URBAN ALBEDO AS A FUNCTION OF THE URBAN STRUCTURE – A MODEL EXPERIMENT

(Part I)

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Abstract. A model experiment has been carried out in order to examine the effect of surface irregularity of an urban structure on the anomalous absorption of incident solar radiation. Several models of an urban structure resembling buildings and canyons were constructed by using concrete blocks in cubic form. By building and dismantling the urban models, the albedo change as a function of solar zenith angle was observed throughout the year. The result shows that the absorption increment originating from the irregular urban structure amounts to about 20% as compared with the absorption by a flat surface of the same material. The amount of additional absorption depends on the relative area occupied by canyons in the model.

1. Introduction

The urban heat island is believed to result from anomalies in the several meteorological parameters of an urban area. The contributions of these meteorological parameters to the heat island phenomena have been discussed in a recent paper describing numerical simulation models (Oke, 1979). Among these parameters, the anomalous absorption of solar radiation by the urban surface must be taken into account, assuming an appropriate value for the surface albedo. However, since the urban surface is quite complex in quality and geometrical structure, the value of the surface albedo is not easily determined. In particular, the complex three-dimensional structures formed by buildings and the canyons between them introduce an additional difficulty in the quantitative estimation of the surface albedo (Terjung and Louie, 1973).

The intent of this study is to examine the relationship between the global (direct and diffuse) solar radiation and its reflection from an experimental model resembling an urban structure. The model of buildings and canyons was constructed by using cubic concrete blocks. The purpose of this study is to determine how the urban surface structure alters its reflectivity properties attributable simply to the geometry if the surface quality is fixed. In other words, we estimate what effect the urban structure may have on the formation of urban heat islands through the anomalous absorption of solar radiation.

2. Description of Model Experiments

Since the geometrical structures of urban surfaces are generally quite complex, it is difficult to represent actual urban structures by model experiments. In order to simplify

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this problem, several systematic urban block-canyon models have been represented using cubic concrete blocks. The experimental model was constructed on the top of a building in the campus of Yokohama National University (35°28′ N, 139°35′ E). A circular flat surface of 3 m diam was formed horizontally by paving the roof with 0.3 m square concrete plates. The building blocks and canyons were built by piling cubic concrete blocks of 0.15 m width (see Figure 1). All of the model plates and blocks were made of identical concrete and of the same surface quality.

The global solar radiation and the reflected radiation from the model were observed by upward and downward looking pyranometers (EKO model MS-4), independently. The pyranometer for the reflected radiation was mounted over the center of the model as shown in Figure 1. The position of the sensor was kept 0.3 m above the top of the blocks in all block-canyon models. In this orientation between the sensor and the model, about 95% of the captured radiation (irradiance) by the sensor is estimated to originate from the reflection by the underlying model surface if the reflected radiation were isotropic. In the preliminary experiment, the outside of the circular model was covered by black cloths to estimate the effect of the reflection from the surrounding area. The result showed that there was no strong influence from this outside area which was made of darker concrete than the model. The urban block-canyon models (i.e., the north-south canyon model, the east-west canyon model and the patched block-canyon model) were

