Observation of SO_2 dry deposition velocity at a high elevation flux tower over an evergreen broadleaf forest in Central Taiwan

Jeng-Lin Tsai[1], Chien-Lung Chen[2], Ben-Jei Tsuang[1*], Pei-Hsuan Kuo[1], Kuo-Hsin Tseng[1], Ting-Fang Hsu[1], Bor-Hung Sheu[3], Chiung-Pin Liu[3]

[1]*Department of Environmental Engineering, National Chung Hsing University, 250 Kuokang Road, Taichung 402, Taiwan*

[2]*Department of Finance, Fortune Institute of Technology, No. 1-10, Nwongchang Rd., Daliao, Kaohsiung 831, Taiwan*

[3] *Department of Forestry, National Chung Hsing University, 250 Kuokang Road, Taichung 402, Taiwan*

* Corresponding author: Email: tsuang@nchu.edu.tw, Fax: +886-4-22862587, Tel: +886-4-22851206

Abstract

A 60-m flux tower was built on a 2100 m mountain for the measurement of the air pollutant concentration and the evaluation of dry deposition velocity in Central Taiwan. The tower was constructed in an evergreen broadleaf forest, which is the dominant species of forest in the world. Multiple-level SO_2 concentrations and meteorological variables at the site were measured from February to April 2008. The results showed that the mean dry deposition velocities of SO_2 were 0.61 cm s^{-1} during daytime and 0.27 cm s^{-1} during nighttime. A tendency was observed that the dry deposition velocity increases with LAI and solar radiation from the comparison of the monthly data. Furthermore, it was observed that the deposition velocity was larger over wet canopy than over dry canopy, that higher deposition velocities in the wet season were mainly caused by non-stomatal uptake of wet canopy. Over wet canopy, the mean dry deposition velocities of SO_2 were estimated to be 0.83 cm s^{-1} during daytime and 0.47 cm s^{-1} during nighttime; and 0.44 cm s^{-1} during daytime and 0.19 cm s^{-1} during nighttime over dry canopy. Comparisons of the results in this study and the predictions of Zhang et al. (2003a) are in a good agreement. The median (geometric mean) of derived r_c during daytime are 233 (266) m s^{-1} over dry canopy and 147 (146) m s^{-1} over wet canopy. It was found that the solar radiation is the critical important meteorological variable determining the stomatal resistance during daytime. For non-stomatal resistance, clear dependencies were observed on the friction velocity and relative humidity.

Keywords: East Asia; Sulfur dioxide; dry deposition; stomatal and non-stomatal resistances; evergreen broadleaf forest

1. Introduction

Sulfur dioxide (SO_2) is not only one of the important specie resulting in acid precipitation, also air pollution and is the precursor of sulfate. By means of dry deposition of these species transferred by air motion to the surface, serious damage was caused to the environment and the ecology and worldwide have become of increasing concern. Consequently, evaluation of dry deposition for SO_2 is a critical issue with respect to ecological impact, crop growing and air quality research.

Observations of SO_2 dry deposition have been carried out over different land use types and vegetation areas in the last two decades, including desert, bare soil, grassland, crops and forest (e.g. Brook et al., 1999). However, scant observation over evergreen broadleaf forest has been reported. In the U.S. Geological Survey (USGS) land cover classification (http://edcdaac.usgs.gov/glcc/globe_int.html), the coverage of forest globally is about 15 % with 38% of that being evergreen broadleaf forest. Hence, it is necessary to understand the behaviors of SO_2 such as its dry deposition rate and related issues to increase knowledge of environmental degradation in this area.

Recently, acidic deposition at high elevation has received much attention (Heuer et al., 2000; Wai et al., 2008). It was found that at high elevations, forests are vulnerable as they are often surrounded by acidic clouds and fog which are thought to contribute to the decline of forests. In view of the unique environmental settings and the extremely scarce data set that is available at high elevations, data from a flux tower on a high mountain with the elevation exceeding 2000 m above sea level was used to provide more valuable information about this issue.

In this paper, multilevel SO_2 concentrations and SO_2 dry deposition velocity (V_d) measured over an evergreen broadleaf forest from the beginning of February to the end of April 2008 are presented. Diurnal and monthly variations of dry deposition velocity were estimated and related to the Leaf Area Index (LAI) and environmental variables. The results were also compared with those studies of similar land use type. The dataset shown in this paper is extremely informative for estimating the dry deposition for the assessment of acid deposition and air pollutants.

2. Site description and Methodology

2.1. Flux tower

Data used in this study was gathered over an evergreen broadleaf forest with a elevation of 2100 m in Huisun Forest flux station of National Chung-Hsing University (24.076 °N, 121.126 °E), Nantou, Central Taiwan (Fig. 1). This flux tower site was constructed with a grant from the Taiwan Ministry of Education and National Chung-Hsing University. Its main purpose was established as one of the research activities of the FLUXNET, which is the global network to assess the energy and trace gas fluxes between the biosphere and atmosphere (Baldocchi et al., 2001). Therefore, most meteorological variables and momentum, energy and CO_2 fluxes are measured at this site. In addition, it is also designed to have capacity for air quality research, including the measurement of air pollutant concentrations at different levels, and evaluation of dry deposition velocities.

The study site is located at the top of a mountain where the general terrain in the surrounding is slightly tilted. It slopes with an angle of 17^o extended over roughly 3 kilometer towards 315^o, approximately northwest (NW) which is the dominating wind direction during study period in central Taiwan. The horizontal distances to the nearest public road and populated area are 4 and 7 km in the west and south areas, respectively, which imply the measurements at this site can be considered an undisturbed results without human management (e.g. Eugster et al., 2006). The dominant species in the native evergreen broadleaf forest are *Castanopsis carlesii*, *Neolitsea konishii* and *Machilus thunbergii*. The height of the canopy top from the ground is about 24 m and the tree density is dense, about 2115 trees ha^{-1}. In the northwest direction, the extent of the homogeneous canopy for optimum footprint conditions was measured to be exceeded 3 km. Besides, no abrupt changes in vegetation roughness and canopy opening were occurred in the upwind areas.

The main structure at the site is a 60-m-high steel tower and a container housing facility near the base of the tower (Fig. 2). The tower is firmly fixed with cement foundations and several steel ropes anchored to the ground. Several platforms extend from the tower at 10 m, 26 m, 46 m and 56 m to observe the profiles of meteorological data and air pollutant concentrations. The SO_2 analyzer and the data storage device are installed in the container house. SO_2 concentrations were measured using a UV fluorescence SO_2 monitor (TECO model 43A) at each platform, controlled by an electric valve system with 10-minute intervals between the upper and lower levels. Intakes were set up at each platform and connected to the analyzer with an 80 m Teflon tube. The attenuation of SO_2 concentration, such as the absorption of tube and time lag between the intake and the analyzer were corrected by using standard gas calibration of known SO_2 concentration.

Friction velocity and surface sensible heat flux were measured by a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.) at a frequency of 10 Hz and consequently, Monin–Obukhov length was determined by using those observations (e.g., Businger et al., 1971). In addition, other meteorological parameters such as four components of radiation, Photosynthetically Active Radiation (PAR), specific humidity, temperatures, etc. were also observed at the same location. Monthly Leaf Area Index (*LAI*) was obtained from satellite data of Moderate Resolution Imaging Spectroradiometer (MODIS) and the values were 4.1 in

February and 6.2 in the other two months. Ancillary measurements were also conducted during study period. By analyzing the leaves of these species, the pH values were found to be from 4.4 to 5.9. The soil pH at our observation site had a pH value of about 4.7 in March.

