Academic Article

First Results of High Resolution Large-Eddy Simulations of the Atmospheric Boundary Layer

M. Keck*[1] S. Raasch*[1] M. O. Letzel*[2] E. Ng*[3]

*[1] Institute of Meteorology and Clymatology, Leibniz Universität Hannover, Germany
*[2] Lohmeyer Consulting Engineers, Karlsruhe, Germany
*[3] School of Architecture, Chinese University of Hong Kong, Hong Kong

Corresponding author: M. KECK, keck@muk.uni-hannover.de

ABSTRACT

As one of the most densely populated cities in the world Macau has to face particular difficulties in terms of creating a comfortable living environment. Narrow streets and high-density districts significantly reduce the natural ventilation. Especially in Macau's humid subtropical climate the natural ventilation should be used to decrease thermal stress. As an aggravating factor, Macau's population is still growing. In order to create new habitable space, five reclamation areas are currently being built around Macau's present coasts. This study investigates the pedestrian level ventilation in Macau using the parallelized large-eddy simulation model PALM. The aims of the study are a) to evaluate the impact of the planned reclamation areas on the ventilation within the present city districts, b) to investigate how urban morphological quantities, e.g. the surface cover fraction, affect the ventilation in cities and c) to show the advantages of urban LES over RANS simulations. The results reveal that the planned reclamation areas might only have a small impact on the average ventilation within the present city districts of Macau.

Key Words: Urban Boundary Layer, Large-Eddy Simulation, PALM, Urban Climate, Thermal Comfort

1. Introduction

Macau is one of the most densely populated cities in the world. Thus, it is a particular challenge to create a comfortable living environment. Especially in Macau's humid subtropical climate people are likely to suffer from thermal stress. Thermal comfort mostly depends on wind velocity, air temperature, radiation, and humidity(1). Even in densely populated cities the velocity ratio, defined as the ratio of wind velocity at a height of 2m above the ground to the undisturbed velocity of the free flow above the city, can be significantly improved by an appropriate alignment of buildings(3).

In order to extend the urban area, the government of Macau is about to create five new reclamation areas around Macau's present coasts (Fig.1). The goal is to align the buildings in the new areas in such a way that the air ventilation within the city does not change for the worse.

In the present study, the turbulent wind field in Macau is simulated and analyzed to get a general impression about the air ventilation within the city. Afterwards, the simulations are repeated including the planned reclamation areas. Comparisons of the simulations with and without the reclamation areas give detailed information about their effect on the ventilation. With this information suggestions for a better alignment of the buildings in the planned areas could be made. Furthermore, the gustiness in some selected public places and parks is investigated. For this purpose, virtual measuring stations are placed in those selected locations.

Although using Reynolds-averaged (RANS) models is the most common approach to simulate flows around obstacles, large-eddy simulation (LES) is used in this study. Using an LES model is far more expensive than using a RANS model, but it has two advantages: In contrast to RANS, LES does not only supply the averaged mean flow field but also resolves the instantaneous turbulent fields. In the urban canopy layer these turbulent fields are of particular importance, because the comfort of pedestrians does not only depend on the mean air ventilation, but also on the occurrence of gusts. For example, an area with low mean wind velocities still might be considered as comfortable, if the wind is gusty and exceeds a certain threshold

Fig. 1 Map of the Peninsula de Macau and the northern part of Macau's southern island. The planned reclamation areas are highlighted in orange.

value from time to time. This kind of data cannot be provided by RANS at all and has to be estimated with empirical laws. Another advantage is that even the mean flow around obstacles is calculated more accurately with LES compared to RANS[4].

2. Model description

The LES code used for this project is the Parallelized LES-Model (PALM), which has been developed at the Institute of Meteorology and Climatology of the Leibniz Universität Hannover since 1997[8]. The basic model is based on the non-hydrostatic, incompressible Boussinesq equations, the first law of thermodynamics and an equation for subgrid-scale turbulent kinetic energy. The aforementioned equations are filtered implicitly using the volume-balance approach of Schumann[9]. The 1.5-order Deardorff scheme is used for turbulence closure[2]. At each surface, both horizontal and vertical, a Prandtl layer is assumed. For the time-integration a 3rd-order Runge-Kutta scheme is used. The advection scheme used is a fifth-order scheme which was developed by Wicker and Skamarock[10].

