Aerosol Deposition and Behavior on Leaves in Cool-temperate Deciduous Forests. Part 3: Estimation of Fog Deposition onto Cool-temperate Deciduous Forest by the Inferential Method

Genki Katata*, Takashi Yamaguchi1, Haruna Sato2, Yoko Watanabe3, Izumi Noguchi1, Hiroshi Hara2 and Haruyasu Nagai

Research Group for Environmental Science, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
1)Environmental Conservation Division, Hokkaido Research Organization, Sapporo 060-0819, Japan
2)Field Science Center, Tokyo University of Agriculture and Technology, Tokyo 183-8538, Japan
3)Field Science Center for Northern Biosphere, Hokkaido University, Sapporo 060-0809, Japan

*Corresponding author. Tel: +81-29-282-5171, Fax: +81-29-282-5857, E-mail: katata.genki@jaea.go.jp

1. INTRODUCTION

Acid deposition of pollutants such as sulfur and nitrogen compounds led to a serious atmospheric pollution in aquatic environments and terrestrial ecosystems as a result of rapid economic growth in East Asia. In general, the processes of acid deposition are well known as dry, wet, and fog (cloud water) deposition (Seinfeld and Pandis, 2006). Although monitoring of wet and dry deposition fluxes in East Asia has been implemented since 2001 by the Acid Deposition Monitoring Network in East Asia (EANET), information on fog deposition is currently lacking. Since fog water has high concentrations of solutes, fog deposition significantly contributes to hydrological, nutrient, and pollutant inputs especially in mountainous regions where fog is frequently observed (Lange et al., 2003; Igawa et al., 2002; Herckes et al., 2002). Thus, with air pollution monitoring networks in other countries, such as the Clean Air Status and Trends Network (CASTNET), quantification of fog deposition in forest areas is an important task for assessing acid deposition in East Asia.

Various approaches have been applied to quantify the fog deposition through direct measurements by canopy throughfall and stemflow method (e.g., Muell er et al., 1991), fog collector resembling the natural surfaces (e.g., Lovett, 1984), and lysimeter (e.g., Fowler et al., 1990) etc. However, lacking spatial or temporal representativeness and re-evaporation of deposited fog water before observations can cause errors in these approaches. The eddy covariance method (e.g., Beswick et al., 1991) is also one of the approaches to
2. MATERIALS AND METHODS

2.1 Parameterizations for Fog Deposition Estimation

According to the inferential technique (Erisman et al., 1994; Hicks et al., 1987), the fog deposition flux \( F \) \( [\text{kg m}^{-2} \text{s}^{-1}] \) is represented as a product of the deposition velocity \( V_d \) \( [\text{m s}^{-1}] \) and LWC \( [\text{kg m}^{-3}] \) and is determined as follows:

\[
F = \text{LWC} \times V_d, \tag{1}
\]

where the downward flux is positive for \( F \). To estimate LWC, the following empirical power-law expression between VIS and LWC is adopted (Stoelinga and Werner, 1999; Kunkel, 1984):

\[
\text{LWC} = \left( \frac{a}{\text{VIS}} \right)^b, \tag{2}
\]

where \( a \) and \( b \) are the empirical parameters determined from the field experiments. Stoelinga and Werner (1999) suggest the values of \( a \) and \( b \) as 0.027 and 0.88, respectively. Although Eq.(2) has a larger error in LWC estimation as compared to a newer parameterization as a function of both LWC and droplet number concentration (Gultepe et al., 2006), Eq.(2) still has an advantage that it needs only one parameter, VIS, which is routinely observed at surface meteorological and road weather stations.

To calculate fog deposition flux by the inferential method, it is necessary to use the parameterization of fog deposition velocity, \( V_d \). Vermeulen et al. (1997) proposed the parameterization of deposition velocity determined from eddy covariance measurements of fog water flux in a coniferous forest in the Netherlands:

\[
V_d = 0.195 u^* z_0, \tag{3}
\]

where \( u^* \) \( [\text{m s}^{-1}] \) is the friction velocity over the tree canopy, which is generally obtained by the following equation (Erisman and Draaijers, 1995):

\[
\begin{align*}
\ln &\left( \frac{z-d}{z_0} \right) - \Psi_m \left( \frac{z-d}{L} \right) + \Psi_m \left( \frac{z_0}{L} \right) \end{align*}^{-1}, \tag{4}
\]

where \( \kappa \) is the von Karman constant (0.4), \( z [\text{m}] \) the reference height, \( d [\text{m}] \) the displacement height (0.7 × \( h \)); \( h [\text{m}] \) is the canopy height), \( U_z \) the horizontal wind velocity at height of \( z \), \( z_0 [\text{m}] \) the roughness length, \( L [\text{m}] \) the Monin-Obukhov length, and \( \Psi_m \) the stability correction function for momentum. Typical values of \( z \) and \( z_0 \) for forest are 20 and 1 m, respectively (Matsuda et al., 2006). L is calculated from solar radiation and cloud cover based on Pasquill stability categories (Matsuda et al., 2006). Thus, Eq.(3) is available with one parameter of friction velocity \( (u^*) \), which can be
calculated from routine meteorological data only (i.e., wind speed, solar radiation, and cloud cover).

