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A Technique for Estimation of Dry Deposition Velocities Based on Similarity with Latent Heat Flux

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Abstract

Field measurements of chemical dry deposition are needed to assess impacts and trends of airborne contaminants on the exposure of crops and unmanaged ecosystems as well as for the development and evaluation of air quality models. However, accurate measurements of dry deposition velocities require expensive eddy correlation measurements and can only be practically made for a few chemical species such as ozone and CO_2. On the other hand, operational dry deposition measurements such as used in large area networks involve relatively inexpensive standard meteorological and chemical measurements but rely on less accurate deposition velocity models. This paper describes an intermediate technique which can give accurate estimates of dry deposition velocity for chemical species which are dominated by stomatal uptake such as ozone and SO_2. This method can give results that are nearly the quality of eddy correlation measurements at much lower cost. The concept is that bulk stomatal conductance can be accurately estimated from measurements of latent heat flux combined with standard meteorological measurements of humidity, temperature, and wind speed. The technique is tested for a field experiment where high quality eddy correlation measurements were made in a soybean field in Kentucky. Over a four month

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period, which covered the entire growth cycle, this technique showed very good agreement with eddy correlation measurements for ozone.

Introduction

Dry deposition is an important removal process of atmospheric trace chemical species and therefore important in ecosystem research and assessment. However, accurate measurements of dry deposition are very difficult and expensive to make on a long-term operational basis. Currently, the most accurate and widely-used technique is eddy correlation, which relies on fast response instruments and requires constant on-site supervision. Consequently, such measurements are typically made as part of special research studies for relatively short periods (weeks to months).

In lieu of difficult and expensive direct measurements, existing dry deposition networks and ecosystem exposure studies often combine simple meteorological and chemical measurements with dry deposition models to estimate deposition fluxes on a continuing basis (Clarke and Edgerton 1993). While such measurements give valuable information on spatial distributions and long term trends of dry deposition fluxes, comparison to eddy correlation measurements on an hourly basis show considerable scatter (e.g. Padro et al, 1991; Meyers et al, in preparation). Thus, for ecosystem and crop exposure studies, as well as dry deposition networks, there is a need for more accurate field measurements of dry deposition of a variety of chemical species.

The dry deposition models used in existing networks are similar to the dry deposition components of air quality modeling systems such as the Regional Acid Deposition Model (RADM) (Chang et al, 1987), and the Urban Airshed Model (UAM-V) (Morris et al, 1992). The main difficulty with these models is the estimation of bulk (canopy level) stomatal conductance, which is the dominant dry deposition pathway for species such as ozone and SO_2 in areas of active vegetation. Generally, stomatal conductance is parameterized as functions of environmental factors such as solar radiation, air humidity and temperature, and soil moisture conditions. Vegetation parameters such as leaf area, vegetation coverage, surface roughness, and plant specific minimum stomatal resistance are also considered. Dry deposition models differ in their details, but they have the common problem of estimating the physiological functions of plants. However, since plant species differ considerably in their response to environmental conditions, and important environmental factors such as soil moisture are very difficult to realistically estimate (or even measure), stomatal conductance estimates are not very accurate. Therefore, a more direct way of determining bulk stomatal function is needed.

During the growing season in areas of dense vegetation, water vapor flux is dominated by the stomatal pathway. Therefore, measurements of latent heat flux can be used to infer bulk canopy conductance, which can then be used to estimate dry deposition velocity of some chemical species. This concept of similarity between chemical dry deposition and evapotranspiration was applied to ozone deposition at a site in eastern Colorado by Massman (1993). Since that site was sparsely vegetated, he used a two source model (Shuttleworth and Wallace, 1985) to estimate the partitioning of latent heat from plants and soil. At more densely vegetated sites, such as forests or crops in the eastern part of North America, the canopy component should dominate. For example, Baldocchi et al. (1987) tested a similar approach to estimate stomatal resistance using the Penman-Monteith equation for a soybean canopy. In the current study, field measurements over a soybean field in southern Kentucky during the summer of 1995 are used to demonstrate that ozone dry deposition velocities estimated assuming similarity to evapotranspiration compare remarkably well to dry deposition velocities measured by eddy correlation. If this technique performs as well at other highly vegetated sites, it could be used for low-cost, accurate dry deposition measurements or field research on ecosystem exposure.

Field deployment of low-cost measurement systems would include standard meteorological measurements, which are needed to estimate aerodynamic and laminar layer resistances, as well as measurements of latent heat flux. Off the shelf systems, such as energy balance Bowen ratio (EBBR) systems, could be used. Such systems require only periodic attention (about once per week) and are therefore relatively inexpensive to operate. However, the results shown here used an eddy correlation (EC) system for the measurement of latent heat flux. Therefore, the utility of a low-cost system specifically designed for dry deposition measurement using latent heat similarity must be inferred from comparisons between EBBR and EC systems. The current study is intended as a proof of concept for the latent heat similarity technique. To the extent that EBBR systems, or any other low-cost measurement system, can produce similarly accurate estimates of latent heat flux as EC systems, the quality of results shown here should be achievable. EBBR and EC measurement systems each have their respective advantages and disadvantages for realistic measurement of latent heat flux as outlined by Kanemasu et al. (1992). The First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) made over tall grass prairie in 1987 afforded an excellent opportunity for comparison of the two types of systems as reported by Smith et al. (1992), Fritschen et al. (1992), and Nie et al. (1992). Other studies have also shown the comparability of EBBR and EC systems (Tanner 1988).

