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Dry Deposition of SO_2 Over Dry Dipterocarp Forest, Thailand

(Pemendapan Kering SO_2 ke atas Hutan Kering Dipterokarpa, Thailand)

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ABSTRACT

The aerodynamic gradient method was applied to estimate dry deposition flux of SO_2 over dry deciduous forest in Nakorn Ratchasima province, Thailand. The meteorological parameters and concentrations of SO_2 were measured in real time for one year on the experimental tower at 36 and 27 m high. The flux observed in the wet season were found two times higher than the value observed in the dry seasons, i.e. 20±7.58 and 10±11.05 ng m^{-2} s^{-1}, respectively. The leaf area index and the ambient humidity were believed to assert the rate of SO_2 deposition. The average friction velocities were estimated to be 0.26±0.02 and 0.48±0.06 m s^{-1}, for the dry and the wet season, respectively. The friction velocity was very much depended on the surface roughness of the forest canopy. The V_d of SO_2 evaluated by the aerodynamic gradient was compared with V_d calculated by the resistance model. It was found that the observed V_d was in close proximity with the model prediction in daytime in all conditions, i.e. wet, dry and annual average. The annual average V_d determined by the Aerodynamic gradient was 0.43±0.06 cm s^{-1}.

Keywords: Aerodynamic gradient; deposition velocity; resistance model; sulfur dioxide

ABSTRAK

Kaedah kecerunan aerodinamik digunakan untuk menganggarkan pemendapan kering SO_2 ke atas hutan kering di wilayah Nakorn Ratchasima, Thailand. Parameter meteorologi dan kepekatan SO_2 diukur pada masa sebenar untuk satu tahun di menara eksperimen pada ketinggian 36 dan 27 m. Fluks yang diperhatikan pada musim hujan mempunyai nilai dua kali ganda lebih tinggi daripada nilai yang diperhatikan pada dalam musim kering, iaitu masing-masing pada 20±7.58 dan 10±11.05 ng m^{-2} s^{-1}. Indeks kawasan daun dan kelembapan sekeliling digunakan untuk mendapatkan kadar pemendapan SO_2. Geseran purata kelajuan dianggarkan masing-masing pada 0.26±0.02 dan 0.48±0.06 m s^{-1} untuk musim kering dan hujan. Halaju geseran sangat bergantung kepada kekasaran permukaan kanopi hutan. V_d SO_2 dinilai melalui kecerunan aerodinamik dibandingkan dengan V_d yang dikira melalui model rintangan. Didapati bahawa penilaian V_d hampir sama dengan ramalan model di siang hari dalam semua keadaan, iaitu basah, kering dan purata tahunan. Purata tahunan V_d yang ditentukan melalui kecerunan aerodinamik adalah pada 0.43±0.06 cm s^{-1}.

Kata kunci: Halaju pemendapan; kecerunan aerodinamik; model rintangan; sulfur dioksida

INTRODUCTION

Due to its effects on humans and on ecological systems, SO_2 is the most extensively measured gas in many countries and regions. SO_2 is one of the three major players in the atmospheric sulfur cycle composed of dimethyl sulfide (DMS), SO_2 and SO_4^{2-}. When SO_2 is released, it undergoes gas-to-particle conversion processes by reacting chemically with atmospheric radicals, dust particles and water vapor in the presence of sunlight (Cooper et al. 1993; Thornton et al. 1996). The acidic sulfate aerosol (SO_4^{2-}) is the main product of the process. SO_2 is considered to be both a source and sink in transportation, transformation (chemical reaction) and removal processes from the atmosphere or surface exchange (Delmas & Servant 1983; Erisaman & Draaijers 1995; Rodhe 1978).

In recent years, many measurements of SO_2 dry deposition fluxes and velocity have been made by various means and in several areas such as in urban (polluted areas), rural and remote areas. SO_2 can be distinguished as being either exported from or imported into a local area or surrounding region depending on their SO_2 balance (Fellenberg 2000). Fowler et al. (2009) developed a monitoring system and continuous determination of dry deposition fluxes and velocities of acidifying gases, as well as gas absorbed as tiny aerosol particles, over a forest canopy. The dry deposition velocity of SO_2 over an evergreen broadleaf forest in Central Taiwan showed that the deposition rate was larger over a wet canopy and in the daytime. It indicated that the dry deposition rate increased with surface wetness (non-stomatal resistance) during the wet season.

