Adjusting Wind Speed Measured over Variable Height Alfalfa for Use in the ASCE Standardized Penman-Monteith Equation

Thomas W. Ley PE, M. ASCE[1], Richard G. Allen M. ASCE[2], and Marvin E. Jensen M. ASCE[3]

[1] Colorado Division of Water Resources, Pueblo, CO 81004; PH (719) 542-3368; FAX (719) 544-0800; email: thomas.ley@state.co.us
[2] Professor, Research and Extension Center, University of Idaho, 3793 N. 3600 E., Kimberly, Idaho 83341; PH (208) 423-6601; email: rallen@kimberly.uidaho.edu
[3] (retired) USDA-ARS and Colorado State University, Ft. Collins, CO; email: MJensen419@aol.com

Abstract

The ASCE Standardized Reference Evapotranspiration Equation expects the weather station wind speed data to represent that occurring at a height of 2 m over and downwind of a smooth measurement surface such as clipped grass. The Task Committee on the Standardized Equation provided guidance for adjusting wind speed measured at height other than 2 m, or, for situations when the wind speed is measured over and downwind of 0.5 m alfalfa. The latter adjustment attempts to account for the effects of both grass and alfalfa crop characteristics (height, roughness) on the wind profile. A more physically representative approach to adjust wind speeds at various heights and various weather measurement surface conditions to equivalent wind speed at 2 m height over clipped grass is tested. Wind speeds were simultaneously measured during the 2008 growing season at 2-m and 3-m heights above ground surface over variable height alfalfa at two Colorado Agricultural Meteorological Network (CoAgMet) electronic weather stations and at the research alfalfa lysimeter installation at the Colorado State University Arkansas Valley Research Center. These wind speed measurements were adjusted to estimated wind speed at 2 m over grass, and compared.

Introduction

In his fourth report (Littleworth, 2003) in the case of Kansas v. Colorado (No. 105, Original, U.S. Supreme Court), regarding compliance with the Arkansas River Compact, the Special Master hearing the case recommended specific changes by which Arkansas River streamflow depletions at the Colorado-Kansas Stateline are determined. One of the major changes was the recommendation to use the ASCE Standardized Reference Evapotranspiration Equation (ASCE-EWRI, 2005) as the method to determine reference crop evapotranspiration and the basis for determining crop consumptive use. Steps taken by the States of Colorado and Kansas to implement this recommendation are discussed fully elsewhere in these proceedings (Book and Brengosz, 2009; Brengosz, 2009; Ley et al., 2009). One activity undertaken by the State of Colorado, in cooperation with the Colorado Climate Center, was to expand and improve the collection of weather data suitable for use in the Standardized Equation. To this end, new Colorado Agricultural Meteorological Network (CoAgMet) electronic weather stations were installed, or existing stations moved, into large, private, commercial irrigated alfalfa fields in the lower Arkansas Valley of Colorado. Locating stations in irrigated alfalfa fields was done because of the need to collect weather data for the Standardized Equation in an irrigated environment with adequate fetch (ASCE-EWRI, 2005), and because of a lack of large irrigated grass or pasture fields that could be used for this purpose.

American Society of Agricultural and Biological Engineers Engineering Practice EP505: Measurement and Reporting Practices for Automatic Agricultural Weather Stations recommends that wind speed be measured at 2 m or 3 m height over uniform, low cover vegetation such as grass (ASABE, 2004). The standard wind speed measurement height on CoAgMet weather stations is 2 m above the surface. Some weather station networks measure wind speed at 3 m to avoid or minimize effects of measurement surface vegetation height.

The parameterization of the ASCE Standardized Reference Evapotranspiration Equation (ASCE-EWRI, 2005) expects the wind speed measurement, if not measured at 2-m height over and downwind of a smooth measurement surface such as clipped grass, to be translated to an equivalent value. Specifically, the zero plane displacement, 0.08 m, used in the Standardized Equation for the tall reference crop, is for a weather measurement surface similar to clipped grass, with vegetation height of 0.12 m. The purpose of this was to accommodate a majority of weather stations collecting data over a smooth surface like grass. The Task Committee on the Standardized Equation provided guidance in Appendix B of EWRI-ASCE (2005) for adjusting wind speed measured at height other than 2 m, or, for situations when the wind speed is measured over and downwind of 0.5 m tall alfalfa using standard logarithmic wind speed profile theory. Equation B.14c (ASCE-EWRI, 2005) was developed to adjust wind speed measured over and downwind of 0.5 m alfalfa to an equivalent wind speed over clipped grass for use in the Standardized Equation.

$$u_2 = u_z \frac{\ln\left(\frac{2-d}{z_{om}}\right)}{\ln\left(\frac{z_w-d}{z_{om}}\right)} = u_z \frac{\ln\left(\frac{2-0.08}{0.062}\right)}{\ln\left(\frac{z_w-0.335}{0.062}\right)} = u_z \frac{3.44}{\ln(16.3 z_w - 5.42)} \qquad \text{(B.14c)}$$

where u_2 is wind speed at 2 m above ground surface (m s^{-1}), u_z is wind speed at height z_w over 0.5 m alfalfa (m s^{-1}), d is zero plane displacement height (m) taken as 0.67 h, and z_{om} is aerodynamic roughness length (m) taken as 0.123 h, where h is crop height (m). The d and z_{om} values in the denominator are for the 0.5 m alfalfa weather measurement surface, while the d and z_{om} in the numerator are a combination of the zero plane displacement for clipped grass (0.08) and roughness length for 0.5 m alfalfa (0.062). This combination is an attempt to account for the effects of both grass and alfalfa crop characteristics (height, roughness) on the wind profile. However, there is some question on whether Eq. B.14c functions correctly in translating wind speed measured over a rough surface such as full cover alfalfa to an equivalent for a smooth grassed standard weather surface.

The States of Colorado and Kansas have agreed to temporarily use Eq. B.14c with a seasonal average alfalfa crop height of 0.3 m to adjust the 2-m wind speed data collected at the CoAgMet weather stations located in commercial alfalfa fields. This results in a nominal 1.7% upwards adjustment to measured wind speeds. It is felt that the true ratio of 2-m wind speed measured over clipped grass to 2-m wind speed over alfalfa will exceed this value on a seasonal average basis, and potentially significantly exceed it, during periods when alfalfa is growing at reference conditions. This paper presents the results of initial studies to better define the adjustment of wind speed data measured at 2-m above ground surface over variable height alfalfa.