Field Measurements

A comprehensive set of meteorological and chemical flux measurements was made in a soybean field in Keysburg, KY, which is near the Tennessee border about 60 km NNW of Nashville. Since these data include eddy correlation measurements of ozone flux and dry deposition velocity, it provides a good testing environment for the development of techniques to derive chemical dry deposition velocity estimates from latent heat flux measurements. A description of the measurements system is presented by Finkelstein et al. (1995) and Katul et al. (1996).

The experiment site was set up in a soybean field at 36.65 N 87.03 W, about 2 km west of Keysburg, KY. Elevation of the site is 585 meters with a gentle NW-SE slope of about 1.5%. The instrument boom was 4.55 m. above the ground, pointing toward 208°. Favorable wind directions were from 110 degrees through 270 degrees. Gently rolling uniform soybean fetch extended out to at least 1500 m through the SE and southern quadrants. A corn field was adjacent to the soybeans, 140 m to the west at the closest point. The boundary ran North-South. Measurements with winds from the Southwest will have some influence from the corn, but are far enough away that the influence is small. Examination of the data by wind direction showed no directional effects.

The soybeans (Asgrow 5560) were no-till planted within wheat stubble June 13. Dry deposition sampling was initiated June 22. An herbicide (Roundup) was applied July 4 which killed most of the weeds and slowed the growth of the beans for several days. The beans went through a rapid growth period from July 10 through August 5. Precipitation was adequate, LAI increased from 1 to about 6, midday leaf stomatal resistance, measured by porometer, was about 40-80 s/m, and the crop attained its maximum height of 1.2 m. Precipitation became very light after late July and by mid August the beans were under water stress. Leaf stomatal resistance increased to about 800 s/m, and LAI gradually decreased to about 3 by the end of September and to 1 by October 11, when the beans were mostly stalks and pods (most of the leaves had fallen). The corn reached full height of 2.5 m in late July and was harvested on August 25.

Theory

Dry deposition velocity (V_d) is usually estimated from a series of resistances to vertical transfer and surface uptake:

$$V_d = (r_a + r_d + r_s)^{-1} \qquad (1)$$

where r_a is the aerodynamic resistance, r_d is the deposition or laminar layer resistance, and r_s is the surface resistance. Aerodynamic resistance is a function of turbulent transfer in the atmospheric surface layer and can be estimated in several ways depending on the instrumentation available.

The deposition layer resistance accounts for diffusional transfer across a thin laminar layer adjacent to surfaces. Because of the no-slip condition, turbulent eddies cannot penetrate to a surface. Therefore, there exists a thin layer of non-turbulent air where molecular diffusion is the primary mechanism for transfer. While this concept is not relevant for momentum, it is relevant for any quantity which directly interacts with the surface such as heat, moisture, and chemical deposition. Therefore, for these quantities, the addition of a resistance based on molecular diffusion is necessary.

The estimation of the surface resistance is generally the most critical and most difficult since it depends on chemical interactions with various surfaces as well as stomatal uptake by the plants. In highly vegetated areas, the surface resistance for chemical species such as ozone and SO_2 is dominated by stomatal uptake. Since evaporation is also dominated by the stomatal pathway, there exists an opportunity to derive bulk stomatal resistance from measurements of latent heat flux. Surface water vapor flux (E) can be estimated using a resistance model similarly to dry deposition flux:

$$E = \frac{\rho\left(q_s(T_g) - q_a\right)}{r_a + r_{dw} + r_s} \qquad (2)$$

where q_a is the ambient specific humidity, $q_s(T_g)$ is the saturation specific humidity at the surface temperature (skin temperature), ρ is the ambient air density, and r_{dw} is the deposition layer resistance for water vapor. If latent heat flux is measured along with the ambient humidity and the surface skin temperature and r_a and r_{dw} are computed from meteorological measurements, then Equation 2 can be solved for r_s. If the stomatal pathway is assumed to dominate the surface moisture flux, then r_s can be taken as a close approximation of bulk stomatal resistance (r_{st}). Then, by adjusting for the difference in molecular diffusivity between water vapor and the chemical species, the bulk stomatal resistance for the chemical species can be estimated. For some species, it is desirable to add a parallel non-stomatal pathway for deposition to surfaces, as is demonstrated below for ozone. Once the surface resistance is estimated, deposition velocity can be computed according to Equation 1. This method requires measurements of latent heat flux, air humidity, surface skin temperature, and wind speed.

Test case procedure

The instrumentation deployed at the Keysburg site does not exactly match the needs envisioned by this method since the field program was designed for other purposes. A minimal field system deployed expressly for derivation of dry deposition velocities from latent heat similarity would not have the fast response instruments which were deployed at Keysburg, but it would have downward looking IR radiometers for measurement of surface skin temperature which were not deployed at Keysburg. Therefore, to evaluate the utility of this technique we needed to compensate for these differences in instrumentation as far as possible.

To compute aerodynamic resistance at a site without fast response instruments a method based on the standard deviation of the wind direction (σ_θ) can be used (Clarke and Edgerton, 1993) as:

$$r_a = \frac{C_a}{u\sigma_\theta^2} \qquad (3)$$

where u is the wind speed at the measurement height, and σ_θ is the standard deviation of the wind direction in radians. The coefficient C_a depends on solar radiation and wind speed such that $C_a = 9$ when solar insolation is greater than 10 W/m^2; otherwise, $C_a = 4$ when $u \geq 2$ m/s, and $C_a = 50\text{-}23u$ when $u < 2$ m/s. At a site where fast response wind measurements are available (i.e. sonic anemometers), r_a can be computed using surface layer similarity theory from eddy correlation measurements of friction velocity and sensible heat flux. For this study, both methods were tested to evaluate the consequence of using the simple system without fast response instruments.

