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Temperature and Wind Distribution in an E-W-Oriented Urban Street Canyon

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Abstract

The air temperature distribution and airflow field in an actual urban street canyon were clarified through intensive observations. The 2-D distribution of temperature and wind was clarified on a N-S vertical cross section of the E-W-oriented street canyon. A steady single vortex, approximately equal to the size of the canyon, was frequently observed. A rather distinct vortex was observed when the ambient winds above the canyon were high and their direction was transverse to the canyon. Thermally unstable stratification also contributed to the formation of the distinct vortex. The vortex airflow advected the cold air mass, which was produced by the shade due to the buildings, upwind of the ambient wind above the canyon.

1. Introduction

The microclimate of an urban street canyon, hereinafter referred to as a canyon, is relatively different from that observed on a flat terrain. It is necessary to know the temperature and airflow in the region of interest in order to clarify the formation of heat islands (Oke et al. 1991) and also to model the city climate accurately (Kusaka et al. 2001; Masson 2000).

Several field surveys have been conducted in canyons (see table 1, Eliasson et al. 2006). However, the majority of them have been restricted to vertical profile measurements despite the potential importance of horizontal variabilities in a canyon. In this regard, while wind tunnel experiments have a considerable advantage with respect to 3-D measurements, they may not provide an accurate recreation of the complexities associated with the outdoor environment, e.g., sun-shade, wetness, variations in the wind direction, etc.

In this study, therefore, measurements were performed in an actual urban canyon that helped clarify the 2-D distribution of temperature and wind on a cross section of the canyon. The focus in this study was the vertical vortex-type airflow in the canyon, hereinafter referred to as a canyon vortex. The assessment of a vortex-type airflow is important in evaluating the pollution dispersion in canyons (Kim and Baik 1999). While numerous field observations have examined canyon vortexes (Nakamura and Oke 1988; Weber et al. 2006), very few studies have characterized their entire structure in an actual city. This study provides a comprehensive description of a canyon vortex: its size and number, an along-canyon airflow accompanying the vortex, and requisite conditions for vortex generation. A simultaneous measurement of the temperature and wind indicated an influence of the canyon vortex on the temperature distribution.

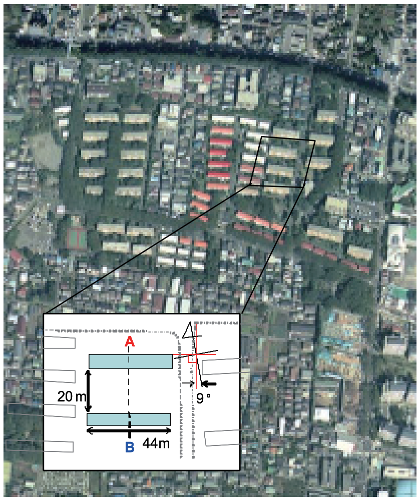

Fig. 1. Study site. Line A−B indicates the position of the measured cross section.

2. Observations

Observations were conducted in an E-W-oriented canyon of an uninhabited area in Tokyo (Fig. 1). The canyon had a height-to-street width (H/W) ratio, i.e., an aspect ratio of 0.56, which is relatively smaller than the aspect ratios of other studies (see Eliasson et al. 2006), but is approximately equal to the aspect ratios commonly encountered in Japanese cities (Sugawara 2001). The test building height (H) and length (L) were 11 m and 44 m, respectively. A 3 m high fence at the eastern edge of the canyon was considered to have disturbed the airflow and was likely to have prevented us from obtaining an ideal wind field in the canyon.

The floor of the canyon was covered with bare soil and short grass, and there was no motor vehicle traffic. Since the area was uninhabited, there was no anthropogenic heat release. The ground surface was inclined in a southerly direction at a gradient of 1/20. The 3-D wind speed and temperature distribution were measured on a cross section of the canyon (A−B in Fig. 1). Figure 2 indicates the position of sensors in the cross section. Thirteen sonic anemometers were set up in a reticular pattern in the canyon. One of the sonic anemometers was used to measure the ambient wind speed at a height of 1.8 times that of the building (1.8H). All the sonic anemometers performed the measurements at 10 Hz. Similarly, a total of 41 thermocouples with forced-ventilation radiation shields were also set up in a reticular pattern. The sampling interval of the thermocouples was 2 s. In addition, the heat budget was measured at six sites on the building walls, and these data were used to determine the heat transfer coefficient in the canyon (Hagishima et al. 2008). The measurements were performed from September to December in 2004, and the