In the daytime, the dry deposition rate depended strongly on the leaf area index (LAI), the stomata uptake and the amount of solar radiation (Tsai et al. 2010). The vegetation characteristics of the canopy also greatly impacted dry deposition velocities of gases, such as SO_2 and O_3, aside from the atmospheric turbulent state and molecular exchange (Padro 1993). The dry deposition velocities of SO_2 were estimated in several different surfaces. It was found that the dry deposition rate of SO_2 was strongly dependent upon the seasonal and diurnal variations. In the daytime, during the summer, the rate was observed to be 0.4, 0.2, 0.5 and 0.8 cm s^{-1} for the forest, cultivated land, grassland and ocean, respectively (Xu & Carmichael 1998a).

The deposition velocity of SO_2 was measured over red pine forest in Japan, and its value was observed to be 0.9 cm s^{-1} (Matsuda et al. 2002). Moreover, the deposition velocity of SO_2 over a tropical teak forest in Northern Thailand was measured using the aerodynamic gradient method for estimation. It was found that higher deposition velocities occurred during the wet season due to non-stomatal uptake. The deposition velocity was higher in the daytime than in the nighttime for both dry and wet seasons and increased with relative humidity and surface wetness (Matsada et al. 2006). The SO_2 dry deposition was found to increase with high relative humidity, dew and rain (Zhang et al. 2003). This finding is in agreement with other studies reported in the literature. In Central Thailand, the dry deposition of SO_2 was measured over a rice paddy field using the Bowen ratio technique. The measurements showed that the deposition velocity varied with solar radiation, with the time of day and with climates (Jitto et al. 2007). The dry deposition of SO_2 was also measured over grass fields (bahiagrass and bermudagrass) along with other key atmospheric species using the relaxed eddy accumulation method. Acid deposition affected our ecosystem by reducing the growth rate, amount and type of forests. Thus, more recent studies of acid deposition are concentrated in remote areas such as the highlands, mountains and areas over natural forests.

This investigation focused on SO_2 deposition over the dry dipterocarp forest (DDF) in tropical climates in northeast Thailand. The micro-meteorological parameters were measured continuously, along with the ambient SO_2 concentration. The deposition flux of SO_2 was evaluated using the gradient method. Once the flux of SO_2 was obtained, the deposition velocity could be determined. The deposition velocity of SO_2 evaluated for this study was then compared with the resistance model in order to see the model applicability in this tropical climate.

Experimental Details

EXPERIMENTAL SITE DESCRIPTION

The experimental tower used in this study was located in dry dipterocarp forest (DDF) at Sakaerat Environmental Research Station (SERS; 14°30´13.68”N, 101°57´8.67”E) at 300 m above sea level in Nakorn Ratchasima province, northeast Thailand. That area is surrounded by a mountain range with heights from 200 to 272 m.

EXPERIMENTAL SET UP

The SO_2 concentrations were measured on the experimental tower at two levels, 36 and 27 m above the ground, in order to measure the sample concentration differences. The ambient airflow to the system was induced constant flow rate of 10 L min^{-1}. The concentration of SO_2 from the two air samplers was determined by ultraviolet fluorescence (UVF-100E). The wind velocity was monitored by a 3D ultrasonic anemometer (YOUNG, 81000). The field measurements were conducted for one year from August 2011 to August 2012. The period from November to April was classified as the dry season for this tropical region. The period from May to October was classified as the wet season.

