Temporal variations of isotopic compositions in gross rainfall, throughfall, and stemflow under a Japanese cedar forest during a typhoon event

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Abstract:
To examine the cause of isotopic difference among gross rainfall, throughfall and stemflow, water sampling with high temporal resolution was conducted in a Japanese cedar forest during a typhoon event. In this event, δ¹⁸O variation of throughfall was similar to that of gross rainfall except for the beginning of the rainfall event. However, isotopic fluctuations of stemflow differed from those of gross rainfall and throughfall throughout the event, although the temporal trend of stemflow volume was similar to that of gross rainfall and throughfall volumes. Comparisons between the observed δ¹⁸O of stemflow and that estimated by a model simulation suggests that isotopic difference between stemflow and gross rainfall or throughfall is caused principally by mixing of waters within canopy and stem storage along their flow paths with secondary effects of evaporation and isotopic exchange with ambient water vapor.

KEYWORDS isotopic composition; stemflow; throughfall; canopy and stem storage

INTRODUCTION
Rainwater fallen in a mountain region greatly contributes to the hydrological biogeochemical cycles of forested catchment. Throughfall and stemflow are the two significant factors responsible for the hydrological cycling system in the forest. However, stemflow studies have often considered to be marginal because its quantitative contribution per unit canopy projection area is much less as compared to throughfall. However, comprehensive literature reviews on stemflow conducted by Levia and Forest (2003) and Ikawa (2007) revealed that stemflow is potentially a very important source for groundwater recharge and nutrients supply to the forest.

Many studies have been conducted on stemflow solute chemistry regarding the addition of nutrients to forest floor and the biogeochemical cycle within the forest (Adams and Attiwill, 1991; Liu et al., 2004; Dezzeo and Chacón, 2006). On the other hand, previous stemflow isotopic characteristics especially for oxygen and hydrogen isotopes are poorly understood. Kubota and Tsuboyama (2003) compared isotopic composition of throughfall and stemflow water collected by bulk sampling during a rainfall event and reported that the oxygen isotopic composition in stemflow is higher than that in throughfall, though no specific reasons were given for the isotopic differences.

Generally, in many hydrological studies, oxygen and hydrogen isotopic compositions have frequently been used as an effective tracer in hydrological phenomenon. Ikawa et al. (2009a) reported that isotopic trend of hourly stemflow sample during a rainfall event differs from that of throughfall and detailed isotopic data of stemflow are available for better understanding of the quantitative contribution from stemflow in rainfall-runoff process at the headwater catchment. However, the cause of isotopic difference between throughfall and stemflow has not been understood. Isotopic composition of stemflow and throughfall is considered to be affected by evaporation and/or isotopic exchange between rain drop and ambient water vapor. As the result, these can be different from isotopic composition of the gross rainfall.

Therefore the objective of this study is to clarify the cause of isotopic difference among gross rainfall, throughfall, and stemflow. To achieve this, we investigated temporal variation in isotopic compositions of gross rainfall, throughfall, and stemflow with employing the high temporal resolution sampling methods under the coniferous tree forest during a typhoon rainfall event.

OBSERVATIONS AND ANALYTICAL METHODS
Gross rainfall, throughfall and stemflow values were measured during a typhoon event that occurred on 18–19 August 2006 (international name = Wukong; Japanese ID = T0610) at the Kahoku experimental watershed. (KHEW: 33.13°N, 130.07°E), located on the northern part of Kumamoto Prefecture in Kyushu Island, Japan. From 2000 to 2003, mean annual precipitation was 2166 mm and mean annual air temperature was 15.5°C.

Gross rainfall volume was measured using a 0.5 mm tipping-bucket rain gauge, and its samples were collected by two troughs and 40 L plastic bucket at an open site outside the watershed. Throughfall and stemflow volumes were monitored in a Japanese cedar (Cryptomeria japonica) forest. Throughfall samples were also collected in two troughs and measured by a 200 ml tipping-bucket flow meter. Stemflow samples were collected from four trees (average DBH: 0.22 m) using a flexible urethane plate fitted around the stem, and the volume was measured by a 500 ml tipping-bucket flow meter. Throughfall and stemflow volumes (ml) were converted to depth (in millimeters) considering with the surface area of the collecting troughs (0.9 m²) and canopy.