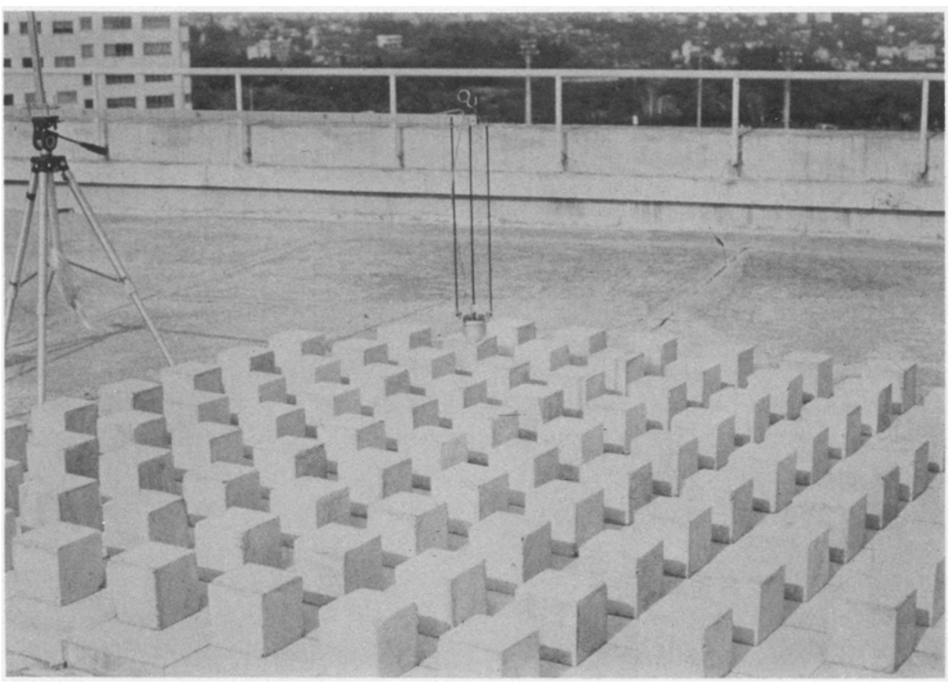

Fig. 1. View of block-canyon model experiment. The downward looking pyranometer was located 0.3 m above the block top. The pyranometer for downward radiation was located in the opposite side of the figure.

compared with the flat model. The structures of the models are shown in Figure 2 and named for simplicity as models 0 to 3, respectively. Some explanation of the urban block-canyon structure is also shown in the figure, where W_1 denotes block width, H is block height and W_2 is canyon width. In the normal models 1 to 3, $W_1 = W_2 = H = 0.15$ m was adopted, and the canyon lengths in model 1 and 2 were limited by the model size. In model 3 the horizontal scale was the same in both the north-south axis and the east-west axis.

The albedo and absorption of solar radiation were estimated by building and dismantling these models in turn. The experiments were mainly undertaken on clear days in order to clarify the effect of the solar zenith angle on the reflection and also to reduce the complexity resulting from cloud effects. In particular, the scrap and build method described below was only applicable in clear conditions.

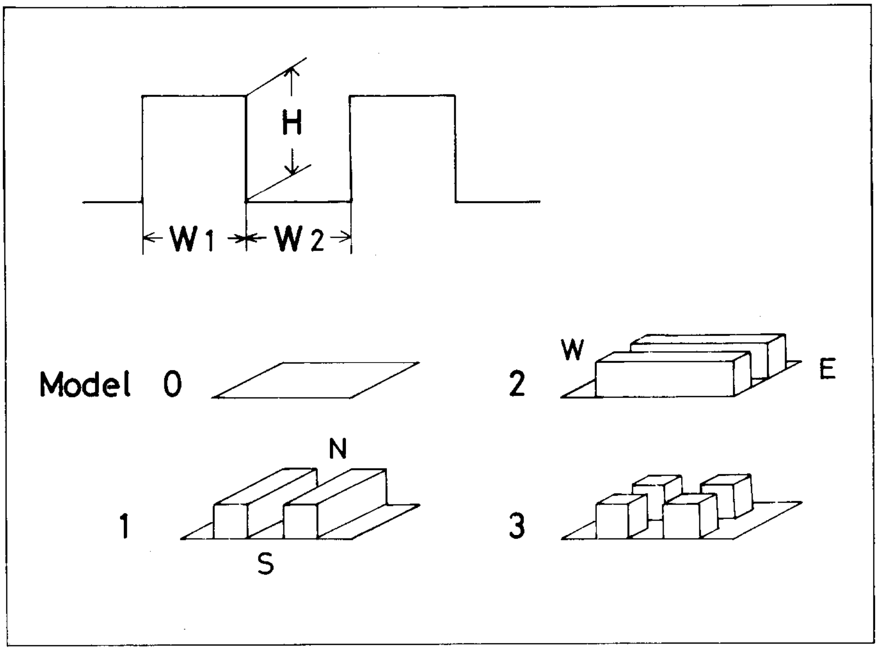

Fig. 2. Illustration of block-canyon models. The dimensions of models 1 to 3 are given in Table I.

3. Results and Discussions

3.1. Scrap and Build Method

In order to clarify the effect of surface irregularities, none of the conditions of the experiment was changed except the urban surface model. That is, models 0 to 3 were built and scrapped in turn. As shown in Figures 3 and 4, the three block-canyon models (model 1 to 3) were compared with the flat model (model 0) which was used as standard throughout the experiment.

