

## High Frequency and Large Deposition of Acid Fog on High Elevation Forest

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We have collected and analyzed fogwater on the mountainside of Mt. Oyama (1252 m) in the Tanzawa Mountains of Japan and observed the fog event frequency from the base of the mountain with a video camera. The fog event frequency increased with elevation and was observed to be present 46% of the year at the summit. The water deposition via throughfall increased with elevation because of the increase in fogwater interception and was about twice that via rain at the summit, where the air pollutant deposition via throughfall was several times that via rainwater. The dry deposition and the deposition via fogwater were dominant factors in the total ion deposition at high elevation sites. In a fog event, nitric acid, the major acid component on the mountain, is formed during the transport of the air mass from the base of the mountain along the mountainside, where gases including nitric acid deposit and are scavenged by fogwater. Therefore, high acidity caused by nitric acid and relatively low ion strength are observed in the fogwater at high elevation sites.

### Introduction

Forest decline is an important environmental problem having a long-term effect. Acid deposition has been implicated as one of the causal factors of the crown thinning of Norway spruce and silver fir in middle and northern Europe (1) and the decline of red spruce in northern America (2), although ozone exposure, drought, multiple stress, etc. are also other possible causes of the decline (3). Forest decline is also observed in East Asia, Japan (4), and China (5). The acidification of soil causes the forest decline (6) of course, but forest decline has now spread to areas other than the acidified soil regions. The direct effect of acid deposition on plants is also important, but it occurs only when the pH is less than 3 (7). The pH of precipitation is normally between 4 and 6, and acid rain with a pH below 3 is a rare case around the world (8). However, the acidity of fogwater is much greater than that of rainwater because air pollutants are more concentrated in fogwater than in rainwater (9), and highly acidified fogwater is observed all over the world (10). The deposition via fogwater is great in mountainside forests (11), and the effect of acid fog on the decline of high elevation forest may be large.

We have observed acid fog at the midslope of Mt. Oyama, about 50 km west-southwest of Tokyo, since 1988 and have

reported that the acid fog frequently occurs at this location (12–14). The base of the mountain is situated along the path of the sea and land breezes between Sagami Bay and the Kanto Plains, which is the largest source of air pollutants in Japan. Fog events occur at Mt. Oyama when the valley wind blows and the relative humidity is high at the base of the mountain. There are many dying fir trees at over 700 m elevation on Mt. Oyama (4), but the soil is not acidified in this region (15).

For the estimation of the effect of fogwater on the forest trees on a mountainside, it is important to determine the deposition of air pollutants via fogwater on the canopies. However, field observation over a long term is difficult, and the chemistry of acid fog has been reported for limited sites and periods (16–19). We have collected fogwater and determined the chemical composition of the samples obtained on the mountainside and the summit of Mt. Oyama in the Tanzawa Mountains of Japan, and we have observed the fog from the base of the mountain using a video camera.

This paper reports the following detailed characteristics of the fog on a mountain forest: (i) the observations of the fog event frequency using a sensitive video camera for the first time as a function of elevation, (ii) the high acidity of fogwater observed at a high elevation site, (iii) the large deposition flux of air pollutants via fogwater and others at high elevation sites, and (iv) the comparison of the throughfall composition in fog events without rain and that strongly affected by rainwater observed in a typhoon.