PALM provides high performance on state-of-the-art massively parallel computers which is mandatory to simulate the turbulent wind field for whole cities. It is validated for flows around solid obstacles[5] and has already been used to study the wind comfort in city districts of Hong Kong[6]. Therefore, the code required only very few changes.

3. Setup

This study is restricted to neutral stratification. For all simulations a geostrophic wind of 1.5m/s is prescribed. Cyclic boundary conditions are used in spanwise direction. In streamwise direction non-cyclic boundary conditions are applied, so that the wind leaving at the outflow does not re-enter at the inflow. Thereby, the buildings and hills within the model domain do not affect the flow approaching the city. In order to guarantee a turbulent inflow, a turbulence recycling method is used[7]. By using this setup the model domain can be kept quite small. Sensitivity studies showed that a topography-free zone of about 1.5km width is required upstream of the city, in order to guarantee a good performance of the turbulence recycling method. This topography-free zone is still shorter than it would have been if cyclic boundary conditions were being used, because they require a large topography-free buffer zone upstream of the built-up areas, in order to prevent that the building induced turbulence re-enters at the inflow and affects the turbulence structures approaching the city.

All simulations cover a time span of 6h and all time-averaged values are averaged over the last 5 hours of a simulation. That is because the turbulence needs approx. 1h to properly develop and 5h proved to be the shortest statistically representative averaging time.

Sensitivity studies concerning the grid size have been performed. Figure 2 a) shows the Frequency distributions of the velocity ratio for a simulation with 4m grid spacing and a simulation with 2m grid spacing. It can be seen that very low and very high velocity ratios occur more often if a 4m grid spacing is used because the flows in narrow streets are not resolved sufficiently. Figure 2 b) shows that the differences between 2m and 1m grid spacing are quite small. These sensitivity studies demonstrated that using the initially desired grid size of 1m is not reasonable, since simulations with 2m grid spacing provide sufficiently resolved results and are about 16 times cheaper. Nonetheless, a simulation with a resolution of 2m still requires an immense amount of computational power.

The model domain for such a simulation contains more than $2.5*10^9$ grid points and each run takes about 45h on 4096 processor cores of an SGI Altix ICE 8200 Plus to simulate a time span of 6h.

In this study the velocity ratios v_r for the four most occurring wind directions in Macau are investigated (S, SSE, SE and N). $v_r = v_p / v_\infty$ is used as a ventilation indicator and is defined as the ratio of the wind velocity v_p at pedestrian level, 2 m above ground, and v_∞ near the top of the model domain (z = 2.5km) where the flow is no longer affected by the city. The model

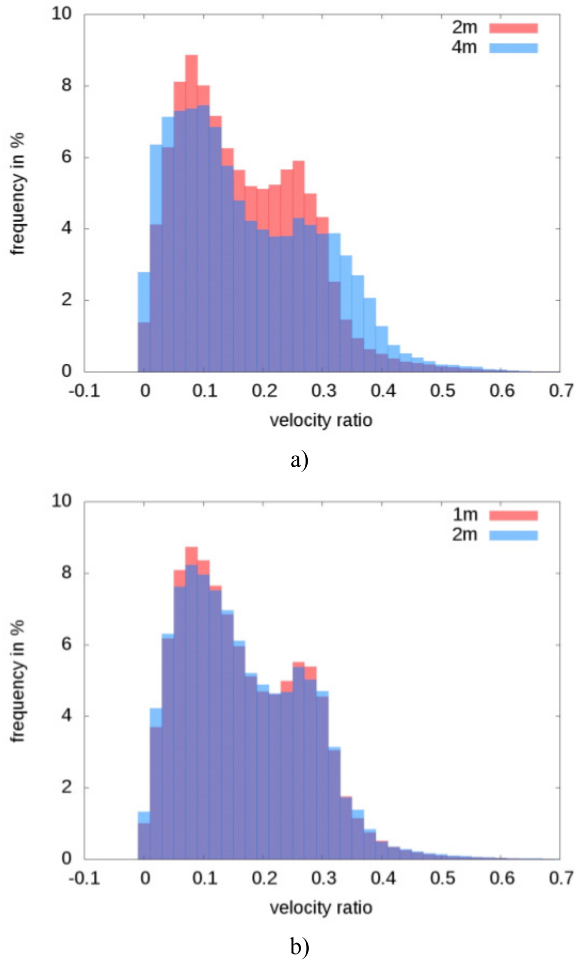


Fig. 2 Frequency distributions of the velocity ratio; a) comparison between 4m and 2m resolution, b) comparison between 2m and 1m resolution.