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projection area (21.4 m$^2$) of the four trees, respectively.

After the volume measurement, throughfall and stemflow samples were stored in 40 L and 60 L plastic buckets, respectively. Then water samples were taken from the buckets one hour interval using an automatic rainwater sampler developed by Ikawa et al. (2009b). The collected samples were analyzed for isotopic compositions ($\delta^{18}$O and $\delta^D$). Oxygen and deuterium stable isotopes were analyzed by mass spectrometer (delta S, ThermoElectron). Oxygen and deuterium samples were prepared by $\text{CO}_2$-$\text{H}_2\text{O}$ equilibration (Epstein and Mayeda, 1953) and Cr reduction (Gehre et al., 1996) techniques, respectively. The isotopic compositions were reported in $\delta$-notation as parts per thousand ($\text{‰}$). The accuracies of measurements are $\pm0.1\%$ for oxygen-18 and $\pm1\%$ for deuterium.

RESULTS AND DISCUSSION

Temporal variations of $\delta^{18}$O values in gross rainfall ($-8.4$ to $-13.9\%$), throughfall ($-7.4$ to $-13.8\%$), and stemflow ($-8.1$ to $-12.6\%$) are shown in Figure 1. Previous studies suggested short-term isotopic fluctuation in rainwater during a typhoon event result from rainfall intensity, moisture source, cloud structure, and wind velocity (Matsuo and Friedman, 1967; Lawrence et al., 1982; Pionke and Dewalle, 1992; Ohsawa and Yusa, 2000). In this study, $\delta^{18}$O values in gross rainfall, throughfall and stemflow showed similar trends and varied markedly during the rain event. However, the isotopic fluctuation of stemflow differed from that of gross rainfall, whereas the fluctuation of throughfall was similar to that of gross rainfall. The difference in isotopic fluctuation of throughfall and stemflow may be due to differences in their generation processes. Beneath the forest canopy, gross rainfall is partitioned into two fractions: throughfall that comprises free throughfall, drips, and splash droplets (Nanko et al., 2006), and stemflow that comprises rainwater flowing down the stem (Kuraji et al., 2001). Although rainwater stored within the canopy contributes to both throughfall and stemflow generations when cumulative rainfall exceeds canopy storage, the stemflow generation was later than throughfall generation. Stemflow generation is affected by bark water storage capacity, and stemflow are usually generated when bark water storage exceed its capacity (Levia and Herwitz, 2005). In the present study, the time lag between the generations of each of the three rainfall components was confirmed to be several hours (Figure 2). The meteorological information of three rainfall components such as duration and total amount is shown in Table I.

The greatest differences between $\delta^{18}$O values of gross rainfall and throughfall were observed at the beginning of the event (18 Aug., 3:00). However, the $\delta^{18}$O values of gross

![Figure 1. Temporal variation of $\delta^{18}$O values in gross rainfall, throughfall, and stemflow. (JST: Japan Standard Time)](image1.png)

![Figure 2. Temporal variation of relative humidity, gross rainfall, throughfall, and stemflow volumes during a rain event (18–19. Aug. 2006).](image2.png)

| Date          | Component  | Total amount (mm) | Duration (h) | Rainfall intensity Max. (mm/h) Min. (mm/h) |
|---------------|------------|------------------|--------------|------------------------------------------|
| 18–19 Aug. 2006 | Gross rainfall | 138.5            | 38           | 13.0                                     | 0.5                                     |
|               | Throughfall     | 96.9             | 38           | 8.9                                      | 0.2                                     |
|               | Stemflow       | 12.5             | 43           | 1.04                                     | 0.02                                    |
rainfall and throughfall rapidly converged, indicating that isotopic fractionation by evaporation occurred on the canopy only at the initial stage of the rain event (18 Aug., 3:00–6:00). In Figure 2, relative humidity shows lowest value at the beginning of the event. A laboratory experiment on isotopic fractionation in water droplets, Friedman et al. (1962) proved that droplet size strongly affected isotopic fractionation within a falling water droplet via evaporation. Raindrops hitting surface of a leaf or branch splash and produce numerous small droplets (Herwitz, 1987; Nanko et al., 2006). Murakami (2006) also proposed that evaporation from splash droplets occurs during rain events. As leaves and branches become wet, many flowlines are established on these surfaces. Therefore, water movement on the canopy becomes smooth (Herwitz, 1987) and consequently, the time lag between gross rainfall and throughfall disappears. This mechanism can explain reason why the difference between the δ¹⁸O values of gross rainfall and that of throughfall at the beginning of the event disappeared after a short time.