Surface skin temperature is very important to this technique since it defines the surface saturation humidity, which is a component of the evaporative flux (Equation 2). Since this measurement was not made at Keysburg, the surface temperature (T_g) was derived from eddy correlation measurements of sensible heat flux (H) as follows:

$$T_g = T_a - \frac{H}{\rho C_p}(r_a + r_{dh}) \qquad (4)$$

where T_a is the air temperature at 3 m and C_p is the specific heat of air. Note that this calculation also depends on r_a, which in this case is computed from the fast response measurements since Equation 4 is used only to compensate for the lack of a skin temperature measurement which will be part of future systems. The deposition layer resistance r_{dh} is for heat, while r_{dw} in Equation 2 represents the resistance to water vapor diffusion. All together there are three deposition layer resistances used in this scheme including one for ozone as in Equation 1. Deposition layer resistance varies by the transported quantity because of differences in molecular diffusivity and is defined as (Wesely and Hicks 1977):

$$r_d = \frac{5}{u_*} Sc^{2/3} \quad (5)$$

where Sc is the Schmidt number defined as the kinematic viscosity of air ($\gamma = 0.146$ cm^2/s) divided by molecular diffusivity (γ/D). For heat, the molecular thermal diffusivity is 0.206 cm^2/s; for water vapor, molecular diffusivity (D_W) is 0.244 cm^2/s; and, for ozone molecular diffusivity (D_{O3}) is 0.159 cm^2/s.

Once the aerodynamic and deposition layer resistances have been estimated the bulk stomatal resistance for water vapor can be computed by rearrangement of Equation 2:

$$r_{stw} = \frac{\rho\left(q_s(T_g) - q_a\right)}{E_{tr}} - \left(r_a + r_{dw}\right) \quad (6)$$

where E_{tr} is evapotranspiration. In this study, the latent heat measurement divided by the heat of vaporization (LE/Lv) is assumed to approximate E_{tr}. Stomatal resistance for ozone is estimated by weighting the stomatal resistance for water vapor by the ratios of molecular diffusivity:

$$r_{stO_3} = \frac{D_w}{D_{O_3}} r_{stw} \quad (7)$$

It should be realized that Equation 6 is only practical when plants are actively transpiring. Therefore, at night (when solar insolation is less than 10 W/m^2), r_{stO3} is set to a relatively high constant value (5000 s/m) to represent resistance through closed stomata. This is not a serious drawback to the technique, since deposition velocities are generally small at night and are primarily modulated by the aerodynamic resistance in the nighttime stable surface layer. In this way, we were able to include all the nighttime data in the analyses presented below.

If the stomatal pathway were the only important avenue for dry deposition of ozone, then r_{stO3} could be used in place of r_s in Equation 1. However, ozone and other chemical species can deposit to surfaces such as leaves, stems, and soil. For example, Massman (1993) included other pathways to the ground or exterior leaf surfaces for both evaporation and ozone deposition in the sparse vegetation of eastern Colorado. Most dry deposition models represent non-stomatal pathways as resistances in parallel to the bulk stomatal resistance. However, there is very little agreement as to the magnitude of these surface resistances. For example, ground resistance for ozone as used in various models ranges from 100 - 2000 s/m. Erissman et al. (1994) suggests that 100 s/m is appropriate for dry soil while 500 s/m should be used for wet soil since ozone has limited solubility. Others have suggested the opposite effect of wetness such that resistance decreases for wet surfaces. Meyers and Baldocchi (1993), on the basis of eddy correlation measurements within a forest canopy, estimated surface resistance at the forest floor to be about 2000 s/m regardless of wetness. Massman et al. (1994) found that, at times, surface resistance decreased when dew was present.

Resistances to ozone deposition on leaf exteriors or cuticles is also somewhat controversial. Cuticle resistance is generally expressed at the leaf level so that the bulk effect at the canopy level is divided by the Leaf Area Index (LAI). Values of cuticle resistance range from 1600 - 15000 s/m. In any case, it is a simple matter to provide for non-stomatal pathways in the calculation. These may be made as elaborate as desired with multiple branches of parallel and serial resistances just as in the various existing dry deposition models. Given the uncertainty in these processes, however, the current study includes a constant resistance as the sum of all non-stomatal pathways (r_{surf}) in parallel with the stomatal pathway such that Equation 1 is modified as:

$$V_d(O_3) = \left[r_a + r_{dO_3} + \left(r_{stO_3}{}^{-1} + r_{surf}{}^{-1} \right)^{-1} \right]^{-1} \qquad (8)$$

A further complication occurs when surfaces are wet from rain or dew. This can affect both the moisture fluxes and dry deposition fluxes. The Keysburg field data suggests an enhancement of ozone dry deposition during periods of surface wetness. Therefore, in this study, r_{surf} is specified at 200 s/m for wet surfaces and 600 s/m for dry surfaces. Surface wetness may also affect moisture fluxes since there is clearly an important non-stomatal source of moisture. When surface wetness is caused by dew, Equation 6 tends to breaks down and does not give a useful result. This is because the difference between air humidity and saturation humidity at the surface temperature is very small and often negative. Clearly, in these saturated conditions, moisture flux is not a good indication for stomatal function. Before sunrise the stomata are closed so that Equation 6 is not needed. However, after sunrise the stomata may be open for a time before the dew evaporates. During such times stomatal resistance should be specified in some other manner, either as a constant or by some modeling approach. Fortunately, this is usually a rather brief period during which the stable surface layer often presents the limiting resistance to deposition. For this study, the bulk stomatal resistance for wet conditions is limited by a minimum value of 100 s/m, while the minimum stomatal resistance for dry conditions is set to 25 s/m.

