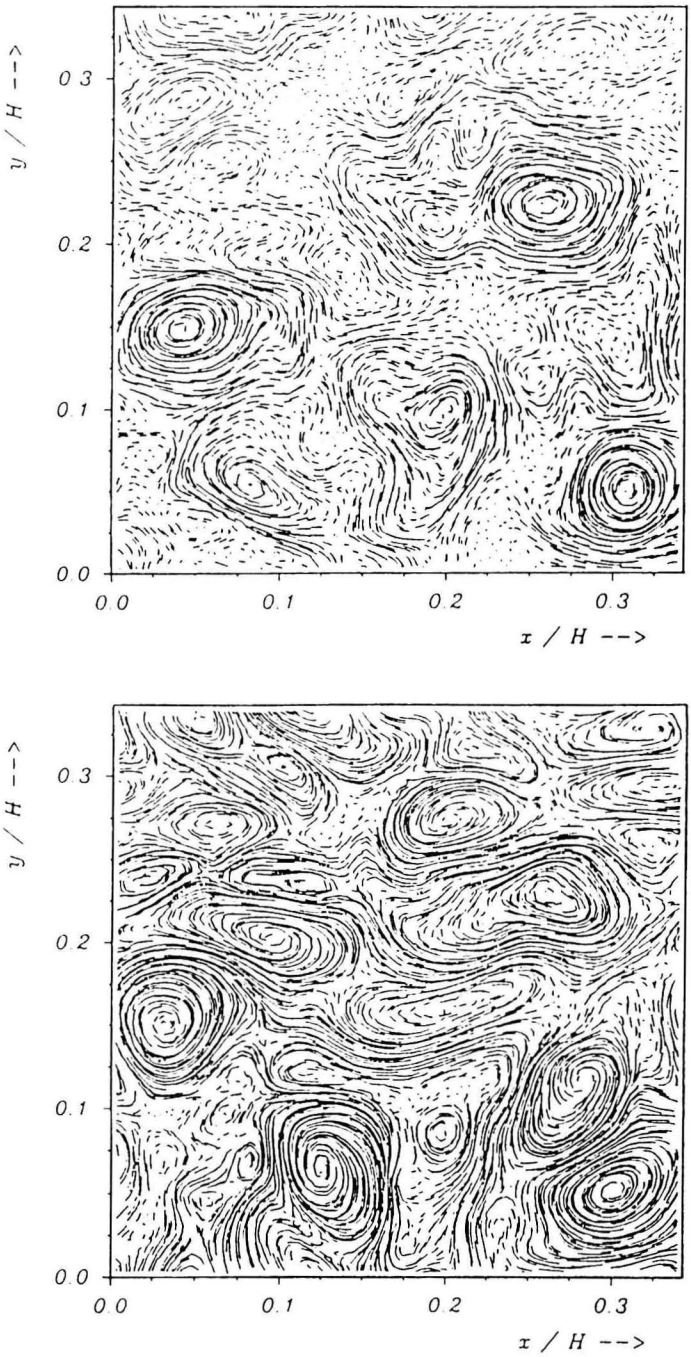

Fig. 2. Streaklines of horizontal motions in a rotating CBL ($f = 0.03\ s^{-1}$, $Ro_c = 0.053$). Horizontal cross section at $z = 0.5$ h (top) and $z = 0.07$ h (bottom).

Conclusions

Through numerical simulations we have shown, that background rotation has a marked influence on turbulence characteristics and flow morphology of a convective boundary layer. But for typical surface heat flux, as observed in the atmospheric CBL, we had to increase the Coriolis parameter up to a factor of 100 compared to situation on earth in order to obtain small Rossby numbers. With $f = 10^{-4}\ s^{-1}$, as usual for geophysical applications, small values of Ro_c can be only obtained for deep convection in the ocean. In this case, the buoyancy flux $q_0/\varrho c$ is in the order of $10^{-8}\ m^2\ s^{-3}$ for $q_0 = 100\ W\ m^{-2}$ at the ocean-atmosphere boundary. If we take $h \approx 2$ km, as observed for deep ocean convection, we obtain $Ro_c \approx 0.4$. Hence it is very likely, that the Earth's background rotation is much more important in oceanic situations than for the atmospheric CBL. Indeed recent field observations (e.g. Schott and Leaman, 1991) and numerical simulations (Jones and Marshall, 1993) on deep convection in the ocean have revealed vortex-like structures like those displayed in Fig. 2, but some more field data are necessary in order to check our numerical results against geophysical observations.

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