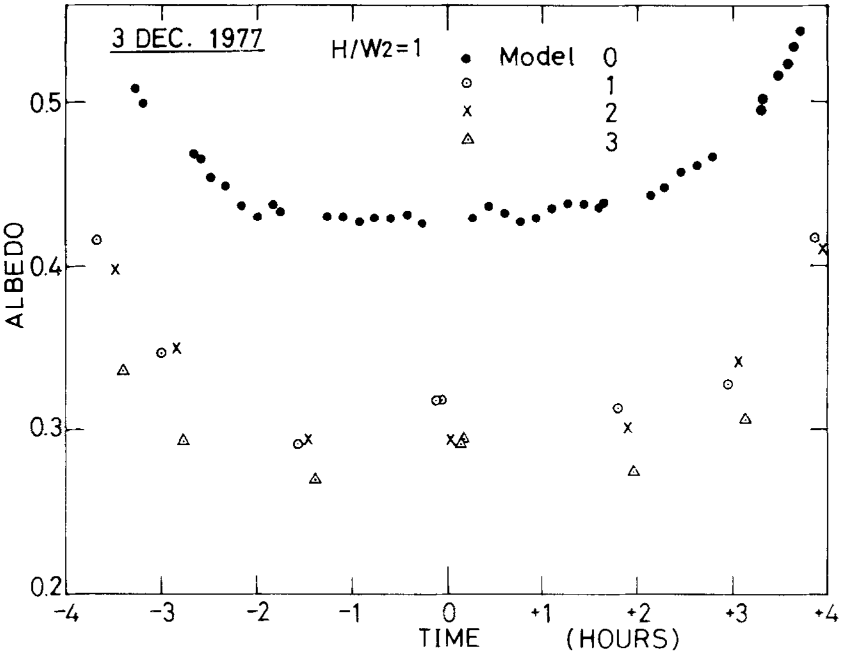

Fig. 3. Diurnal albedo variation of block-canyon models for a winter example by the scrap and build method.

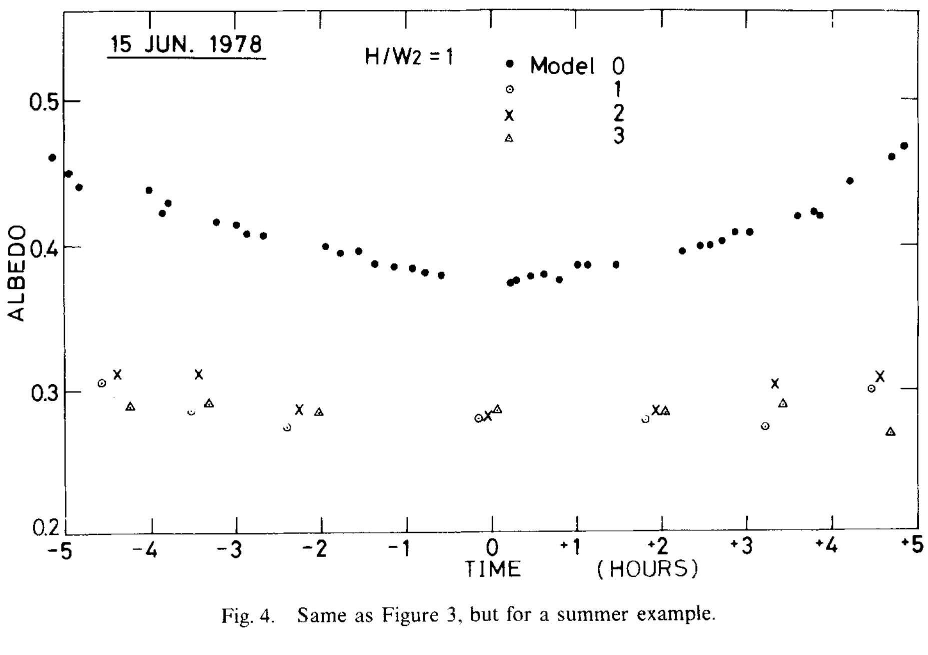

Fig. 4. Same as Figure 3, but for a summer example.

An example (3 December 1977) shown in Figure 3 indicates that the albedo decreases as the surface irregularity increases. Model 3 which has a wider canyon area than model 1 or 2 shows a larger decrease in the albedo. The canyon area amounts to 3/4 of the model area in model 3 but 1/2 of the area for models 1 and 2. Also, the diurnal variations of albedo in these models show a general pattern of the surface albedo having a minimum at noon. The albedo increases with increasing solar zenith angle (Kondratyev, 1972).

The albedo dependence on the surface irregularity is also a function of the solar zenith angle. That is, when the Sun is high (15 June, 1978) the difference among models 1 to 3 is not so clear as compared with the example of Figure 3 (see Figure 4). However, the difference between model 0 and the others exists clearly as in the case of Figure 3.