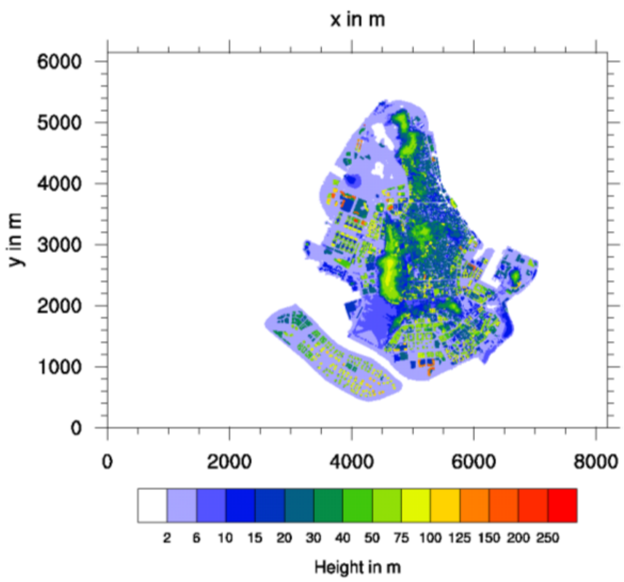


Fig. 3 Model domain of the simulation with southeast wind. The topography is rotated so that the wind enters the model domain from the left side.

domain for the simulations with southeast wind covers about 8x6km² and only contains the Peninsula de Macau (see Fig. 3). In these simulations a grid spacing of 2m is used. The model domains for all the other simulations cover about 16x8km² and also include Macau's southern island. Due to the very large model domain the grid spacing had to be coarsened to 4m for the simulations including the southern island.

4. Results

The results of all simulations show that the time averaged wind velocities at pedestrian level are spatially highly variable. In many cases v_r demonstrates high values for streets aligned with the mean wind and low values for those streets perpendicular to the mean wind direction. However, the results also reveal that there are numerous exceptions, which are proof for the complexity of an urban canopy flow.

Figure 4 shows the effect of the planned reclamation areas on v_r for wind from southeast. For this wind direction the reclamation areas showed the greatest impact on the flow field of the Macau Peninsula. The model domain is rotated so that the wind enters the domain from the left. The strongest effect can be seen in the wake of the reclamation area A at the bottom of the graphic, where the ventilation is strongly reduced. However, the areas in the already existing parts of Macau that will be affected by the reclamation areas are quite small. In some of these parts the ventilation will even increase, due to channelling and overflowing. The other simulations confirm that the planned reclamation areas only have a small effect on the ventilation within the already existing districts, regardless of the wind direction.

Figure 5 shows that there is a linear correlation between v_r and a) the surface cover fraction (SCF) and b) the frontal area density (FAD). SCF is defined as the area covered with buildings divided by the total surface area, and FAD is the area of all building walls facing the mean wind direction divided by the total surface area. For low v_r values there seems to be a second linear correlation, which can especially be seen in Figure 5 b). All of those data points with very low v_r values belong to an area around a small but steep hill. This leads to the assumption that the linear correlations between v_r and FAD (and also v_r and SCF) depend on the complexity of the orography, i.e. that the linear correlations in Fig. 5 (green lines) are only valid for flat terrain. The impact of complex terrain on the correlations between v_r and SCF, and v_r and FAD is currently being investigated. All values were averaged over an area of 1km². In order to get more data points, the averaging areas overlap. This way it is also guaranteed that results are not influenced by random positioning of the averaging areas. Yoshie et al. found a similar linear correlation between the SCF and v_r using wind