2.2. The gradient method

Within the atmospheric surface layer, the vertical profile of scalar can be depicted by the similarity theory (e.g., Brutsaert, 1982). Based on the assumption that heat and mass are transported in a similar way, the flux of SO_2 can be determined using the gradient method (Baldocchi et al., 1988) as:

$$F = -u^* c^* \quad (1)$$

$$c^* = k\Delta c / \left[\ln\left((z_2 - d_0)/(z_1 - d_0)\right) - \Psi_h\left((z_2 - d_0)/L\right) + \Psi_h\left((z_1 - d_0)/L\right)\right] \quad (2)$$

where u^* is the friction velocity (m s^{-1}); c^* is the eddy concentration (μg m^{-3}); Δc is the difference of SO_2 concentrations at a height between z_2 and z_1 (μg m^{-3}); k is the Von Karman constant; L is the Monin–Obukhov length (m); Ψ_h is the integrated stability correction function for heat defined by Businger et al. (1971); d_0 is the zero-plane displacement height (m), which is typically 60-75% of the height of the vegetative canopy (Wesely and Hick, 2000). To determine d_0 in each month, a relationship, which predicts the ratio of d_0 to canopy height (h) to vary with LAI, proposed by Perrier (1982) was used:

$$\frac{d_0}{h} = 1 - \left(1 - \left[e^{\frac{-aLAI}{2}}\right]\right)\left(\frac{2}{aLAI}\right) \quad (3a)$$

$$a = \begin{cases} 2f, & f \geq 0.5 \\ \left(2(1-f)\right)^{-1}, & f < 0.5 \end{cases} \quad (3b)$$

where a is an adjustment factor for LAI distribution within the canopy and f is the proportion of LAI lying above $h/2$. Here the f is approximately estimated to be 0.75

for the native evergreen broadleaf forest in each month. Using Eq (3a) and (3b), the d_0 are determined as 0.70*h* for February and 0.78*h* for March and April. Once the SO_2 flux has been determined, the dry deposition velocity V_d, can be estimated by the following equation:

$$V_d = F/C \qquad (4)$$

where C is the SO_2 concentration at height z_2 (μg m^{-3}). In this study, F is positive when the flux is towards the surface and negative when flux occurs in the opposite direction.

In the resistance analogy models, the primary resistances to the transport of the pollutant from the atmosphere to the surface are the aerodynamic resistance (r_a), the quasi-laminar sublayer resistance (r_b) above the canopy, and the overall canopy resistance (r_c) (e.g. Wesely, 1989; Feliciano, et al., 2001; Zhang et al., 2003a). Therefore, the observed r_c can be obtained, from the observed deposition velocity, the calculated r_a and r_b, as following:

$$r_c = \frac{1}{V_d} - r_a - r_b \qquad (5)$$

Expressions for r_a and r_b can be found in many dry deposition studies (e.g. Padro et al., 1991; Erisman et al., 1994; Massman et al., 1994) and the uncertainties in r_a and r_b in the different models are small (Massman et al., 1994). The following equation was adopted to calculate r_a and r_b (e.g. Seinfeld and Pandis, 1998):

$$r_a = \frac{\ln(z/z_0) - \psi_h}{ku^*} \qquad (6)$$

$$r_b = \frac{5}{u^*}\left(\frac{\nu}{D_{SO_2}}\right) \qquad (7)$$

where z is reference height (m), z_0 the roughness length (m), ν the viscosity of air and D_{SO_2} the diffusivity of SO_2. The value of z_0 is estimated as 0.1 times as height of forest canopy (e.g. Baldocchi et al., 1998).

3. Results and discussions

3.1. Meteorological conditions and data screenings

In order to study the dry deposition of SO_2 over forest, it is first necessary to understand the meteorological variables affecting the vegetation physiology. Field measurements were conducted from 1 February to 30 April 2008 which is late winter to early spring in the North Hemisphere. During this period, winds from north to northwest occurred during 60% of the time approximately (Fig 3). As mentioned in Section 2, within the directions we consider this site to be the one of those with the possible footprint conditions for micrometeorological and dry deposition velocities of pollutants studies. Since a truly flat terrain with reasonable horizontal extent does probably not exist at this altitude range in mountainous Taiwan (e.g. Klemm et al., 2006).

In the parameterization of canopy resistance for SO_2 dry deposition of Wesely (1989), solar radiation and air temperature were consider as the key meteorological variables. ~~The hourly values of measured meteorological variables that affected the SO_2 dry deposition during this period are presented in Fig. 2, including solar radiation, air temperature, wind speed, relative humidity and precipitation.~~ The mean monthly values of these variables were divided into daytime (7:00–17:00) and nighttime (18:00–6:00) groups and summarized in Table 1. During clear days, solar radiation can be more than 1000 W m^{-2} around noon; in contrast, it decreased to less than 200 W m^{-2} during cloudy days and under foggy conditions. Other variations seen were the mean daily solar radiation in March and April being larger than that in February. There were obvious variations in temperature (T_a) during the study period. Daytime T_a ranged from low levels (< 5 ◦C) in February to normal levels (～ 15 ◦C) near the end of April. The total amount of precipitation during the study period was 251 mm which is approximate 10 % of the mean annual precipitation from 2001 to 2008 according to a weather station 7.5 km to the southeast. In addition, due to the local circulation at such high altitude, mist occurred occasionally in the afternoon.

A total of 2116 hourly data were screened to eliminate or minimize the influence of periods associated with inadequate meteorological conditions, low precision of measured concentration and other errors arising both from measurements and mathematical approaches. Less reliable data were removed from the sampled datasets using the following data-screening criteria (Feliciano et al., 2001; Matsuda et al., 2005):

(1) Wind speed was less than 1m s^{-1},

(2) SO_2 concentration was lower than 0.1 ppb,

(3) Absolute value of V_d exceeded potential max dry deposition velocity ($V_{d,\max}$) by 1.5 times (i.e., 1.5 $V_{d,\max}$), where the potential max dry deposition velocity is defined as $V_{d,\max} \equiv (r_a + r_b)^{-1}$.

After screening the data with the criteria, only 934 records were used in the following analysis.

It is generally agreed that V_d over dry and wet canopies are different. With the existence of aqueous layers on the surface, the wetness increases the SO2 uptake. Consequently, data in this study were separated into those over dry and wet canopies to discuss the individual characteristics of SO_2 V_d. Canopy wetness may be caused by rain, fog, mist and dewfall from the atmosphere in the study site and its duration is a difficult variable to measure. Here, two criteria were adopted for the identification of wet canopy. The first was the estimation of the rain period. Data recorded precipitation and the one following just after precipitation took into account a continuation of wet conditions by rain (e.g. Matsuda et al., 2006). The second was the estimation of dew condensation. In this study we adopted the work of Sentelhas et al. (2008) who pointed out that the constant relative humidity threshold method could be a practical and useful tool for estimating dew condensation. Here a constant value of RH = 90% was chosen as the threshold for wetness presence.

3.2. Concentration Profiles of SO_2

Composite vertical profiles of SO_2 concentration at four levels are presented in Fig. 3. The variation patterns of the 3-hourly profiles can be classified into two groups, the ascending (Fig. 3a) and the descending (Fig. 3b) with increasing time. During daytime, the profile of SO_2 concentration showed a generally increasing trend with increasing time, and reached a maximum at 15:00 (Fig. 3a); in contrast, the profile of SO_2 concentration at nighttime showed a generally decreasing trend with increasing time, and reached a minimum at 3:00 in the wee hours of the morning. Such diurnal variation is attributed to the development of mixed layers and SO_2 pollutant transfer from regional areas.

Above the canopy, whether daytime or nighttime, there were positive gradients for all the profiles. In each profile, it can be seen that the minimum concentration of SO_2 always occurred at 26 m where is close to the height of canopy. Occasionally, negative gradients of SO_2 were occurred when the SO_2 concentrations at 26 m were larger than those at upper levels and consequently, resulted in the V_d <0. This probably originated from the random measurement errors under conditions of low SO_2 concentration and weak turbulence where random measurement error leading to random errors in deposition velocity becomes high (e.g. Matsuda et al., 2006). By means of choosing height intervals sufficiently large to yield concentration differences and adequate criteria for data screening, only small number of available data obtained under such situation.