### Experimental Section

Since July 1988, we have collected fog samples using an automatic string-type collector with a refrigerator to store the fog samples and a time recorder at 680 m elevation on Mt. Oyama. The collector was a CALTECH-type active collector (20): air was aspirated through the duct at a rate of  $34 \text{ m}^3 \text{ min}^{-1}$  ( $9.6 \text{ m s}^{-1}$ ), the diameter of each Teflon string was 0.40 mm, and fog droplets in the range of 3–100  $\mu\text{m}$  diameter were efficiently collected. The collector was activated by a sensor only when fog was present. Fogwater collected on the strings flows down to Teflon bottles in the refrigerator, and 50–60 mL of the fogwater samples was stored in each bottle from the beginning of a fog event (12). The liquid water content (LWC) of fog droplets can be calculated by dividing the weight of the sample in the bottle by both the volume of the aspirated air by the collector during the collection period of the sample and the collection efficiency of the collector (20). The Teflon strings were rinsed with pure water every week just after collecting the samples. The schematic diagram of the collector is shown in Figure 1. During August 24–September 6, 1998 (called the 1998 summer campaign), we collected samples not only at 680-m elevation but also at the summit at 1252 m, where we used a string-type active collector and manually changed the sample bottles. Rain samples in open spaces and throughfall samples under cedar trees have also been collected at four sites for several years. At 680 m, one rain sample and four throughfall samples have been collected every week. The samples have also been collected at 500, 890, and 1252 m; one rain sample and one throughfall sample have been collected at each site every month. In the 1998 summer campaign, a rain sample and four throughfall samples at 680 m and a rain sample and two throughfall samples at the summit were collected every 12 h. Cedar and fir trees are the

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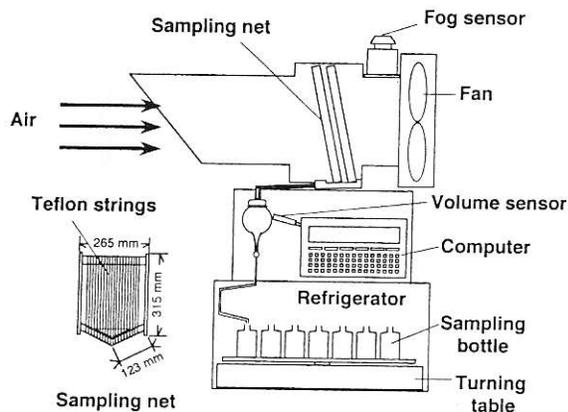


FIGURE 1. Fog sampler.

dominant conifer trees on Mt. Oyama, but the data for throughfall under the cedar trees were used instead of those under fir trees in this investigation because cedar trees are widely distributed on Mt. Oyama, and they are not declining. The rain and throughfall collectors were composed of a funnel, a polypropylene bottle, and a filter holder with a 1.2- $\mu\text{m}$  pore size membrane filter (Millipore RAWP04700) mounted between the funnel and the bottle as reported earlier (21). Each apparatus was rinsed with pure water just after collecting the sample. Aerosols and gases ( $\text{SO}_2$ ,  $\text{HNO}_3$ ,  $\text{HCl}$ , and  $\text{NH}_3$ ) were also observed at the 680-m sampling station. A low-volume air sampler (Nippon Kagaku Kogyo, Ltd., model 9023) equipped with a silica fiber filter (Advantec, Co., QR-100, 55 mm diameter) was used for the collection of aerosols smaller than 7.07  $\mu\text{m}$  in particle diameter at a pumping rate of 15 L  $\text{min}^{-1}$ . The gases were collected by the filter method (22, 23) at a pumping rate of 2 L  $\text{min}^{-1}$ . In the 1998 summer campaign, aerosol and gas samples were collected every 12 h at the 680-m sampling station and at the summit. After the sample collection, the filters were irradiated with ultrasonic waves in pure water to dissolve water-soluble components in the aerosol and the gaseous components, which were trapped on the filters. The details of the sampling method are described in previous papers (12–14).

The pH, conductivity, and concentrations of the major ions ( $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{NH}_4^+$ ) in the fog, rain, throughfall, and aerosol samples were measured. The charge balance was examined after the determination, and the data whose cation and anion ratios were larger than 1.5 or smaller than two-thirds were excluded in the analysis of fog chemistry. For the analysis of gaseous components,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{NH}_4^+$  were determined. The pH and the conductivity were measured with a Toa Electronics HM-60S pH meter and a Kyoto Electronics CM-117 conductivity meter, respectively. The anions were determined by a Dionex DX-100 ion chromatograph with a column of Dionex IonPac AS12A. The cations, other than protons, were determined by a Dionex DX-100 ion chromatograph with a column of Dionex IonPac CS12. The determined values were corrected by the measured blank values of the filters.

