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MECHANISM ON URBAN RAINFALL INTERCEPTION

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Abstract

Rainfall interception (RI) over a comprehensive outdoor urban scale model (COSMO) was investigated from the perspective of water and energy balance. The RI was 6% of the total rainfall on average and smaller than the typical values in forests. No correlation was found between RI and total rainfall or rainfall duration unlike the correlations found in forests. Instead, most RI occurred in the first several hours of rainfall. RI depended on the saturation deficit at the beginning of the rainfall event. Latent heat for RI was approximately balanced by heat conduction from the concrete surfaces. As the possible reasons for the different behaviors of RI between COSMO and forests, differences in the canopy structure are considered: 1) complete surface area index (SAI), 2) efficiency for scalar transfer in relation to roughness size, and 3) heat balance in relation to volumetric heat capacity on the roughness elements.

Key words: Urban Rainfall Interception, Urban Heat Balance during Rainfall, COSMO

1. INTRODUCTION

Understanding of the water vapor exchange process between cities and the atmosphere is important in urban meteorology and hydrology. A number of field campaigns in urban area have been investigated about the characteristics of urban latent heat flux on non-precipitation days (e.g., Moriwaki and Kanda, 2004). Meanwhile, studies on the latent heat flux during rainfall, that is rainfall interception (RI), are limited (Grimmond and Oke, 1991; Ragab et al., 2003). Ragab et al. [2003] (hereafter RAGAB) pioneered urban RI measurements. However, their focus was on "local RI" on the roofs of houses. No "bulk RI" measurements of entire urban canopies have yet been conducted. One reason for the scarcity of research on urban RI is the difficulty of making hydrological and meteorological measurements in real cities on precipitation days.

The objective of this study is to investigate the magnitude and mechanisms of urban "bulk RI" using data obtained from the Comprehensive Outdoor Scale MOdel (COSMO). COSMO is an idealized miniature city which has no vegetation, no human activity, and no heterogeneity of the surface geometry. The model has been created by arranging large concrete cubes on a concrete base to ensure thermal inertia similarity, dynamical similarity, and geometrical similarity with real cities (Kanda et al, 2007). The simple and idealized setup of COSMO allows for detailed examinations of RI on entire urban canopies from the perspective of both the energy and the water balance. This report is based on the work by the authors (Nakayoshi et al., 2009).

2. METHODOROGY

A portion of COSMO site (6 m x 6 m) was used as a catchment for the current study (Figure 1, shaded area). This catchment was enclosed by water-proof fencing (5 cm high), and all surfaces in the catchment were coated with a transparent water-impervious paint over the original paint. Therefore, horizontal water exchange between the catchment and its surrounding area and infiltration into the concrete were assumed to be zero. The runoff was collected and measured by a flow meter (UIZ-TB1000, UIZIN Ltd.) with a resolution of 1.0 liter per tip. Gross rainfall (GR) was measured at 1 m above the ground using a tipping-bucket rain gauge (TR-525M, Texas Electronics Inc.) with a resolution of 0.1 mm per tip. RI was calculated as follows;

$$RI = GR - Runoff \; . \qquad (1)$$

All units are in volume of water per unit horizontal area (mm). One component of RI is the canopy water storage (St). St was carefully examined and estimated to be 0.25 mm.