Background

The second and third authors have performed a considerable amount of research along with Dr. James L. Wright, USDA-ARS (retired), in the development of Penman and Penman-Monteith type evapotranspiration equations, including the ASCE Standardized Reference ET Equation. Much of this work was done at the USDA-ARS research facility in Kimberly Idaho using alfalfa as the reference crop and with wind measurement over a standard grassed weather station surface. This ultimately influenced the final values for surface resistance used in the Standardized Equation, and thus, the wind data input to the equation should be collected over grass (or adjusted to a grass condition) (Allen et al., 1989; Allen and Wright, 1997; ASCE-EWRI 2005). In that case, the wind profile adjusted to grass should be constructed using zero plane displacement and roughness for grass, which, as discussed above, may not be properly done in Eq. B.14c.

A suggested better approach (than Eq. B.14c) to adjust wind data collected over non-standard measurement surface conditions to an equivalent wind at 2 m over clipped grass is to use the full wind speed translation algorithms presented in Allen and Wright (1997) that correctly account for impacts of height and roughness of vegetation of each surface. These algorithms apply the concept of 'blending height' where the wind profiles over the measurement surface and the surface to which wind is being translated are both extended upward to the top of the internal (or inertial) boundary layer, IBL, over each respective surface. At this elevation, the wind speeds (or at least friction velocity) can be assumed to be equal for both surface conditions. The wind speed at the top of the IBL is then extrapolated downward from this height to the surface to which the wind speed is being translated. Equation 13 of Allen and Wright (1997), repeated here as Eq. 1, illustrates this translation algorithm:

$$u_{z,v} = u_{z,w} \frac{\ln\left(\frac{z_{IBL,w} - d_w}{z_{om,w}}\right) \ln\left(\frac{z_{IBL,v} - d_R}{z_{om,R}}\right) \ln\left(\frac{z_v - d_v}{z_{om,v}}\right)}{\ln\left(\frac{z_w - d_w}{z_{om,w}}\right) \ln\left(\frac{z_{IBL,w} - d_R}{z_{om,R}}\right) \ln\left(\frac{z_{IBL,v} - d_v}{z_{om,v}}\right)} \quad (1)$$

where $u_{z,w}$ is the measured wind speed (m s^{-1}) at a weather station at height z_w (m) having vegetation type W, and $u_{z,v}$ is the equivalent wind speed (m s^{-1}) estimated to have occurred at height z_v (m) above a surface of vegetation type V. $z_{IBL,w}$ and $z_{IBL,v}$ are the heights (m) of the IBL over the weather measurement surface (W) and over the surface (V) to which wind is being translated. d_w, d_R, and d_v are the zero plane displacement heights (m), taken as 0.67 h, for the weather measurement vegetation, the regional vegetation, and, the vegetation of surface V. $z_{om,\,w}$, $z_{om,\,R}$, and $z_{om,\,v}$, are aerodynamic roughness lengths (m) taken as 0.123 h, for the weather measurement vegetation, the regional vegetation, and, the vegetation of surface V. The variable h is vegetation height (m) for each surface condition (W, R, and V).

Eq. 1 is a multiplicative combination of the basic logarithmic wind speed profile relationship and extrapolates wind measured at z_w upward to $z_{IBL,w}$, then from $z_{IBL,w}$ upward to $z_{IBL,R}$, then from $z_{IBL,R}$ downward to $z_{IBL,v}$, and finally from $z_{IBL,v}$ downward to z_v. The intermediate steps to extrapolate up from the weather measurement surface IBL to the regional internal boundary layer and back down to the IBL for surface V is necessary when the heights of the IBL's for the weather measurement surface and for surface V are expected to be different from each other due to different vegetation roughness and fetch lengths for each condition. The regional IBL is assumed to occur directly above the IBL's of the two underlying surfaces and integrates the effects of surface conditions for a large area on the regional wind speed profile. One limitation of the approach of Eq. 1 is that it assumes that neutral boundary layer buoyancy conditions hold. This is generally the case for reference and agricultural conditions when vegetation is near full-ground cover (Allen and Wright, 1997) and the same assumption is used in the derivation and application of the standardized reference ET equation (ASCE-EWRI 2005).

Use of Eq. 1 requires estimating the thickness or height the IBL for each surface condition and the region. The thickness of the IBL depends on the size of the area having similar surface properties, including roughness, vegetation characteristics, and moisture conditions. Allen and Wright (1997) present an approach developed by Brutsaert (1982) to approximate the growth of the IBL over an individual field downwind of a surface discontinuity. Their Eq. 14 is repeated here as Eq. 2:

$$z_{IBL} = d + 0.33 z_{om}^{\ 0.125} x_f^{\ 0.875} \quad (2)$$

where z_{IBL} is the height of the IBL over a surface having roughness, z_{om}, and zero plane displacement, d, at a horizontal distance downwind, x_f, of a substantial change in surface or vegetation characteristics, all in (m). Surface roughness, z_{om}, and zero plane displacement, d, are approximated as 0.123 h, and 0.67 h, respectively, where h is vegetation height (m).

It should be noted that when the weather station measurement surface (W) and the surface to which wind speed is being translated (V) are both alfalfa with the same fetch conditions, then Eq. 1 reduces to the standard wind speed profile adjustment equation, which is simply an adjustment for wind speed measurement height. The leftmost part of Eq. B14c (as presented above) shows this adjustment, where the d and z_{om} values in both the numerator and denominator are for variable height alfalfa. For example, the adjustment could be from wind speed measured at 3 m above ground surface over alfalfa to 2 m above ground surface over alfalfa.

