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Non-uniform ground-level wind patterns in a heat dome over a uniformly heated non-circular city

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ABSTRACT

Urban heat island-induced circulation, or urban heat dome flow, significantly influences urban thermal environments and air quality in calm wind conditions with stable stratification. An urban heat dome is characterized by convergent inflow at the ground level, divergent outflow at the upper level and upward flow over the city center in calm conditions. We report a new city-shape effect on heat dome flow patterns in a laboratory modeling experiment. For a circular city, both the inflow at the lower level and the outflow at the upper level are axisymmetric. For a square urban area, a non-uniform flow pattern was observed with four dominant diagonal inflows at the ground level and four dominant side outflows (perpendicular to city edges) at the upper level, indicating that the inflow changes direction as it rises over the urban area. The experiments were carried out in two water tank models with stable stratification, using thermal image velocimetry and particle image velocimetry. "Cell-like" and "stripe-like" eddy structures were identified over the modeled urban area, depending on the mean flow speed. To the best of our knowledge, this study reveals for the first time that in calm conditions the shape of an urban area may significantly affect the winds within a city, and thus the local heat transfer coefficients, urban air temperature and urban haze distribution will not be uniform under such conditions. Results on the eddy structures and mean flow fields can provide insights for theoretical analysis on heat transfer models in future studies.

1. Introduction

Urban climate influences energy consumption [1–3], pollutant dispersion [4–7], urban ecology [8–10] and thermal comfort [11]. Energy consumption, pollutant dispersion and urban ecology can also modulate the urban climate [12,13]. A better understanding of the urban climate could present a new perspective to policy makers and urban planning engineers [14–16].

Urban climate is influenced by both the large-scale climate [17–19] and the local environment. Local urban environments are mainly determined by local topography and aspects of urban morphology including city size [20], building area density [21–23], building height [24–26] and built-up areas [27], and human factors such as traffic, industry and heating or cooling load [28]. Variations in urban morphology occur over a relatively long timescale (years), whereas human activities can vary over hours or days. Urban morphology and human activities are largely influenced by a city's economy [29,30] and can exert a mutual influence [31–33].

Understanding urban air flow in calm wind conditions is crucial, as most urban heat waves and severe air pollution episodes occur when wind calmness and inversion coexist, leading to the formation of a heat dome or urban heat island circulation. Urban heat dome flow, which is driven by the urban heat island effect, occurs in conditions of calm/weak winds and stable stratification [34,35], and is characterized by convergent inflow at the lower level, divergent outflow at the upper level and upward flow over the center of the urban area. Urban heat dome flow is known to be determined by city size, background buoyancy frequency and sensible surface heat flux in the urban area [36–38]. In this study, we explored the effect of a city's shape, where "city shape" is the geometry of the plan view of the urban built-up area, assuming that the heat flux is uniform under ideal conditions. In some other studies, such as Batty [30] and Zhang et al. [27], "urban shape" indicates the compactness (compact, sprawled, dispersed, fragmented or extensive as categorized by Schneider and Woodcock [39]) of an urban built-up area.

In reality, urban areas always have different shapes, and the asymmetry of the urban heat dome flow caused by the shape of an urban area has a significant influence on ventilation and pollutant dispersion in the area when background wind is absent.

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To the best of our knowledge, Giovannoni [40] is the only study to date on the shape effect on city ventilation under stably stratified environment, although it offers only qualitative descriptions and an observation of a "dead" zone near the square plate corner. That study revealed different types of inflow caused by heated areas of different shapes based on smoke visualization in a stably stratified environment. For the natural convective heat transfer studies over a horizontal plane, the heat transfer coefficient is usually expressed as $Nu = CRa^n$, where $Nu = h\delta/\lambda$ and $Ra = g\beta\Delta T\delta^3/\nu^2$ are Nusselt number and Rayleigh number respectively. C and n are coefficients. h is the heat transfer coefficient. δ is the length scale. λ and ν are the thermal diffusivity and kinematic viscosity respectively. β is the thermal expansion rate. g is the gravity acceleration. ΔT is the temperature difference between the heated surface and ambient fluid. Giovannoni [40] gave the above coefficients as C = 0.60 and n = 0.29. Some other studies have examined natural convection above up-facing heated plates in neutral conditions, with "partitioned flows" first observed by Husar and Sparrow [41], followed by Lewandowski et al. [42] and Kitamura et al. [43]. Kitamura et al. [43] suggested 0.135 and 0.33 should be used for C and n respectively in natural convection ($7 \times 10^7 < \mathrm{Ra} < 3.5 \times 10^8$) over rectangular surfaces with different aspect ratios (the length to width), where the length scale should be the hydraulic diameter. These studies only focused on the bulk heat transfer coefficient, and only neutral conditions were considered.

The detailed 3-D structure of urban heat dome flow (the outflow in the upper part) has also not been described. Those special regions on the partition lines caused by the shape effect were described as "dead zones" by Giovannoni [40]. The mean speed in these "dead zones" is actually greater than that in the other regions based on our measurements. Ohashi and Kida [44,45] studied the urban heat island–induced circulation over square urban areas using numerical simulations, but the influence of the urban shape (defined as square in their model) was not reported.