When surface wetness is caused by rain, there is the possibility that a significant portion of the measured moisture flux is direct evaporation from wet surfaces and therefore not stomatal. In these cases, Equation 6 should underestimate stomatal resistance since the evaporative flux overestimates the evapotranspiration. However, during periods of appreciable rainfall, the air quickly saturates and Equation 5 again becomes a poor estimator of stomatal resistance. Therefore, to improve estimates during wet periods, a back-up model to parameterize stomatal resistance could be added.

Comparison analyses

The method for estimating ozone dry deposition velocity assuming similarity to evapotranspiration as outlined above is compared to deposition velocities derived from eddy correlation measurements. Figure 1 shows a scatter plot of calculated versus observed 30 minute average dry deposition velocities. The observed velocities are ozone flux measured by eddy correlation divided by the measured ozone concentration at approximately 4.5 m above the ground. This plot includes all data points from June 22 - October 11, 1995 for which the quality of the measurements was considered acceptable. Screening criteria included wind direction between 110°-270°, for uniform fetch over soybeans, and net energy balance within 100 W/m^2. The soybeans varied from a canopy height of 0.15 m with a LAI of 1 at the beginning of the period to 1.15 m and LAI of 5.75 at the peak growth stage in mid to late August and back down to 1.1 m with an LAI of 2 by the end of the period. Thus, the data include a variety of vegetation and soil moisture conditions including nighttime and periods of rain.

Figure 1 indicates that the moisture similarity technique shows considerable skill in estimating ozone dry deposition velocity. With judicious constraints on the calculation, such as a dry minimum bulk stomatal resistance of 25 s/m which is reasonable for soybeans, the technique results in realistic values of deposition velocity between 0 and 1.8 cm/s. Point by point comparison shows excellent agreement considering the short averaging time (1/2 hour) and the variety of conditions. A linear regression on Figure 1 gives a correlation coefficient of $r = 0.82$. Figure 2 shows a histogram of observed minus predicted deposition velocities which shows that 56% of the data are within 0.1 cm/s and 92% of the calculated values are within 0.3 cm/s of the measurements. The mean bias of observed minus predicted is 0.0062 cm/s and the standard deviation of the bias is 0.18.

As discussed above, the use of moisture flux measurements to estimate bulk stomatal resistance is not very valuable in wet conditions where moisture gradients are very small. Therefore, stomatal resistance is set to the minimum for most of the wet data points. Also, at night the stomata are closed and the stomatal resistance is very high. Thus, the moisture similarity technique is important only for a fraction of the data points, namely daylight, dry conditions, which is about half of the total dataset. The fact that the results compare so well to EC measurements for the full data set suggests that for wet and/or nighttime conditions the surface resistance is usually not the controlling process.

Figure 3 shows a scatter plot of daytime dry conditions only. The linear regression correlation coefficient is r = 0.86. The criteria for this subset is that the solar insolation be greater than 10 W/m^2 and that the wetness sensor indicate dry conditions. However, since there was only one wetness sensor, there may be times, such as after a rain event or when the morning dew is evaporating, when parts of the canopy may still be wet when the sensor indicates dry conditions. Some of the most extreme outlying points in Figure 3 are probably associated with mistaken classification as dry by the wetness sensor. For example the two highest predictions in the "dry" subset were during the day on August 5 which was quite wet from rainfall and all the other data points during this day were classified as wet. Therefore, accurate determination of wetness of the leaves and ground is helpful to this technique.

A time series of measured and computed ozone dry deposition velocity for six days in early August is presented in Figure 4. The first four days show remarkable agreement between the computed and measured values during both day and night. These days had mostly clear skies with light to moderate winds from the south and southeast. This suggests that under dry, clear sky conditions the technique is nearly exact in reproducing measured dry deposition velocities. The latter two days of this period were quite different, starting on August 5 when the remnants of Hurricane Erin passed through, dropping over an inch of rain at the site. Other than the two outliers, which were probably misclassified as dry, the predictions compared quite well with the observations even though the surfaces were wet. The very windy conditions lead to high deposition velocities which were well simulated by the calculations of the aerodynamic and deposition layer resistances. August 6 was characterized by variable cloudiness, very light winds, and no rain but continuous surface wetness according to the sensor. During the middle of the day when the winds were light, the calculations significantly underestimate the deposition velocities compared to the measurements. It is curious that surface wetness was indicated for the whole day when no rainfall was recorded and solar insolation was substantial. If these data points were classified as dry, the predictions would be much closer to the measured values as shown in Figure 5.

To help assess how well this technique would perform in an inexpensive network, a test was made using aerodynamic resistance computed from variations in wind direction (1 minute averages) according to Equation 3 rather than sonic anemometer measurements. Using this estimate of r_a in Equations 6 and 8 resulted in very similar estimates of dry deposition velocity such that the linear correlation coefficient was $r = 0.79$ rather than 0.82. Thus, simple measurements not requiring fast response instrumentation should be sufficient for estimation of r_a.

Discussion

The technique described in this paper can be considered as a combination of field measurement and modeling methods for discernment of dry deposition velocities at a relatively low cost. By using similarity of gaseous dry deposition flux to moisture flux the bulk stomatal resistance, which is the most important and difficult to model component of the dry deposition process, is derived from surrogate measurements. The advantage of this technique with regard to field networks is that measurements of moisture flux can be made much more inexpensively than can direct measurements of ozone flux. From a modeling perspective, an estimate of bulk stomatal resistance derived from moisture flux is more realistic and responsive than parameterizations based on functions of environmental factors. Therefore, this technique is not meant replace current models but to augment them by providing more accurate estimates of the stomatal pathway which is then used in combination with parameterizations of the other important dry deposition pathways. Similarly, this method will not replace direct eddy correlation measurements, and in fact relies on such studies for development and verification, but will enable relatively cheap high quality deployment of dry deposition networks.