Within the canopy, the SO_2 concentration was only measured at 10 m, where is lower than the bottom of the canopy. Whether day or night, data showed that the SO_2 concentrations at 10 m were slightly larger than those at 26 m. The vertical profiles of pollutants were influenced by meteorological conditions, canopy structures and other factors (e.g. Meng et al., 2007). In this study, it is considered that this phenomenon might be caused by remained SO_2 in the canopy for the weak wind speed (e.g. Lovett and Lindverg, 1992; Walton et al., 1997), though no meteorological measurement was conducted with the canopy during the study period. Besides, the SO_2 concentration gradient could not be determined for only one level with the canopy, hence, the effect of soil uptake for SO_2 from the observation is out of discussion in this study.

3.3. Evaluation of SO_2 dry deposition velocity

The hourly values of V_d obtained in this study are presented in Fig. 4a which shows such a large diurnal variation that dry deposition velocities were higher during daytime than at night in all periods. The values of V_d are so widely distributed that the maximum value of observed V_d can reach 3 cm s^{-1}; in contrast, the minimum V_d is negative. Fig. 4b showed the composite diurnal cycle of SO_2 V_d. During daytime, the dry deposition velocity of SO_2 ranged from 0.28 cm s^{-1} to 0.89 cm s^{-1} with a mean value of 0.61 cm s^{-1}; during nighttime, the V_d ranged from 0.22 cm s^{-1} to 0.36 cm s^{-1} with a mean value of 0.27 cm s^{-1}. In addition, the standard deviations of SO_2 V_d during daytime were larger than those during nighttime.

It was found that the diurnal variation of V_d was highly dependent on incoming solar radiation so that the daytime V_d increased with the solar radiation and the daily maximum value of V_d always occurred around noon when the incoming solar radiation was the most intense. Due to the absence of solar radiation during nighttime, the V_d were usually smaller than those during daytime. The V_d also increased with u^*.

The larger u^* resulted in not only smaller aerodynamic resistance but also non-stomatal resistance (Zhang et al., 2003a).

3.4. Monthly variations of SO_2 deposition velocity over dry and wet canopies

Fig. 5 presents the composite diurnal cycles of V_d over dry and wet canopies for each month. It can be seen that both V_d show obviously diurnal variations and in both the daytime and nighttime, V_d over wet canopy were higher than those over dry canopy. Over dry canopy, stomatal uptake is an important sink of SO_2 when vegetation is biologically active. During daytime, stomata are opening for photosynthesis and, in the mean while, stomatal resistance for SO2 deposition was reduced. In the absence of solar radiation during nighttime, however, the stomata would be close and resulted in huge stomatal resistance. Over wet canopy, wetness would decrease stomatal uptake, but substantially increases non-stomatal uptake (Feliciano et al., 2001; Zhang et al., 2003a, 2003b). In the presence of aqueous layers on the surface, it is assumed that stomatal uptake is not important in light of stomata blocking by water drops and the presence of weak solar radiation (Zhang et al., 2003a). On the contrary, SO2 is a reasonably soluble gas in pure water and is effectively removed at higher rates under moist conditions in this study. Therefore, it is considered that higher deposition velocities over wet canopy were mainly caused by non-stomatal uptake.

The comparison of monthly diurnal variations of $\mathrm{V_d}$ showed that the daytime V_d in February were smaller than those in the other two months. The results implied that V_d tends to be larger with a larger leaf area index (LAI) in March and April. That the canopy resistance, which is the major factor determining the V_d in vegetation areas, has been shown to be correlated with individual leaf stomatal resistance divided by the LAI is also demonstrated in other studies (Kelliher et al., 1995; Wilson et al., 2002). In addition, more intense radiation also results in the increasing of V_d (Jitto et al., 2007). As shown in Table 1, the mean daytime value of solar radiation in March and April are 1.5 times of that in February.

Fig. 5 also showed that the V_d in the nighttime is similar in each month over dry and wet canopies respectively. It implies that LAI is not the major variable determining the V_d in the nighttime.

3.5. Comparisons with the observations from other studies over forest

A review of published results for V_d of SO_2 determined by several methods over forest at different locations is presented in Table 2. The mean values of V_d range from about 0.1 cm s^{-1} over deciduous forest during winter nighttime to 2.3 cm s^{-1} over coniferous forest during wet daytime. It reveals general phenomena that daytime V_d is higher than that in nighttime and V_d over canopy higher than that over dry canopy. The daytime V_d (0.61 cm s^{-1}) during wintertime in this study is lower that (about 1 cm s^{-1}) of Finkelstein et al. (2000) during summertime. Over dry canopy, the daytime V_d (0.47 cm s^{-1}) over broadleaf evergreen forest in this study is higher than that (0.21 cm s^{-1}) of dry season over deciduous forest in Thailand (Matsuda et al., 2006) and that (0.3 cm s^{-1}) over deciduous forest in Netherlands (Erisman, 1994). This is probably caused by forest conditions in seasonal differences when deciduous forest is more active during summer time and defoliated during wintertime. On the other hand, over wet canopy, daytime V_d over broadleaf evergreen forest in Taiwan (this study) and that over deciduous forest in Thailand (Matsuda et al., 2006) are at the same level which means not so large differences in wet canopy V_d between Taiwan and Thailand. However, significant differences of V_d over wet canopy are also observed over coniferous forest and deciduous forest in Erisman (1994). From discussions above, it indicates that, in addition to the deviations caused by the random and systematic instrumental errors and inaccuracies following from theoretical assumptions, V_d also varies with underlying forest physiology, time of day and season (e.g. Brook et al., 1999). Compared with the results listed in this Table, the observed V_d in this study are reasonable.

3.6. Comparisons with modeled deposition velocities

Zhang et al. (2003a, 2003b, denoted as Z03 hereafter) proposed a resistance analogy parameterization for calculating gaseous dry deposition based on study results over 5 different vegetation types in the North America. The structure of Z03 in the parameterization of r_c is separated into two parallel paths; one is stomatal resistance (r_{st}) with its associated mesophyll resistance (r_m), and the other is non-stomatal resistance (r_{ns}). In addition, look-up tables, classified according to the land types, seasonal category, and canopy wetness, were also used to calculate SO_2 dry deposition velocity. More detail is referred to Zhang et al. (2002, 2003a). In this study, Z03 was applied to evaluate SO_2 dry deposition velocity and discuss the applicability to the mountain forest area.

Fig. 7 shows the hour values of observed and modeled V_d of Z03 over dry and wet canopy. For dry canopy, Z03 seemed to predict reasonable SO_2 V_d during nighttime, but underestimated SO_2 V_d during daytime. Similar result was also reported by Zhang et al. (2003a) for SO_2 V_d in deciduous forest. The correlation coefficient between the observed and the modeled V_d is 0.96, the bias is -0.05 cm s^{-1} and the RMSE is 0.07 cm s^{-1}. For wet canopy, Z03 slightly overestimated the V_d not only during daytime but also in the nocturnal. The correlation coefficient between the observed and the modeled V_d is 0.9, the bias is 0.06 cm s^{-1} and the RMSE is 0.12 cm s^{-1}. In general, Z03 can estimate SO_2 V_d for dry and wet canopy approximately, not only the magnitude but also the diurnal pattern of V_d.