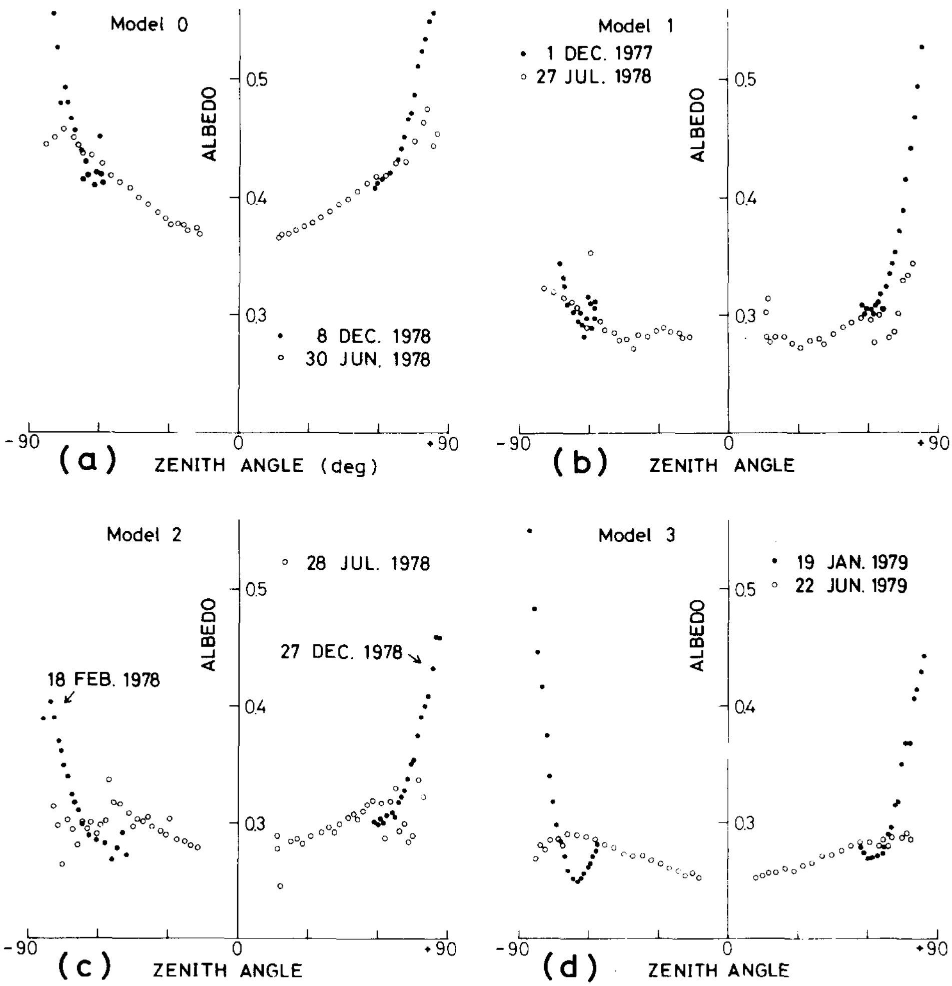

Fig. 5. Albedo dependence on the zenith angle observed by the standing method. Morning data are plotted in deg on the left side of the diagram. (a): model 0, (b): model 1, (c): model 3, (d): model 4.

The scrap and build method is adequate for pointing out differences amongst the models, but there are delays waiting for fine weather. Therefore, the main data of the present experiment were obtained by the standing method described in the next section.

3.2. Standing method

This method was used regularly to observe the albedo changes for days and seasons. One of the models mentioned above or some derivative model was built in advance in case of fine weather. After finishing a one-day experiment for a model, a new model was built. Observations were made continuously, but only the data from fine days were analyzed for the present experiment. Since completely clear days were scarce, some of the half-day data were also included.

Typical examples of the albedo experiment are shown in Figure 5 for each model as a function of solar zenith angle (a negative zenith angle corresponds to morning data). In the figures, the diurnal albedo changes are shown for the two seasons with typical zenith angle ranges; from this the possible variation and limit among the models can be inferred. However, the diurnal albedo change shows a seasonal variation in its pattern depending on the seasonal change of atmospheric transmissivity. This effect is evident when the Sun is low; compare the data for model 0 which shows a flat surface without any directional orientation against the direct solar radiation (Figure 5a). Although the data are selected from very clear days in summer and in winter for this comparison, even on fine days of the same season the relative change of albedo in the morning and evening can be different. This fact is strongly dependent on atmospheric transmissivity as inferred from the albedo values of different seasons.