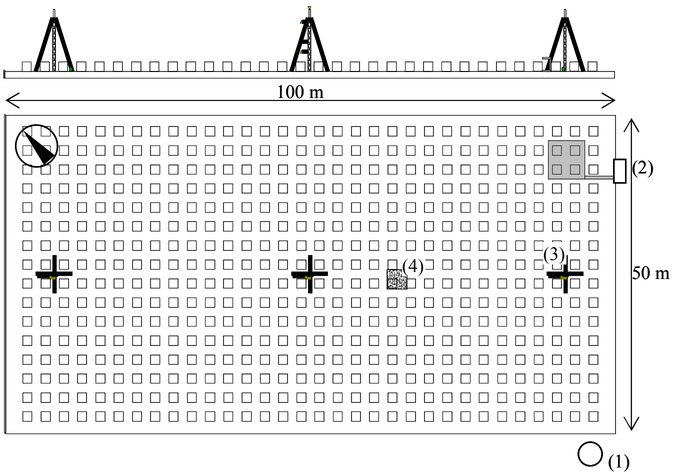

Figure 1 Schematic of COSMO (top: side view; bottom: plan view). The shaded area (6 m x 6 m) is the RI catchment area. The numbers in parentheses represent the locations of the instruments: (1) rainfall gauge, (2) flow meter, (3) three-cup anemometer and Ta and RH sensors, and (4) ground heat flux and Tc sensors (heat flux plates).

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For the aerodynamic analysis of RI, wind velocity (03001-L, Campbell), ambient temperature (Ta), and relative humidity (RH) (Hummitter 50U/50Y, Vaisala) were measured at 1 Hz at 3 m above the ground (Figure 1). Heat storage and surface temperature were also directly measured using highly-accurate heat flux plates (HF-300T, Captec) at 1 Hz. A total of 164 heat flux plates were attached to a sample unit that consisted of a block and its surrounding streets for the precise measurement.

The present dataset allowed the investigation of RI from the perspectives of aerodynamics and heat balance.

3. RESULT

3.1. Statistical summary of RI

In the period from September 2006 to January 2007, 30 rainfall events were observed. The ranges of total rainfall, maximum hourly rainfall, rainfall duration, and average wind velocity during rainfall are 0.2 to 134.5 mm, 0.1 to 10.5 mm hr^{-1}, 2 to 50 hours, and 0.2 to 2.8 m $sec.^{-1}$, respectively. The estimated values of RI ranged from 0 to 5.1 mm. Table 1 shows the statistical summary of the rainfall events. Average value of RI was 6% of the total rainfall, and was smaller than the average value of RI estimated for the roofs of houses in the UK by RAGAB. The different values of RI between COSMO and RAGAB may offer insight into the difference between "bulk RI" of entire urban canopies and "local RI" of roofs (see Section 4.2). The average value of RI in COSMO was also significantly smaller than that reported for forests, 10-50%. In forest regions, high correlations between RI and total rainfall and between RI and rainfall duration have been observed. However, there was neither a clear dependency of RI on total rainfall (Figure 2) nor on rainfall duration (Figure 3) in COSMO. These differences may be attributable to the dissimilarity in the canopy structure between COSMO and forests. The different behaviors of RI between COSMO and forests will be further discussed in section 4.1.

Table 1 Statistical summary of rainfall events

Gross rainfall [mm]	Gross runoff [mm]	Gross RI [mm]	Average RI fraction	Average runoff fraction
455.7	428.88	26.70	0.06	0.94

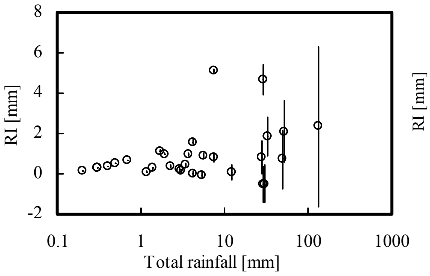

Figure 2 Relationship between RI and total rainfall

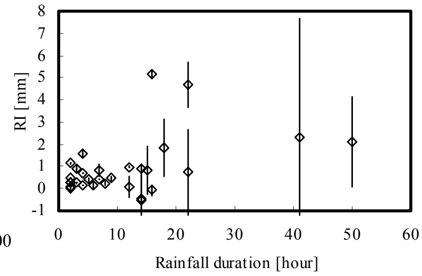

Figure 3 Relationship between RI and rainfall duration

3.2. Temporal changes of RI

Figure 4(a) shows the ensemble-averaged values of the temporal changes of RI and indicates that most of the RI occurred in the first several hours of rainfall and that RI rapidly decreased with time.