The peaks in stemflow volume occurred simultaneously with peaks in gross rainfall and throughfall volumes (Figure 2). However, magnitude of isotopic fluctuation of stemflow differed to those of gross rainfall and throughfall throughout the event. This means that the mixing of rainwater with different isotopic compositions occurred on the canopy and stem at the stemflow generation process. In previous studies, it was suggested that stemflow generation is strongly affected by canopy interception, bark water storage capacity, bark morphologies (i.e. bark thickness and bark furrows depth), and meteorological condition (i.e. rainfall intensity and wind velocity) (Levia and Herwitz, 2005; Staelens et al., 2008).

Therefore, the formation of isotopic composition in stemflow may be strongly affected by rainwater storage in canopy and stem. As mentioned above, isotopic fluctuation of stemflow differs from that of gross rainfall and throughfall. To evaluate the influence of water storage in canopy and stem on isotopic composition of stemflow water, we conducted a model simulation.

Firstly, stemflow volume was estimated by a mathematical model which represents forest interception process in Japanese cedar stand (Yoshida et al., 1993). Water storages of canopy and stem were estimated by an individual tank (Figure 3 and Appendix), and the model parameters shown in Table II were calibrated by a global optimization method, namely Shuffled Complex Evolution Metropolis algorithm (Vrugt et al., 2003). Simulation results of the stemflow and throughfall volumes is shown in Figure 4. The goodness of fit for these results were evaluated by Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970). These coefficients between observed and simulated values for stemflow and throughfall were 0.95 and 0.77 respectively, and an especially good result was obtained for the stemflow. Secondly, the isotopic values of stemflow were calculated by using the estimated model parameter and observed hourly data (volumes and δ¹⁸O values) of gross rainfall. In the study, the stemflow isotopic values were calculated as the output by giving both volume and isotopic values of gross rainfall as the input to this model.

The comparison between observed and simulated stemflow isotopic values is shown in Figure 5. Simulated

![Figure 3. Schematic illustration of rainfall interception model (Yoshida et al., 1993). The explanation of each parameter is shown in the appendix.](image)

![Figure 4. Simulation results of stemflow and throughfall volumes by the mathematical model.](image)

| Table II. Lateral and vertical parameters for the simulation model |
|------------------|--------|--------|--------|--------|--------|--------|--------|--------|
|                  | λ₁ₐ    | λ₁₈    | λ₁₉    | λ₁₂    | h₁ₐ    | h₁₈    | h₁₉    | P₁     | P₂     |
| During rain      | 0.57   | 0.96   | 0.98   | 0.12   | 3.8    | 27.4   | 15.8   | 0.81   | 0.04   |
| After rain cease | 0.54   | 0.00   | 0.10   | 0.36   | 32.6   | 0.0    | 25.1   | 0.81   | 0.04   |
isolated values showed similar behavior to observed stemflow values. This suggests that water storage in canopy and stem influences not only stemflow yield but also stemflow isotopic formation. The difference between observed and simulated values at the initial stage of rain event with lower relative humidity may be due to isotopic fractionation by the evaporation from canopy and stem interception. Moreover, isotopic difference between them was also found at the latter part of rain event with higher relative humidity. Friedman et al. (1962) proved that, under high humidity conditions, the cause of isotopic fractionation between water droplet and its environment is neither evaporation nor condensation but rather isotopic exchange between water droplet and ambient water vapor in laboratory experiment. In addition, based on the experimental result, they proposed that isotopic composition of rainwater droplet and ambient water vapor were equilibrated within the distance between cloud and ground surface. At the end of rain event, observed stemflow $\delta^{18}$O values was similar to gross rainfall and throughfall $\delta^{18}$O values (Figure 1). Meanwhile, stemflow intensity gradually became low (Figure 2), and water holding time on canopy and stem consequently became longer than that at high intensity period. Based on the assumption proposed by Friedman et al. (1962), $\delta^{18}$O values of ambient water vapor within the forest equilibrates with that of throughfall or gross rainfall. Therefore, the disagreement between observed and simulated values of $\delta^{18}$O in stemflow water may be due to isotopic exchange between stemflow and ambient vapor, and it is possible that stemflow $\delta^{18}$O values become similar to those of throughfall or gross rainfall.