This study has demonstrated the potential of using latent heat flux measurements to estimate ozone dry deposition velocities. The data used here were from an intensive field study which included eddy correlation measurements of heat, moisture, and ozone flux. Clearly, the measurements envisioned for an inexpensive network would be different which may affect the accuracy of the results. In particular, EBBR systems are not considered as accurate as eddy correlation for measurement of moisture flux. On the other hand, a system designed for this use would include skin temperature measurements, via IR radiometry, which should improve the calculations due to better estimates of surface humidity. Therefore, the next step is to deploy a system designed for this method, including EBBR and skin temperature, as part of a more extensive field experiment which includes eddy correlation measurements of ozone and moisture fluxes. Another challenge is to extend this technique to other chemical species. Theoretically, it should work for any species which has a significant stomatal pathway such as SO_2. The main obstacle to testing the technique for SO_2 is making accurate eddy correlation measurements for comparison. Also, this work should be extended to other environments, such as other types of crops, grasslands, and forests.

DISCLAIMER

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FIGURES

Figure 1. Ozone dry deposition velocity computed from latent heat flux similarity versus ozone dry deposition velocity derived from eddy correlation (EC) measurements for entire Keysburg dataset, June 22 - October 11, 1995.

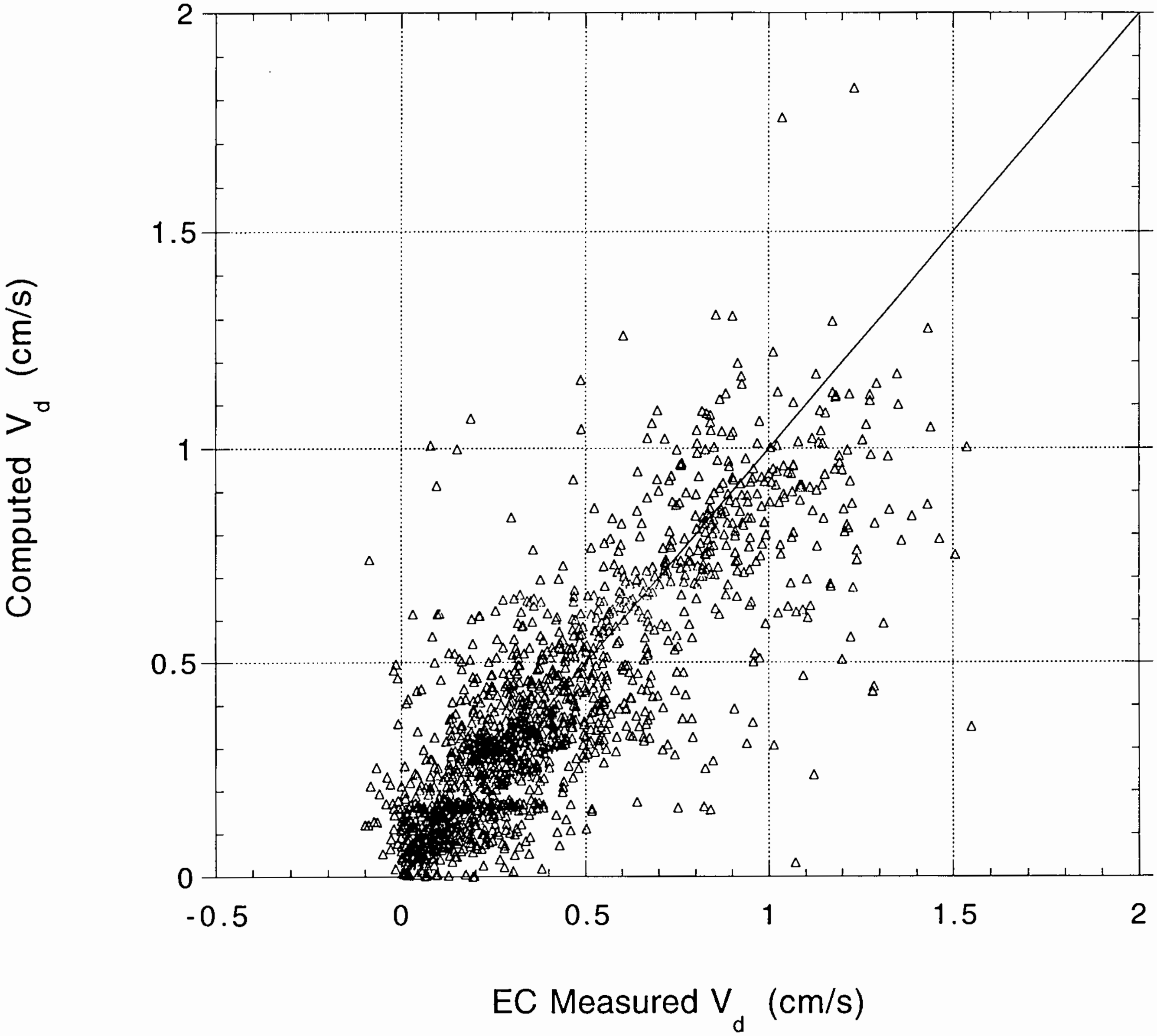
Figure 2. Histogram of observed (EC measurements) minus predicted (similarity computations) ozone dry deposition velocity for entire dataset.