AERODYNAMIC GRADIENT

The gradient method was applied to estimate the dry deposition fluxes of SO_2. The mass flux of SO_2 gas can be calculated using (1):

$$F = -u^* c^*, \tag{1}$$

where u_* is the friction velocity and c^* is the eddy concentration. The latter is expressed in (2) (Feliciano et al. 2001; Matsuda et al. 2012),

$$c^* = k\Delta c/[ln(z_2\text{-}d/z_1\text{-}d)\text{-}\Psi_h(z_2\text{-}d/L)+ \Psi_h(z_1\text{-}d/L), \tag{2}$$

where Δc is the difference between SO_2 concentrations at heights between z_1 and z_2; d is the displacement height (d =10, 12 and 14 m) (different values of d were selected, depending on the season) (Matsuda et al. 2012); k is the Von Kaman constant (0.4); L is the Monin-Obukhov length; and Ψ_h is the integrated stability correction function for heat. In this experiment, the sampling points were located on the tower at heights of 27 and 36 m for the lower height (z_1) and upper height (z_2), respectively. From (1) and (2), the mass flux F, can be defined in (3):

$$F = -ku_* \Delta c/[ln(z_2\text{-}d)/(z_1\text{-}d)\text{-}\Psi_h(z_2\text{-}d/L)+\Psi_h(z_1\text{-}d/L), \tag{3}$$

values for u_* and L were averaged every 10 min. The transfer velocity, D (m s^{-1}), which was a part of the flux calculation was computed using (4):

$$D =ku_*/[ln(z_2\text{-}d/z_1\text{-}d)\text{-}\Psi_h(z_2\text{-}d/L)+\Psi_h(z_1\text{-}d/L). \tag{4}$$

In this study, the value of D was averaged over 1 h period. The value was then multiplied by the difference in the concentrations between the two heights (Δc). From the previous study, this method was used to estimate both aerosol and trace gas fluxes (Hayashi et al. 2011; Matsuda et al. 2010, 2005). The deposition velocity, Vd, is determined using (5):

$$Vd = -F/C, \tag{5}$$

where F is the dry mass deposition flux and C is the concentration at the reference point.

RESISTANCE MODELING

The resistance estimation of atmospheric gases (Wesley & Hicks 2000), SO_2 is expressed in (6):

$$V_d = (R_a + R_b + R_c)^{-1}, \quad (6)$$

where R_a is the aerodynamic resistance; R_b is the quasi-laminar boundary layer resistance and R_c is the surface resistance. R_a and R_b were determined as a function of meteorological conditions each day in each season, following (7-8) (Hicks et al. 1987; Myles et al. 2007):

$$R_a = \bar{u}(z)u^{*-2}, \quad (7)$$

$$R_b = 5(Sc^{0.67}\, u^{*-1}), \quad (8)$$

where $\bar{u}$ is the wind speed at the top of the canopy; u^* is the friction velocity; and Sc is the Schmidt number (defined as the ratio of the kinematic viscosity of air to the molecular diffusivity coefficient). R_c was expressed by Wesely resistance model (Erisman & Baldocchi 1994; Matsuda et al. 2001; Zhang et al. 2003): The important parameter, u* was expressed in terms of R_a and R_b.

RESULTS AND DISCUSSION

METEOROLOGICAL PARAMETER MEASUREMENT

Figure 1 shows the variations of meteorological parameters, including wind speed, rainfall levels, temperature, relative humidity, solar radiation and net radiation during the wet and the dry seasons. Rainfall levels during the wet season (May to October) ranged from 75 to 246 mm, whereas the measured precipitation ranged in value from 0 to 34 mm during the dry season (November to April). The wind speed showed some fluctuation during the transitional period from wet to dry weather (September-November) and then increased continuously from the dry ambient (December 2011) towards the wet ambient environment (April 2012) as shown in Figure 1(a). The ambient temperature in the tropical climate does not vary substantially (Figure 1(b)). It was in the range of 22-27°C. The average temperature throughout the year was 26°C. The relative humidity was found to be somewhat lower in the dry season (58%-65%) than in the wet season (70%-80%), Figure 1(b). Normally, the temperature in the dry season (December and January) would be around 3-4°C lower than the ambient average. The weather during the dry season was characterized by lower average temperature and humidity and no precipitation (November-April). The weather during the wet season was characterized by higher average temperature and humidity with large amount of precipitation (August–October). The solar radiation (SR) and the net radiation (Rn) were found to be in the ranges of 0.12-0.2 and 0.08-0.14 kW/m², respectively. The intensity of solar energy was influenced by the amount of cloud cover in the daytime (Figure 1(c)).

