TRANSLATING WIND MEASUREMENTS FROM WEATHER STATIONS TO AGRICULTURAL CROPS

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ABSTRACT: Logarithmically based functions were used to translate wind-speed measurements from weather stations to cropped fields. The translations adjusted the wind measurements for both instrument siting height and effects of vegetation height and roughness. The roughness of the original measurement site, of the vegetation for which wind data were desired and of the general region, were considered. The transfer function is necessary for wind measurements over clipped grass in order to directly predict evapotranspiration from agricultural crops using the Penman-Monteith equation. Differences in crop height and roughness between clipped grass and taller agricultural crops can reduce wind speed over the taller crops by as much as 50% in the lower internal boundary layer.

INTRODUCTION

Wind-speed profiles within the internal boundary layer (IBL) are determined by the roughness of the underlying surface and the general velocity of the air mass. Most evapotranspiration (ET) estimation equations, especially the Penman or Penman-Monteith types, employ this principle by measuring weather data at an elevation z above the ground surface. Aerodynamic resistance algorithms used in the Penman-Monteith equation assume that wind speeds measured at height z are characteristic of the crop being evaluated and can be extrapolated to the vegetation surface using logarithmic profiles characteristic of the crop roughness and height. In many studies, however, meteorological data are from standard types of weather stations situated over clipped grass or bare soil, rather than the surface in question. Differences in aerodynamic roughness affect measured wind velocities and the subsequent predictions of aerodynamic resistance (r_a). Magnitudes of r_a and bulk surface (stomatal) resistance for agricultural crops are often similar, averaging about 40–60 s/m^{-1} when wind speeds 2 m above the crops range from 2 to 3 m/s^{-1}. Although surface resistance is generally known with less certainty than r_a, it still may be important to translate wind-speed data to better predict r_a and ET using the Penman-Monteith equation for a specific crop.

The IBL is the well-mixed, lower atmospheric layer that is in equilibrium with the surface below; its logarithmic wind velocity profile can be characterized by aerodynamic attributes of the underlying surface (Panofsky and Townsend 1964; Brutsaert 1982). On the regional scale, the IBL exhibits, on average, a logarithmic wind profile that integrates the roughness of encompassed vegetation types. The regional IBL has, as a lower boundary, individual IBLs that develop above patches or fields of specific vegetation types. The upper boundary of the regional IBL is defined as the elevation below which wind velocity profiles are not significantly affected by Coriolis forces or by the free air stream, and can be described using the von Karman constant K-theory (Prandtl 1932), provided the IBL has neutral buoyancy. K-theory is a simplified model for predicting the mean horizontal wind-speed profile, where it is assumed that at any height z, the product of the square

root of wind shear stress and the logarithm of z divided by aerodynamic roughness is proportional to the constant k multiplied by wind speed at height z and by the square root of air density. Although instability or stability of the boundary layer and near-surface aberrations often invalidate assumptions implicit to K-theory, the procedure is a robust method and is used routinely in evapotranspiration modeling to predict the aerodynamic resistance to flow of sensible heat and vapor from the surface.

Individual IBLs that develop below a regional IBL reflect discontinuity in terrain roughness or vegetation height. The thickness of an individual IBL is a function of the distance downwind from the discontinuity and the length of the new roughness. In general, the thickness of a developing IBL is about one-tenth that of the horizontal fetch (Elliot 1958; Panofsky and Townsend 1964; Bradley 1968; Peterson 1969). A procedure for estimating the thickness of a developing IBL is described in the following section.

The upper boundary of the individual IBL is the elevation where the shear stress, τ, and friction velocity, u_*, equal that of the regional surface upwind and where mean horizontal wind velocities for both the regional and local IBL intersect. Friction velocity is equivalent to the square root of the ratio of τ to air density.