Methods and Materials

Concerns on the effects of full canopy alfalfa on wind speed measured at 2 m above the ground surface prompted the outfitting of three weather stations along the Arkansas River valley of southeastern Colorado that were in the interiors of alfalfa fields with additional wind speed measurement instrumentation at 3-m height. The three stations comprised two CoAgMet stations located in large alfalfa fields, Las Animas and Holly 02, and the meteorological station at the research alfalfa lysimeter site at the Colorado State University Arkansas Valley Research Center (CSU-AVRC) near Rocky Ford. The outfitting was completed in early June 2008 (see Table 1). In all instances, RM Young Wind Sentry cup anemometers were used at both 2-m and 3-m heights above the ground surface. The existing 2-m height cup anemometers were serviced with new upper and lower shaft bearings and were cleaned at the time of the installation of the 3-m height anemometers, which were all brand new. The CSU-AVRC lysimeter installation is also equipped with a RM Young Wind Monitor (propeller anemometer with integrated vane). The CoAgMet stations are equipped with CR-10X data loggers programmed to measure attached sensors every 10 seconds. Final wind speed data values stored in the CoAgMet database are the mean hourly wind speed (m s^{-1}) and the daily wind run (km d^{-1}). The CSU-AVRC lysimeter meteorological instrumentation is measured by a CR-7X data logger programmed to measure on a 6-sec interval. Final output data includes 5-minute, 15-minute, and daily average wind speed (m s^{-1}).

The typical growth pattern of alfalfa (green chopped or harvested for hay) in the lower Arkansas Valley of Colorado is for spring greenup to begin in late March/early April. Four harvests are usual, occurring approximately the first week of June, the middle of July, the end of August and mid to late October. Fall dormancy and or killing frosts occur by late October. Alfalfa crop growth and harvest data were documented at the CSU-AVRC site, and monitored and documented with photos at the two CoAgMet sites. Cutting dates were obtained from the cooperators at the CoAgMet sites. See Table 1. Crop height curves through the season were approximated at each site using these data, and a simple linear-segmented crop height model similar in structure to the simple single crop coefficient model described in

Table 1. 3-m anemometer installations and crop growth dates during 2008 at the three study sites.

Site	Lat	Long	Elev (m)	3-m anem. installation date	Spring Greenup	First harvest	Second harvest	Third harvest	Fourth harvest
CSU-AVRC	38.04	103.70	1274	Jun 12	Apr 1	Jun 11	Jul 19	Aug 29	Nov 3
Las Animas	38.15	102.86	1187	Jun 4	Apr 1	Jun 14	Jul 22	Aug 28	Nov 11
Holly 02	38.14	102.24	1088	Jun 4	Mar 20	May 30	Jul 8	Aug 21	Oct 18

FAO-56 (Allen et al., 1998). Crop height during the initial growth stage was taken as 0.12 m, and during full canopy stage as 0.50 m, except during the last growth cycle of the season, when maximum alfalfa height attained was only about 0.35 m at all sites. Crop growth between harvests was broken into 3 or 4 intervals, the initial period, rapid development, full canopy, and late. The initial period is normally 5-7 days, except during the first cycle when growth is slower due to cooler temperatures. Rapid development occurs over about 20 days, and full canopy and late stages are from 10-15 days during the mid-season. The impact of alfalfa vegetation height on reducing the ratio of wind speed measured at 2-m height above ground surface to that made at 3-m height above ground surface became more pronounced as the alfalfa grew.

Eqs. 1 and 2 were used to translate both the 2-m and 3-m measured mean daily wind speeds (m s^{-1}) at each site to an equivalent 2-m mean daily wind speed (m s^{-1}) over clipped grass, termed adjusted 2-m and adjusted 3-m mean daily wind speeds in the discussion of results. The alfalfa weather station measurement surface (crop height) at each site varied with time as described above. The fetch of similar surface conditions in each case, i.e., x_f, in Eq. 2, was taken as 200 m for all three deployments, although in the case of CSU-AVRC, there were corn fields or plots 83 m to the north and 100 m to the south of the meteorological instrumentation on the lysimeter field. East and west fetch distance was well over 200m.

An additional measure of wind speed was made at the Rocky Ford CoAgMet station during 2008, over a surface that approximates a standard clipped grass surface. However, these wind data were not reliable for 2008 because corn research plots were located in the near vicinity of the anemometer (5-60 m to the south and west/NW). During June – mid October, when the corn on the plots was taller than about 1 m, sheltering effects on wind speed measurements from the CoAgMet station were evident. Therefore, and unfortunately, the wind speed measurements from the grassed Rocky Ford CoAgMet station could not be used for comparison and as a reality check for the alfalfa wind speed data that were translated to an equivalent wind speed at 2 m over grass.

Eq. 1 was applied to translate measured wind speeds to values representing equivalent wind speeds expected to have occurred over 0.12-m grass having 200 m of fetch and at the 2-m height (i.e., conditions for a standard weather station). The regional condition in each case was taken as having 1000 m of irrigated fetch with an average vegetation height of 0.5 m. The 0.5 m height represents a mixture of agricultural crops including alfalfa, field corn, grains and vegetables.

Eq. 1 was also applied in reduced form (as discussed above) to translate the 3-m measured wind speeds over alfalfa to estimated 2-m wind speeds over alfalfa at each site. The estimated 2-m wind speeds were then compared to the measured 2-m wind speeds. This translation allows a check on the whether the logarithmic adjustment holds over the alfalfa fields and that the assumption of neutrality is generally valid.

Results

The measured 3-m mean daily wind speed is plotted against measured 2-m mean daily wind speed (upper graph), and the adjusted 3-m mean daily wind speed is plotted versus the adjusted 2-m mean daily wind speed (lower graph), for each of the three sites, respectively, in Figures 1, 2, and 3. Wind speeds typically increase as one moves west to east in the Lower Arkansas Valley of Colorado. For the period June 15 to Oct 31, 2008, the cumulative daily wind run measured at 2-m and 3-m height, respectively, was 23,143 km and 26,577 km at CSU-AVRC; 33,511 km and 37,379 km at Las Animas; and, 33,900 km and 39,180 km at Holly02. The average ratio of measured 3-m to 2-m mean daily wind speeds for this period was 1.148 at CSU-AVRC; 1.116 at Las Animas; and, 1.156 at Holly02. During this period, CSU-AVRC had 62 days, Holly02 had 63 days, but Las Animas had only 41 days when the alfalfa height was 0.35 m and taller. This partially explains the smaller 3-m to 2-m wind speed ratio at Las Animas for the period.