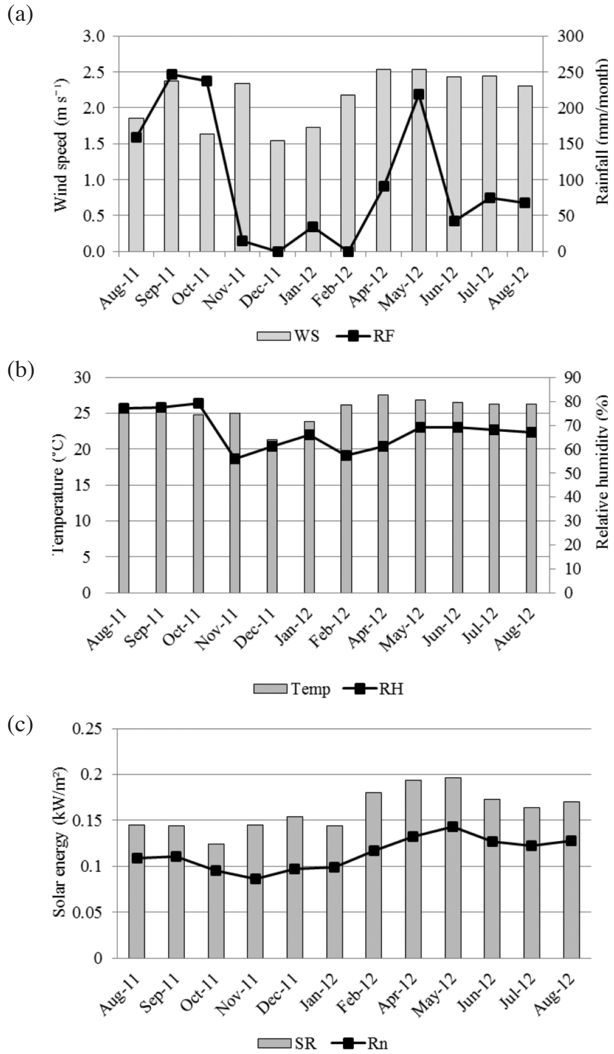

FIGURE 1. Meteorological parameters measured during August 2011-August 2012

EVALUATION OF DRY DEPOSITION FLUX

The dry deposition flux, F, of SO_2 was estimated using (1) and the median values were shown in Figure 2. The study showed a seasonal effect on deposition fluxes. The flux observed during the wet season (20±7.58 ng m^{-2} s^{-1}) was two times higher than the value observed during the dry season (10±11.05 ng m^{-2} s^{-1}). The important meteorological parameters that affected the SO_2 deposition flux were found to be the friction velocity, u^*, and the humidity. The value of u^* that was calculated in a wet environment was 0.48±0.06 cm s^{-1}. This was also two times higher than the value that was calculated in a dry environment (0.26±0.02 cm s^{-1}). The monthly average value of the humidity, as shown in Figure 1(b), was also in line with the deposition flux. Other meteorological parameters, i.e. temperature and solar intensity, showed less effect on the deposition flux. The annual average F was determined to be 16.76±5.82 ng m^{-2} s^{-1}.

The leaf area index (LAI) has been studied for its influence in increasing the rate of SO_2 deposition. In this experiment, the LAI was measured to be 5.0-6.0 during a leafy-transitional period (wet season) and 2.5-3.5 during transitional-leafless period (dry season).