The temperature difference between the ambient air (Ta) and the surface (Tc) and the saturation deficit were also calculated (Figure 4(b), (c)). As for the surface temperature, the complete surface temperature was applied. The saturation deficit was estimated from Ta, Tc, and RH with the following assumptions. RH was assumed to be 100% when the RH data exceeded 90%. This assumption was made because RH measurements in high humidity conditions are considered unreliable. Figure 4(b) indicates that Tc is always higher than Ta during rainfall. This result is attributable to the large heat capacity of the urban material.

The temporal changes of RI, temperature difference between Ta and Tc, and saturation deficit in Figure 4 appear to be correlated. This result indicates that RI was governed by the conventional aero-dynamic mechanism.

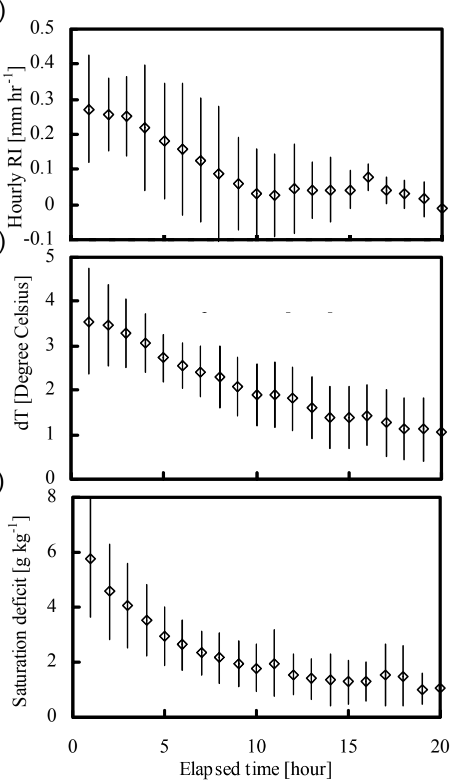

Figure 2 Temporal change of (a) hourly RI, (b) temperature difference between the Tc and Ta, and (c) saturation deficit. Symbols and error bars indicate ensemble means and standard deviations, respectively.

3.3. Aero-dynamical evaluation of RI

The direct application of an aero-dynamic method to the prediction of RI is difficult because of the difficulty in obtaining accurate measurements of the saturation deficit during rainfall. As an alternative, RI was related to the saturation deficit at the beginning of the rainfall event (Figure 5). This figure suggests a dependency of RI on the saturation deficit at the beginning of the rainfall event, which may also be inferred from Figure 4.

3.4. Energy balance of RI

Figure 6 represents the relation between the latent heat flux required for the RI and the conductive heat flux, G, from the canopies during rainfall. Negative values of G mean the heat was transferred from the subsurface to the surface. The correlation between the latent heat flux and G (Figure 6) indicates that the energy necessary to evaporate RI was mainly supplied from the concrete substrate (correlation coefficient = -0.75).

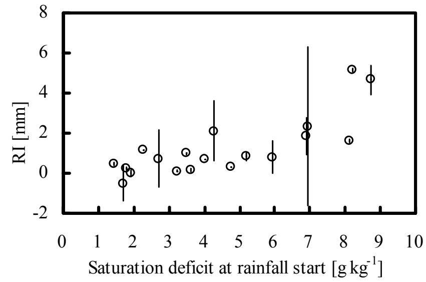

Figure 5 Relationship between RI and saturation deficit measured at the beginning of each rainfall event.

4. DISCUSSION

4.1. Difference in RI between COSMO and forests

The RI characteristics in COSMO were different from those in forests: smaller RI and no clear dependencies of RI on gross rainfall nor on rainfall duration in COSMO. A possible reason for the dissimilarities is the difference in the canopy structure between COSMO and forests. Here, three aspects of the canopy structure will be discussed: 1) complete surface area index (SAI), 2) scalar roughness parameter (kB^{-1}), and 3) heat balance in relation to volumetric heat capacity of the roughness elements.

