3.4 TURBULENT STRUCTURES IN THE CONVECTIVE BOUNDARY LAYER, SUCH AS PLUMES AND PUFFS, IN RELATION TO THE THERMAL CHARACTERISTICS OF THE SURFACE

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1 Introduction

We consider a thermally conducting slab or solid base lying between the levels at $z = -h_b$ and $z = 0$ with the thermal diffusivity κ_b. Above this base between $z = 0$ and $z = h$ there is a layer of fluid with thermal diffusivity κ and kinematic viscosity ν (see figure 1). Above $z = h$ there is an insulating solid (or approximately stationary fluid above a stable inversion layer). A uniform vertical heat flux H_0 is applied below the solid base. At the bottom of the fluid layer, i.e. $z = 0$, this flux is reduced to $\rho c_p F_\theta = H_0 h/(h + h_b)$. The mean temperature at the interface at $z = 0$ is T_0, and at $z = h$ is T_h leading to $\Delta T = T_0 - T_h$.

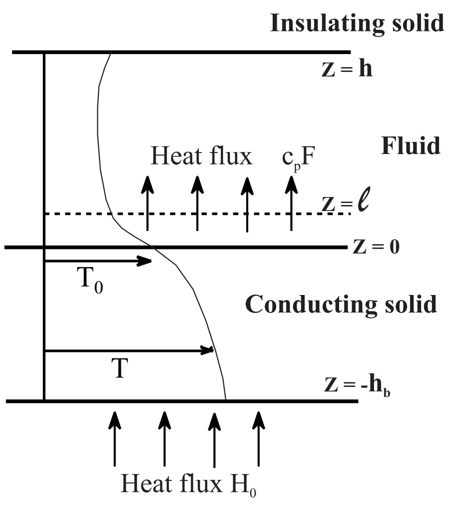

Figure 1: Schematic representation of the mean temperature profile in a convective fluid layer ($h < z < 0$) and in a solid base ($0 < z < h_b$) with a uniform heat flux H_0 at the bottom of the base.

When the Reynolds and Peclet numbers lie in the range of $1 \ll Re \leq 10^2$ and $1 \ll Pe \leq 10^2$, the eddies develop as Rayleigh-Taylor bulge-like instabilities growing on the heated surface layer.

2 DNS

To check our analysis we have conducted a DNS (Hunt *et al.* [1]). In the fluid the velocity- and temperature equations are discretized by means of a second-order finite volume method on a staggered grid (the temperature and pressure are located in the centre of a grid cell). For the time advancement a second-order Adams-Bashforth scheme is used. In the solid, the energy equation is discretized by means of a second-order finite volume method in the vertical and a direct solver using a Fourier transform in applied in the horizontal directions. For the time advancement a backward Euler method is applied. In the horizontal directions periodic boundary conditions are assumed for the temperature and the velocities in both the fluid layer and the base. At the lower and the upper boundary of the fluid layer a no-slip condition for the velocity is set. A zero heat flux is prescribed at the upper boundary and at the bottom of the base a heat flux is applied so that the mean heat flux at the bottom of the fluid layer is $\rho c_p F_\theta$.

Computations are carried out for two values of the Rayleigh number $\mathrm{Ra}_* = 10^4$ and 10^5 and with $0.1 \leq \kappa_b/\kappa \leq 10$. In all cases the Prandtl number is $\mathrm{Pr} = 0.7$. The simulations are performed in a rectangular box with an aspect ratio of the fluid domain equal to 5:1. The depth of the conductive layer is the same as the depth of the fluid ($h_b = h$). The resolution in the fluid layer is 40^3 grid points for $\mathrm{Ra}_* = 10^4$ and 100^3 for $\mathrm{Ra}_* = 10^4$.

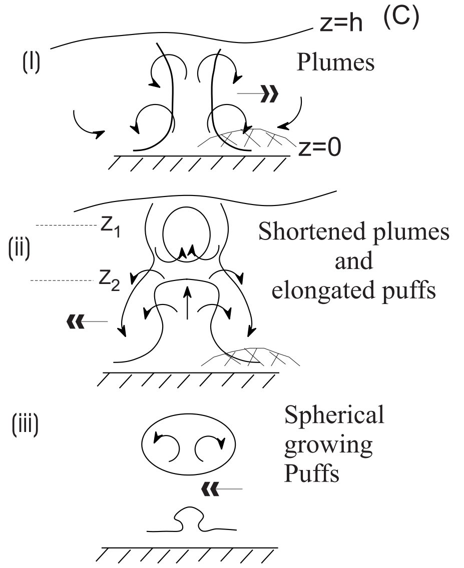

Figure 2: The three types of buoyant eddy structure depending on the ratio of the base to layer conductivity κ_b/κ: (i) plume; (ii) shortened plume or elongated puff; (iii) puff .

3 Results

It is found from the numerical solutions that the largest temperature fluctuations near the surface occur with a constant flux boundary condition and the minimum with a highly conducting boundary. The spatial scales of eddy structures in the lowest surface layer of the fluid layer become significantly smaller as κ_b/κ is reduced from 10 to 0.1. In the core of the convective layer a transition from long duration plumes to shorter duration and smaller length scale elongated puffs is found as quantified by autocorrelation and spatial correlation functions (see figure 3 and 4).

The hypothesis introduced above has been tested qualitatively in a laboratory set-up. The flow structure was observed as it changed from being characterized by nearly steady plumes, into unsteady plumes and finally into puffs where the thickness of the conducting base was first increased and then the conductivity was decreased.

4 High Reynolds numbers

At very high Reynolds numbers, approximately greater than 10^4 such as occur in geophysical applications, the surface boundary layer below each puff/plume is highly turbulent with a log-

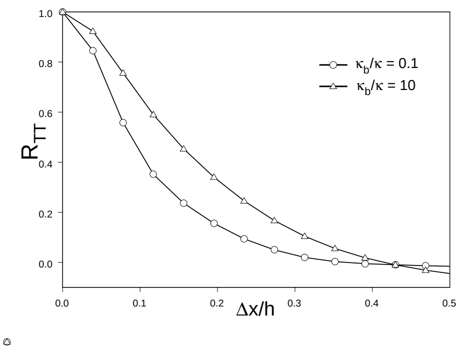

Figure 3: Spatial correlations of the temperature fluctuations for the two cases of κ_b/κ. at $z = 0$

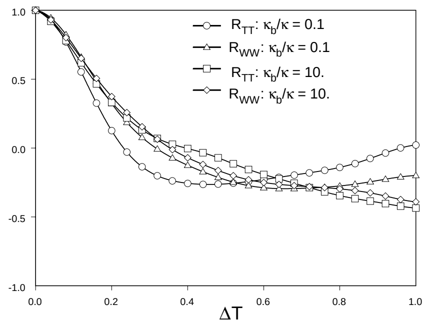

Figure 4: Time correlation of the temperature and vertical velocity fluctuations for the two cases of κ_b/κ at $z/h = 0.1$.

arithmic velocity and temperature profile. In that case the analysis shows that plumes can only develop if the surface flux is uniform, for example by radiant heat transfer or if the base is very thin (assuming constant heat flux below the base). Otherwise puffs form (Hunt *et al.* [1]).

References

[1] J. C. R. Hunt, A. J. Vrieling, F. T. M. Nieuwstadt and H. J. S Fernando. The influence of the thermal conductivity of the lower boundary on eddy motion in convection. In preparation.