The authors have proposed another formulation of deposition velocity (Katata et al., 2008) based on numerical simulation using the one-dimensional multilayer atmosphere-soil-vegetation model (SOLVEG) in a coniferous forest in Germany. The equation is represented as a function of the horizontal wind speed over the canopy \( U_z \), the leaf area index (LAI), and the canopy height \( h \):

\[
V_d = A U_z, \quad (5)
\]

where \( A \) [non-dimensional] is the slope of \( V_d \) that depends on vegetation characteristics. Through Eq.(6), the calculations of \( A \) agreed with observations in various cloud forests with LAI/\( h > 0.2 \) (Katata et al., 2008).

Since the forest in the study site is sparse as LAI/\( h \simeq 0.15 \) (see subsection 2.2), the value (0.04) was directly obtained from the curve of \( A \) when \( h = 10 \) m (Fig. 11a in Katata et al., 2008). Eq.(5) has the advantage of considering not only meteorological data but also vegetation parameters (LAI) compared to Eq.(3).

Fig. 1 shows the comparison of fog deposition velocity estimated by two parameterizations at the study site from 10 August to 15 October 2010 (see subsection 2.2). Using the parameterization of Katata et al. (2008), deposition velocity linearly increases with wind speed as represented by Eq.(5). In contrast, Vermeulen et al. (1997) shows that the function of deposition velocity is proportional to the square of wind speed and represented by Eq.(3), and produces a large value compared with Katata et al. (2008), when \( U_z > 5 \) m s\(^{-1}\). However, such a high wind speed could not be considered while applying Eq.(3) because this equation was validated in the range of \( U_z \) from 0 to 3 m s\(^{-1}\) (Vermeulen et al., 1997).

Eq.(5) was parameterized in the range of \( U_z \) from 0 to 8 m s\(^{-1}\) (Katata et al., 2008) indicating a wide availability for estimation of fog deposition under strong high-wind conditions. The impact of wind speed on fog deposition flux is discussed in subsection 3.2.

2.2 Site Description and Observational Variables

The study area is characterized as a cool-temperate forest on the somma of a crater lake, Lake Mashu, in Hokkaido in northern Japan (Yamaguchi et al., 2013, the companion paper). The dominant plant species is a deciduous broad-leaved tree, Betula ermanii Cham. (Fujinuma et al., 2004). The authors focused on fog and throughfall events occurring in the study area from 10 August to 15 October 2010. Hourly meteorological data of VIS and horizontal wind speed at 1.5 m height were observed at the road weather station and were used for calculations of LWC and friction and deposition velocities by Eqs.(2), (4), and (5), respectively. Wind speed at the reference height \( U_z \) in Eqs.(4) and (5) was derived from that observed at 1.5 m in height by assuming a logarithmic profile of wind speed in the surface boundary layer. To compute the atmospheric stability \( L \) in Eq.(4), the hourly data of solar radiation and cloud cover observed at the nearest surface weather stations of Nemuro and Kushiro, respectively, were used. Weekly mean LWC of fog water sampled by an active string-fog collector (Daisho Engineering Co. Ltd., FSK-01) placed at the 1.2 m above the roof terrace of observation deck was compared with that calculated using Eq.(2). The data of throughfall from three tree stands (plots A, B, and C) observed using tipping-bucket rain gauges (Ogasawara Keiki Co. Ltd., RS-102) set at approximately 1 m height above the forest floor and rainfall collected at the road weather station at 3 m height above the ground surface were used for calculating fog deposition flux. As shown in Fig. 1 in the companion paper (Yamaguchi et al., 2013), all plots are located under the trees near the edge of the woodland and have little upwind fetch. The reason we have chosen such a location is that the study area is ecologically protected of nature. As a result, the possible difference in throughfall amounts is expected among three plots as discussed in subsection 3.2. The fog deposition flux was simply determined as the difference between throughfall and rainfall by neglecting the evaporation
loss from intercepted fog or rain water at the wetted canopy (Yamaguchi et al., 2013, companion paper). Canopy height and LAI observed using a VERTEX IV hypsometer (Haglof Co., Sweden) and LAI-2000 plant canopy analyzer (LI-COR Co., USA), respectively, were used for Eqs. (4) and (5). Measured values of canopy height and LAI on 10 August 2010 were approximately 10 m and 1.5 ± 0.16, respectively. Details of the site description and sampling method for weekly LWC and throughfall are provided in the companion paper (Yamaguchi et al., 2013).