For model 3 in Figure 5d, the winter values show a different pattern from the summer ones when the zenith angle is around 60°. This is due to the different orientation of the model against the direction of the direct solar radiation. That is, the direct beam is parallel to the north-south canyon in winter while not parallel in summer even at the same zenith angle. This effect is also noticed for the canyon models around noon in Figure 3.

3.3. Seasonal variation of average albedo

By integrating the downward and upward irradiance for a day, the daily average of albedo was obtained. That is, the daily average is defined as follows:

$$A_i = \int U_i(t)\,\mathrm{d}t \bigg/ \int D_i(t)\,\mathrm{d}t\,, \tag{1}$$

where $U_i(t)$ and $D_i(t)$ are the upward and downward irradiances for model i, respectively.

In the present analysis, the integration limit was from −4 hr to + 4 hr from local noon. For the summer data, a limit of ± 5 hr was adopted. However, no significant difference appears in the figure. Three data points were added in Figure 6 by interpolating some results from the scrap and build method.

The seasonal change of the daily average albedo is shown in Figure 6 as a function of minimum solar zenith angle at local noon. Model 3 is compared with model 0 in the same coordinate and models 1 and 2 are also shown.

From this figure it is obvious that there is a seasonal variation in the surface albedo not only in the flat model but also in the irregular models, although there are insufficient data in spring and autumn. (In Japan, completely clear days are rare in these seasons.) Moreover, the irregular models show a very large decrease in albedo compared with the flat model throughout the year.

The anomalous absorption of solar radiation due to the effect of surface irregularity can be estimated by using the results of Figure 6. That is, defining the absorptivity $B_i = 1 - A_i$ for model i, where A_i is the albedo of model i, the ratio

$$R_i = (B_i - B_0)/B_0\,, \qquad i = 1, 2, 3\,. \tag{2}$$

gives the rate of anomalous absorption by the surface irregularity to the flat surface of the same quality. The values of B_i as a function of minimum zenith angle are shown in Figure 7, interpolating all of the data for each model given by the curves in Figure 6. The values corresponding to the scrap and build method are also shown.

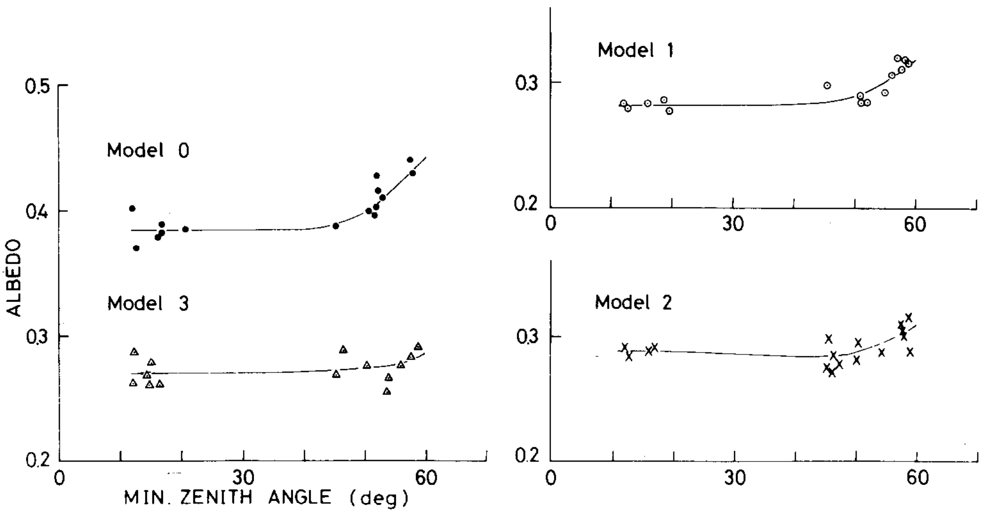

Fig. 6. Seasonal variations of daily mean albedo for models 0 to 3. The abscissa shows the daily minimum solar zenith angle in degrees. The solid lines represent the most probable seasonal changes.

From the figure it may be concluded that the urban irregularity increases the surface absorption of solar radiation more than 10% throughout the year compared with a flat surface of the same material. In particular, the absorption increment exceeds 20% in the winter season when the solar elevation is low. This result implies that the surface irregularity itself decreases the surface albedo in the urban area and tends to increase surface temperature due to additional absorption of solar radiation.