The air pollution and the meteorological phenomena were measured at a meteorological station (the city hall of Isehara situated at the base of Mt. Oyama) by the Air Preservation Section of Kanagawa Prefecture. The temperature, relative humidity, and concentration of suspended particulate matter (SPM) were measured at the city hall, and we used these data in this paper.

For observation of the fog frequency, Mt. Oyama was observed using a night-view video camera (Litton Systems, Inc., Intellivu IV-2400) from the base (the roof of Isehara City Hall), and images were recorded every hour on a digital still-recorder (Sony Co., DKR-700). The altitude of the fog base

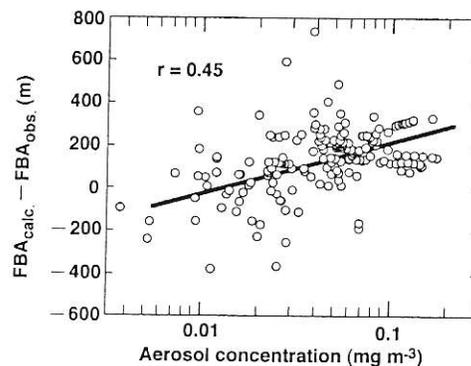


FIGURE 2. Effect of aerosol concentration at the base of the mountain at fog base altitude (FBA).  $FBA_{\text{calc}}$  is the FBA calculated by the following equation:  $FBA \text{ (m)} = 125 \times (T_0 - D_0) + h_0$ , where  $T_0$  and  $D_0$  are the temperature ( $^{\circ}\text{C}$ ) and dew point ( $^{\circ}\text{C}$ ), respectively, at the meteorological station at the base of the mountain; 125 is the constant ( $\text{m}/^{\circ}\text{C}$ ); and  $h_0$  (m) is its elevation. The  $FBA_{\text{obs}}$  is the FBA observed from the base of the mountain using a video camera (from 1997 to 1999). The solid line was calculated by regression analysis.

was measured from the images by comparing the fog base with the outline of the mountain. The images were not obtained on some dark nights, but it was possible to observe the mountain even at night if the mountain was brightened by the town lights and moonlight.

## Results and Discussion

### Observation of Fog Base Altitude with a Video Camera.

The fog characteristics depend on the air pollution, the liquid water content (LWC), and the fog base altitude (FBA). It is possible to roughly estimate the concentrations of major inorganic ions in fogwater from these factors (14). The FBA is an important dominating factor, and the scavenging effect is largest at the fog base. Fogwater with a low ion content is formed at an elevation much higher than the fog base because air pollutants are dissolved in the fogwater. The polluted fog droplets then collide with the canopies (24) and are scavenged near the fog base, and new droplets of up-slope fog are formed in the scavenged air mass at the high elevation sites. The FBA is calculated from temperature and humidity at the base of the mountain using Henning's equation:

$$FBA \text{ (m)} = 125 \times (T_0 - D_0) + h_0 \quad (1)$$

where  $T_0$  and  $D_0$  are the temperature ( $^{\circ}\text{C}$ ) and dew point ( $^{\circ}\text{C}$ ), respectively, at the meteorological station at the base of the mountain; 125 is the constant ( $\text{m}/^{\circ}\text{C}$ ); and  $h_0$  (m) is its elevation (25). It is difficult to exactly estimate the elevation because of the local meteorology on the mountainside, the lag time of the transport of the air mass from the base to the fog sampling station, the increase in the humidity by transpiration from the canopies, etc. Therefore, we observed the mountain fog using a sensitive camera, with which we determined the altitude of the fog base all day long.