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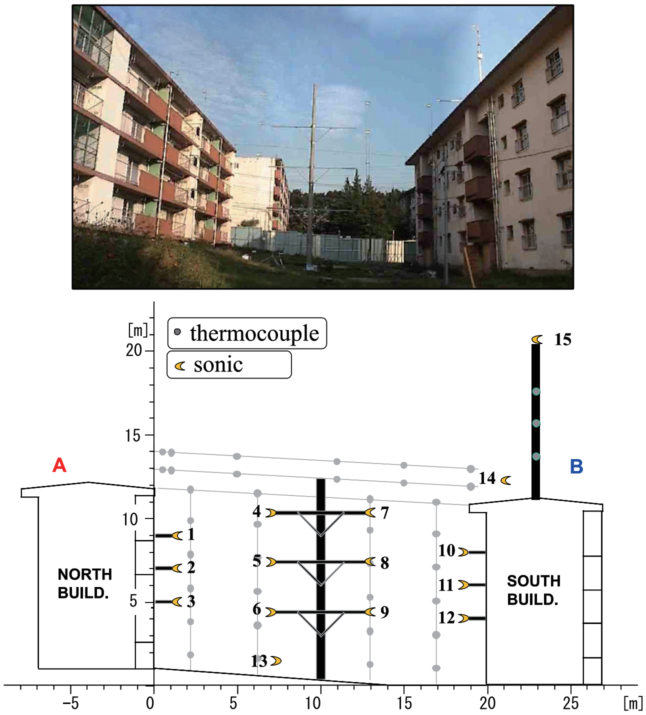


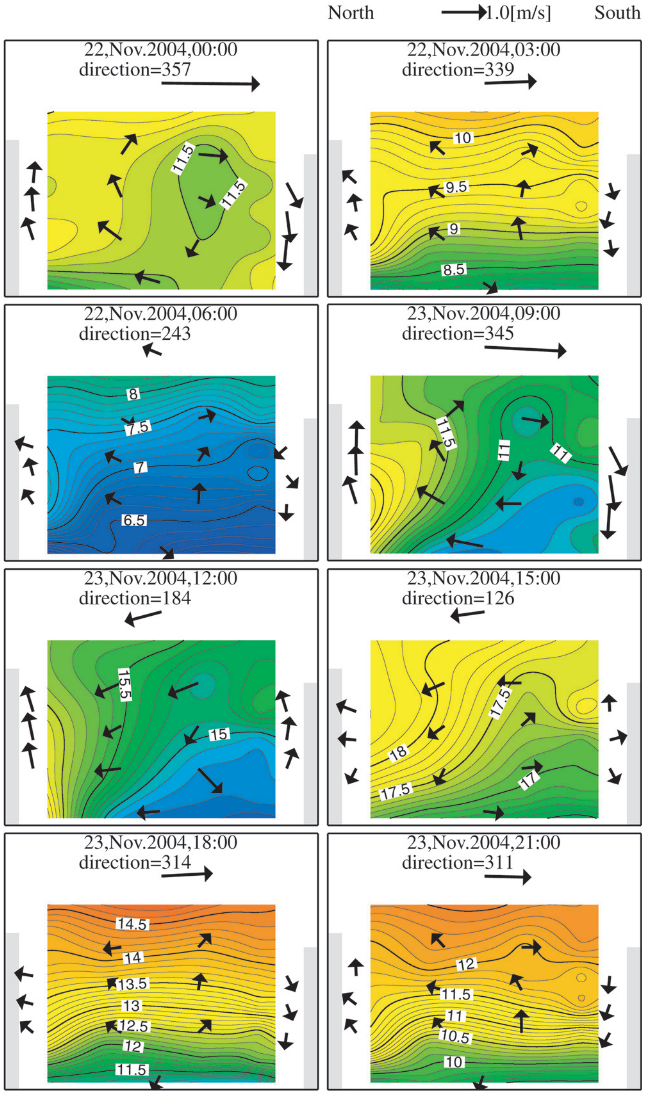
Fig. 2. Position of instruments on the measured cross section. The bold numbers indicate the sonic anemometers. The right-hand side of the figure is south.

data from 15 fine days were analyzed. All of the data were averaged over 10 min.

We used local coordinates in this study to describe the wind field. The component u is defined as being along the canyon, positive from left to right, in Fig. 1. A horizontal component v is transverse to u, positive from bottom to top, in Fig. 1. The component v points 9° east of the true north. The vertical component is w. The wind direction is also described in terms of the local coordinates. The u and v components represent 270° and 180°, respectively. The height is illustrated as a multiple of the building height H.