The mean values of albedo for the models and the absorption increments throughout the year are summarized in Table I, which includes a comparison among the derivatives

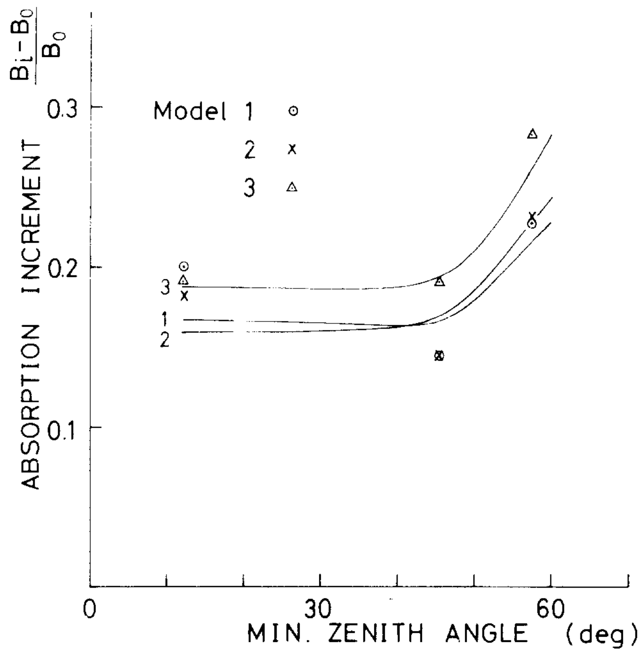

Fig. 7. Absorption increment due to the model irregularity compared with the flat model. The solid lines are inferred from Figure 6; some results obtained by the scrap and build method are also shown.

TABLE I

The average albedo throughout the year. The absorption increment is defined by Equation (2)

Model	Dimensions		Average albedo	Absorption increment (%)
	H/W_1	W_1/W_2		
0	0	–	0.40	–
1	1	1	0.29	18
2	1	1	0.29	18
3	1	1	0.27	21
3f	0.5	0.5	0.32	13
3t	2	1	0.23	27

from model 3. A flatter model 3f shows a larger albedo value than model 3 and a taller model 3t gives a smaller value, as expected from the above discussion. This result shows that as the buildings become taller, the urban areas absorb more solar radiation. However, the absorption increase is proportional to the surface area of the canyon top at the block roof level, while the air volume in the canyon increases as a function of the three-dimensional size of the canyon. Therefore, it is not in any simple way that the urban atmosphere is heated by this anomalous absorption (especially in the deep urban canyons such as in New York City).

4. Conclusions

The urban block-canyon model experiment to examine the effect of the surface irregularity on the absorption of solar radiation leads to the following conclusions:

(1) The urban surface irregularity introduces an anomalous absorption of solar radiation even if the surface quality is fixed for all surfaces in the urban model. Among three models, i.e., the north-south canyon model, the east-west canyon model and the patched block-canyon model, the patched model yields the largest anomalous absorption, compared with the standard flat model throughout the range of solar zenith angle. This absorption amounts to about 20% more than for the flat surface model. The amount of absorption increment depends mainly on the relative canyon area with respect to the whole model area. The north-south canyon shows almost the same property as the east-west canyon in the absorption of solar radiation.

(2) In the comparison of the height of the urban block examined by the patched model, the taller model shows the smaller albedo value. This means that the deeper urban canyons capture more solar radiation per canyon top area, due to multiple reflections from the canyon walls. It is possible that this anomalous absorption tends to produce a temperature increase inside the canyon.

The model experiment suggests the use of a numerical experiment to simulate the multiple reflection of a photon entering the canyon model. A Monte-Carlo method which tracks photons at each reflection may be employed to estimate the diffusive irradiance from the canyon top. A simple two-dimensional numerical experiment will be discussed in the following paper (Aida and Gotoh, 1982).

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References

Aida, M. and Gotoh, K.: 1982, 'Urban Albedo as a Function of the Urban Structure – A Two-dimensional Numerical Simulation', *Boundary-Layer Meteorol.* **23**, 415–424 (this issue).

Kondratyev, K. Ya.: 1972, *Radiation Processes in the Atmosphere*, WMO No. 309, WMO, Geneva, 214 pp.

Oke, T. R.: 1979, *Review of Urban Climatology 1973–1975*, Tech. Note No. 169, WMO, Geneva, 100 pp.

Terjung, W. H. and Louie, S. S.-F.: 1973, 'Solar Radiation and Urban Heat Islands', *Annals, Assoc. Amer. Geogrs.* **63**, 181–207.