The observed FBA ( $FBA_{\text{obs}}$ ) deviated from the calculated FBA ( $FBA_{\text{calc}}$ ). The correlation coefficient between them was 0.34. The relationship between them was obtained by regression analysis using the following equation:

$$FBA_{\text{obs}} \text{ (m)} = 0.42 \times FBA_{\text{calc}} \text{ (m)} + 67 \quad (2)$$

The observed FBA was lower than the calculated FBA in many cases, and one of its causes may be the transpiration from the canopies in the forest. Figure 2 shows the effect of the concentration of aerosols smaller than 10  $\mu\text{m}$  at the base of the mountain, Isehara City Hall, on the difference between

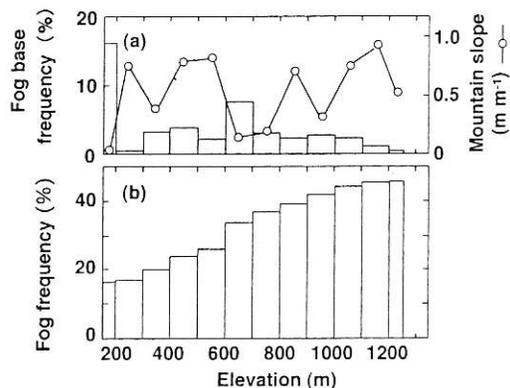


FIGURE 3. Fog base frequency and the mountain slope (a) and fog frequency (b) as a function of elevation observed between April 1997 and March 1998. The fog frequency shown in panel b is the summation of the fog base frequency shown in the bar graph in panel a.

the calculated FBA and the observed FBA. When the aerosol concentration at the base of the mountain is high, the water vapor is readily changed to liquid water on the coagulation nuclei of the aerosol particles in the air mass arising along the mountainside. The up-slope fog is then formed at an altitude much lower than the FBA calculated by Henning's equation. The correlation coefficient (0.45) was not high, but it was statistically significant ( $P < 0.01$ ) because of the large numbers of samples ( $n = 142$ ). Some calculated FBA values were lower than the observed FBA values, which may be caused by the local meteorology on the mountainside.

The frequency of the fog base for every 100-m elevation on Mt. Oyama is shown in Figure 3a. The frequency was different for each elevation, but it was dependent on the mountain slope. The frequency increased at the mountainside where the slope was small. There is a good correlation between the frequency and the reciprocal of the slope, and the correlation coefficient between them was 0.96. The relation between fog frequency and slope may be explained by the changes in turbulent mixing caused either by the slope change or by the change in vegetation with slope. The fog event frequency at each elevation can be obtained by the summation of the frequency values at the fog base under that elevation. Fog covered only a low elevation site, and the high elevation site was clear in some fog events, but these cases were very rare and negligible. The fog event frequency shown in Figure 3b increased with the elevation, and the summit of Mt. Oyama is covered with fog 46% of the year, which is comparable with the reported values (11); for example, Roundtop Mountain (970 m) in Quebec, Canada, was in fog 47% of the year at 0800 and 41% at about 1500 (26).

#### Comparison of Ion Concentration of Fogwater between Midslope (680 m Altitude) and Summit (1252 m Altitude).

The fogwater concentration is affected by the FBA, although other factors such as LWC and air pollution also affect the concentration (14). There was a linear relationship between the logarithms of the total ion concentration of fogwater and the elevation difference between the sampling station and the observed fog base. The correlation coefficient was  $-0.23$ , which is statistically significant ( $P < 0.01$ ) due to the large numbers of samples ( $n = 142$ ). However, there is a large deviation because of many factors controlling the concentration other than the FBA. Furthermore, the effect of the elevation difference is complicated when different cloudy air advection reaches the high elevation site.

Figure 4 shows the average concentrations of major inorganic ions in fogwater measured simultaneously at the summit (1252 m) and at 680-m elevation on the mountainside