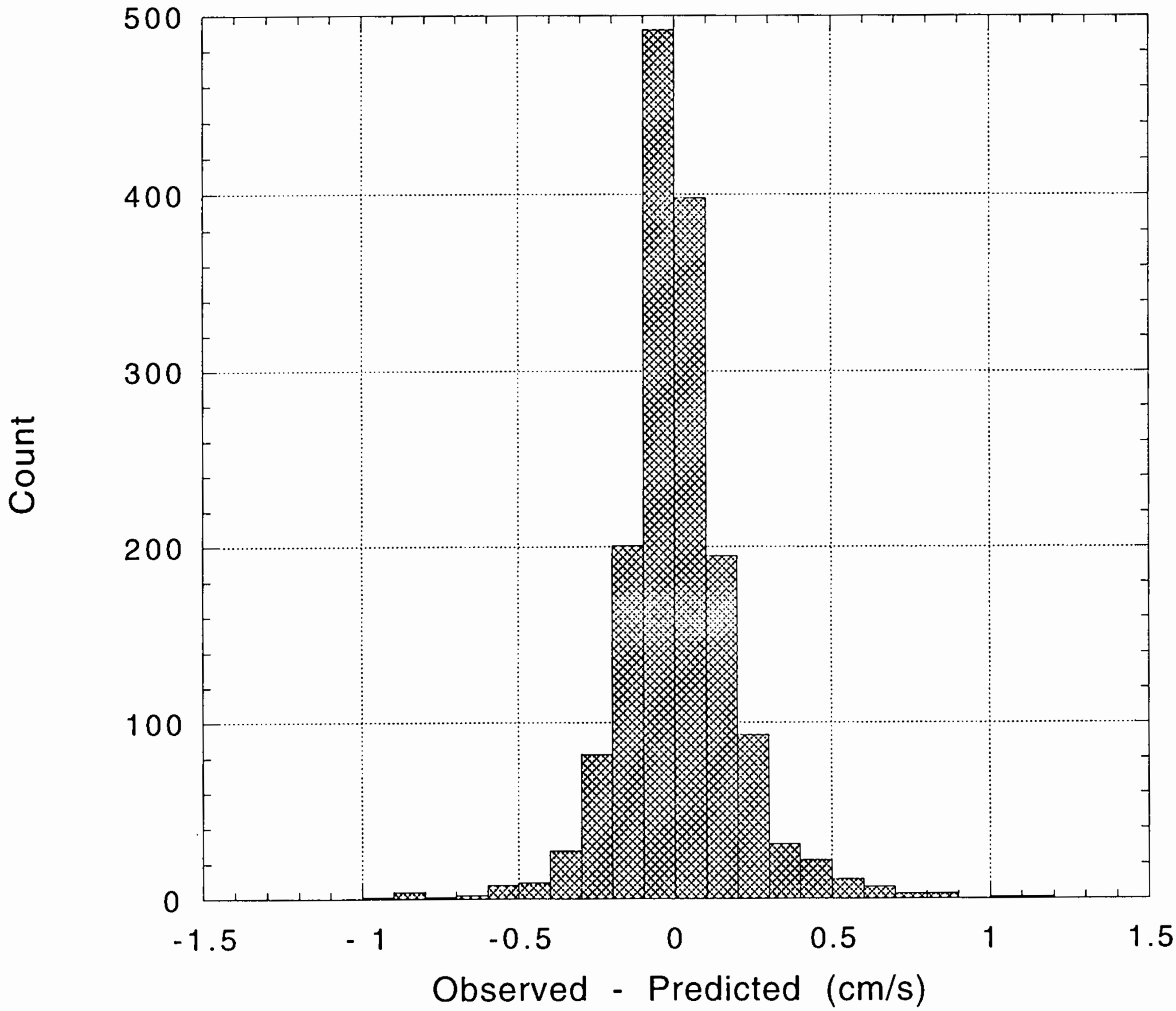
Figure 3. Same as Figure 1 except for dry daytime conditions only.

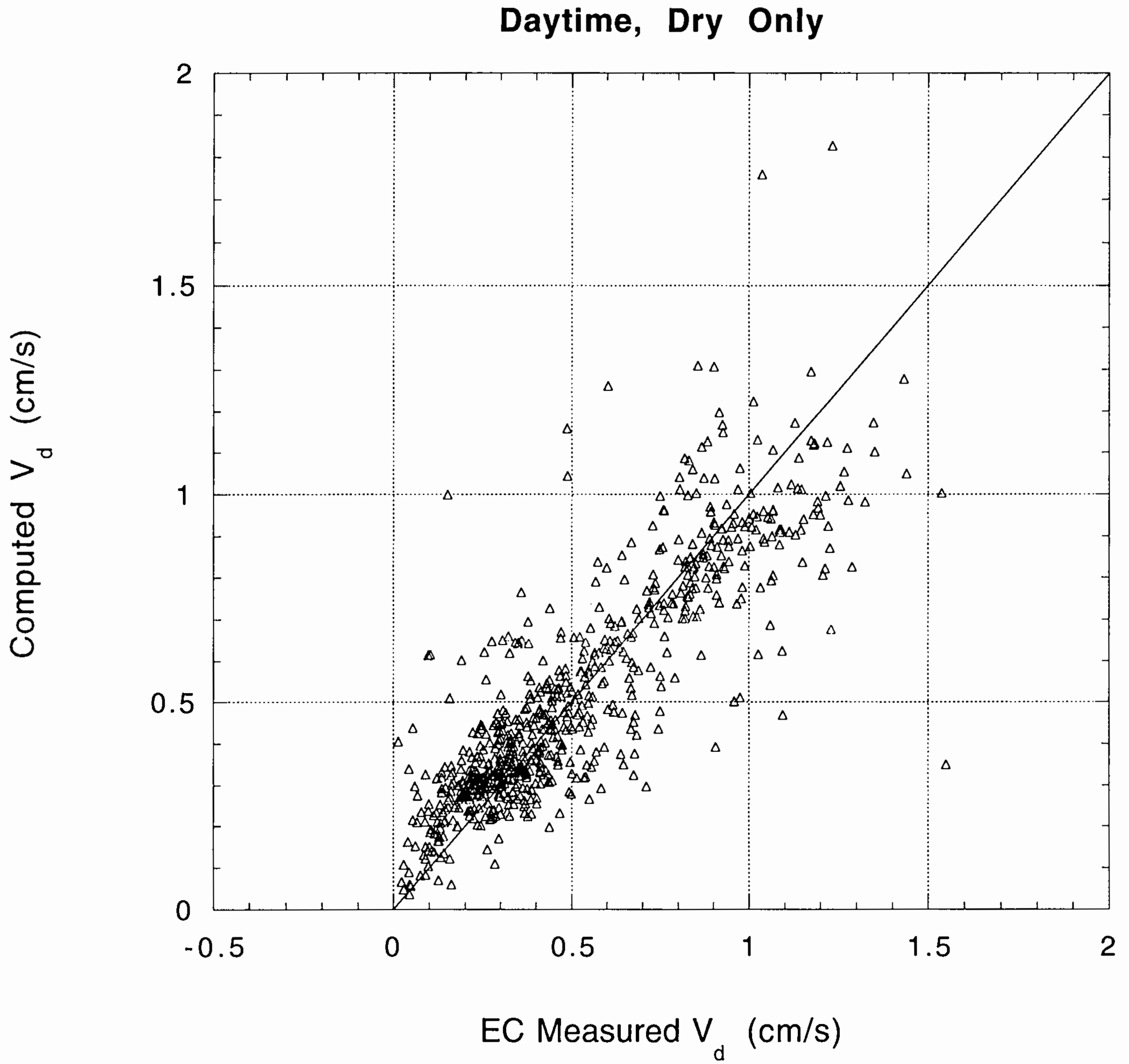
Figure 4. Time series of observed (EC measurements) and predicted (similarity computations) ozone dry deposition velocity for August 1 - 6, 1995.