The factor, computed using Eqs. 1 and 2, to adjust the measured 2-m wind speed to the standard weather station condition ranged from 1.00 to 1.18 for alfalfa crop heights of 0.12 m and 0.50 m, respectively, at all 3 sites. The average adjustment factor for April 1 to October 31 across all three sites was 1.09. Conversely, the factor to adjust the measured 3-m wind speed ranged from 0.92 to 1.03 for crop heights of 0.12 m and 0.50 m, respectively, with an April 1-October 31 average adjustment factor of 0.98 across all three sites. The 3-m adjustment factor ranged from 0.98 to 1.03 during periods when the alfalfa crop could be considered at full canopy, 0.30 to 0.50 m in height.

An objective of this study was to adjust measured 2-m and 3-m wind speeds so that the adjusted wind speeds from both heights, representing equivalent wind speeds measured at 2 m over 0.12 m grass, was the same and reflected wind speeds expected over a grassed surface. In Figures 1-3, the measurements made at 2 m over the ground surface for alfalfa were increased following adjustment, and acquired values similar to those derived when adjusting the 3-m measurements over alfalfa to 2 m over a standardized grass surface. Table 2, part (A) is a summary of the measured and adjusted 2-m and 3-m wind speed data for all three sites for the study intervals

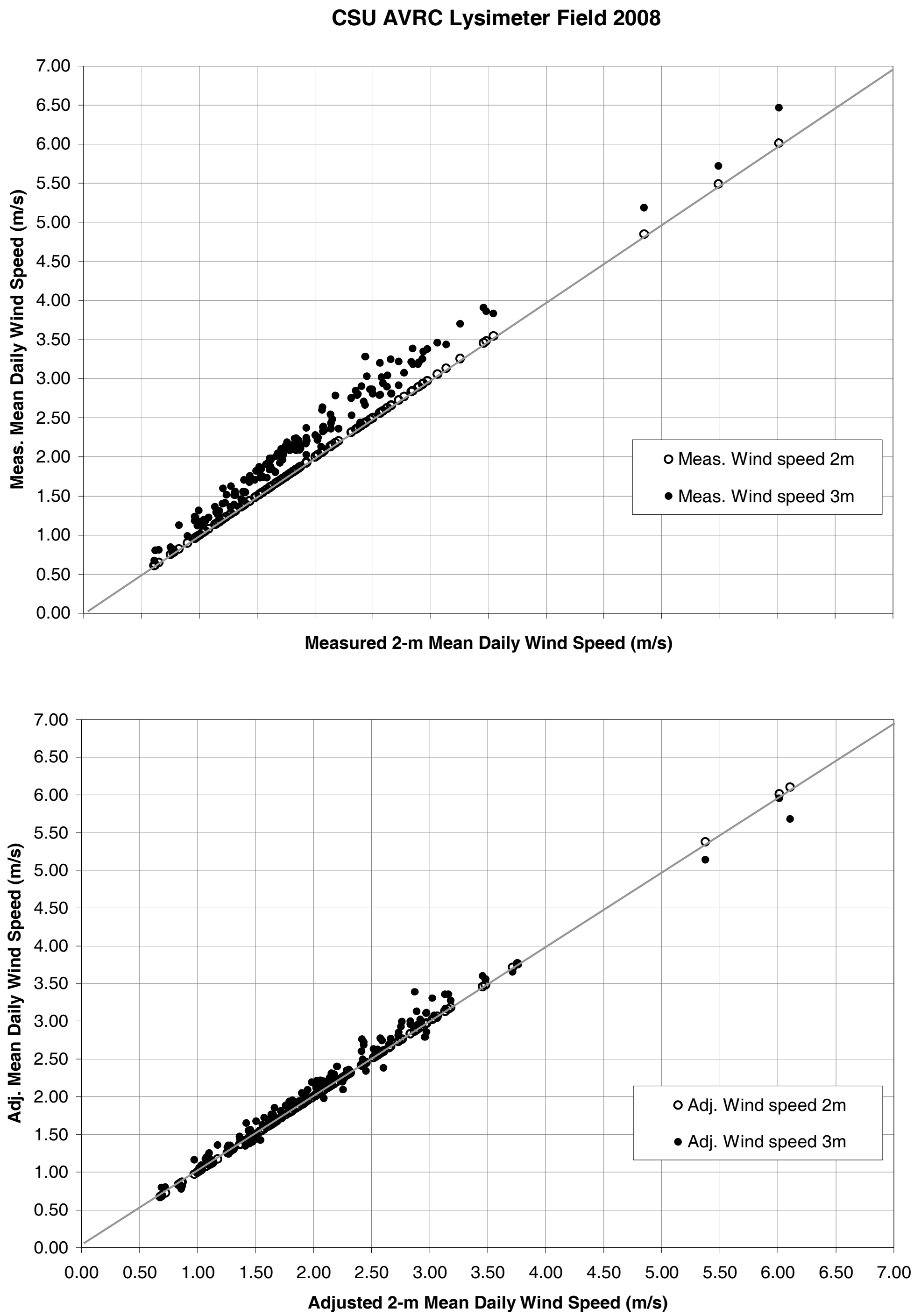
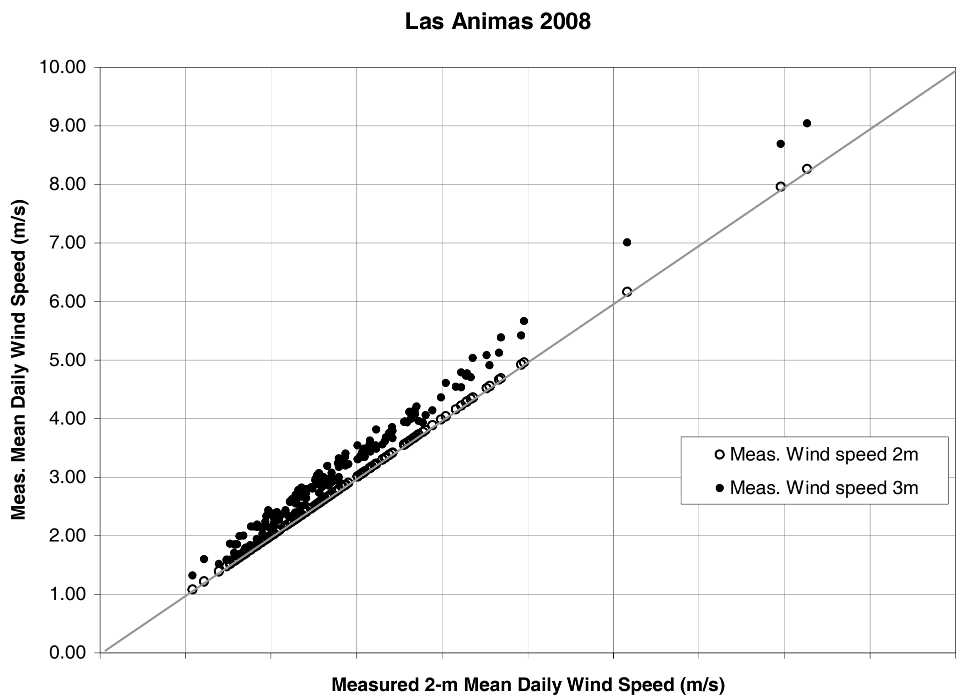