Z03 also provided a lookup table for an indication of the typical V_d of SO_2 under different meteorological conditions with the dominant values of meteorological variables in each category of land use and the predictions are consistent with the published measurements. Therefore the results in this study may be reliably compared with the predicted values in Zhang et al. (2003a). It is noticed that this prediction was designed for summer season. For the location of Taiwan, however, is in the subtropical area where the climate is hotter and wetter, comparison of the result and the prediction is with reference value for the scientists in this community. In this prediction, u^* values of the V_d over evergreen broadleaf trees are prescribed as 0.7 for dry or rainy days, 0.35 for dry or rainy nights and 0.2 for dewy nights. The observed u^* in this study were similar with those in Z03 except the value for dry or rainy days where 0.51 for dry or rainy days, 0.31 for dry or rainy nights and 0.22 for dewy nights, and more 0.29 for dewy days. Moreover, the V_d were 0.88 (0.22) cm s^{-1} under dry day (night) and 2.47 (1.12) cm s^{-1} under rainy day (night). Moreover, the predicted maximum V_d was also presented such that the maximum V_d over dry canopy is 1.7 cm s^{-1} and 3.9 cm s^{-1} over wet canopy. Overall, the observed V_d in this study are close to the predictions of Zhang et al. (2003a). Though the observed V_d over wet canopy is smaller than the prediction, it is noted that the prediction of Zhang et al. (2003a) excluded the results under dew when the V_d is small with stable atmospheric conditions (Zhang et al., 2003b). In addition, all the values of observed V_d are smaller than the predictions.

3.7. Evaluation of canopy resistance of evergreen broadleaf forest

Fig. 8 presents the composite observed $r_a + r_b$ during the study period calculated from Eqs. (5) and (6). A typical "U" shaped diurnal variation was observed with the minimum mean value occurring at 32 s m^{-1} approximately around noon and the mean values being larger than 65 s m^{-1} during nighttime. The values of $r_a + r_b$ were larger during nighttime due to smaller u^*, when the atmosphere was under stable conditions compared to those during daytime. In addition, it was also found that $r_a + r_b$ were larger under dew conditions compared to rain conditions for the smaller u^* (Zhang et al., 2003b).

Fig. 8 also presents the composite observed r_c over dry and wet canopies during the study period, calculated from Eq. (4) with the observed values of V_d, r_a and r_b. The diurnal pattern of r_c is similar to that of $r_a + r_b$ in that the minimum occurred around noon. The values of r_c over day (wet) canopy were about 225 (112) s m^{-1} in the daytime and 735 (366) s m^{-1} in the nighttime. Compared to the results of Zhang et al. (2003b) observed at mixed forest and deciduous forest sites for a full growing season, the estimated r_c in this study are relatively large. Note that the observation in this study was conducted during the transition between late winter and early spring, when the environmental conditions, such as solar radiation and air temperature, were not the most suitable for vegetative activity. Therefore, it is deduced that the representative value of r_c for evergreen broadleaf forest in growing season should be smaller than that in this study.

In studying dry deposition of air quality models over areas covered by vegetation (e.g. Wesely, 1989; Zhang et al., 2003a, 2003b) canopy resistance is often partitioned into two resistances, the stomatal resistance (r_{st}) and the non-stomatal resistance (r_{nst}). Separation of these processes is important in estimating the accurate representation of diurnal variations of dry deposition because stomatal uptake usually occurs during the daytime, during which time it predominates over non-stomatal uptake for many chemical species; in contrast, during nighttime, when the stomata are closed, r_c over dry canopy was mainly controlled by r_{nst} (Zhang et al., 2003a). In this study, it was found that the daytime r_c were mainly determined by the solar radiation, which is consistent with those in Wesely (1989) and Zhang et al., (2003a). Because the vegetation obtains the required nutrients for living through photosynthesis which acts with the Photosynthetically Active Radiation of solar radiation, it is expected that the variation of daytime r_c will follow the intensity of the solar radiation. During the study period, the air temperatures were lower than 20 ℃ which is relative low compared to the optimal air temperature of evergreen broadleaf forest, 30 ℃, assigned in Zhang et al. (2003a). This situation limited the vegetative growth and showed that r_c is only slightly dependent on air temperature. A similar phenomenon was also observed for r_c dependency on vapor pressure deficit. Lower air temperatures result in a lower vapor pressure deficit so that during the study period the values of the vapor pressure deficit were lower than 900 pa.

During nighttime, r_c was considered to be equal to r_{nst} when the r_{st} is less important and can be ignored. Fig. 9 shows canopy resistance versus friction velocity during nighttime over dry canopy where r_c is limited to within 5000 s m^{-1} and u^* ranges from 0.1 to 1 m s^{-1}. It shows that r_c values decreased as u^* increased, which is consistent with other studies (Zhang et al., 2003b; Matsuda et al., 2005). Large u^* values, which represent strong turbulence, can facilitate the transportation of SO_2 between the atmosphere and the underlying canopy (Hicks et al., 1989), thus enhancing non-stomatal uptake. It is also found that nighttime r_c versus RH over dry canopy showed that r_c only slightly depends on RH. There was also a clear tendency towards a smaller and less variable r_c for RH > 90% (Fig. 8) while, for RH < 90%, r_c was highly variable. The relationship between r_c and RH for SO2 were similar to the relationships found by Feliciano et al. (2001) and Zhang et al. (2003b).

4. Conclusion

A study on SO_2 dry deposition was performed in an evergreen broadleaf forest in central Taiwan. The study period was from the beginning of February to the end of April 2008 which was the drier and colder season in this area. To evaluate the SO_2 dry deposition velocity with the gradient method, the multilevel SO_2 concentrations, meteorological variables and energy fluxes were measured by an eddy covariance system and other instruments during the same period. The results show that mean SO_2 dry deposition velocity in the daytime is 0.61 cm s^{-1} and 0.27 cm s^{-1} in the nighttime. Compared with those results in the literature that were carried out over forest areas using the observations and resistance methods, the results in this study are reasonable.

It was observed that the deposition velocity was larger over wet canopy than over dry canopy. Over wet canopy, the mean dry deposition velocities of SO_2 were estimated to be 0.83 cm s^{-1} during daytime and 0.47 cm s^{-1} during nighttime; and 0.44 cm s^{-1} during daytime and 0.19 cm s^{-1} during nighttime over dry canopy. It is clear that higher deposition velocities were mainly caused by non-stomatal uptake of wet canopy, especially during nighttime. A tendency was also observed that dry deposition velocity increases with LAI and solar radiation from the comparison of the monthly data.

Compared with the predictions of Zhang et al., (2003), the results showed that the observed V_d are in agreements with the predictions over dry and wet canopies. The observed u^* in this study were similar with those in Z03 except the value for dry or rainy days where 0.51 for dry or rainy days, 0.31 for dry or rainy nights and 0.22 for dewy nights, and more 0.29 for dewy days.

The patterns of diurnal variation for $r_a + r_b$ and r_c showed obvious diurnal variations so that the median (geometric mean) of derived r_c during daytime are 233 (266) m s^{-1} over dry canopy and 147 (146) m s^{-1} over wet canopy. During daytime, solar radiation is the major meteorological variable determining the SO_2 uptake so that the values of canopy resistance were minimized around noon and increased as time became close to the early morning and late afternoon. It was found that wetness and high humidity enhanced canopy SO2 uptake and thus decreased non-stomatal resistance. For non-stomatal resistance, evident dependencies were observed in the friction velocity and relative humidity.

This study provides valuable information regarding dry deposition velocity for SO_2 in evergreen broadleaf forest, being the dominant species of forest worldwide but with relatively few studies focused on this area. The knowledge of dry deposition velocity for SO_2 obtained in this study, such as the diurnal and monthly variations, effects resulting from meteorological variables and vegetation physiology, not only helps to extend the observation to longer periods and to different locations, but is also useful in the examination and evaluation of parameterization.

