24th Australasian Fluid Mechanics Conference - AFMC2024
Canberra, Australia
1-5 December 2024

Paper No: AFMC2024-96

Inner-layer turbulence of a vertical buoyancy layer

K. R. Maryada[1*], S. W. Armfield[2], M. MacDonald[1], P. Dhopade[1] and S. E. Norris[1]

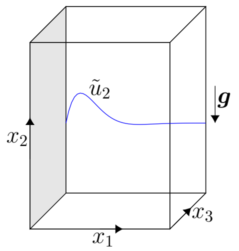
[1] Department of Mechanical and Mechatronics Engineering, The University of Auckland, Auckland 1010, New Zealand
[2] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, New South Wales 2006, Australia
*mailto: kmar699@aucklanduni.ac.nz

1 Introduction

Vertical natural convection boundary layers (NCBLs) form an important class of buoyancy-driven flows, with applications ranging from natural ventilation to modelling anabatic flows over cliffs and the melting of ice sheets. The turbulence development of vertical NCBLs is drastically different from canonical wall turbulence. At moderate Reynolds numbers (*Re*), in NCBLs, turbulence is primarily observed in the outer layer in the form of large-scale motions (LSMs), and the inner layer is weakly turbulent without exhibiting the predominant characteristics of canonical wall turbulence. This regime is termed the classical regime. At sufficiently high *Re*, the inner layer becomes fully turbulent and exhibits statistical signatures that are synonymous with canonical wall turbulence, termed the ultimate regime. Despite Wells & Worster (2008) hypothesising the existence of these regimes in vertical NCBLs over a decade ago, we still do not fully understand the nature of inner-layer turbulence. In this study, we investigate the statistical properties of streamwise velocity fluctuations in the inner layer using the vertical buoyancy layer (Maryada *et al.* 2023) as a model for a vertical NCBL.

2 Methodology

The inner layer turbulence was investigated using direct numerical simulation (DNS). The governing equations and the numerical method are the same as described in Maryada *et al.* (2023). The schematic and the domain and grid sizes of the DNS are given in figure 1 and table 1, respectively.



Case	Re	Domain ($x_1^+ \times x_2^+ \times x_3^+$)	$N_{x_1} \times N_{x_2} \times N_{x_3}$	Δx_{1w}^+	$\Delta x_{1\delta_{bl}}^+$	$\Delta x_2^+ \times \Delta x_3^+$
F1400	1400	$3185 \times 4414 \times 4095$	$355 \times 906 \times 816$	0.42	6.3	4.8×4.8
M1400	1400	$3235 \times 986 \times 493$	$355 \times 200 \times 100$	0.43	5.99	4.93×4.93
C1400	1400	$166 \times 1060 \times 530$	$100 \times 200 \times 100$	0.46	2.02	5.30×5.30
L3500	3500	$4694 \times 2380 \times 873$	$360 \times 500 \times 184$	0.33	14.08	4.76×4.76
M3500	3500	$5079 \times 1226 \times 450$	$350 \times 250 \times 92$	0.34	11.48	4.89×4.89
C3500	3500	$308 \times 1302 \times 478$	$100 \times 250 \times 92$	0.36	5.37	5.19×5.19

Figure 1 & Table 1. Schematic and details of the numerical simulations. Here, $\Delta x_{1\delta_{bl}}^+$ is the viscously-scaled cell size at the edge of the domain for C1400 and C3500. For the rest, it is at the edge of the boundary layer.

The case F1400 resolved the LSMs and outer-layer turbulence accurately. The LSMs are not fully captured in cases with prefixes M and L, as the domain was truncated in the streamwise/vertical (x_2) and spanwise (x_3) directions. No restrictions were imposed in the wall-normal (x_1) direction. These are comparable to the minimal domains of canonical wall turbulence (Jiménez & Moin 1991). The wall-normal, streamwise and spanwise domain sizes were constricted for cases with the prefix C, hindering the development of LSMs, outer-layer turbulence and wall-normal turbulent transport. These diverse simulations were chosen to isolate the processes in the inner layer. If certain scales of the inner-layer turbulence are similar across all the simulations, then these eddies are self-sustaining and autonomous (cf. Jiménez & Moin 1991). The contrary suggests significant inner-outer interaction.