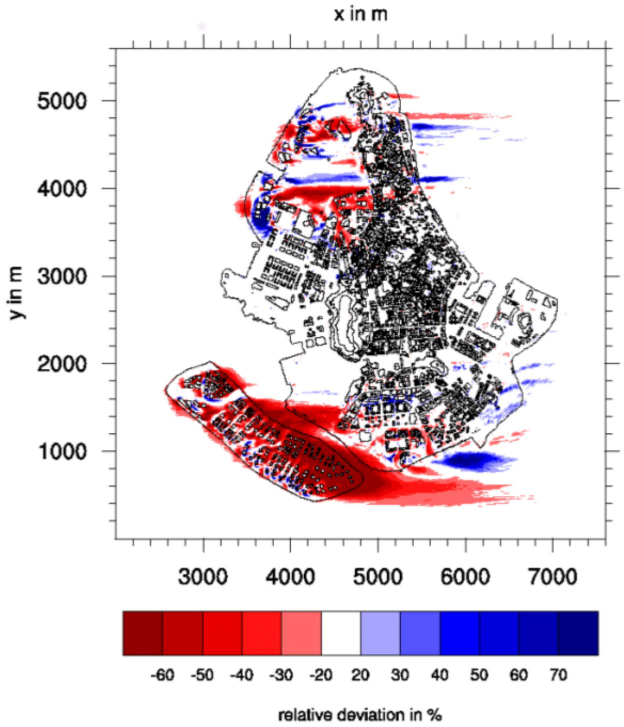
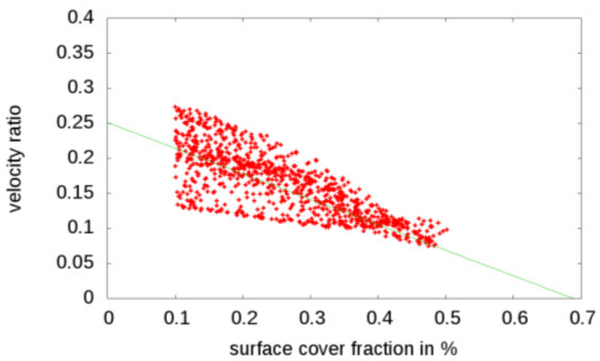
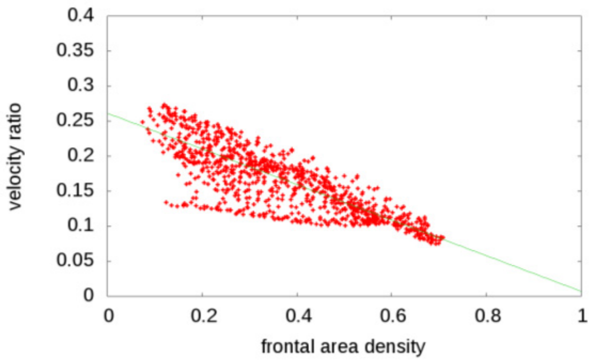


Fig. 4 Relative deviations of between the results of a simulation without and a simulation including the planned reclamation areas for wind from the southeast; red: lower velocity ratios with reclamation areas, blue: higher velocity ratios with reclamation areas; the wind enters the model domain from the left side.



a)

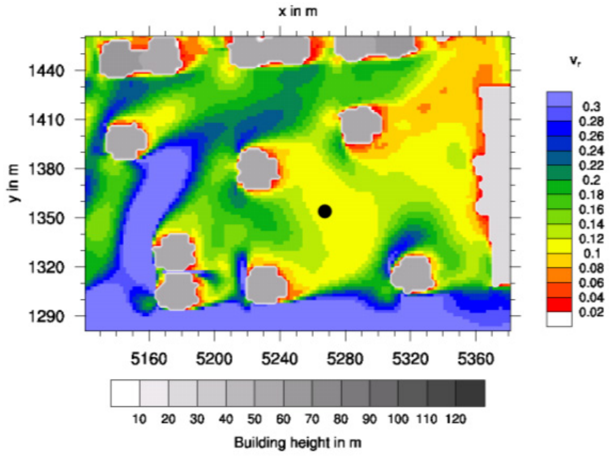


b)

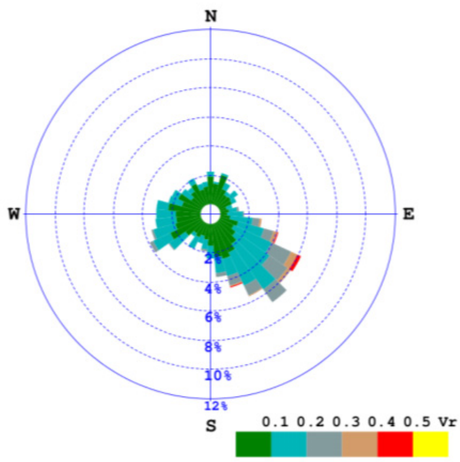
Fig. 5: Correlation between v_r and a) the surface cover fraction and b) the frontal area density.

tunnel experiments and field measurements[11]. Furthermore, the results showed that the building volume per surface area is also linearly correlated to v_r (not shown in the figures).