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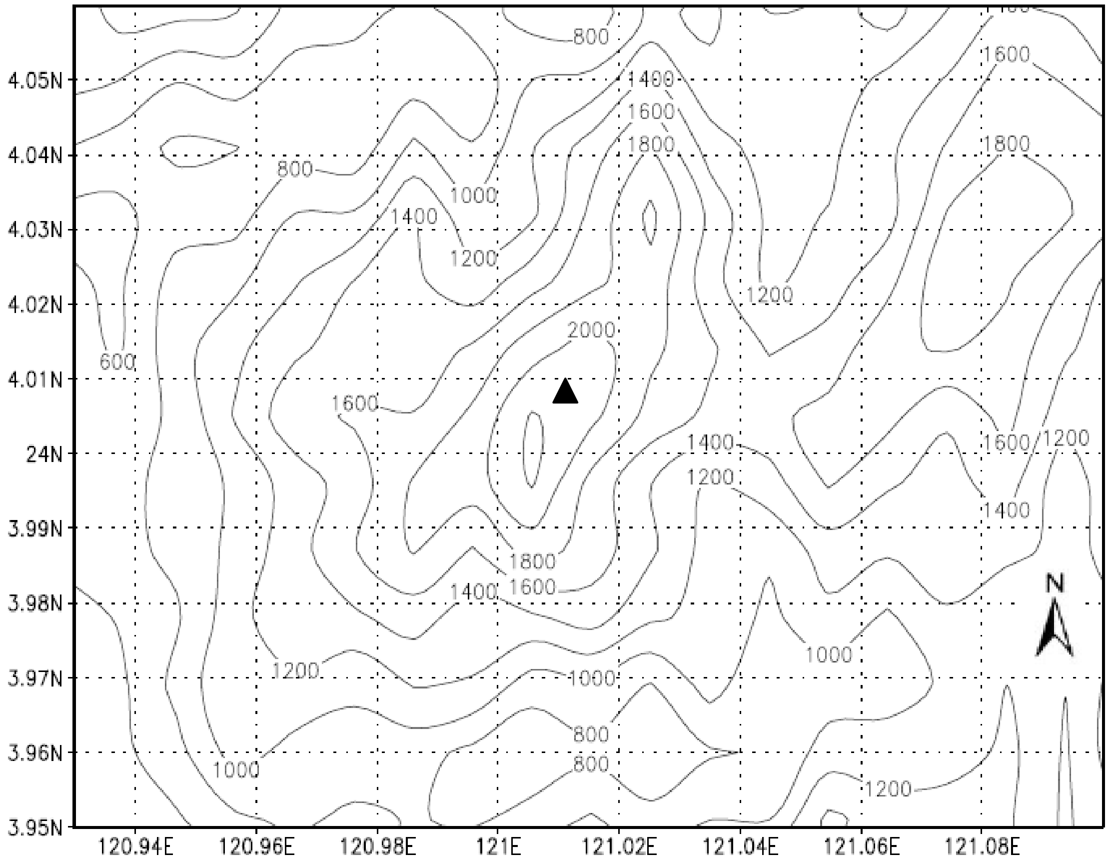


Fig. 1. Topographic map of the flux site with the position of the eddy covariance tower shown by a solid triangle. Contour interval is 200 m.

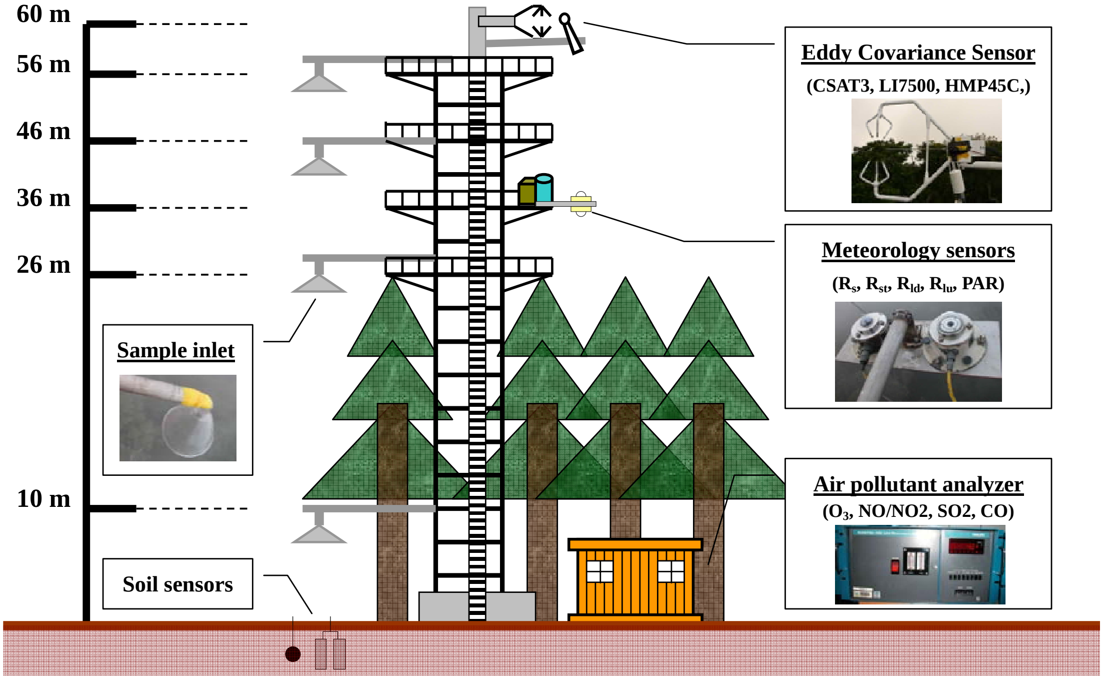


Fig. 2. The sketch of Huisun Forest flux tower in Taiwan.

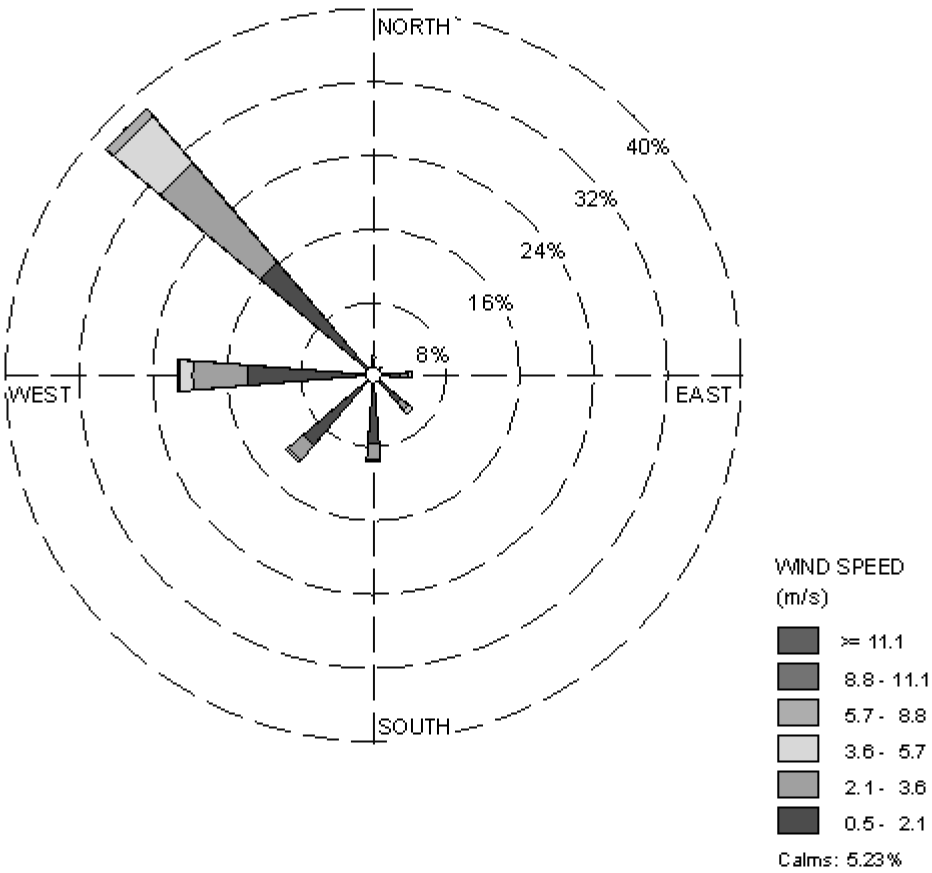


Fig. 3. Relative distribution of the wind speeds and directions for the time period February 1–April 30 2008 at the study site.