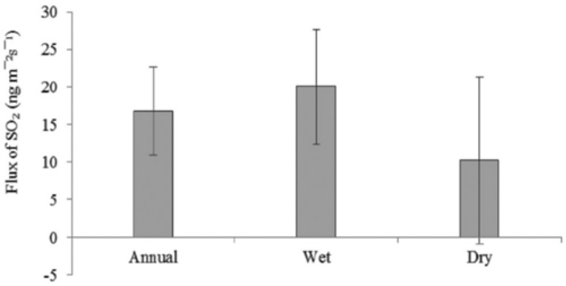

FIGURE 2. Dry deposition flux of SO_2 evaluated using the aerodynamic gradient method

EVALUATION OF DRY DEPOSITION VELOCITY

The dry deposition velocity, V_d, of SO_2 was estimated using (5) and shown in Figure 3. The median value of V_d in daytime was determined to be 0.50±0.06 and 0.45±0.02 cm s^{-1} during the wet and the dry season, respectively. The annual median value of V_d in daytime was 0.43±0.06 cm s^{-1}. For nighttime, V_d was estimated to be 0.69±0.07 cm s^{-1} in the wet season and nearly zero in the dry season. Daytime and nighttime V_d values determined during the wet season were close due to the significant role of the high humidity present during both day and night. Dissolution of SO_2 in the wet environment occurred while descending downward. The nearly zero value of V_d, observed during the dry season and in the nighttime, was commonly found by previous studies (Chimjan & Khummongkol 2012; Jitto et al. 2007). This indicated the effect that, under low humidity conditions, it causes upward motion, due to buoyancy of air during the night. The higher heat capacity of soil caused the soil surface temperature to remain high during the night while the atmospheric air temperature was decreasing.

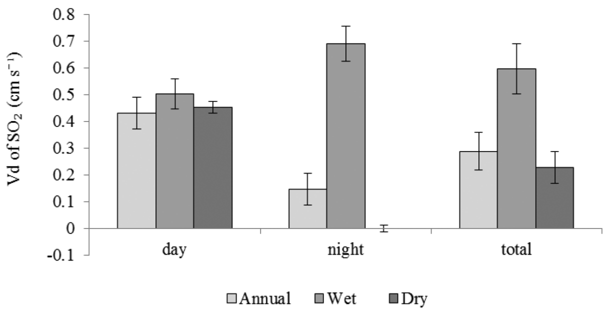

FIGURE 3. Dry deposition velocity of SO_2 evaluated using the aerodynamic gradient method

DRY DEPOSITION VELOCITY ESTIMATED BY A RESISTANCE MODEL

For this study, the average $u*$ values used in (7) and (8) were estimated to be 0.26±0.02 and 0.48±0.06 m s^{-1}, for the dry and the wet seasons, respectively. The annual mean value of $u*$ was determined to be 0.42±0.06 m s^{-1} (Figure 4). The friction velocity was very much dependent upon the surface roughness of the canopy of the forest. Naturally, the value of the leaf area index (LAI) would be high in the wet season and low in the dry season. In addition, the seasonal forest canopy at the experimental site changed from a leafy condition (April-October) to a leafless condition (November-March). The LAI values measured at the site were in the range of 5-6 during the leafy-transitional period (wet season) and 2.5-3.5 during the transitional-leafless period (dry season). The averaged $u*$ value observed in this study increased with LAI and vice versa.

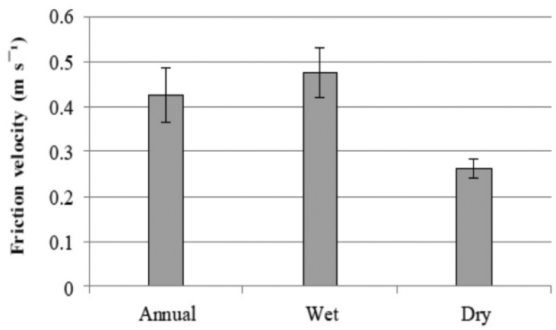

FIGURE 4. Seasonal and annual variation of friction velocity

From the field data, the amount of rainfall in the wet season greater than 1 mm day^{-1} was regarded as wet canopy, which was recommended by the previous experiment (Matsuda et al. 2006). The R_c in this study was applied from the previous report for dry conditions, having values of 115 and 437 s m^{-1} for the daytime and nighttime, respectively; and for wet conditions, having values of 69 and 211 s m^{-1} for the daytime and nighttime, respectively (Zhang et al. 2003). This indicated that seasonal variation affected the R_c value.