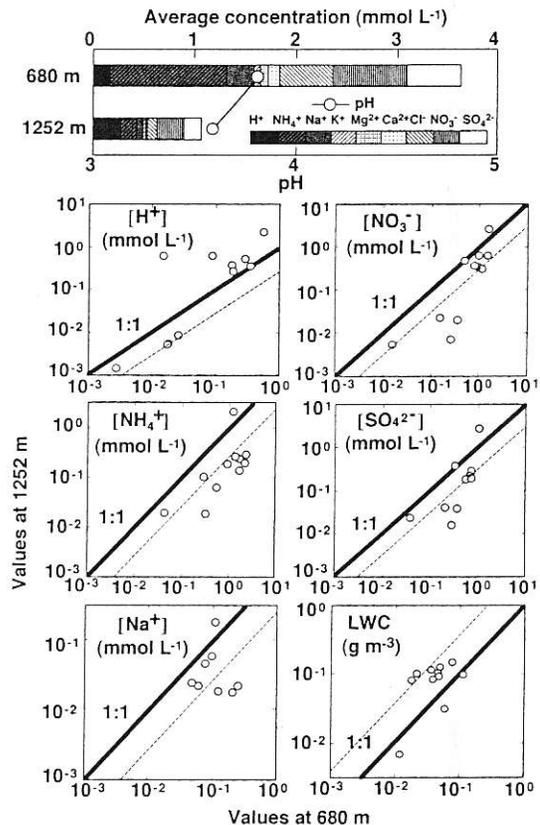


FIGURE 4. Comparison of the fogwater characteristics between the samples collected at the summit (1252 m altitude) and the midslope (680 m altitude). The solid line is the line of the slope of 1:1. The dashed lines represent the ion concentration, 0.29:1, which is the concentration ratio of total ions in the fogwater at the summit to that at the midslope. The dashed line for the liquid water content (LWC) is the reciprocal of the ratio.

in the 1998 summer campaign and the comparison of the fogwater characteristics between the two sites. There were 11 samples simultaneously collected at both sites, and the concentration ratio of total ions at the summit to that at 680-m elevation was 0.29. The pH values of most of the fogwater samples at the summit were lower than those on the mountainside, while the concentrations of all ions except for protons decreased with elevation. LWC values are also shown in Figure 4, and the LWC of most of the samples at the summit was larger than that at 680 m; a dilution effect occurred due to the increase in LWC with elevation. However, the dilution effect was not large enough to compensate for the concentration ratio, 0.29. The possible causes of the concentration decrease with elevation other than the dilution effect are the scavenging effect for the interaction of the fog droplets with the canopies in low elevation sites, the air pollutant deposition on the mountainside, the advecting cloudwater, etc. We simultaneously measured the acid gases and ammonia gas at the summit and on the mountainside in the 1998 summer campaign. The ratios of the mean concentration at the summit to that on the mountainside for the gases were as follows:  $SO_2$ , 0.57;  $HNO_3$ , 1.35;  $HCl$ , 0.58;  $NH_3$ , 0.63. The ratio of nitric acid was greater than unity not only in the daytime but also at night. Nitric acid may be formed on the mountainside by the reaction of nitrogen dioxide with OH radicals in the daytime and via the hydrolysis of  $N_2O_5$  at night (27). Nitric acid was readily dissolved in the fogwater. At a high elevation site, the major neutralizing component, ammonia gas, is not sufficiently supplied to the fogwater because the concentration of ammonia gas is lowered by dry deposition and scavenging by the fogwater

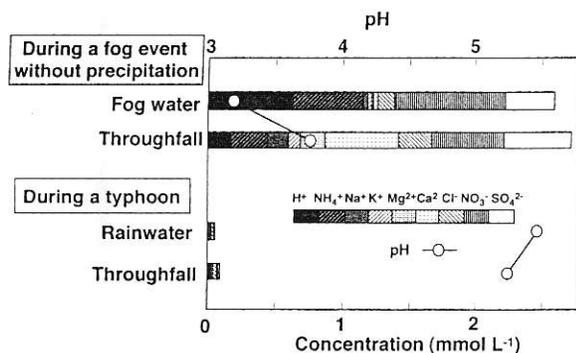


FIGURE 5. Concentration of major inorganic ions in fogwater, rainwater, and throughfall under cedar trees during a fog event without rain (September 3–6, 1998) and during a typhoon (August 27–September 1, 1998).

formed at the low elevation sites. Although aqueous sulfur dioxide oxidation also occurs in fog droplets, only nitrate ions and protons increased in the proportions of the fogwater components between 680-m elevation and the summit; therefore, the fogwater at a high elevation site was primarily acidified by nitric acid. It was also reported that nitric acid was the dominant acid species when the fogwater was highly acidified at Mt. Oyama (14).