3. Vortex airflow in an urban canyon

Some typical distributions of the airflow and air temperature on the measured cross section are illustrated in Fig. 3. Note that each panel is picked up from time series of two consecutive days. The ambient wind direction was transverse to the canyon, i.e., northerly or southerly, during this period. The color contours indicate isotherms of 0.1 K intervals. The arrows indicate the v–w vectors at each site. The arrow at the center-top of each panel indicates the ambient wind (anemometer No. 15) at 1.8H. The generation of a canyon-scale vortex was observed. The vortex direction corresponded to that of the ambient airflow above the canyon; the vortexes at 9:00 and 12:00 on 23 Nov. were in the opposite directions in response to a change in the ambient wind direction. The upward airflow near the northern building at 12:00 was not consistent with the downward airflow to its immediate right. This may have been due to the complex airflow during the transition process that changed the ambient wind direction (see Supplement A). Some previous studies have stated that airflow patterns become indistinct under a weak wind condition (DePaul and Sheih 1986; Eliasson et al. 2006). However, this was not always true in this study (e.g., 15:00 on 23 Nov. in Fig. 3). A rather distinct pattern obtained in this study was a result of the aspect ratio (H/W) being larger than that used in the previous studies. The slightly inclined canyon floor might also have influenced the airflow field under the weak wind condition. The vortex appeared to be more distinct in the unstable stratification during the daytime (15:00 on 23 Nov.) rather than in the stable stratification during the night-time (21:00 on 23 Nov.). The vortex was also influenced by the ambient wind speed. A more distinct vortex was observed under a high wind condition at 03:00 as compared to that at 06:00 on 22 Nov.; nonetheless, they were equally thermally stable. The number of vortexes in a canyon is an important consideration in the assessment of pollutant dispersion. Kim and Baik (1999) demonstrated the formation of possible multiple vortexes with the help of a numerical simulation. In this study, only a single vortex was frequently observed using 10 min averaged airflow data. Multiple vortexes would have been visible if a shorter interval had been used (Eliasson et al. 2006).


North 1.0[m/s] South

22,Nov.2004,00:00 direction=357

22,Nov.2004,03:00 direction=339

22,Nov.2004,06:00 direction=243

23,Nov.2004,09:00 direction=345

23,Nov.2004,12:00 direction=184

23,Nov.2004,15:00 direction=126

23,Nov.2004,18:00 direction=314

23,Nov.2004,21:00 direction=311

Fig. 3. Temperature and wind distribution on the canyon cross section on 22 and 23 Nov. 2004. The air temperatures are illustrated using color contours of 0.1 K intervals. The gray boxes on both sides represent buildings, and the right-hand side of the figure is south, similar to Fig. 2. The arrow at the center-top of each panel indicates the ambient wind (anemometer No. 15 at 1.8H). The ambient wind direction is indicated at the upper portion of each panel.

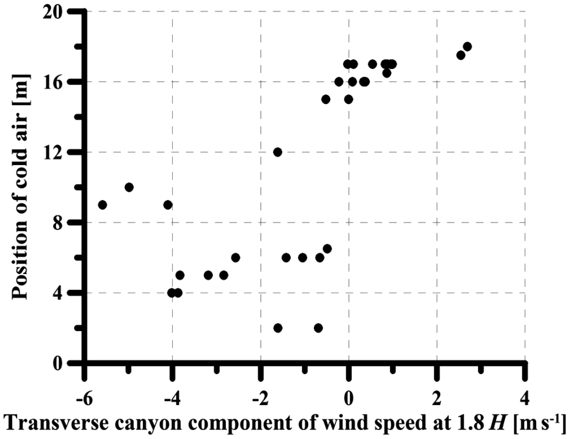


Fig. 4. Position of the cold air mass on the canyon floor. The y-axis represents the distance from the northern building to the cold air mass. The positive direction of the x-axis corresponds to a south-to-north airflow.