Figure 5 shows a comparison of the observed V_d of SO_2, determined by the aerodynamic gradient method with that determined using the resistance model. The observed V_d was found to be in close agreement with the model prediction in the daytime in all conditions, i.e., wet, dry and annual average. The observed and the predicted values of the annual average V_d were determined to be 0.43±0.06 and 0.53±0.07 cm s^{-1}, respectively.

Table 1 summarizes the results of dry deposition velocity range to difference surface and several experimental investigation of SO_2 deposition from the previous studies.

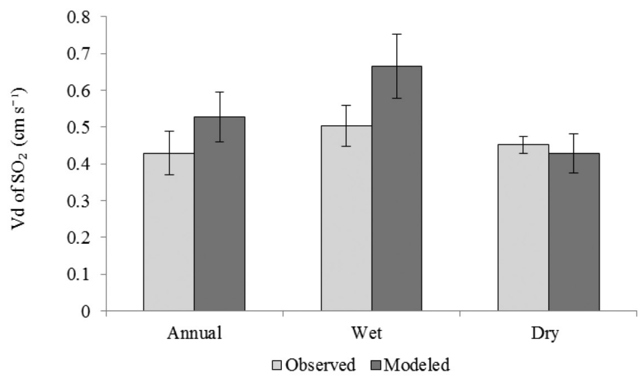

FIGURE 5. Comparison of the dry deposition velocity of SO_2 determined by the aerodynamic gradient method with that determined using the resistance model

TABLE 1. Deposition velocities value of SO_2 compared with other studies

Surface type	Location	Condition	Method	Vd (cm s^{-1})	References
Deciduous forest	Netherland	Winter day	Resistance method	0.3 dry 0.6 wet	Erisman et al. 1993
Coniferous forest	Sweden	Summer and winter	Enclosure technique	0.33	Granat & Richter 1995
Speulder forest	Netherland	3 years	Gradient method	1.5	Erisman et al. 1999
Low grassland	USA	May 2002	REA	0.45±0.98	Myles et al. 2007
Grassland* Healhland**	Netherland	3 years	Gradient method	1.2±0.3* 0.8±0.4**	Erisman et al. 1993
Forest (mixed)	Asia	Summer	Resistance method	0.4 day ≤0.2 night	Sorimachi et al. 2003; Xu & Carmichael 1998b
		Winter		0.1-0.2	
Deciduous forest	Japan	Jul.-Dec.	Resistance method	0.36	Wesley & Hicks 2000
Short vegetation	Germany	September	Gradient method	0.19-0.20	Horvath et al. 1998
Broadleaf evergreen forest	Taiwan	Early spring	Gradient method	0.61 day 0.27 night Dry canopy; 0.44 day 0.19 night Wet canopy; 0.83 day 0.47 night	Tsai et al. 2010
Deciduous forest	Thailand	Yearly	Gradient method	0.43±0.06 annual 0.45±0.02 dry 0.50±0.06 wet	This study
			Resistance method	0.53±0.07 annual 0.43±0.06 dry 0.67±0.09 wet	

CONCLUSION

The flux of SO_2 was evaluated in the wet and dry season using the aerodynamic gradient method. The value of the deposition flux observed in the wet season was higher than the value observed in the dry season by a factor of 2 (20±7.58 and 10±11.05 ng m^{-2} s^{-1}, respectively). The meteorological parameters that most significantly affected SO_2 deposition flux were the friction velocity and the humidity. The leaf area index (LAI) was also found to impact the rate of SO_2 deposition. Naturally, the value of LAI would be high in the wet season and low in the dry season. In addition, the seasonal forest canopy at the experimental site changed from a leafy condition (April-October) to a leafless condition (November-March). The value of the LAI measured at the site ranged from 5 to 6 during the leafy-transitional period (wet season) and 2.5 to

3.5 during the transitional-leafless period (dry season). The average u^* value observed in this study also increased with LAI and vice versa. A comparison was made of the observed V_d of SO_2, determined by the aerodynamic gradient method, with the V_d determined using the resistance model. The observed V_d was in close proximity with the model prediction for the daytime in all conditions, i.e., wet, dry and annual average. The observed and the predicted values for the annual average V_d were determined to be 0.43±0.06 cm s^{-1} and 0.53±0.07 cm s^{-1}, respectively.