An investigation of the detailed 3-D structures of urban heat dome flows over urban areas of different shapes is presented in this paper. The shape influence on the local heat transfer coefficients is discussed. The implications of the city shape effect for thermal environment, urban ventilation and pollutant transport are also discussed.

2. Methodology and experimental setup

Modeling experiments were carried out with a small water tank (0.4 m in length, 0.4 m in width and 0.5 m in height) and a large water tank (1.2 m in length, 1.2 m in width and 1.1 m in height). The walls of the two tanks were made of transparent glass. The so-called "two buckets" method [46] was used to create the required stable stratification with salt water in the water tank to simulate stable stratification in the atmosphere. The two buckets used for creating stable stratification had the same size and were named as Bucket 1 and 2 respectively. Two buckets were connected at the bottom. Buckets 1 and 2 initially contained salt water and pure water respectively. The salt water in Bucket 1 was first pumped into the water tank and thus the pressure in Bucket 1 dropped, resulting in the pure water flow from Bucket 2 to 1. There was a circulating pump to keep the water in Bucket 1 well-mixed and thus the salt water density in Bucket 1 would gradually decrease. Therefore, the water pumped into the water tank would get lighter and lighter and thus form the stable stratification. The detailed procedure for creating the linear density profile and measurement methods are described in Fan et al. [47].

The experimental set-up for the tanks is shown in Fig. 1.

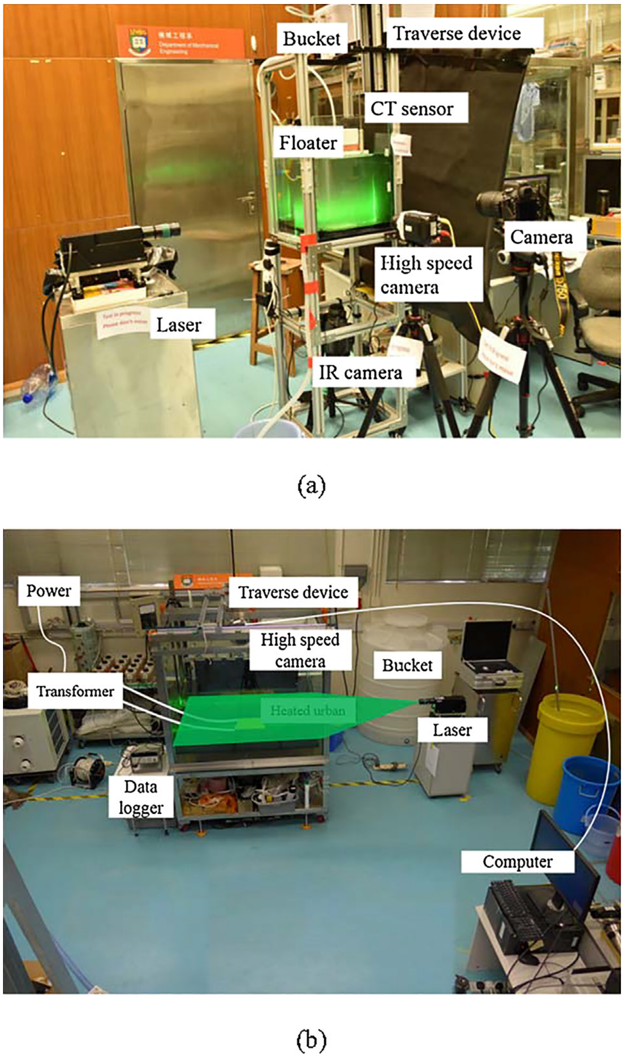

Fig. 1. Experimental apparatus. (a) The small water tank. (b) The large water tank.

The areas surrounding the heated city model at the tank bottom were thermally well insulated by using acrylic plates (20 cm depth, for the small water tank) or silica pads (10 cm depth, for the large water tank). Polyimide film heaters were used in the small tank to provide a uniform heat flux. The power was controlled by a transformer. Aluminum heaters were used in the large tank, and were electrically well insulated from the salt water. Flat copper plates (to simulate the city region) were attached to the heaters to provide a uniform heat flux. The copper plates were 0.2 mm and 10 mm in depth for the small and large water tanks, respectively.

The density profiles of the salt water in the tank were measured by a conductivity and temperature (CT) sensor (MSCTI, PME Inc., CA, U.S.A.). The CT sensor was installed on a traverse device that can traverse in three directions (longitude, latitude, and vertical). The vertical movement of the device was controlled by a step motor, which enabled the vertical density profiles to be measured during the experiment. The traverse speed of the sensor in the vertical direction was 10 mm s^{-1} and its acquisition frequency was 5 Hz. Thus, the density was measured every 2 mm in the vertical direction. The velocity field was measured by a particle image velocity (PIV) system (Dantec Dynamics A/S, Denmark). A Ray-Power 10 W 532 nm continuous green laser and Speed Sense M140 high-speed camera operating at 30 Hz in single frame mode were used. During the measurements, a total of 900 images (30 s) were acquired for each set of data. Polyamide seeding particles (20 μm) were used for the PIV application. An advanced adaptive PIV algorithm (Dantec Dynamics A/S, Denmark) was applied, which