**Effect of Fogwater and Rainwater on Throughfall.** The concentration of major inorganic ions in fogwater and the throughfall during the fog event period without rain (0600 on September 3 to 0600 on September 6 in 1998) in the 1998 summer campaign at the summit are shown in Figure 5. The water deposition via fogwater intercepted by the canopy was 6.8 mm during this period, although it was not collected at the elevation of 680 m. The concentration of total ions in the throughfall was slightly higher than that in the fogwater, but the concentrations of cations in the throughfall were much different from those in the fogwater. The concentrations of potassium, calcium, and magnesium ions in the throughfall are higher, and the concentrations of ammonium ions and protons were lower than those in the fogwater. The deposited fogwater was neutralized to some extent in the throughfall by these metal cations leached from the canopy (28). A comparison of the concentrations of the major ions in the throughfall with those in rainwater is also shown in Figure 5. In the latter case, the precipitation amount of throughfall was dominated by the rainwater because the samples were collected from August 27 to September 1, 1998, when a typhoon reached the Kanto District. During the typhoon period, the fog collection at the summit ceased due to a thunderstorm. The water depositions via rain and throughfall were 443 and 394 mm, respectively. Although there was a high precipitation amount in this period, the concentration of throughfall was 1.62 times that of rainwater.

**Deposition of Air Pollutants via Fogwater on the Mountainside of Mt. Oyama.** It is well-known that water deposition via fogwater is very high as throughfall where the fog event frequently occurs on a high mountain (11). Miller et al. reported that the deposition velocity of fogwater depends on the wind speed, LWC, and forest canopy composition and structure (29). The conditions affecting the deposition velocity depend on the characteristics of each mountain. The increase in throughfall could also be caused by the impact of wind-driven rain on an exposed tree top (30). Because of the wind, raindrops fall at an angle, and an exposed tree collects all of the rain that would have fallen in its rain shadow. The higher the wind speed, the larger the rain shadow, the more rain is collected by the tree, and the larger is the amount of throughfall. The water deposition ( $\text{mm yr}^{-1}$ ) of the throughfall,  $D_{\text{throughfall}}$ , is defined by the

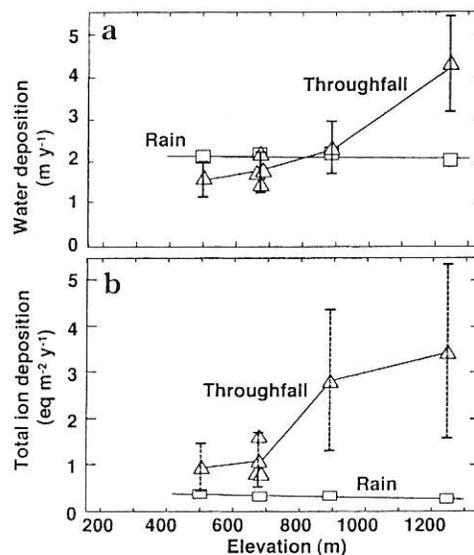


FIGURE 6. Water deposition and deposition of air pollutants as a function of elevation on Mt. Oyama. Throughfall under cedar trees and rainwater were collected at four elevations on the mountain, and the data shown here are the average values for 1997 and 1998. The error bars involved 95% confidence intervals calculated from the average values of four throughfall data at 680 m elevation.