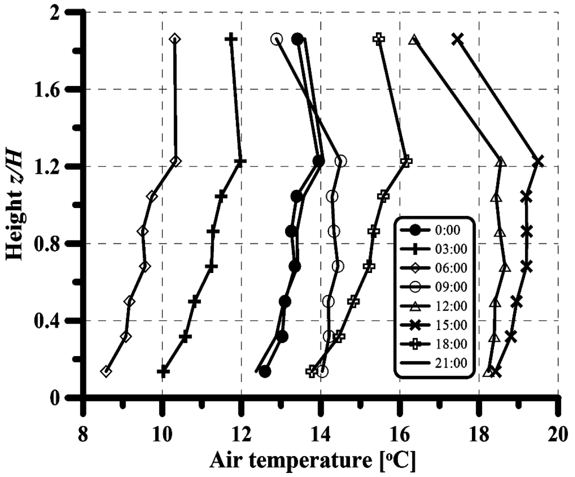


Fig. 5. Air temperature profile averaged over 15 fine days.

4. Wind-affected air temperature distribution

The air within the canyon exhibited marked thermal stratification on calm nights (21:00 on 23 Nov.), as shown in Fig. 3, and an almost homogeneous temperature field at high wind speeds (00:00 on 22 Nov.). During the daytime (12:00 on 23 Nov.), a horizontal temperature variation of approximately 2 K existed between the northern and southern portion of the canyon, which was larger than the vertical gradient.

The shade due to the buildings covered 80% of the canyon floor at noon. The sun-shade distribution resulted in the northern region of the canyon being warmer than the southern region. The horizontal advection of temperature from south to north at the lower portion of the canyon was roughly estimated as 70 $\mathrm{Wm^{-2}}$ at 09:00 on 23 Nov. It was approximately equal to the sensible heat flux at the wall surface (Hagishima et al. 2008). A daytime stable layer inside a canyon has to be focused on while assessing the pollution dispersion (Kanda et al. 2005); however, the present study indicates that the horizontal gradient of the temperature can be rather significant. The daytime stable layer is required to be discussed with regard to its horizontal locality.

Figure 3 suggests that a cold air mass at the bottom of the canyon was shifted by the airflow, e.g., due to the difference in the horizontal position of the cold air core between 09:00 and 12:00 on 23 Nov. Figure 4 indicates the position of the cold air mass at the bottom of the canyon. The x-axis in Fig. 4 represents the transverse-canyon component (v) of the ambient wind at $1.8H$. A positive value corresponds to a south-to-north direction (right to left in Fig. 3). The y-axis indicates the distance from the northern building to the cold air mass, which is determined by eye on the temperature contour. As the wind speed increased, the cold air mass was shifted upwind by the ambient wind, which was a result of the canyon vortex, i.e., a reverse airflow at the canyon floor. Such horizontal advection of air corresponds to a high concentration of vehicle exhaust gas as it drifts sideways downwind (Weber et al. 2006; Kikuchi et al. 2007).

Now, we will discuss how to measure the representative air temperature of an entire canyon. We will propose guidelines for measurements in an canyon. Our results indicate that a 2 K difference could develop as a result of the presence of both sunny and shaded regions in a canyon. In order to obtain an accurate representative air temperature, it would therefore be necessary to have multiple sites for measurement−at least one for each sunny and shaded region. Cold air masses and possibly warm air masses, too, move across a street depending on the wind direction above the buildings.

The depth and strength of the stable layer can be discussed using its vertical profile. Figure 5 presents the air temperature profile averaged over 15 fine days. The temperature indicated at each height is an average of four horizontally aligned thermometers (see Fig. 2). The maximum height of the stable layer was observed during the night-time, extending to approximately $0.6H$. In addition, a stable layer was observed below $0.3H$ during the daytime (15:00). The maximum temperature gradient was observed in the evening (18:00 in Fig. 5) rather than during the night-time. The reason for this could be that insolation occurred only along the upper portions of the building walls in the evening. Note that the stable layer could be a result of the less amount of heat from the canyon floor with the short grass and bare soil. Furthermore, it would be different from that in a canyon with anthropogenic heat due to motor vehicle traffic.

5. Canyon vortex and channeling airflow

The requisite conditions for vortex generation are discussed with regard to the ambient wind. Figure 6 presents the wind speed profile averaged over 15 fine days. The profile is an average from two vertical sets of anemometers placed at the center of the canyon (4−6 and 7−9 in Fig. 2). The panels indicate cases when the ambient wind direction was transverse to the canyon (panel A) and along the canyon (panel B). The selection criterion was a 15° wind direction sector centered on the respective canyon axis. For other wind directions between the sectors, see Supplement B that reveals the relationships between the wind directions above and inside a canyon. In Fig. 6A, the transverse-canyon component (v) and scalar speed (S) both exhibit a dogleg-shaped profile that is larger at the bottom than at the center of the canyon. The canyon vortex increased the wind speed at the bottom of the canyon. This was not observed in Fig. 6B, along the canyon.