3. RESULTS AND DISCUSSION

3.1 Estimation of Liquid Water Content of Fog

Fig. 2 shows the time series of observed and estimated LWC from 10 August to 15 October 2010. The highest values of weekly LWC were found during the periods from 9 to 17 on August and 4 to 12 October, while fog was not observed from 21 to 27 September. A similar pattern of weekly LWC averaged from hourly LWC was also found in the estimation results except for slight overestimations on 9 and 29 September. Fig. 3 shows comparisons between observations and estimations of weekly LWC. A good correlation between estimations and observations was found (R² = 0.734). Average error and root-mean-square error (RMSE) of weekly LWC between the estimations and observations are 0.051 and 0.018 g m⁻³, respectively, which are small compared with the mean value of estimated weekly LWC (0.094 g m⁻³). These results indicate that the empirical relationship between VIS and LWC is useful in prediction of LWC in the study area.

3.2 Estimation of Fog Deposition in Cool-Temperate Deciduous Forest

Fig. 4 shows the temporal changes in observed rainfall and throughfall and estimated fog deposition in the calculation period. From 9 to 10 and 27 to 29 September, fog deposition is considered to be overestim-
ed due to overestimations of LWC calculated from VIS (Fig. 2). In other periods in August and September, however, fog deposition was also often overestimated when no throughfall event was observed. This phenomenon may be explained by the evaporation loss of rain and fog droplets intercepted by tree canopies as discussed in subsection 3.3. As shown in Fig. 4, many throughfall events accompanied rainfall in observations. Under rain-free conditions, there was one event of fog deposition from 7 to 9 October (Fig. 5). During this period, fog occurrence and deposition were well predicted by the parameterization of Katata et al. (2008). This indicates that the inferential method using the parameterizations of deposition velocity and LWC reasonably predicts fog deposition under rain-free conditions.

Table 1 summarizes meteorological variables and cumulative fog deposition from 10 August to 15 October 2010. For calculations of cumulative fog deposition

![Fig. 4. Temporal changes in estimated fog deposition (solid and dashed lines) and observed rainfall (open circles) and mean throughfall under three tree stands (crosses) at Lake Mashu (a) from 10 to 31 August, (b) from 1 to 30 September, and (c) from 1 to 15 October 2010. Vertical bars with crosses show the range of maximum and minimum values among three tree stands.](image)

![Fig. 5. Temporal changes in estimated (solid lines) and measured fog deposition (open circles) under rain-free conditions from 7 to 9 October 2010. Observations represent the averaged values of fog deposition for three tree stands (plots A, B, and C).](image)
tion amount, throughfall events are considered when fog sensors of an active string-fog collector were activated. The throughfall data varied considerably at plots A, B, and C in all months. This is considered to be due to sampling errors in the throughfall measurements caused by spatial variation in amounts of intercepted rainfall (Holwerda et al., 2006); i.e., when rainfall occurred, additional spatial variation in throughfall may have resulted from differential interception of inclined rainfall by the canopy surface and redistribution of intercepted rain within the canopy (Herwitz and Slye, 1992; Lloyd and Marques, 1988). The amounts of fog deposition estimated by the parameterizations were small, approximately a half or third of observations in all months (Table 1). This is similar to the comparisons of fog deposition in a mountainous coniferous forest in Japan (Katata et al., 2011). As suggested by Katata et al. (2011), the underestimation is probably due to enhancement of fog deposition by the “edge effect” which causes considerable increase in fog deposition compared to that inside the forest stand due to inflow and advection processes (e.g., Hasselrot and Grennfelt, 1987). In the study area, it is expected that the edge effect might be large when the wind flows from the west of plots A, B, and C along grassland areas without trees (Yamaguchi et al., 2013, companion paper). The largest values in throughfall data among three plots (Table 1) may reflect the fact that plot C is closer to the edge than plots A and B. When fog appeared, the frequencies of observed westerly wind were 50-60% per a month in all three months (not shown). Thus, by considering the enhancement of fog deposition due to the edge effect for the whole calculation period in similarity with Katata et al. (2010), the current parameterization can reasonably simulate fog deposition events.

