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Influence of Diabatic Stratification on the Ventilation of Large Cities

Tobias Gronemeier[1], Siegfried Raasch[2]

[1] PhD student, Institute of Meteorology and Climatology, Leibniz Universität Hannover
[2] Professor, Institute of Meteorology and Climatology, Leibniz Universität Hannover

Abstract

The ventilation of cities is crucial for the well-being of its inhabitants. Local governments, therefore, inquire air ventilation assessments (AVAs) prior to the construction of new buildings. In a standard AVA, only neutral stratification is considered, although diabatic (unstable) conditions might be more frequently observed. Unstable stratification has a strong influence on the actual ventilation in a weak-wind situation due to the enhanced vertical mixing. Our results show a stronger ventilation inside most city areas, while in the vicinity of exposed buildings, unstable stratification causes reduced ventilation. Also, the influence of building parameters such as the plain area index λ_p on the ventilation is altered by the actual atmospheric stratification. Therefore, consideration of different stratifications for AVAs will give a better estimation of the ventilation to be expected around planned buildings.

1. Introduction

The air ventilation of cities is a crucial factor of the city climate and has a high impact on the well-being of the urban population. Due to the high number of pollutant resources in urban areas, weak ventilation can form cities into a dangerous environment for people. As many studies pointed out (e.g. [1], [2]) the actual building setup has a high influence on the wind field inside a city and therefore on the ventilation. Local governments, especially of larger cities, started to react to the need of good ventilation and created by-laws based on the findings of prior studies. As a consequence, an air ventilation assessment (AVA) is usually required to obtain legalization for large building projects inside cities [1]. However, as AVAs often require wind tunnel experiments, which are usually only capable of reproducing neutrally stratified atmospheric conditions, effects of diabatic stratification are neglected. This is often justified when focusing on high wind speed, where mechanically induced turbulence has a higher influence on ventilation than thermally induced turbulence. In weak-wind situations, however, turbulence produced by shear might be significantly weaker than thermally induced turbulence. An AVA solely analyzing neutral conditions might therefore not cover the real ventilation effect of planned buildings inside the study area. Thus, the AVA would not achieve its purpose.

In this study, we focus on the difference in ventilation under neutral and unstable atmospheric stratification with the goal to estimate the errors made when only analyzing neutral conditions. The ventilation analysis is made for Kowloon City, Hong Kong, using large-eddy simulations (LES). The local government of Hong Kong initiated its AVA program especially focusing on summer weak-wind conditions. These conditions will also be targeted in our research as we expect the largest differences between different atmospheric conditions during weak-wind situations.

In Chap. 2, the setup of the conducted simulations is described. Chapter 3 presents the results of the comparison of the ventilation between neutral and unstable stratification. Finally, the conclusions are given in Chap. 4.

2. Simulation setup

The difference in ventilation between varying stratification is analyzed by means of LES, applying the LES-model PALM [3]. The simulation domain extends 9km to 12km in along-wind direction, depending on the simulated stratification. Domain width and height are 6km and 2.5km, respectively. A grid size of 2m is used in each direction inside the lower 1100m of the domain. At higher levels the vertical grid size increases linearly by 4% to a maximum of 40m. The evaluated city area of Kowloon City covers an area of $4x5km^2$. Upstream of the city area (windward side), a turbulence-recycling area is included in the domain. This area is required due to the applied turbulence-recycling method creating a turbulent inflow in the simulations [3]. The size of the recycling area varies between the neutral (3km) and unstable (6km) case owing to the size of the largest turbulent structures. As we focus on a weak-wind situation, the background wind speed at the top of the domain is set to $1.5ms^{-1}$ with southerly wind direction. For the neutral case, effects of temperature are completely ignored in the simulation. For the unstable case, a uniform sensible heat flux of $200Wm^{-2}$ is prescribed at the lower boundary. So far, differences in surface type are neglected in order to isolate the pure effect of the stratification on the ventilation. The initial temperature is constant at 308K inside the lower 700m of the atmosphere, capped by an inversion layer with a constant gradient of $0.01Km^{-1}$.

3. Results

In the following, we analyze and compare the ventilation of Kowloon City for neutral and unstable stratification, focusing on the pedestrian height level 2m above ground. All presented data are averaged over a period of four hours unless otherwise stated.