Figure 5. Same as Figure 4 except that the similarity computations assumed dry conditions for the daytime portion of August 6.

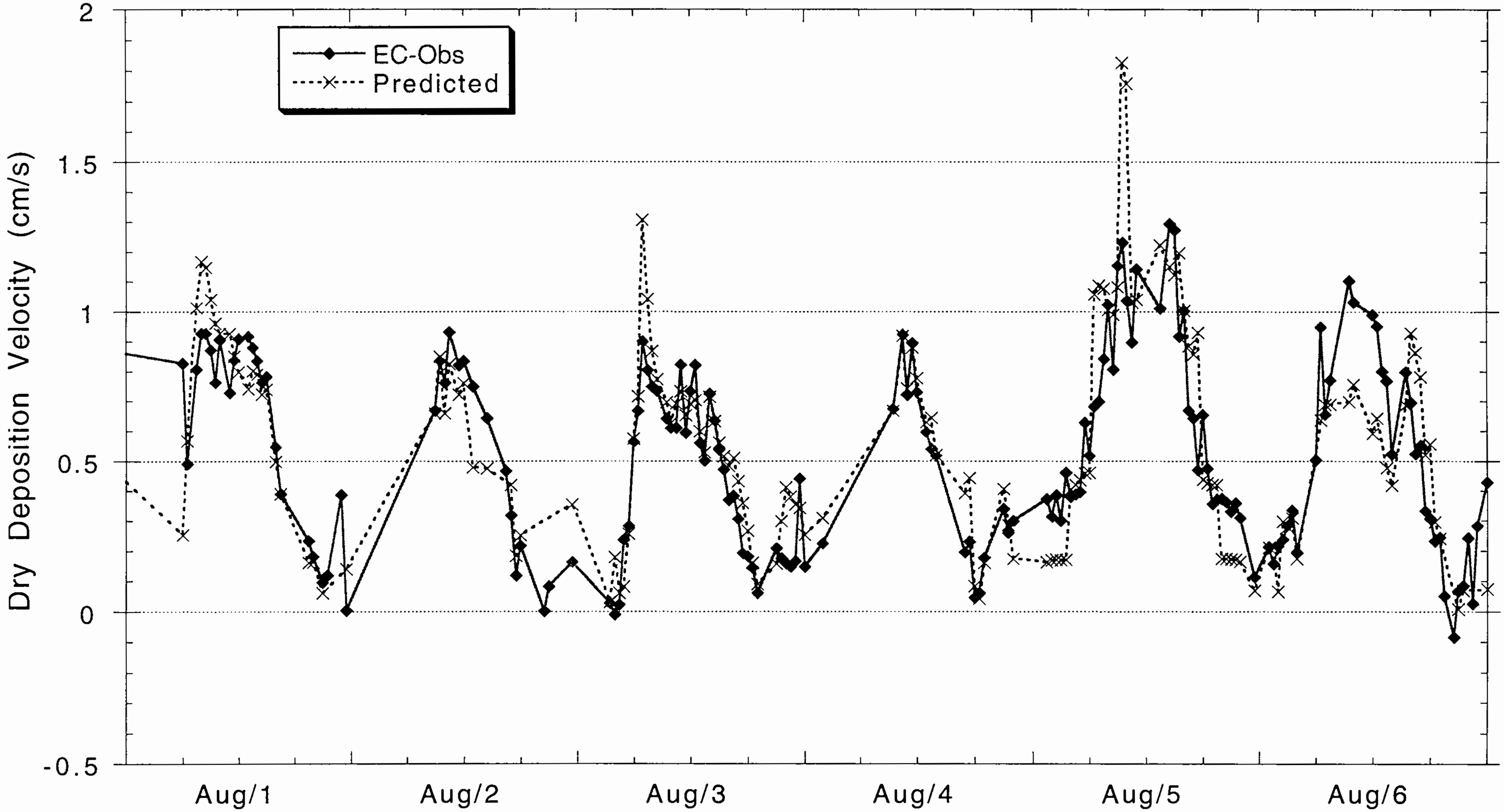
Keysburg, KY, June 22 - October 11, 1995