The developing IBL can be viewed as a perturbation layer that represents the average perturbation in the mean wind profile caused by a discontinuity in surface roughness. Within the lower portion of a developing IBL, shear stress and friction velocity are essentially constant and are in equilibrium with the underlying surface. In the lower portion of the developing IBL, termed internal equilibrium sublayer (ESL) by Brutsaert (1982), friction velocity, u_*, is constant with elevation and K-theory applies directly. Peterson (1969) and Brutsaert (1982) suggest that the thickness of the ESL is generally 5–10% of the thickness of the complete IBL and can be defined as the lower portion of an IBL where values of u_* are within 10% of the u_* at the surface. Meteorological instruments should be located within the ESL if simple logarithmic K-theory is used to extrapolate measurements to the evaporating surface. Above the ESL, τ and u_* are no longer constant, but increase or decrease toward the value of τ and u_* characterizing the regional IBL.

At the other extreme, instruments can be placed so close to the ground that they are within the "roughness sublayer" (Cellier and Brunet 1992) where mechanical disturbances by individual roughness elements cause profiles to deviate from standard relationships and where momentum, heat, and vapor transfer is more efficient than predicted by logarithmic similarity (K-theory) using general stability corrections (Thom et al. 1975; Cellier and Brunet 1992). Cellier and Brunet and Jacobs et al. (1989) suggest placing wind, temperature, and

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vapor sensors at elevations that are at least two to three times the mean plant height to avoid these effects.

Several approaches have been suggested to estimate characteristics of developing IBLs and to extrapolate horizontal wind velocities within these IBLs. Elliot (1958) used logarithmic K-theory to characterize the velocity profile within a developing IBL and assumed that u_* was constant throughout all elevations within the IBL and was representative of the ground surface. A simple procedure for estimating the change in u_* with elevation within an IBL is based on ratios of u_* for the region and u_* for the underlying surface (Panofsky and Townsend 1964). This makes it possible to extrapolate velocity profiles within the IBL using a modified logarithmic procedure without creating a discontinuity in u_* at the upper IBL interface. On artificial surfaces, Bradley (1968) and Peterson (1969) found the Panofsky and Townsend (1964) procedure predicts velocity profiles of developing IBLs when surface roughness changes from smooth to rough, but is not as accurate when surface roughness changes from rough to smooth.

DEVELOPMENT OF FIRST WIND-SPEED TRANSLATION ALGORITHM

Under logarithmic K-theory where momentum flux density and u_* are assumed to remain constant with elevation within the IBL, the following proportion holds (Prandtl 1932):

$$\frac{u_*}{(z - d)\, du/dz} = k \tag{1}$$

where u_* = friction velocity; z = elevation above the ground surface; d = zero plane displacement height of the logarithmic wind profile; u = mean horizontal wind speed; and k = von Karman constant that can be taken as 0.41. u_* and u in (1) have equivalent units. When integrated between the surface and height z, (1) becomes

$$\frac{u_*}{u_z} \ln\left(\frac{z - d}{z_{om}}\right) = k \tag{2}$$

where z_{om} = surface roughness height for momentum transfer (same units as z, d), so that wind speed u_z at any elevation z within the IBL is estimated as

$$u_z = \frac{u_*}{k} \ln\left(\frac{z - d}{z_{om}}\right) \tag{3}$$

If u_* is assumed to be constant with increasing z within an IBL, the following (4) can be developed from (2) for computing wind speed at any elevation z_2 within the IBL given wind speed at z_1:

$$u_2 = u_1 \frac{\ln\left(\dfrac{z_2 - d}{z_{om}}\right)}{\ln\left(\dfrac{z_1 - d}{z_{om}}\right)} \tag{4}$$

where u_1 and u_2 = mean horizontal wind speeds at elevations z_1 and z_2, respectively. As is apparent from (4), the roughness and zero plane displacement characteristics of the underlying vegetation affect velocities and shapes of the logarithmic wind profile within an IBL. Eq. (4) follows the approach of Elliot (1958) where u_* is considered to remain constant within the entire IBL.