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REFERENCES

Chimjan, O. & Khummongkol, P. 2012. Evaluation of dry deposition velocity of SO_2 by Bowen ratio and resistance model over rice paddy in tropical climate. *Sains Malaysiana* 41(6): 747-754.

Cooper, D.J. & Saltzman, E.S. 1993. Measurements of atmospheric dimethylsulfide, hydrogen sulfide and carbon disulfide during GTE/CITE 3. *Geophys. Res*. 98: 23397-23409.

Erisman, J.W. & Baldocchi, D. 1994. Modelling dry deposition of SO_2. *Tellus* 46(B): 157-171.

Erisman, J.W. & Draaijers, G.P.J. 1995. Atmospheric deposition in relation to acidification and eutrophication. *Studies in Environmental Science* 63: 55-75.

Erisman, J.W., Hogenkamp, J.E.M., Van Putten, E.M., Uiterwijk, J.W., Kemkers, E., Wiese, C.J. & Mennen, M.G. 1999. Long-term continuous measurements of SO_2 dry deposition over the speulder forest. *Water, Air and Soil Pollution* 109: 237-262.

Erisman, J.W., Versluis, A.H., Verplanke, T.A.J.W., de Haan, D., Anink, D., van Elzakker, B.G., Mennen, M.G. & van Aalst, R.M. 1993. Monitoring the dry deposition of SO_2 in the Netherlands: Results for grassland and heather vegetation. *Atmospheric Environment* 27(7): 1153-1161.

Delmas, R. & Servant, J. 1983. Atmospheric balance of sulfur above an equational forest. *Tellus Series B. and Chemical Meteorology* 35: 110-120.

Feliciano, M.S., Pio, C.A. & Vermeulen, A.T. 2001. Evaluation of SO_2 dry deposition over short vegetation in Portugal. *Atmospheric Environment* 35: 3633-3643.

Fellenberg, G. 2000. *The Chemistry of Pollution*. London: John Wiley and Sons.

Fowler, D., Pilegaard, K., Sutton, M.A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J.K., Granier, C., Neftel, A., Isaksen, I.S.A., Laj, P., Maione, M., Monks, P.S., Burkhardt, J., Daemmgen, U., Neirynck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J.P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C., Cieslik, S., Paoletti, E., Mikkelsen, T.N., Ro-Poulsen, H., Cellier, P., Cape, J.N., Horváth, L., Loreto, F., Niinemets, Ü., Palmer, P.I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M.W., Vesala, T., Skiba, U., Brüggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini, M.C., de Leeuw, G., Flossman, A., Chaumerliac, N. & Erisman, J.W. 2009. Atmospheric composition change: Ecosystems-Atmosphere interactions. *Atmospheric Environment* 43: 5193-5267.

Granat, L. & Richter, A. 1995. Dry deposition to pine of sulphur dioxide and ozone at low concentration. *Atmospheric Research* 29: 1677-1683.

Hayashi, K., Matsuda, K., Takahashi, A. & Nakaya, K. 2011. Atmosphere-forest exchange of ammoniacalitrogen in a subalpine decidous forest in Central Japan during a summer week. *Asian Journal of Atmospheric Environment* 5-2: 134-143.

Hicks, B.B., Baldocchi, D.D., Meyers, T.P., Hosker Jr., P.R. & Matt, D.R. 1987. A preliminary multiple resistance routine for deriving dry deposition velocities from measured quantities. *Water, Air, and Soil Pollution* 36: 311-330.

Horvath, L., Nagy, Z. & Weidinger, T. 1998. Estimation of dry deposition velocity of nitric oxide, sulfur dioxide, and ozone by the gradient method above short vegetation during the TRACT campaign. *Atmospheric Environment* 32: 1317-1322.

Jitto, P., Vinitnantarat, S. & Khummongkol, P. 2007. Dry deposition velocity of sulfur dioxide over rice paddy in tropical region. *Atmospheric Research* 85: 140-147.