3 Results

The one-dimensional premultiplied spectra of streamwise velocity fluctuations (u_2) in the spanwise (x_3) direction at $Re = 1400$ are shown in figure 2(a). The spectra do not exhibit a peak at $\lambda_{x_3}^+ \approx 100$ and $x_1^+ \approx 15$ (corresponding to the buffer-layer streaks in canonical wall turbulence), indicating that the inner layer is weakly turbulent at $Re = 1400$ (the classical regime). The spectra of M1400 and C1400 at $\lambda_{x_3}^+ \lessapprox 200$ and $x_1^+ \lessapprox 20$ are similar to that of F1400 in the inner layer, indicating that the spectral characteristics of these eddies in the near-wall region do not significantly depend on large-scale motions and outer-layer turbulence. A spectral peak at $\lambda_{x_3}^+ \approx 100$ and $x_1^+ \approx 15$ is present at $Re = 3500$ (figure 2(b)), indicating that the inner layer is turbulent in the same sense as canonical wall turbulence. This implies that the buoyancy layer is no longer in the classical regime but has transitioned into the ultimate regime. The spectra at $\lambda_{x_3}^+ \lessapprox 200$ and $x_1^+ \lessapprox 30$ are similar across the different cases, suggesting that the turbulence at these scales is autonomous, i.e., largely independent of the large-scale motions and outer-layer turbulence. All the simulations were run for over 1×10^5 viscous time units, and the turbulence did not decay in any of the cases, even in the absence of LSMs and well-developed outer-layer turbulence (especially cases C1400 and C3500). This indicates that the small-scale turbulence in the near-wall region is also self-sustaining.

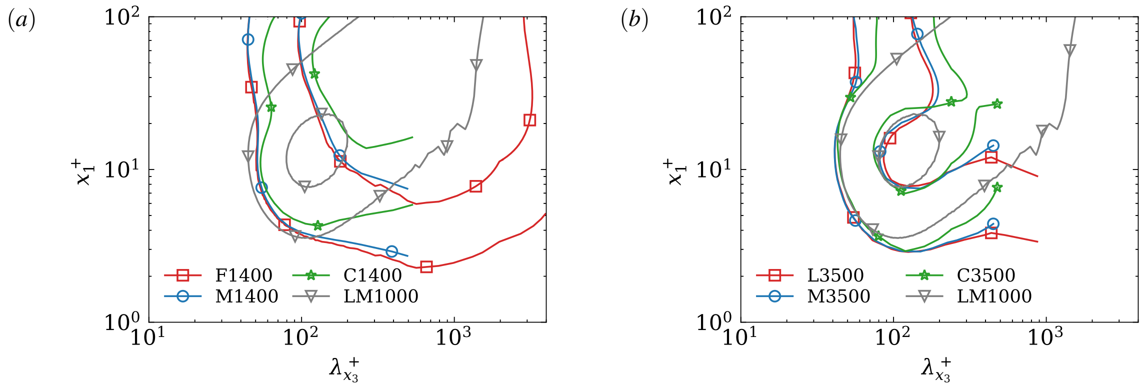


Figure 2. Premultiplied one-dimensional spanwise spectra of streamwise velocity fluctuations (u_2) at (a) $Re = 1400$ and (b) $Re = 3500$. The contours for the vertical buoyancy layer are 0.1 and 0.5 times the maximum value of C3500. The contours are 1 and 3 for LM1000 (channel flow at $Re_\tau \approx 1000$, from Lee & Moser (2015)).

4 Conclusions

The results of this study reveal that the small-scale turbulence in the inner layer is self-sustaining and autonomous in both classical and ultimate regimes. It also does not depend on the dominance of near-wall streaks, akin to the autonomous process of canonical wall turbulence. Therefore, similar fundamental processes govern turbulence in the near-wall region of vertical buoyancy layers and canonical wall turbulence despite the current flow being solely driven by buoyancy.

Acknowledgments

We thank New Zealand eScience Infrastructure (NeSI) for providing computational resources.

References

Jiménez, J., and Moin, P. 1991, The minimal flow unit in near-wall turbulence, *J. Fluid Mech.*, **225**, 213–240.

Lee, M., and Moser, R. D. 2015, Direct numerical simulation of turbulent channel flow up to $Re_\tau \approx 5200$, *J. Fluid Mech.*, **774**, 395–415.

Maryada, K. R., Armfield, S. W., Dhopade, P., and Norris, S. E. 2023, Large-scale motions in a turbulent natural convection boundary layer immersed in a stably stratified environment, *J. Fluid Mech.*, **967**, A40.

Wells, A. J., and Worster, M. G. 2008, A geophysical-scale model of vertical natural convection boundary layers, *J. Fluid Mech.*, **609**, 111–137.