When the ambient wind direction was transverse to the canyon (Fig. 6A), u was approximately equal to v and w, indicating that the canyon airflow exhibited a spiral-type shape, i.e., a combination of the canyon vortex (v and w) and the along-canyon channeling airflow (u). The channeling component (u) was more dominant than the vortex (v and w) when the ambient wind direction was along the canyon (Fig. 6B). On the

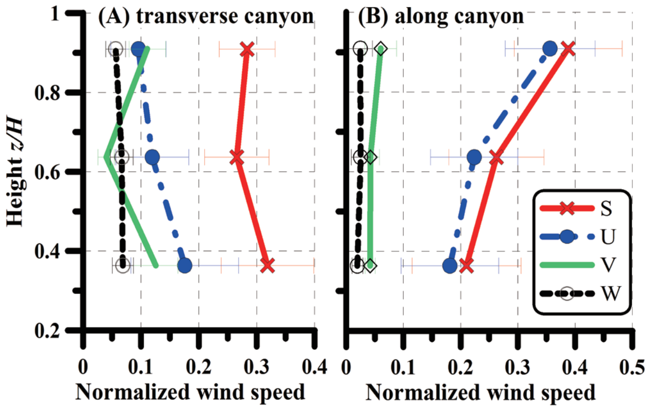


Fig. 6. Wind speed profile inside the canyon. *u*, along-canyon component; *v*, transverse-canyon component; *w*, vertical component; and *S*, scalar speed. Each component is normalized using the scalar speed at 1.8*H*. The error bars indicate standard deviation. The ambient wind direction is A) transverse to the canyon and B) along the canyon.

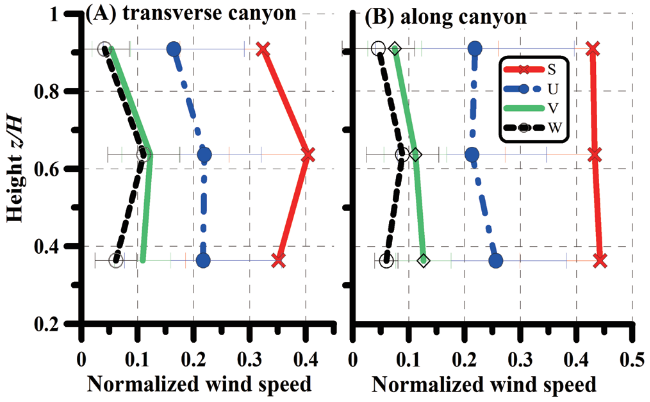


Fig. 7. Similar to Fig. 6, but the scalar wind speed at 1.8*H* was less than 1 m s^{-1}. Error bars are not illustrated for *S* due to lack of space.

other hand, the channeling component was dominant in both the ambient wind directions under weak wind conditions (Figs. 7A, B). This may be because a larger amount of kinetic energy was required for vortex generation as compared to that required for the channeling component. In conclusion, a canyon-vortex was generated under high transverse-canyon ambient winds.

6. Conclusions

The air temperature distribution and airflow field in an urban street canyon were clarified through intensive observations. The street canyon was oriented in the E–W direction, and the aspect ratio of the building height to the street width was 0.56. Measurements were performed on a N–S vertical cross section of the canyon. A steady single vortex approximately equal to the size of the canyon was frequently observed in the canyon. A rather distinct vortex was observed under high ambient wind and thermally unstable conditions. When the ambient wind direction was transverse to the canyon, this vortex affected the vertical profile of the scalar wind, forming a dogleg-shaped profile. When the ambient wind direction was along the canyon, the canyon airflow field was a combination of the vortex and the along-canyon channeling airflow. The channeling component was dominant in this case.

A stable layer with the maximum height extending halfway up the canyon developed inside the canyon during the night-time. During the daytime too, a cold air mass was formed due to the building shade. The air mass was shifted upwind of the ambient wind by the reverse airflow at the bottom of the canyon, which was a part of the canyon vortex.

Acknowledgments

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Comments and supplements

1. A graphical presentation of air temperature distribution and wind field is illustrated in Supplement A. It is identical to that shown in Fig. 3, but with complete diurnal variations over 10 min intervals for 22–23 Nov. 2004.
2. The relationships between the ambient wind (1.8*H*) direction and the canyon airflow direction at each measurement site are revealed in Supplement B.

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