following equation:

$$D_{\text{throughfall}} = D_{\text{rainwater}} + D_{\text{rainwater}'} + D_{\text{fogwater}} - A_{\text{stem flow}} - B_{\text{evaporation}} \quad (3)$$

where  $D_{\text{rainwater}}$ ,  $D_{\text{rainwater}'}$ , and  $D_{\text{fogwater}}$  denote the water deposition via rainwater, wind-driven rainwater, and fogwater, respectively; and  $A_{\text{stem flow}}$  and  $B_{\text{evaporation}}$  denote the loss of the water deposition via stem flow and via evaporation from the canopy, respectively. Figure 6a shows the water deposition via rain (precipitation amount) and via throughfall. The precipitation amount measured in an open space was almost constant at the sampling stations, while the precipitation amount at the base of the mountain was significantly smaller than that on Mt. Oyama. The precipitation amount was  $1600 \text{ mm yr}^{-1}$  in the same duration at a meteorological station for the measurement of precipitation amount in Hiratsuka City, which is 13 km southeast from the summit, and its elevation is lower than 50 m. The precipitation amount increases, in general, with elevation (31), and the specific geographical features of Mt. Oyama may cause this phenomenon. Namely, Mt. Oyama has a steep slope (2.2 km distant from the summit to the sampling station at 500 m), and Mt. Oyama is very close to the Pacific Ocean (17 km distant from the summit to the coast). In contrast to the precipitation amount, the water deposition via throughfall increased with elevation to a great extent. Water deposition via throughfall generally scatters. In this study, four throughfall samples have been collected at 680 m every week for many years, and both the precipitation amount and the total ion concentration have deviated from each other to various extents, although each sampling site was fixed. The data at 680 m in Figure 6 is shown as each average value for four different cedar trees. The values were different, and the water deposition and total ion deposition via throughfall at other sampling sites may also have some uncertainties. The 95% confidence intervals were then calculated from the average values of four throughfall data at 680-m elevation not only for water deposition but also for total ion deposition; the intervals are shown as error bars for each elevation site on the assumption that the ratio of the confidence interval to the average value does not depend on elevation. The increase

in the deposition is dominated by the fogwater deposition and the impact of wind-driven rain,  $D_{\text{rainwater}}$  and  $D_{\text{fogwater}}$  in eq 3. The contribution of the terms  $A_{\text{stem flow}}$  and  $B_{\text{evaporation}}$  to the increase in the throughfall may be small because the ratio of the total water deposition on the forest floor via stem flow to that of throughfall was reported to be 4.2% for a cedar tree (32), and the evaporation rate may decrease with elevation due to an increase in the relative humidity with elevation. It is very difficult to distinguish between these two kinds of water deposition,  $D_{\text{rainwater}}$  and  $D_{\text{fogwater}}$  (26). However, the water deposition via throughfall shown in Figure 5 was not larger than that via rainwater measured in an open space even at the summit during a typhoon (maximum wind speed,  $14.5 \text{ m s}^{-1}$  in Yokohama), and the contribution of the impact of wind-driven rain is estimated to be much smaller than that of fogwater deposition on the mountain. Therefore, it may be possible to roughly estimate the water deposition via fogwater from the water depositions via rainwater and throughfall. The value of  $D_{\text{fogwater}}$  in eq 3 can be obtained based on the assumption that  $D_{\text{fogwater}}$  at the 500-m elevation and the effect of values of  $A$  and  $B$  on the increase in the water deposition via throughfall were negligible. On the basis of this assumption, the difference between  $D_{\text{throughfall}}$  at an elevation and  $D_{\text{throughfall}}$  at 500-m elevation is regarded to be caused by  $D_{\text{fogwater}}$ . The value of zero for the assumption of  $D_{\text{fogwater}}$  at 500-m elevation may be underestimated but can be accepted as a rough estimation; the fog frequency at 500 m was about the half that at the summit, and it was reported that the deposition velocity of fog droplets at 600-m elevation was 12% of that at 1350 m in the case of the growing season at Whiteface Mountain, NY, because of higher wind speed and higher LWC of fog at 1350 m than at 600 m (29). The difference between water deposition via rain and that via throughfall in Figure 6 then refers to the water deposition via the interception of fogwater on the canopy. The water deposition via the fogwater interception increased with elevation, which was caused by the changing gross fog deposition rates depending on the elevation. The deposition rate ( $v$ ,  $\text{mm h}^{-1}$ ) was defined using  $D_{\text{fogwater}}$  ( $\text{mm yr}^{-1}$ ) and the fog event period of a year, FEP ( $\text{h yr}^{-1}$ ):

$$v = D_{\text{fogwater}} / \text{FEP} \quad (4)$$

The deposition rate was calculated to be  $0.074 \text{ mm h}^{-1}$  at 700 m and  $0.68 \text{ mm h}^{-1}$  at 1250 m, which were comparable with the reported values (29, 33).