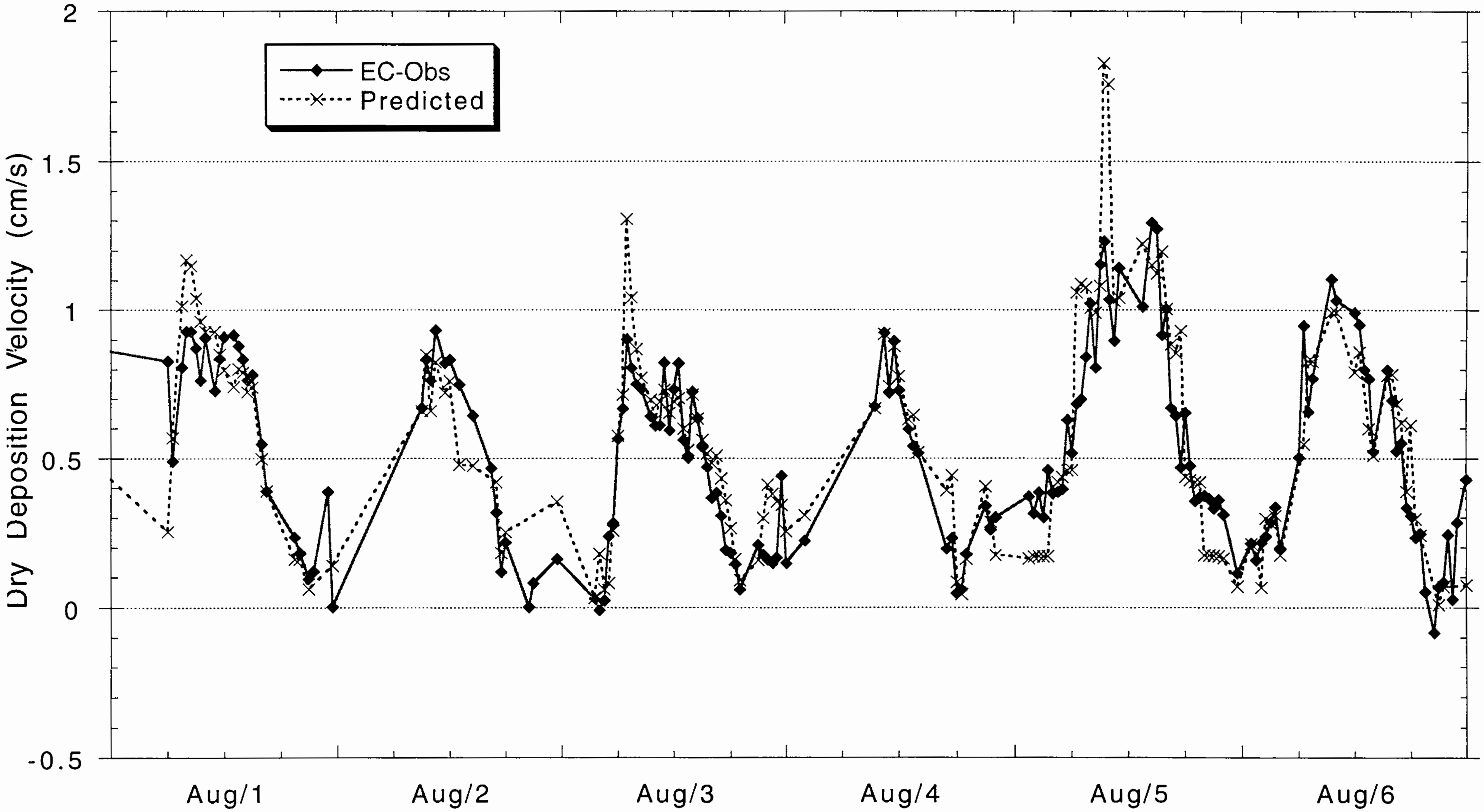

500
400
300
200
100
0
Count
-1.5
- 1
-0.5
0
0.5
1
1.5
Observed - Predicted (cm/s)



Daytime, Dry Only
Computed V_d (cm/s)
EC Measured V_d (cm/s)
0
0.5
1
1.5
2
-0.5
0
0.5
1
1.5
2



EC-Obs
Predicted
Dry Deposition Velocity (cm/s)
2
1.5
1
0.5
0
-0.5
Aug/1
Aug/2
Aug/3
Aug/4
Aug/5
Aug/6



EC-Obs
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0.5
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Aug/1
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Aug/3
Aug/4
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Aug/6

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16. ABSTRACT

Field measurements of chemical dry deposition are needed to assess impacts and trends of airborne contaminants on the exposure of crops and unmanaged ecosystems as well as for the development and evaluation of air quality models. However, accurate measurements of dry deposition velocities require expensive eddy correlation measurements and can only be practically made for a few chemical species such as ozone and CO_2. On the other hand, operational dry deposition measurements such as used in large area networks involve relatively inexpensive standard meteorological and chemical measurements but rely on less accurate deposition velocity models. This paper describes an intermediate technique which can give accurate estimates of dry deposition velocity for chemical species which are dominated by stomatal uptake such as ozone and SO_2. This method can give results that are nearly the quality of eddy correlation measurements at much lower cost. The concept is that bulk stomatal conductance can be accurately estimated from measurements of latent heat flux combined with standard meteorological measurements of humidity, temperature, and wind speed. The technique is tested for a field experiment where high quality eddy correlation measurements were made in a soybean field in Kentucky. Over a four month period, which covered the entire growth cycle, this technique showed very good agreement with eddy correlation measurements for ozone.

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