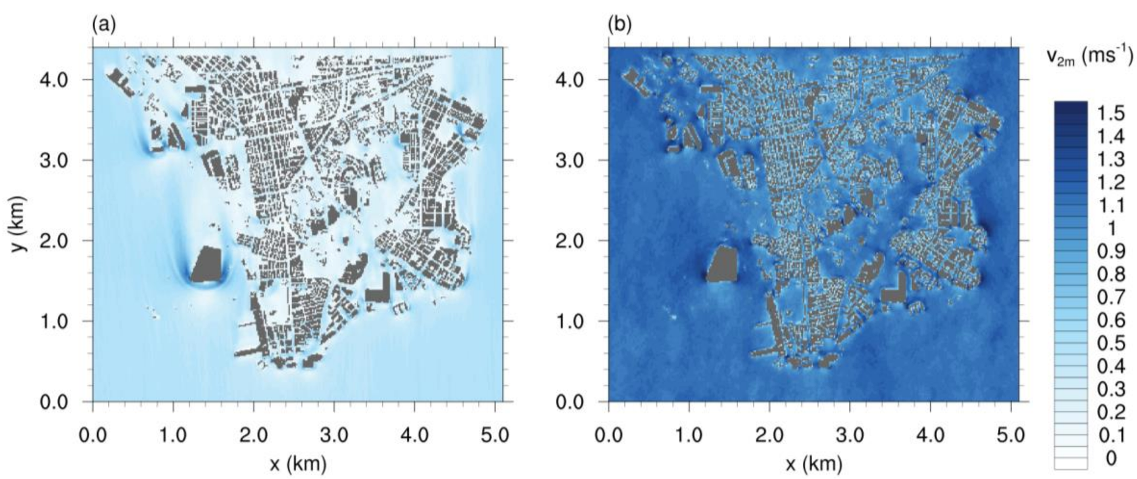

Figure 1: Wind velocity at 2m height, v_{2m}, for a) neutral and b) unstable case, averaged over 4 hours.

Figure 1a and b depict the wind velocity v_{2m} for the neutral and unstable case, respectively. In the unstable case, v_{2m} is significantly higher throughout the whole city area and its surroundings, compared to v_{2m} in the neutral case. The reason for this generally higher wind velocity in the unstable case is the stronger vertical mixing causing a larger transport of momentum to lower height levels. The difference in wind velocity therefore arises from the different atmospheric stratification. According to [4] and [5] the ventilation v_r is calculated as follows:

$$v_r = \frac{v_{2\mathrm{m}}}{v_{\mathrm{ref}}}, \tag{1}$$

where v_{ref} denotes a reference velocity which is defined as the average velocity at a height well above the city area. However, as v_{ref} is equal for both the neutral and unstable case, this definition naturally shows a general increase in v_r for the unstable case due to the increased v_{2m}. That makes it very difficult to detect the differences in ventilation between both simulations caused by the pure impact of the building setup under the different stratifications. Therefore, we redefine v_{ref} to be calculated upstream of the city area at a height of 2m. With this adapted definition of v_{ref} the large difference in wind velocity between both cases due to the pure stratification effect is excluded. Now, v_r represents purely the impact of the buildings on the ventilation.