In order to investigate the additional benefits of LES over RANS simulations 54 virtual measuring stations were place in the model domain. These stations saved time series of the local velocity ratios. Figure 6 shows as an example the average velocity ratios in a small park as well as a wind rose created from a time series that was virtually measured at a point in the park (black dot). The average velocity ratio at the measuring point is 0.11 and the average wind direction is SSE. However, the wind rose shows that the wind blows mostly from southeasterly directions but approximately 20% of the time also from westerly directions. Moreover, it can be seen that velocity ratios greater than 0.22 (double of the average value) are detected more than 11% of the time.



a)



b)

Fig. 6 a) Average v_r in a small park for wind from the southeast. The black dot shows the position of the virtual measuring station. b) Wind rose of v_r values detected at the virtual measuring station. The wind enters the model domain from the left side.

5. Conclusions

The study revealed that the effect of the planned reclamation areas on the average wind velocities in the present Macau city districts is rather small. Only in very few open places and wide roads v_r was significantly decreased. However, in some areas the wind velocities even increase due to channelling and overflowing effects. Most parts of the city won't be affected by the creation of the planned reclamation areas. Analysis of the output data showed that there are linear correlations between v_r and SCF, and v_r and FAD, respectively. For city planners these correlations can be used as an orientation for the expected average ventilation within city districts. The conducted virtual measurements demonstrated that LES could be an important tool for future urban studies, because it not only gives the average wind velocities and directions but also information about variances and peak values. The ongoing study is currently extended for the effects of thermal stratification, in order to better capture the real meteorological conditions in Macau.

References

(1) V. Cheng and E. Ng, Thermal comfort in urban open spaces for Hong Kong, Architectural Science Review, 49, 236-242 (2006)
(2) J. W. Deardorff, Stratocumulus-capped mixed layers derived from a three-dimensional model, Bound-Lay. Meteorol., 18, 495-527 (1980)
(3) J. Hang, Y. Li, M. Sandberg, R. Buccolieri and S. Di Sabatino, The influence of building height variability on pollutant dispersion and pedestrian ventilation in idealized high-rise urban areas. Building and Environment, 56, 346-360 (2012)
(4) M. O. Letzel, M. Kanda and S. Raasch, A new dimension of urban climate modelling with parallel large-eddy simulation. 6th International Conference on Urban Climate, 296-299 (2006)
(5) M. O. Letzel, M. Krane and S. Raasch, High resolution urban large-eddy simulation studies from street canyon to neighborhood scale. Atm. Env., 42, 8770-8784 (2008)
(6) M. O. Letzel, C. Helmke, E. Ng, X. An and S. Raasch, LES case study on pedestrian level ventilation in two neighbourhoods in Hong Kong. Meteorol. Z., 21, 575-589 (2012)
(7) H. Kataoka and M. Mizuno, Numerical flow computation around aeroelastic 3D square cylinder using inflow turbulence. Wind and Structures, 5, 379-392 (2002)
(8) S. Raasch and M. Schröter, PALM – A large-eddy simulation model performing on massively parallel computers. Meteorol. Z., 10, 363-372 (2001)
(9) U. Schumann, Subgrid scale model for finite difference simulations of turbulent flows in plane channels. J. Comp. Phys., 18, 376-404 (1975)
(10) L. J. Wicker and W. C. Skamarock, Time-splitting methods for elastic models using forward time schemes. Mon. Wea. Rev., 130, 2088-2097 (2002)
(11) R. Yoshie, H. Tanaka, T. Shirasawa and T. Kobayashi, Experimental study on air ventilation in a built-up area with closely-packed high-rise buildings. J. Environ. Eng., 73, 661-667 (2008)

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