### 3.3 Limitations of the Current Parameterizations

By comparing fog deposition amounts estimated by two parameterizations (Table 1), the parameterization of Vermeulen et al. (1997) produced a larger value than that of Katata et al. (2008) in August and September 2010. This is due to the difference in expressions of deposition velocity in terms of momentum transfer ($U_z$ or $u^*\) in the parameterizations. As described in subsection 2.1, under windy conditions, Eq.(3) produces a large deposition velocity compared with Eq.(5) (Fig. 1). In fact, averaged wind speed at 20 m height ($U_z$) was estimated to be as large as 6.0 and 7.6 m s$^{-1}$ in August and September, respectively (Table 1). In such situations, however, fog deposition may be overestimated because the observed wind speed was beyond the range of availability of Eq.(3), i.e., $U_z < 3$ m s$^{-1}$. Unfortunately, it is difficult to validate the parameterization of Vermeulen et al. (1997) under the strong wind speed by comparing with the throughfall data in the present study because the data varied very large among three plots (Table 1). It is necessary to validate the parameterization of Vermeulen et al. (1997) with more observational data collected over the areas with a sufficient upwind fetch under windy conditions.

As shown in subsection 3.2, the current parameterizations computed the fog deposition even when throughfall was not observed because evaporation loss of rain or fog droplets intercepted by tree canopies was not considered (Fig. 4). Although the effect of evaporation loss is not considered to be particularly large in such situations as the fog episode continued without a long fog-free period (Kobayashi et al., 1999), error associated with evaporation loss probably accumulated while estimating fog deposition (e.g., Bruijnzeel et al., 2011). Moreover, when throughfall events were not detected, fog was less dense (hourly LWC<0.1 g m$^{-3}$, Fig. 2) and appeared from midnight to the early morning in most cases. This indicates that intercepted rain or fog water can easily evaporate with an increase of ambient temperature during the morning. If estimated fog deposition flux was accumulated independent of the throughfall events, then the total amount of estimated fog deposition in the calculation period would be increased by approximately 60% (Table 1). Consequently, the effect of evaporation loss on fog deposition cannot be neglected for accurate prediction of the amount of fog deposition using the current parameterizations.

### Table 1. Summary of averaged wind speed at 20 m in height ($U_z$) and liquid water content of fog (LWC), and cumulative fog deposition from 10 August to 15 October 2010. Values in parentheses show the accumulated fog deposition amount independent of throughfall events.

| Periods   | $U_z$ (m s$^{-1}$) | LWC (g m$^{-3}$) | Observed fog deposition (mm) | Calculated fog deposition (mm) |
|-----------|-------------------|-----------------|------------------------------|--------------------------------|
|           |                   |                 | Plot A | Plot B | Plot C | Mean | Katata et al. (2008) | Vermeulen et al. (1997) |
| 10-31 Aug.| 6.0               | 0.064           | 20.5   | 5.0    | 55.5   | 27.0  | 9.4 (22.6)           | 11.0 (23.7)            |
| 1-30 Sep.| 7.6               | 0.052           | 8.0    | 0.5    | 11.5   | 8.5   | 5.1 (14.9)           | 8.5 (22.1)             |
| 1-15 Oct.| 4.7               | 0.073           | 7.5    | 4.5    | 4.5    | 5.5   | 4.0 (7.1)            | –                  |
| All periods | 6.1               | 0.063           | 36.5   | 10.0   | 71.0   | 39.2  | 18.5 (44.5)          | –                  |
Although the parameterization of Eq.(5) underestimated monthly cumulative fog deposition (Table 1), the observed fog deposition under rain-free condition is well predicted (Fig. 5). This discrepancy can be explained by the effects of tree physiology by indicating a decrease of LAI of deciduous forest due to defoliation. In the study area, leaves fell onto the ground surface during the period from the end of September to the beginning of October 2010 (Yamaguchi et al., 2013, companion paper). The effect of defoliation is not considered in the present estimation due to the lack of LAI data for September and October, which can cause over-estimations of fog deposition during the fall season. The parameterization of Eq.(5) has not yet been tested with data collected in tree canopies with low leaf areas because many cloud forests in the world have a large LAI (Katata et al., 2008). More investigation of seasonal changes in fog deposition with LAI of deciduous forests is required for further discussion.

4. CONCLUSIONS

Prediction accuracy of fog deposition onto a cool-temperate deciduous forest in northern Japan was investigated using the available parameterizations. The hourly liquid water content of fog (LWC) was estimated using the empirical function of horizontal visibility (VIS). By using the estimated values of LWC, fog deposition was calculated using the inferential method through parameterizations of deposition velocity for European forests. A good correlation between estimations of LWC using the parameterizations and observations of LWC through an active string-fog collector was found on a weekly basis. By considering the enhancement of fog deposition due to the edge effect, the inferential method reasonably predicted fog deposition calculated from rainfall and throughfall data. When high wind speed was observed, the use of the parameterization of Katata et al. (2008) may be preferred for a reasonable estimation of fog deposition compared with that of Vermeulen et al. (1997). The effect of evaporation loss on fog deposition cannot be neglected for accurate prediction of fog deposition by the inferential method. More investigation of seasonal changes in fog deposition with LAI of deciduous forests is required.

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