Figure 1. Comparison of measured 2-m and 3-m mean daily wind speeds (upper graph) and adjusted 2-m and 3-m mean daily wind speeds (lower graph) at CSU AVRC.



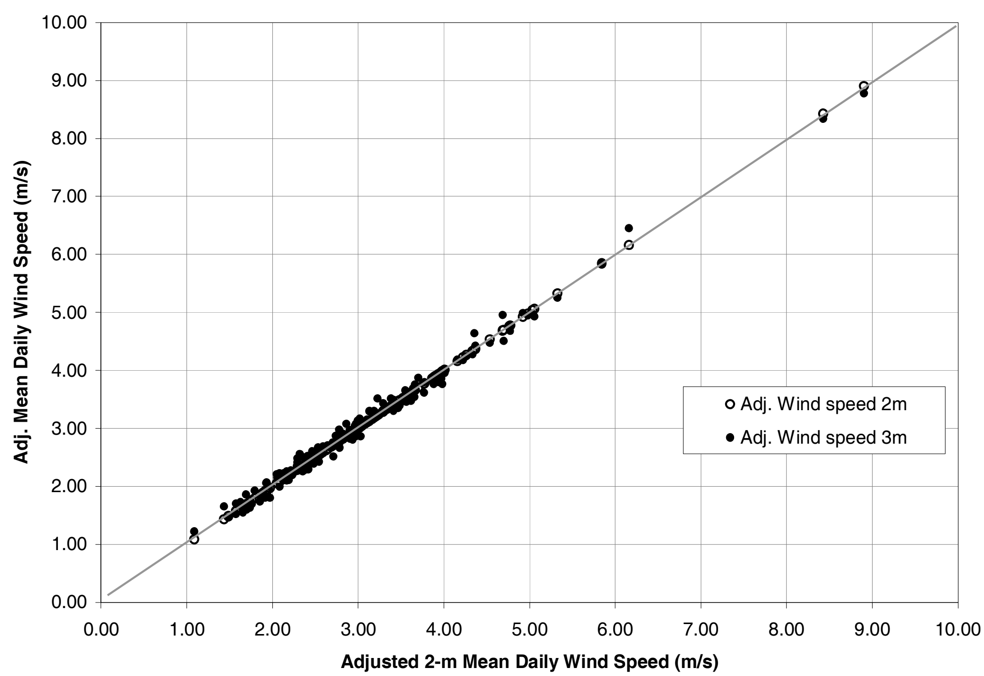


Figure 2. Comparison of measured 2-m and 3-m mean daily wind speeds (upper graph) and adjusted 2-m and 3-m mean daily wind speeds (lower graph) at Las Animas CoAgMet station.