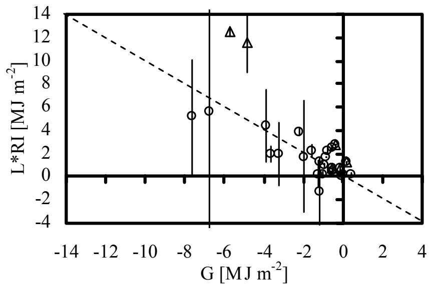

Figure 6 Relationship between the latent heat for RI (L*RI) and the total storage heat flux into the ground (G). Triangles in this figure are data that were affected by sunlight during rainfall.

1) Complete surface area index, SAI

The complete surface area index (SAI) is the ratio of all surface areas to the horizontally projected ground surface area. In a forest, the SAI is approximately twice the leaf area index (LAI). The SAI is a measure of the wettable surface area. Accordingly, a high correlation is found between SAI and St for a variety of forests that were studied in the literature (Figure 7(a), see Nakayoshi et al, 2009 for the detailed information). In addition, SAI is also well-correlated to RI regardless of forest types or climate conditions (Figure 7(b)). Figure 7 suggest that the small value of SAI in COSMO is one of the reasons for the small value of RI.

2) Scalar roughness parameter, kB^{-1}

The difference in water vapor transfer efficiency between COSMO and forests is discussed using an analogy to heat transfer. The aerodynamic resistance of heat transfer between the atmosphere and the surface is larger than that of momentum transfer. This enhancement of resistance for heat transfer is expressed as the ratio of the roughness length for momentum (z_0) to that for heat (z_T):

$$kB^{-1} = \ln\left[z_0 / z_T\right]. \quad (2)$$

The value of kB^{-1} is larger in both real cities and COSMO than in forests [e.g., Kanda et al, 2007]. Applying this idea to the evaporation process during rainfall, the larger value of kB^{-1} in COSMO and real cities is expected to yield a lower efficiency of water vapor transfer there than that in forests.

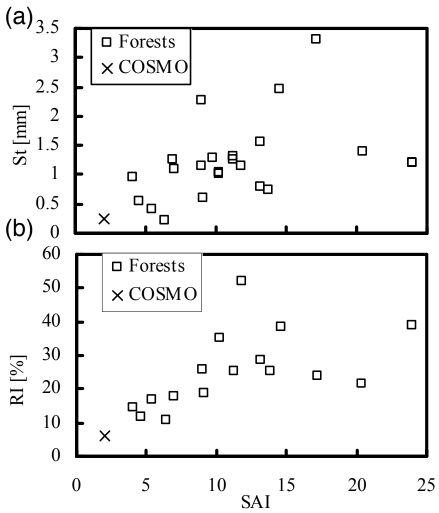

Figure 7 Relationship between surface area index (SAI) and (a) water storage capacity (St) and (b) rainfall interception (RI) as a percentage of total rainfall.

3) Heat supply from roughness elements

In forests, sensible heat flux from the atmosphere and net radiation are regarded as the possible heat sources for RI. Leaves can not be a heat source for RI due to small volumetric heat capacity. However, the small heat capacity of leaves makes the leaf surface temperature to be lower than the ambient air; the lower leaf temperature induces sensible heat supply from the atmosphere. Rn is supplied to the forest canopies during rainfall in daytime. Continuous heat supplies from both the sensible heat and Rn can sustain RI during rainfall, and this mechanism may account for the good correlation between RI and rainfall duration in forests. Gross rainfall amount generally increases with rainfall duration. Therefore, the relationship between RI and gross rainfall amount is essentially the same as the relationship between RI and rainfall duration.