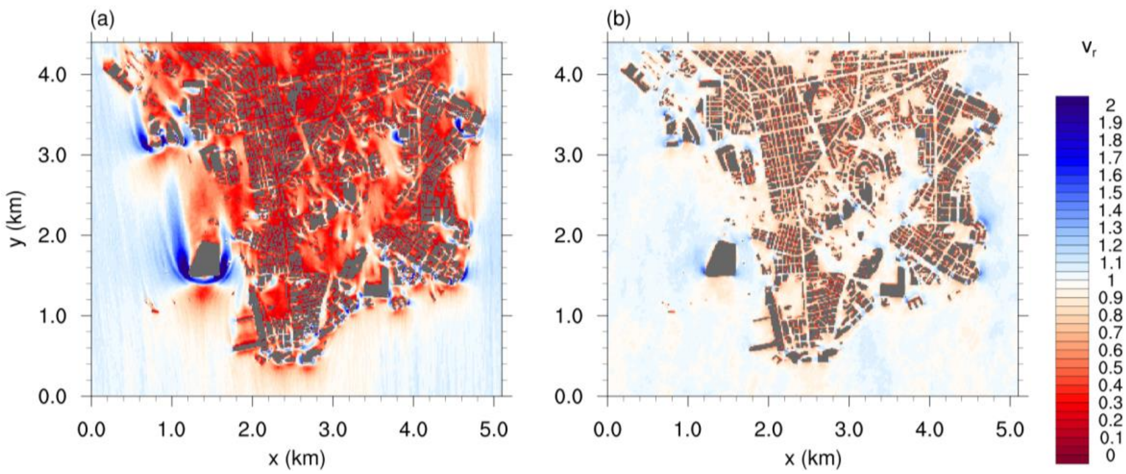

Figure 2: Ventilation v_r for a) neutral and b) unstable case, averaged over 4 hours.

Figure 2a and b show v_r for the neutral and unstable case, respectively. In the neutral case, buildings have a large potential to block the airflow and significantly reduce v_r inside the city. Exposed buildings, however, cause large v_{2m} at their edges and therefore increase v_r in their vicinity. In the unstable case, due to the strong vertical mixing, the blocking effect of the buildings is efficiently reduced leading to an enhanced ventilation inside the city, while v_r around exposed buildings is reduced compared to the neutral case. This can also be seen in Fig. 3 where the difference in v_r is shown. Positive (blue) values show better ventilation in the unstable case while negative (red) values show better ventilation in the neutral case. In this figure, the overall increase in v_r throughout the city area is clearly visible. Also, the reduction in v_r at the edges of exposed buildings due to the increased vertical mixing is obvious. In the neutral case, buildings block the airflow forcing the air to move around them which results in high velocities at the edges of exposed buildings and low velocities at the leeward side of the buildings and inside the city area. In the unstable case, this blocking effect is reduced due to the enhanced vertical mixing, enabling the air to move in vertical direction more efficiently. Consequently, less air is forced around the building edges, preventing the strong increase in velocity in the vicinity of exposed buildings. At the same time, the increased vertical mixing transports higher momentum from above the city downwards leading to higher v_r at the leeward side of buildings and inside the city area.

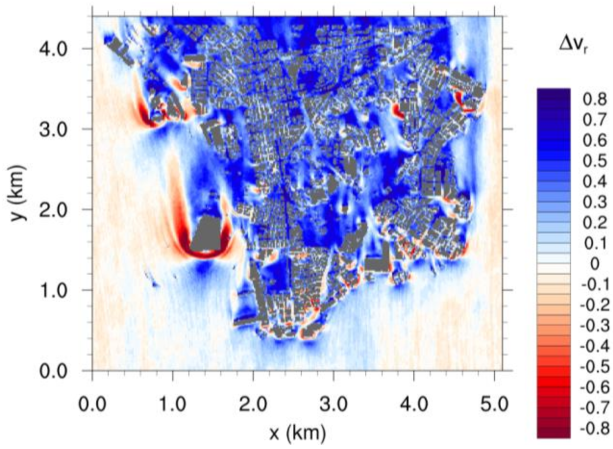

Figure 3: Difference in v_r between unstable and neutral case.