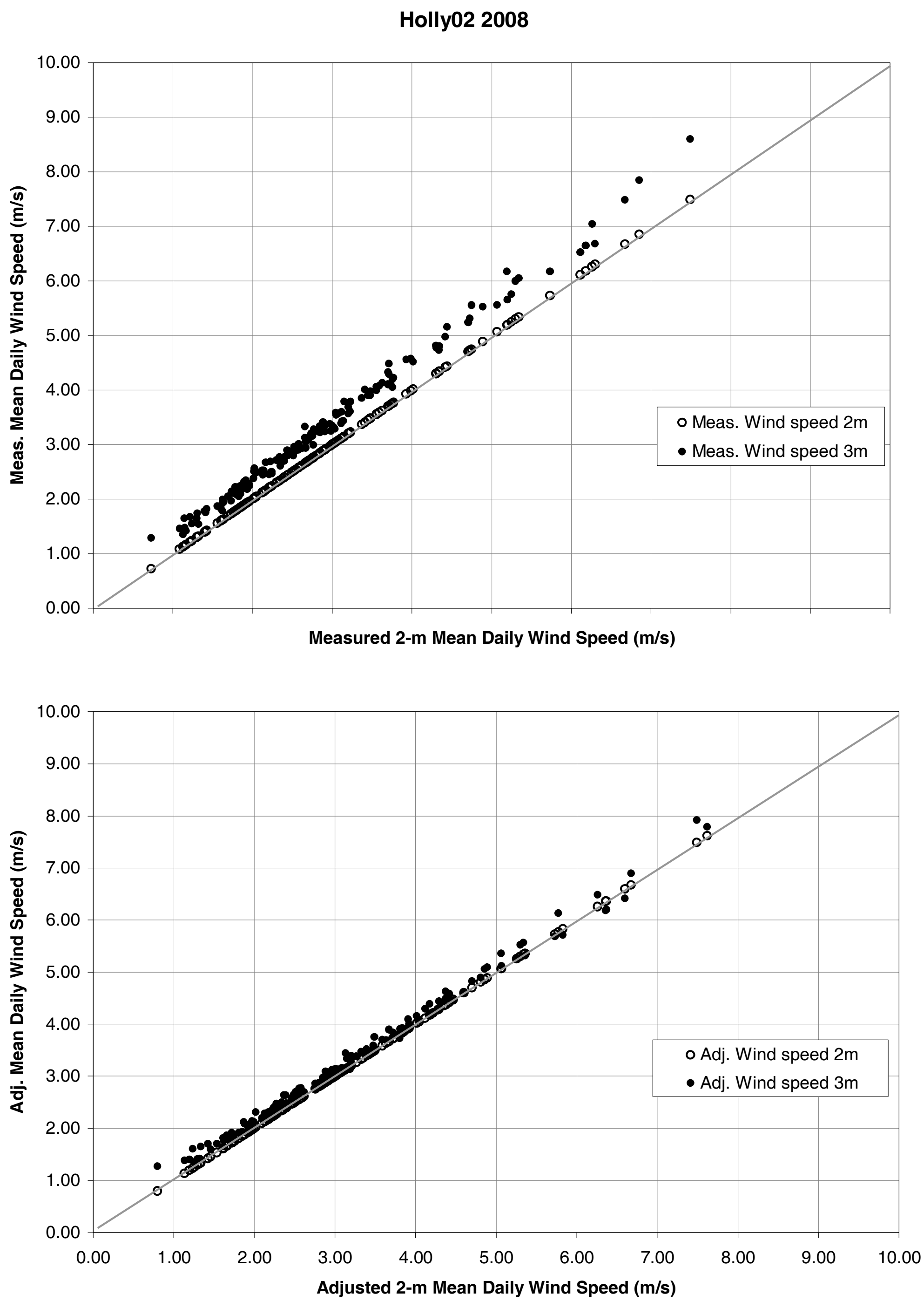


Figure 3. Comparison of measured 2-m and 3-m mean daily wind speeds (upper graph) and adjusted 2-m and 3-m mean daily wind speeds (lower graph) at Holly02 CoAgMet station.

indicated. These results and lower graph in each of Figures 1-3 show the adjustment method is relatively effective and internally consistent, in that the adjusted wind speeds are similar. For example, the results in Table 2 show the mean difference between the measured 2-m and 3-m daily wind speeds was 0.28 m s^{-1} at CSU-AVRC, 0.33 m s^{-1} at Las Animas, and 0.43 m s^{-1} at Holly02. After adjustment using Eq. 1, the mean difference between the adjusted 2-m and 3-m daily wind speeds was 0.07 m s^{-1} at CSU-AVRC, 0.02 m s^{-1} at Las Animas, and 0.12 m s^{-1} at Holly02. The adjustment procedure reduced the difference by 75% at CSU-AVRC, by 94% at Las Animas, and by 72% at Holly02. The variability of the performance of the adjustment algorithm suggests additional investigation is needed on the sensitivity of the error closure to the values used for regional fetch length, regional vegetation height, the estimation method for the height of the IBL's, etc.

The last column of Table 2 indicates the standard deviation of the average difference between the adjusted daily 2-m and 3-m wind speeds to be within 3-5% of the mean adjusted 2-m wind speeds.

At CSU-AVRC, adjustment statistics were also computed for a subset of days, designated as CSU-AVRC (subset) in Table 2, when mean daily wind direction was from either of two 90-degree sectors: NE to SE or SW to NW. This was done to determine if the corn crops to the north and south of the lysimeter field affected the measured and adjusted wind speeds. The measured and adjusted mean daily 2-m and 3-m wind speeds were slightly less for the subset of days at CSU-AVRC. The standard deviation of the daily difference between adjusted 2-m and 3-m wind speeds was also slightly less. Filtering days from the data set when the mean wind direction was from the areas of the corn fields does not appear to have much impact on the results.

Least squares linear regression relationships were computed for each of the adjusted 2-m and 3-m wind speeds versus the measured 2-m wind speed at all three sites. As well, least squares linear regression relationships were computed for adjusted 3-m wind speed versus the adjusted 2-m wind speed at all three sites. At CSU- AVRC, these linear regressions were computed for both the full data set and the wind direction-filtered subset of days. Results are summarized in Table 3. The values for r^2 were high, as expected, due to the large covariance between wind speed measurements at the two heights. In general, no improvement in r^2 was found for the CSU-AVRC subset, when the data were filtered for wind direction. The individual site regression equations, or the overall mean regression equations for adjusting 2-m wind speed measured over alfalfa and presented at the bottom of Table 3, part (A) may provide a simple means for adjusting wind speeds collected over variable height alfalfa to equivalent wind speeds for the standard weather station conditions when nothing is known about alfalfa growth periods and harvest dates, especially in the case where wind speed measurement height is to be standardized at 2 m, as in the case of CoAgMet. Adjustments to measured 2-m wind speeds over alfalfa using the overall mean regression equation developed using the CSU-AVRC subset compared to those made using the full logarithmic wind speed profile translation algorithm, Eq.

Table 2. Comparison of measured mean daily wind speeds, adjusted mean daily wind speeds, average difference between adjusted wind speeds, standard deviation of the difference, and standard deviation of the difference as percent of mean adjusted 2-m mean daily wind speed at the three study sites: (a) comparison for Eq. 1-adjusted 2-m and 3-m mean daily wind speeds, (b) comparison for Eq. 1-adjusted 2-m mean daily wind speed and regression equation adjusted 2-m mean daily wind speed, and (c) comparison for 2.7 m mean daily wind speeds over alfalfa with Eq.1 adjusted 2-m mean daily wind speeds (grass equivalent).