Matsuda, K., Sase, H., Murao, N., Fukazawa, T., Khoomsub, K., Chanonmuang, P., Visaratana, T. & Khummongkol, P. 2012. Dry and wet deposition of elemental carbon on a tropical forest in Thailand. *Atmospheric Environment* 54: 282-287.

Matsuda, K., Fujimura, Y., Hayashi, K., Takahashi, A. & Nakaya, K. 2010. Deposition velocity of PM2.5 sulfate in the summer above a deciduous forest in central Japan. *Atmospheric Environment* 44: 4582-4587.

Matsuda, K., Watanabe, I., Wingpud, V., Theramongkol, P. & Ohizumi, T. 2006. Deposition velocity of O_3 and SO_2 in the dry and wet season above a tropical forest in northern Thailand. *Atmospheric Environment* 40: 7557-7564.

Matsuda, K., Watanabe, I., Vitsanu, W., Phunsak, K., Pojanie, K., Supat, W. & Totsuka, T. 2005. Ozone dry deposition above a tropical forest in the dry season in northern Thailand. *Atmospheric Environment* 39: 2571-2577.

Matsuda, K., Aoki, M., Zhang, S., Kominami, T., Fukuyama, T., Fukuzaki, N. & Totsuka, T. 2002. Dry deposition velocity of sulfur dioxide on a red pine forest in Nagano, Japan. *Society for Atmospheric Environment* 37: 387-392.

Matsuda, K., Fukuzaki, N. & Maeda, M. 2001. A case study on estimation of dry deposition of sulfur and nitrogen compounds by inferential method. *Water, Air and Soil Pollution* 130: 553-558.

Myles, L.T., Meyer, T.P. & Robinson, L. 2007. Relaxed eddy accumulation measurements of ammonia, nitric acid, sulfur dioxide and particulate sulfate dry deposition near Tampa, FL, USA. *Environmental Research Letters* 2: 034004.

Padro, J. 1993. Seasonal contrasts in modeled and observed dry deposition velocities of O_3, SO_2 and NO_2 over surfaces. *Atmospheric Environment* 27: 807-814.

Rodhe, H. 1978. Budgets and turn-over times of atmospheric sulfur compounds. *Atmospheric Environment* 12(1-3): 671-680.

Sorimachi, A., Sakamoto, K., Ishihara, H., Fukuyama, T., Utiyama, M., Liu, H., Wang, W., Tang, D., Dong, X. &

Quan, H. 2003. Measurements of sulfur dioxide and ozone dry deposition over short vegetation in northern China - A preliminary study. *Atmospheric Environment* 37: 3157-3166.

Thornton, D.C., Bandy, A.R., Blomquist, B.W., Davis, D.D. & Talbot, R.W. 1996. Sulfur dioxide as a source of condensation nuclei in the upper troposphere of Pacific Ocean. *Geophys. Res*. 101: 1883-1890.

Tsai, J.L., Chen, C.L., Tsuang, B.J., Kuo, P.H., Tseng, K.H., Hsu, T.F., Sheu, B.H. & Liu, C.P. 2010. Observation of SO_2 dry deposition velocity at a high elevation flux tower an evergreen broadleaf forest in Central Taiwan. *Atmospheric Environment* 44: 1011-1019.

Wesley, M.L. & Hicks, B.B. 2000. A review of the current status of knowledge on dry deposition. *Atmospheric Environment* 34: 2261-2282.

Xu, Y. & Carmichael, G.R. 1998a. An assessment of sulfur deposition pathways in Asia. *Atmospheric Environment* 33(21): 3473-3486.

Xu, Y. & Carmichael, G.R. 1998b. Modeling the dry deposition velocity of sulfur dioxide and sulfate in Asia. *Applied Meteorology and Climatology* 37(10): 1084-1099.

Zhang, L., Brook, J.R. & Vet, R. 2003. Evaluation of a non-stomatal resistance parameterization for SO_2 dry deposition. *Atmospheric Environment* 37: 2941-2947.

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