**CONCLUSIONS**

A cause of differences in isotopic composition among gross rainfall, throughfall, and stemflow during a typhoon event was examined by the comparison of high temporal resolution isotopic data and the model simulation. While the $\delta^{18}$O values of throughfall were almost equal to those of gross rainfall, the $\delta^{18}$O values of stemflow differed from those of gross rainfall and throughfall throughout the event. This suggests that the generation process of the stemflow be more complex than that of throughfall and the mixing of rainwater with different isotopic compositions occurred on the canopy and stem at the stemflow generation.

The result of comparison between the observed $\delta^{18}$O values of stemflow and that estimated by a model simulation suggests that difference of isotopic composition between stemflow and gross rainfall or throughfall is caused principally by mixing of waters within canopy and stem storage along their flow paths with secondary effects of evaporation and isotopic exchange with ambient water vapor. Isotopic signal of stemflow is different from that of gross rainfall or throughfall, thereby this isotopic characteristic of stemflow will be available to some hydrological investigation such as hydrograph separation during a runoff event and estimation of groundwater recharge via a stemflow at the catchment scale. To better generalize calculation of isotopic value in stemflow water, further field observation and improvement of simulation model are needed.

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APPENDIX

Variables

\( r \) : rainfall intensity (mm/h)

\( E_p \) : potential evaporation intensity (mm/h)

\( d_1 \) : drip intensity from canopy tank (mm/h)

\( d_2 \) : drip intensity from stem tank (mm/h)

\( f \) : inflow intensity from canopy tank to stem tank (mm/h)

\( q \) : stemflow intensity (mm/h)

\( S_1 \) and \( S_2 \) : storage of canopy and stem (mm)

\( \lambda \) : water vaporization heat

\( \alpha \) : coefficient (\( \alpha = 1.26 \) in this study)

\( \Delta \) : saturated vapor pressure

\( \gamma \) : psychrometer constant

\( R \) : global solar radiation

Equation

<During rain>

\[
\begin{align*}
d_1 &= \begin{cases} 
0 & (0 \leq S_1 \leq h_d) \\
\lambda_d (S_1 - h_d) & (h_d < S_1)
\end{cases} \\
f &= \begin{cases} 
0 & (0 \leq S_1 \leq h_h) \\
\lambda_b (S_1 - h_b) & (h_b \leq S_1)
\end{cases} \\
d_2 &= \begin{cases} 
0 & (0 \leq S_2 \leq h_c) \\
\lambda_d (S_2 - h_c) & (h_c \leq S_2)
\end{cases} \\
q &= \begin{cases} 
0 & (0 \leq S_2 \leq h_h) \\
\lambda_c (S_2 - h_h) & (h_h \leq S_2)
\end{cases}
\]

<After rain ceases>

\[
\begin{align*}
d_1 &= \begin{cases} 
\lambda_d (S_1 - h_d)^2 & (h_d \leq S_1) \\
0 & (0 \leq S_1 \leq h_d)
\end{cases} \\
f &= 0 \\
d_2 &= \begin{cases} 
\lambda_d (S_2 - h_c)^2 & (h_c \leq S_2) \\
0 & (0 \leq S_2 \leq h_c)
\end{cases} \\
q &= \begin{cases} 
\lambda_c (S_2 - h_h)^2 & (h_h \leq S_2) \\
0 & (0 \leq S_2 \leq h_h)
\end{cases}
\]

<Potential evaporation>

\[
E_p = \frac{\alpha}{\lambda} \frac{\Delta}{\Delta + \gamma} R
\]