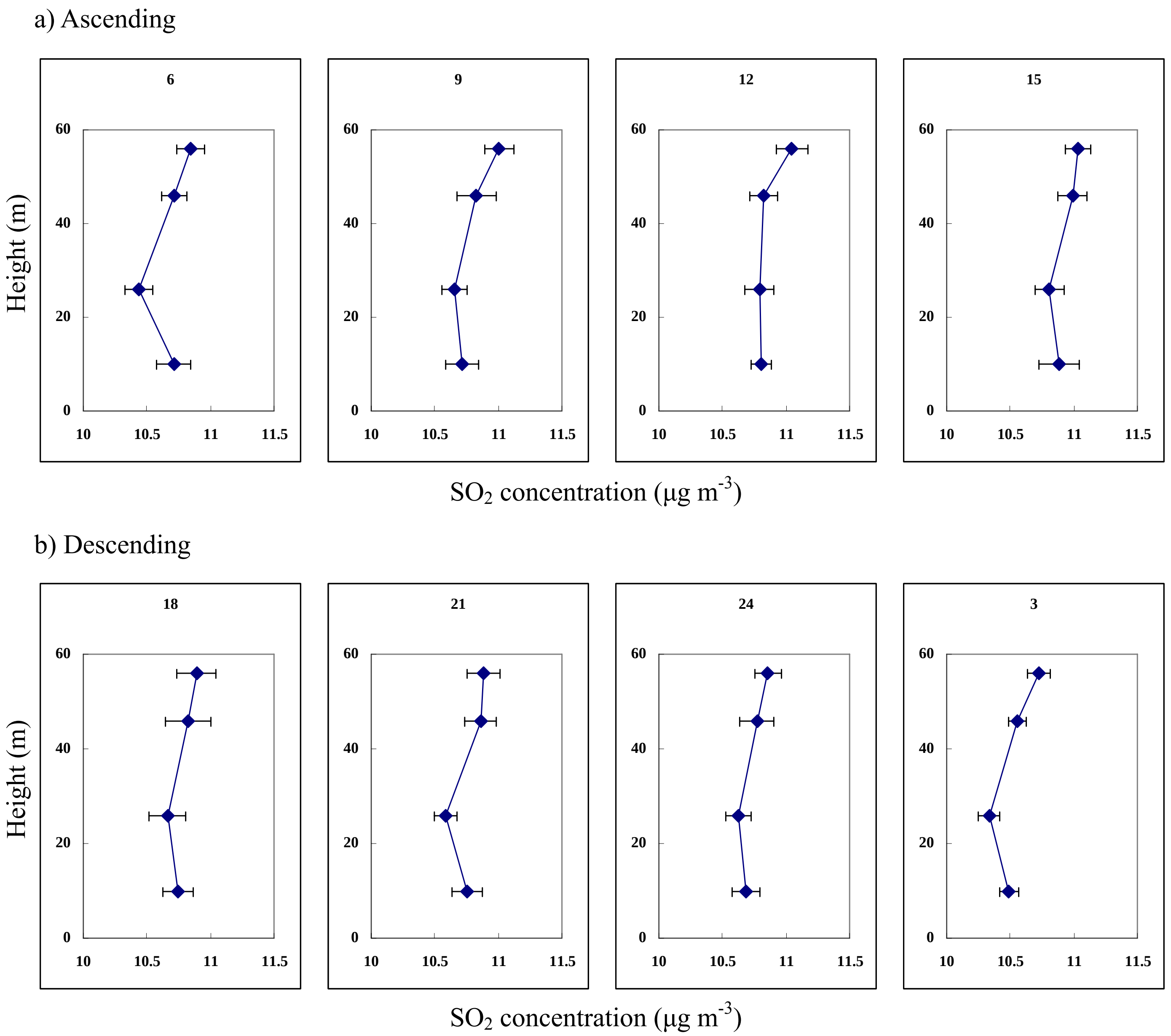
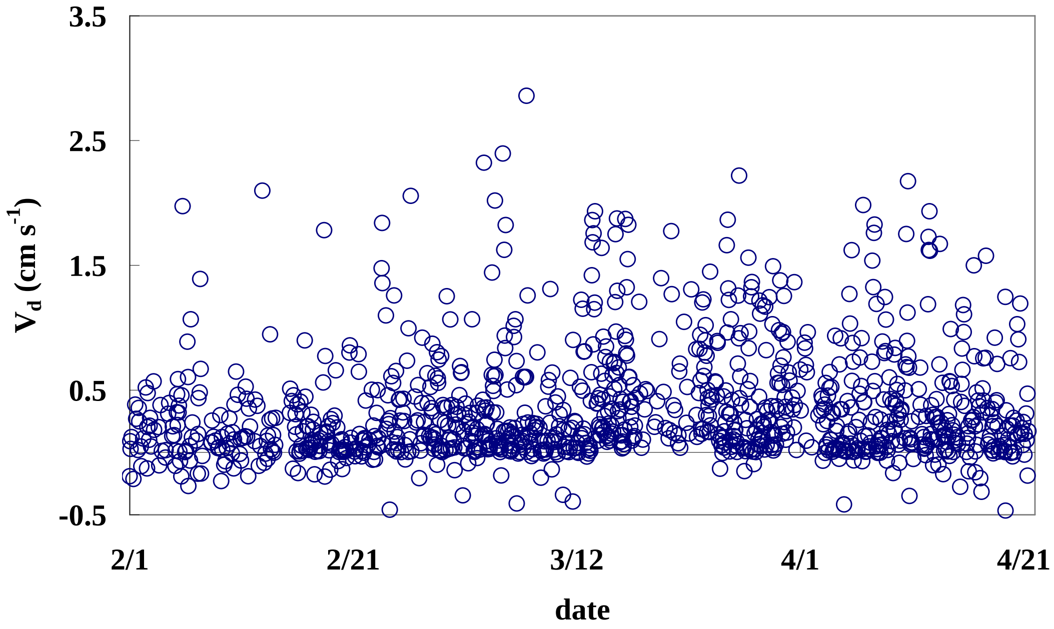


Fig. 4. The composite vertical profiles of SO_2 concentration measured at 10 m, 26 m, 46 m and 56 m with 3-hours bin.

a)



b)