The observed deposition fluxes of total ions via throughfall,  $F_{\text{throughfall}}$ , and rainwater,  $F_{\text{rainwater}}$ , are also shown in Figure 6b. The deposition flux via throughfall,  $F_{\text{throughfall}}$ , was defined as follows:

$$F_{\text{throughfall}} = F_{\text{rainwater}} + F_{\text{rainwater}} + F_{\text{fogwater}} + F_{\text{dry deposition}} - A'_{\text{stem flow}} + C \quad (5)$$

In eq 5,  $F_{\text{rainwater}}$ ,  $F_{\text{fogwater}}$ ,  $F_{\text{dry deposition}}$ ,  $A'_{\text{stem flow}}$ , and  $C$  indicate the deposition flux via the impact of wind-driven rain, the deposition flux via fogwater, the deposition flux via aerosols and gases, the loss via stem flow, and the uptake and leaching of the canopy, respectively. The water deposition increases with elevation as shown in Figure 6a, and the flux of air pollutants increases with the increase in the water deposition. The dry deposition also increases with an increase in the elevation because of an increase in the wind speed with elevation (34). The fogwater concentration is much larger than that of rainwater; therefore, the difference in the total ions deposition between throughfall and rain may be dominated by fog deposition and dry deposition, but the contribution of each term in eq 5 to the deposition flux via throughfall is difficult to estimate. However, the flux of total ions at the summit by fog deposition can be calculated to be

$1.1 \text{ equiv m}^{-2} \text{ yr}^{-1}$  based on the fog deposition rate,  $0.68 \text{ mm h}^{-1}$ ; the fog frequency, 46%; the concentration of total ions,  $1.4 \text{ mmol/L}$ , which was the average value at 680 m during 1997–1998; and the concentration ratio of total ions in fogwater at the summit to that at 680-m elevation, 0.29, obtained in the 1998 summer campaign. Although the values used in the calculation were approximate values, it can be concluded that the total ion deposition via throughfall is dominated by both fogwater deposition and dry deposition rather than by rainwater deposition.

The deposition of total ions via throughfall in a high elevation forest is much larger than that estimated from the precipitation amount and the concentration of rainwater. The deposition of air pollutants via throughfall has been measured at many places and reported. At 1350-m elevation on Whiteface Mountain, NY, the nitrate ion deposition was  $0.157 \text{ equiv m}^{-2} \text{ yr}^{-1}$ , the sulfate ion deposition was  $0.268 \text{ equiv m}^{-2} \text{ yr}^{-1}$ , and the deposition of total ions except for NaCl was  $0.736 \text{ equiv m}^{-2} \text{ yr}^{-1}$  (29). Lovett and Kinsman summarized the total depositions on many mountains in the United States, and the sulfate ion and the nitrate ion depositions ranged from 0.010 to 0.27 and from 0.0068 to  $0.27 \text{ equiv m}^{-2} \text{ yr}^{-1}$ , respectively (17). The deposition fluxes of the air pollutants on Mt. Oyama are much greater than the values determined for the other mountains mentioned above, although the values in Figure 6 contained many uncertainties as shown by the error bars. The large flux may be caused by the geographical features and the location of Mt. Oyama. The high water deposition is caused by the geographical features, and high air pollutant concentration is caused by the location of Mt. Oyama, which abuts the Kanto Plains, a big urban area including Tokyo.

The water deposition and the deposition flux of air pollutants to the canopies are very high at a high elevation on the mountainside. Because the acidity of the deposition depends on the elevation, the effect of the acid deposition on the forest may also depend on the elevation.

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