Site	Interval	Measured mean daily wind speed (m/s)		Adjusted mean daily wind speed (m/s)		Ave. Difference (m/s)	Std. Dev. of Diff. (m/s)	Std. Dev. of Diff. as Percent of Adj. 2-m Mean Daily Wind Speed
(A)		**2-m**	**3-m**	**2-m**	**3-m**			
CSU-AVRC	6/13-10/31	1.95	2.23	2.11	2.18	0.07	0.11	5.27
CSU-AVRC (subset)	6/13-10/31	1.91	2.20	2.09	2.16	0.07	0.10	4.90
Las Animas	6/5-10/31	2.83	3.16	3.06	3.08	0.02	0.11	3.53
Holly 02	6/5-10/31	2.94	3.37	3.16	3.28	0.11	0.11	3.36
(B)		**2-m**	**3-m**	**2-m**	**Regression Eq.[1/]**			
CSU-AVRC	6/13-10/31	1.95	2.23	2.11	2.12	0.01	0.14	6.41
CSU-AVRC (subset)	6/13-10/31	1.91	2.20	2.09	2.09	-0.01	0.13	6.32
Las Animas	6/5-10/31	2.83	3.16	3.06	3.03	-0.03	0.20	6.65
Holly 02	6/5-10/31	2.94	3.37	3.16	3.14	-0.02	0.19	6.13
(C)				**grass**	**alfalfa**			
		2-m	**3-m**	**2-m**	**2.7-m**			
CSU-AVRC	6/13-10/31	1.95	2.23	2.11	2.11	0.00	0.11	5.08
Las Animas	6/5-10/31	2.83	3.16	3.06	3.06	0.00	0.16	5.07
Holly 02	6/5-10/31	2.94	3.37	3.16	3.17	0.01	0.16	5.20

[1/] Adjusted mean daily wind speed computed using overall mean regression of adjusted 2-m wind speed versus the measured 2-m wind speed for all sites and the CSU-AVRC subset of days (see Table 3).

Table 3. Results of linear regression analyses of: a) adjusted 2-m and 3-m mean daily wind speed (m s^{-1}) to a standardized wind speed at 2 m over clipped grass versus measured 2-m mean daily wind speed (m s^{-1}) over alfalfa, b) adjusted 3-m mean daily wind speed (m s^{-1}) versus adjusted 2-m mean daily wind speed (m s^{-1}) where both are adjusted to a standardized wind speed at 2 m over clipped grass, and c)) adjusted 3-m mean daily wind speed (m s^{-1}) versus measured 2-m mean daily wind speed (m s^{-1}) where both are over alfalfa.

Regression Parameter	CSU-AVRC (all days)	CSU-AVRC (subset of days)	Las Animas	Holly02
(A)				
regression of adjusted 2-m wind speed versus the measured 2-m wind speed				
slope	1.04	1.07	1.06	1.01
intercept	0.09	0.05	0.07	0.19
r^2	0.98	0.97	0.97	0.98
regression of adjusted 3-m wind speed versus the measured 2-m wind speed				
slope	1.01	1.05	1.05	0.99
intercept	0.21	0.14	0.13	0.35
r^2	0.95	0.95	0.97	0.98
overall mean regression of adjusted 2-m wind speed versus the measured 2-m wind speed				
	All sites (all days)	All sites (CSU-AVRC subset of days)		
slope	1.04	1.03		
intercept	0.11	0.12		
r^2	0.98	0.98		
(B)				
regression of adjusted 3-m wind speed versus the adjusted 2-m wind speed				
slope	0.98	0.99	0.98	0.98
intercept	0.11	0.09	0.07	0.16
r^2	0.98	0.98	0.99	0.99
(C)				
regression of adjusted 3-m wind speed versus the measured 2-m wind speed (both over alfalfa)				
slope	0.98	0.99	0.99	0.99
intercept	0.10	0.09	0.05	0.14
r^2	0.99	0.98	0.99	0.99

1, with time variable crop height data, resulted in less than ±1% difference in the adjusted seasonal mean daily wind speed. See Table 2, part (B).

The results shown in Table 3, part (B) are best fit equations for the data plotted in the lower graph of each of Figures 1-3 (with the exception that the CSU-AVRC subset data have not been plotted). The r^2 values are generally higher in this case compared with those in Table 3, part (A), because the time-variable impacts of alfalfa vegetation height are factored out, i.e., both data sets have been adjusted to the same datum (grass roughness). These regression results (with slopes near 1.00 and small intercepts) indicate the wind speed translation algorithm (Eq. 1) is internally consistent, i.e., the adjusted 3-m wind speeds are nearly the same as the adjusted 2-m wind speeds.

Table 3, part (C) shows the results of regressions of the measured 3-m wind speed adjusted to a 2-m height above ground over alfalfa versus the measured 2-m wind speeds above ground over alfalfa at each site. These results indicate the logarithmic wind profile adjustment holds over the alfalfa fields and that the assumption of neutrality is generally valid.

Estimate of neutral wind speed measurement height over alfalfa. The range of the adjustment factors to adjust the 2-m and 3-m mean daily wind speeds measured over alfalfa (as computed using Eq. 1) to equivalent mean daily wind speed at 2 m over grass suggests there is an intermediate height for wind speed measurement above ground surface over variable height alfalfa that is neutral and approximates wind speed at 2 m over grass without need for adjustment. By setting $u_{z,w}$ equal to $u_{z,v}$ in Eq. 1, one can solve directly for z_w, the alfalfa wind speed measurement height as a function of the alfalfa crop height. The result is a z_w time series reflecting the alfalfa growth and harvest periods. Neutral, seasonal mean wind speed measurement height over alfalfa that is equivalent to mean wind speed measured at 2 m over grass was computed in this fashion for the periods of data collection at all three locations in 2008. The mean neutral alfalfa weather station wind speed measurement heights were 2.73 m for CSU-AVRC, 2.67 m for Las Animas, and 2.70 m for Holly02; or, across all three sites, the average is 2.70 m. Anemometers deployed at this height in actively growing and harvested alfalfa fields (having similar growth and harvest patterns as the study area, Table 1) would be expected to measure wind speeds over alfalfa that do not need adjustment prior to computing alfalfa reference ET_{rs}. This was evaluated by adjusting the measured 2-m wind speeds at each location to a height of 2.70 m using logarithmic wind profile adjustment for height (discussed previously), and comparing the resultant values with the Eq.1 adjusted 2-m wind speeds (that represent equivalent wind speed at 2 m over grass). Results are shown in Table 2, part (C), in the format similar to previously discussed results. The results show there is very good agreement between the two sets of wind speed estimates at all three sites (average differences near 0.00), but with more scatter/dispersion in the differences, (similar or larger values for the std. deviation of the differences).