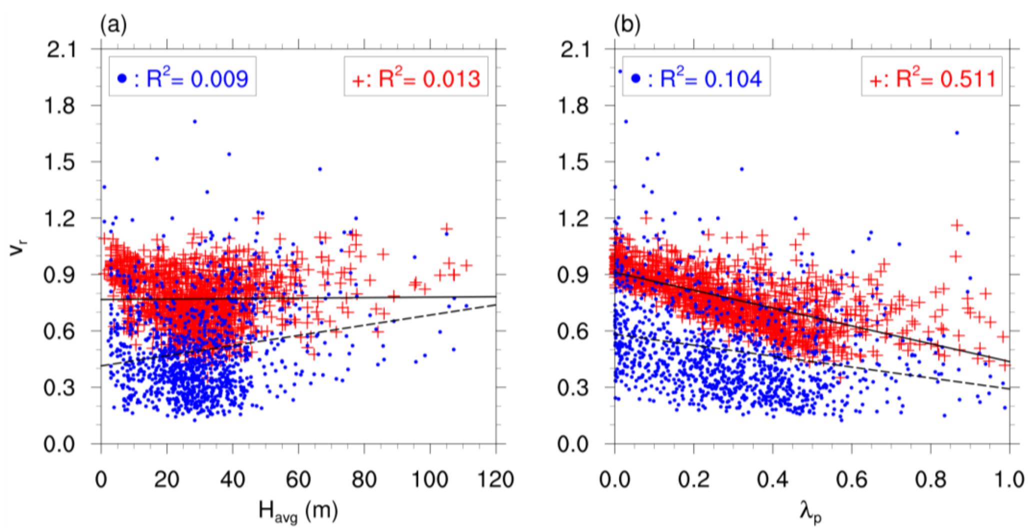

Figure 4: Correlation between v_r and a) H_{avg} and b) λ_p for the neutral case (blue dots) and unstable case (red crosses). Each data point represents average values inside a squared area of 100m edge length.

To further identify the different impact of the buildings on the ventilation under different atmospheric stratification, we analyzed the correlation between v_r and different building parameters. Throughout the city, the mean building height H_{avg} and the plain area index λ_p have been calculated for squared patches with 100m edge length and, in addition, v_r has been averaged inside these patches. The correlations are illustrated in Fig. 4a and b for H_{avg} and λ_p, respectively. Blue dots represent the neutral case while red crosses represent the unstable case. No significant correlation, neither for the neutral nor for the unstable case, can be found between H_{avg} and v_r implying that H_{avg} has no influence on v_r. However, a correlation is present between λ_p and v_r where higher v_r correspond to lower λ_p. The reason for this is that a lower λ_p corresponds to fewer buildings blocking the airflow which results in a higher velocity. This holds true for both cases, but the variance of v_r for a specific λ_p is much larger in the neutral case compared to the unstable case. The larger variance of v_r for a fixed λ_p is caused by different building configurations. For example, streets orientated along the wind direction are well ventilated as buildings do not block the airflow. Changing the orientation of the street being perpendicular to the wind direction while keeping λ_p unchanged, results in a poor ventilation as the buildings now block the airflow through the street. In the unstable case, the enhanced vertical mixing reduces the influence of the orientation of the buildings. This results in a smaller variance of v_r for a fixed λ_p and a higher correlation coefficient compared to the neutral case (R^2=0.511 in the unstable case and R^2=0.104 in the neutral case).

4. Summary and conclusion

The comparison of the ventilation in Kowloon City under neutral and unstable atmospheric stratification revealed significant differences. While the wind flow is strongly blocked by buildings inside the city in the neutral case leading to poor ventilation, enhanced vertical mixing leads to a stronger ventilation in the unstable case. The stronger vertical mixing, however, also reduces positive effects of the buildings on the ventilation, e.g. strong ventilation in the vicinity of exposed buildings is reduced. The difference in ventilation between neutral and unstable stratification is therefore not linear but complex at least for weak background wind speeds considered in this study. For stronger background wind, the influence of vertical mixing on the ventilation might become weaker than the influence of horizontal mixing induced by the strong background wind. Regarding air ventilation assessments (AVA) focusing especially on weak-wind conditions, it is necessary to analyze unstable conditions as well as neutral conditions. Ventilation effects of buildings may be considerably different between these two atmospheric conditions. As our study shows, the plain area index λ_p has a high influence on the ventilation while other building parameters such as the orientation of buildings become less important in the unstable case. City planners and architects should therefore focus on reducing λ_p to improve the city ventilation.

To further investigate the differences of the ventilation between the neutral and unstable case, it is planned to study different wind directions and building setups. Also, the sea-breeze effect will be included by applying different surface heating over the sea and land surface.

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Authors' addresses

Tobias Gronemeier (gronemeier@muk.uni-hannover.de)
Institute of Meteorology and Climatology, Leibniz Universität Hannover
Herrenhäuser Str. 2, 30419 Hannover, Germany

Prof. Siegfried Raasch (raasch@muk.uni-hannover.de)
Institute of Meteorology and Climatology, Leibniz Universität Hannover
Herrenhäuser Str. 2, 30419 Hannover, Germany