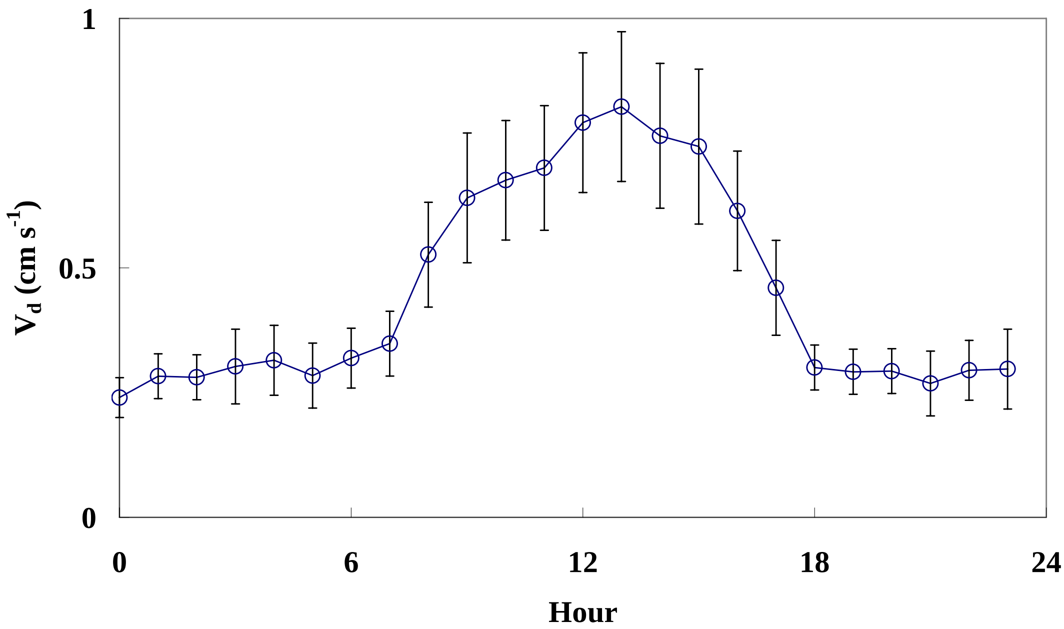


Fig. 5. The time series and composite diurnal cycle of SO_2 dry deposition velocity from observations, where the high–low bars denote standard deviations of observations.

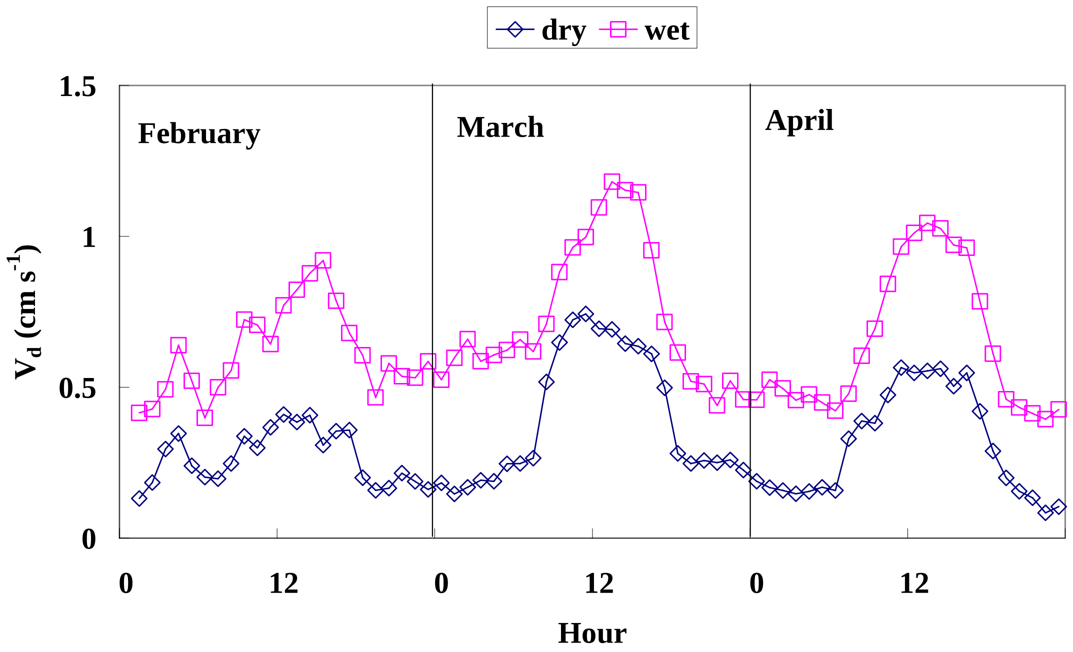


Fig. 6. Composite diurnal variations of SO_2 dry deposition velocity over dry and wet canopies at each month.

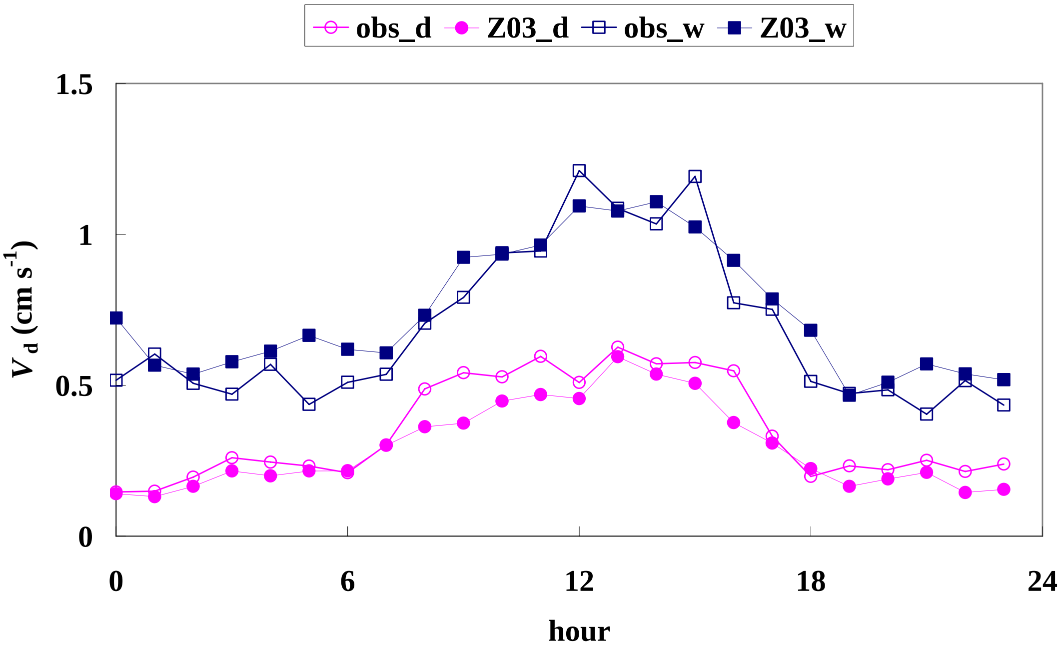
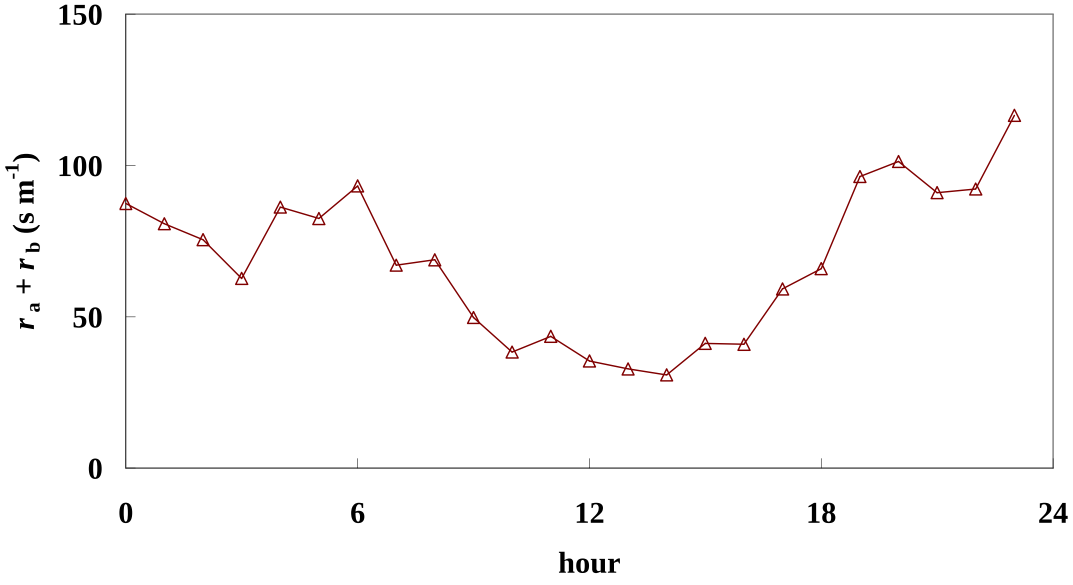