Impacts on computed reference ET. ASCE standardized equation alfalfa reference ET_{rs} was computed for the period of data collection during 2008 at all three sites using the following wind speed data sets: a) measured 2-m mean daily wind speed, b) measured 3-m mean daily wind speed, c) Eq. 1 adjusted 2-m mean daily wind speed, d) Eq. 1 adjusted 3-m mean daily wind speed, and e) mean daily wind speed adjusted using the overall mean regression equation for all sites with the CSU-AVRC wind direction-filtered subset of days (i.e., Equiv. 2-m wind speed over grass (m s^{-1}) = 1.04 * measured 2-m wind speed over alfalfa (m s^{-1}) + 0.12). Results are presented in Table 4. The period of data collection at each site essentially covers three alfalfa growth cycles. Computed ET_{rs} using measured 3-m mean daily wind speed is from 4.3-5.6% greater, using adjusted 2-m mean daily wind speed is from 1.4-3.2% greater, and using adjusted 3-m mean daily wind speed is from 3.1-4.5% greater than when computed using the measured (over alfalfa) 2-m mean daily wind speed. Using the regression-equation adjusted mean daily wind speed (based on the general equation listed earlier in this paragraph) results in an increase of computed alfalfa reference ET by 2-3% compared to using measured (over alfalfa) 2-m mean daily wind speed. The 'true' ET_{rs} values, (i.e., as computed using measured wind speed at 2 m above ground surface over clipped grass), would likely have been in the range of 2 to 4% greater than the ET_{rs} calculated using the wind speeds collected at 2-m height above ground surface over the alfalfa crops. On average, ratios of the 3-m to 2-m unadjusted wind speeds averaged about 1.15, as noted earlier, and ratios of ET_{rs} using these two wind data sets averaged about 1.05. This suggests that, in the context of weather data along the Arkansas River, the 15% increase in measured wind speed from 2-m to 3-m height causes the seasonal ET_{rs} estimate to increase by 5%, or a ratio of about 1 to 3.

Table 4. Comparison of computed Standardized Alfalfa Reference ET for measured and Eq. 1 adjusted 2-m and 3-m mean daily wind speed data sets, and regression equation adjusted mean daily wind speed data. Values in parentheses are the ratio of the ET_{rs} value to the ET_{rs} computed using the measured 2-m mean daily wind speeds.

Standardized Alfalfa Reference ETrs (mm)						
Site	Period (DOY)	Meas. 2-m mean daily wind speed	Meas. 3-m mean daily wind speed	Adj. 2-m mean daily wind speed	Adj. 3-m mean daily wind speed	Regression equation adj. mean daily wind speed
CSU-AVRC	165-305	999	1042 (1.043)	1013 (1.014)	1030 (1.031)	1019 (1.020)
Las Animas	157-305	1058	1110 (1.049)	1092 (1.032)	1098 (1.038)	1090 (1.030)
Holly02	157-305	975	1030 (1.056)	1003 (1.029)	1019 (1.045)	1001 (1.027)

Summary and Conclusions

Wind speed data measured at 2-m and 3-m height above ground surface over variable height (growing) alfalfa during 2008 at three sites in the lower Arkansas Valley of Colorado were adjusted to represent wind speeds expected at 2 m over 0.12-m grass having 200 m or more fetch. Wind speed translation algorithms were applied where the wind profiles over the measurement surface and the surface to which wind is being translated are both extended upward to the top of the internal boundary layer over each respective surface. At this elevation, the wind speeds (or at least friction velocity) are assumed to be equal for both surface conditions. The adjustment method was found to be internally consistent—i.e., the adjusted 2-m and 3-m wind speeds at each site were nearly equal in value. This requires, however, careful documentation of alfalfa growth and harvests at the alfalfa weather station. The sensitivity of the method to weather measurement surface fetch, and the vegetation height of the general region, which affects the height of the internal boundary layer over the measurement surface and the translation surface, needs further study.

Measured 3-m wind speed over alfalfa was adjusted to 2-m height above ground over alfalfa and compared to the measured 2-m wind speeds above ground over alfalfa at each site. Results indicate the logarithmic wind profile adjustment holds over the alfalfa fields and that the assumption of neutrality is generally valid.

Ideally, adjusted wind run should be compared to measured 2-m wind run over 0.12-m grass at a standard weather station with 200 m or more fetch. The Rocky Ford CoAgMet site, which is near the CSU-AVRC lysimeter site, approaches these conditions, however, measured wind speed data at this site during 2008 were affected by nearby corn crops.

Adjustments made to wind speed measured at 2-m height above ground over alfalfa to translate the measurements to that expected at 2-m height above ground over clipped grass ranged from 1.00 to 1.18, when the alfalfa height ranged from 0.12 m to 0.50 m. The seasonal (Apr 1-Oct 31) average adjustment factor was 1.09. The maximum, 1.18, and average, 1.09, upward adjustment factors are substantially greater than the 1.7% upward adjustment calculated using Eq. B.14c (ASCE-EWRI, 2005) with seasonal average alfalfa height of 0.30 m. Eq. B.14c appears to underestimate the required adjustment, and we recommend that it not be used to adjust wind speed measured over a rough surface such as alfalfa to the standardized smoother surface of clipped grass that is expected by the standardized reference ET equation.

A single mean regression relation developed using data collected in 2008 may be a suitable method to adjust wind speeds collected over variable height alfalfa to represent wind speeds at 2 m over 0.12-m grass with 200 m of fetch, especially in cases where nothing is known about alfalfa growth periods and harvests at the weather station, and when standard wind speed measurement height is 2 m. Such regression equation-based adjustments when compared to those made using the full logarithmic wind speed profile translation algorithm, Eq. 1, with time variable crop height data, resulted in less than ±1% difference in seasonal mean daily wind speed. This approach needs further study and would benefit from an additional year or two of data to assess variability.

A mean neutral wind speed measurement height over alfalfa (for the alfalfa growth conditions of this study), i.e., which produces equivalent wind speeds at 2-m over grass, of 2.70 m was determined through manipulation of the full wind speed adjustment algorithm expressed here as Eq. 1. Measured 2-m wind speeds over alfalfa adjusted for height to 2.70 m compared well with Eq. 1 adjusted 2-m wind speeds (grass equivalent).

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