In contrast to forests, the latent heat necessary to evaporate RI in COSMO was mainly supplied from the concrete substrate (Figure 6) thanks to a large volumetric heat capacity of concrete materials. Large values of RI were observed mainly in the early stages of each rainfall event (Figure 4(a)). Tc in COSMO was always higher than Ta during rainfall (Figure 4(b)), which is opposite of the situation found in forests. These results suggest that RI in COSMO was mostly determined by the saturation deficit or by the heat storage of urban materials at the beginning of the rainfall event; the influences of the rainfall duration and gross rainfall amount were quite small.

4.2. Difference in RI between COSMO and RAGAB

The value of RI as a percentage of total rainfall in COSMO, 6%, was smaller than that reported in RAGAB, 23.9% for the 22° roof-slope case, and 33.8% for the flat roof case. In this section, causes of the difference in the urban RI between the present study, COSMO, and RAGAB are discussed.

One possible reason for the difference in RI is the difference in the surfaces included in the control volume used for water budget between the two studies; RAGAB focused on the "local RI" of roofs whereas COSMO focused on the "bulk RI" of the entire urban canopy. The local RI of roofs can be larger than bulk RI for the following three reasons. First, the local transfer efficiency for scalar quantities is larger on roofs than on other surfaces (Narita, 2007). Second, roofs are better located to receive solar radiation than other surfaces, thus there is more available radiative energy on roofs than on other surfaces. Third, splash-loss of raindrops from the roof surfaces can increase with time and rainfall intensity in RAGAB. Because of their objectives, the catchment in RAGAB was not enclosed by a water-proof fence, and splash-loss likely increased with increasing time and rainfall intensity. In contrast, in COSMO, the splash-droplets that fall to the floor from the roofs and walls are counted as runoff or evaporation from the floor. The splash-loss of raindrops may have increased the measured values of the local RI with respect to the actual evaporation in RAGAB, and created a dependency of the local RI on the gross rainfall, similar to that observed in forests.

4.3. Considerations for rainfall interception in real cities

It is expected that the fundamental mechanism of RI in COSMO is also valid in real cities since COSMO was designed to satisfy aero-thermodynamic similarity with real cities. Nevertheless, the highly-idealized setup of COSMO is different from the complexity of real cities so that the findings in the present study may not be directly applicable to real cities. One difference between COSMO and real cities is storage, St. Real cities with the same value of SAI as COSMO would have a larger value of St than COSMO because real cites include multiple concave surfaces and vegetation. In addition, porous materials of building facades also increase St as they can absorb rain water. Another difference between COSMO and real cities is the influence of anthropogenic heat emission, which can be a heat source for RI. Thus, 1) larger values of St due to concave surfaces and vegetation and due to uptake of water by the porous materials of buildings and 2) additional heat sources in real cities will increase the value of RI even if the cities have the same geometric parameters as COSMO.

5. CONCLUSIONS

Rainfall interception (RI) was evaluated as the residual of the measured rainfall and the runoff at COSMO over a period of 5 months. Average RI during the period was 6% of the gross rainfall. Unlike the forest RI, there was no clear dependency of RI on total rainfall, nor on rainfall duration. Instead, there was a high correlation between RI and the saturation deficit measured at the beginning of a rainfall event. Most of RI occurred in the first several hours of a rainfall event, and RI rapidly decreased with time during rainfall. A similar trend was observed for the temperature difference between the surface and the ambient air and for the saturation deficit. The latent heat required for RI was closely related to heat conduction from the substrate to the surface during rainfall. The possible reasons for the different behaviors of RI between COSMO and forests are attributable to the differences of canopy structures. Three possible differences caused by the differing canopy structures include dissimilarities in: 1) the complete surface area index (SAI), 2) scalar transfer efficiency in relation to roughness size, and 3) heat balance in relation to volumetric heat capacity of roughness elements.

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