Fig. 7. The composite hour values of predicted V_d of Z03 versus the observations over dry and wet canopies.

a)



b)

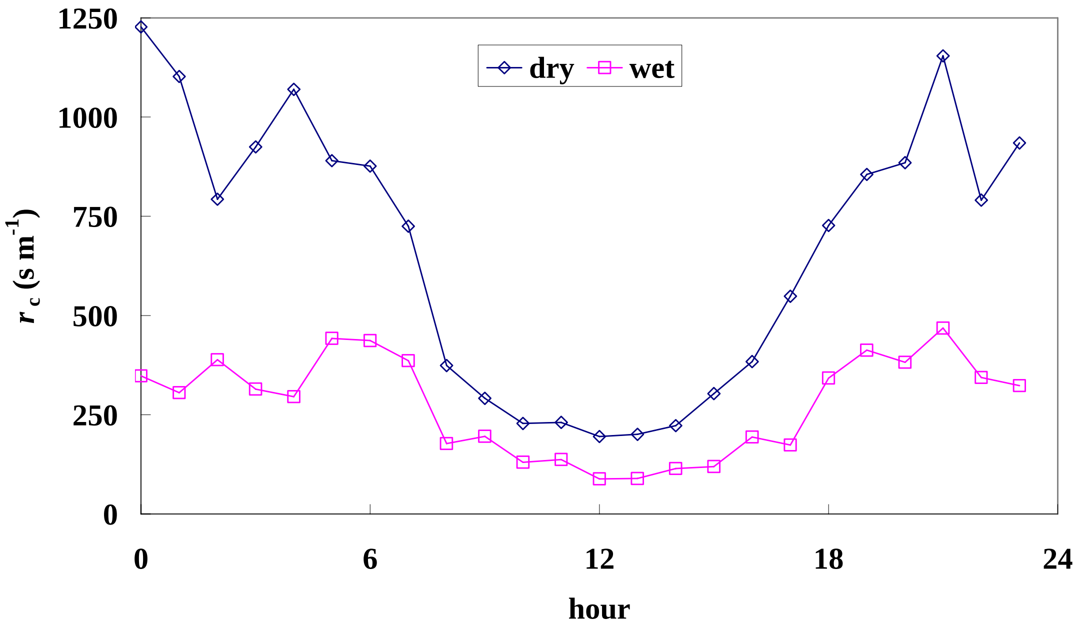


Fig. 8. Composite diurnal cycles of observed a) aerodynamic and quasi-laminar layer resistances and b) canopy resistances over dry and wet canopies.

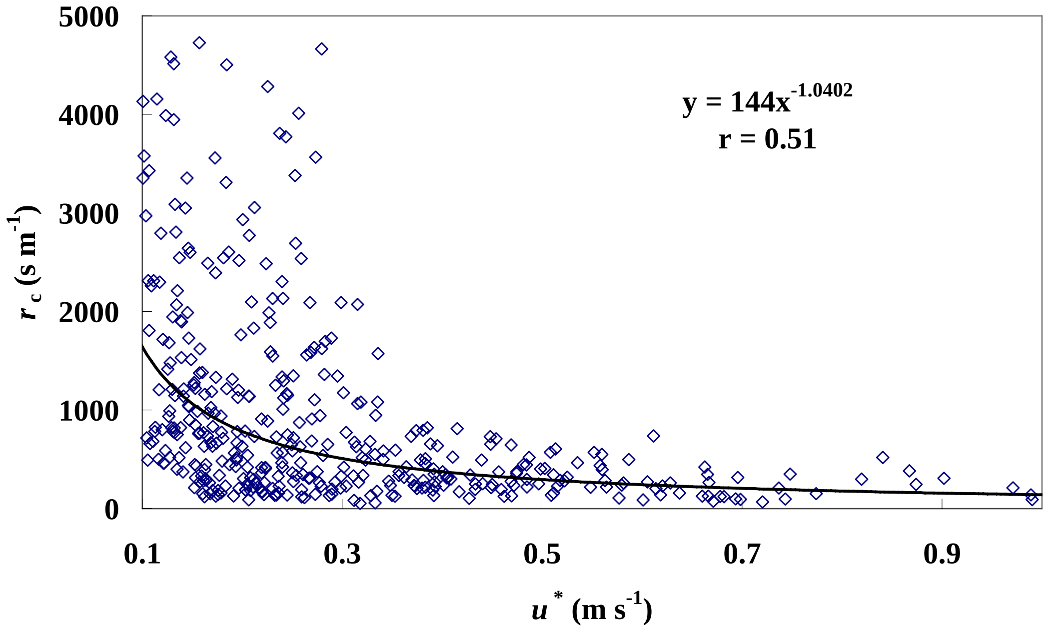


Fig. 9. The observed canopy resistance versus friction velocity over dry canopy during nighttime.

Table 1. Mean values of meteorological observation at flux tower during the study period in 2008.

	Daytime			Nighttime		
	Feb.	Mar.	Apr.	Feb.	Mar.	Apr.
Wind speed (m s^{-1})	2.3	2.1	1.8	2.4	1.8	1.8
Friction velocity (m s^{-1})	0.41	0.35	0.33	0.36	0.26	0.28
Solar radiation (W m^{-2})	181	261	254	-	-	-
Temperature (℃)	7	9.2	14.5	6.7	7.8	13.6
Relative humidity (%)	79	82	94	75	74	91
Total precipitation (mm)	16.6	8.6	6	10.6	18.6	7

Table 2. Comparisons of dry deposition velocity for SO_2 in this study and those of other studies over forest areas.

Forest types	Location	Condition	methods	V_d (cm s^{-1})	Reference
Broadleaf evergreen forest	Taiwan	Early spring (Feb.-Apr.)	Gradient method	Day 0.61; Night 0.27 Dry canopy Day 0.44; Night 0.19 Wet canopy Day 0.83; Night 0.47	This study
Deciduous forest (teak)	Thailand	Dry season (Jan. – Apr.) Wet season (May – Aug.)	Gradient method	Dry season Day 0.21; Night 0.09 Wet season Day 1.17; Night 0.34	Matsuda et al., 2006
Coniferous forest (pine)	Japan	Sep. – Nov.	Bowen ratio	Day 0.9	Matsuda et al., 2002
Coniferous forest (pine)	Sweden	Summer and winter	Enclosure technique	0.33	Granat and Richter, 1995
Coniferous forest (pine)	Japan	Jul. – Dec.	Resistance method	0.4	Matsuda et al., 2001
Deciduous forest	Japan	Jul. – Dec.	Resistance method	0.36	Matsuda et al., 2001
Deciduous forest	USA	Apr. – Oct.	Resistance method	Day 1.04 Night 0.3	Finkelstein et al., 2000
Mixed Coniferous-deciduous forest	USA	May – Oct.	Resistance method	Day 1.01 Night 0.27	Finkelstein et al., 2000
Mixed Coniferous-deciduous forest	China	Feb., May, Aug. and Dec.	Resistance method	Summer Day 0.4 Winter Day 0.15	Xu and Carmicheal, 1998
Coniferous forest	Netherlands	Yearly	Resistance method	Dry Day 0.7; Night 0.7 Wet Day 2.3; Night 2.5	Erisman, 1994
Deciduous forest	Netherlands	Winter	Resistance method	Dry Day 0.3 Wet day 0.6	Erisman, 1994