Panofsky and Townsend (1964) estimated the shape of the mean horizontal wind-speed profile within a developing IBL over surface "V" by varying the value of u_* linearly between u_{*V} near the surface and u_{*R} at the top of the IBL. u_{*V} represents the friction velocity in the lower, fully adjusted portion of the IBL (ESL) and u_{*R} is the friction velocity characteristic
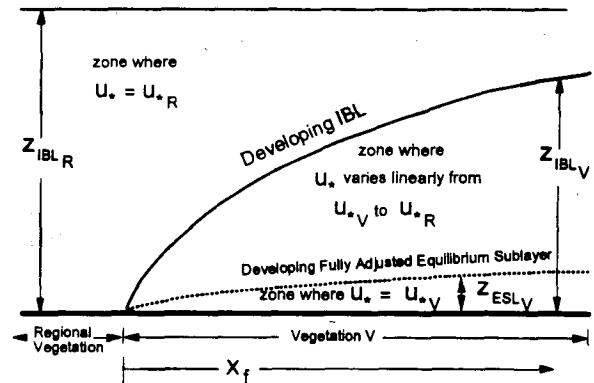

FIG. 1. Schematic Showing a Developing Internal Boundary Layer over Vegetation Type V and Definition of Friction Velocity, u_*, at Various Levels Following Panofsky and Townsend (1964)

of the upwind, regional surface. They used a linear variation in u_* between u_{*V} and u_{*R} proportional to the ratio of z or $z - d_V$ to $z_{IBL\ V}$, where d_V is zero plane displacement height and $z_{IBL\ V}$ is the developed height of IBL over vegetation V. This scheme provides continuity in shear stress at the interface between the developing and regional IBLs. A schematic diagram of a developing IBL and zones for u_*, assuming u_* varies linearly within an IBL, is shown in Fig. 1.

Based on these assumptions, the resulting equation of Panofsky and Townsend (1964) is modified to include zero plane displacement

$$u_z = \frac{u_{*R}}{k}\left[(1 - S)\ln\left(\frac{z - d_V}{z_{om\ V}}\right) + S\frac{z - d_V}{z_{IBL\ V}}\right] \tag{5}$$

where S = relative change in friction velocities between the two surfaces (dimensionless); and $z_{IBL\ V}$ = height of the upper boundary of the IBL developing over a vegetative surface having roughness length and zero plane displacement $z_{om\ V}$ and d_V. S is defined as

$$S = \frac{u_{*R} - u_{*V}}{u_{*R}} \tag{6}$$

where u_{*V} = friction velocity characteristic of the vegetated surface. If the mean horizontal wind profile for the region is defined as in (3), where d and z_{om} are replaced by d_R and $z_{om\ R}$, representing average zero plane displacement and roughness length for momentum transfer for the region, then, assuming continuity of velocity at the upper IBL$_V$ interface where $z = z_{IBL\ V}$, (3) and (5) can be combined and solved for S resulting in

$$S = \frac{\ln\left(\dfrac{z_{om\ R}}{z_{om\ V}}\right)\dfrac{z_{IBL\ V}}{z_{IBL\ V} + d_V - d_R}}{\ln\left(\dfrac{z_{IBL\ V}}{z_{om\ V}}\right) - 1} \tag{7}$$

where $z_{om\ R}$ = average roughness length for the region; d_R = average zero plane displacement for the region; and z in (3) = $z_{IBL\ V}$. If differences between d_V and d_R are small relative to the value of $z_{IBL\ V}$, they can be ignored and (7) reduces to that suggested by Panofsky and Townsend (1964) where

$$S = \frac{\ln\left(\dfrac{z_{om\ R}}{z_{om\ V}}\right)}{\ln\left(\dfrac{z_{IBL\ V}}{z_{om\ V}}\right) - 1} \tag{8}$$

APPLYING EQS. (5-8) TO TRANSLATE WIND VELOCITY OVER NEW VEGETATION

Eq. (5) can be solved for u_{*R} using wind-speed measurements taken over a weather surface as

$$u_{*R} = \frac{k u_{z\ w}}{\left[(1 - S_W)\ln \left(\frac{z_W - d_W}{z_{om\ W}} \right) + S_W \frac{z_W - d_W}{z_{IBL\ W}} \right]} \quad (9)$$

where S_W, d_W, $z_{om\ W}$, and $z_{IBL\ W}$ = solution of S and d, z_{om}, and z_{IBL} for the weather measurement surface; and $u_{z\ W}$ = wind measurement at z_W height over the weather station surface. If (9) is substituted into (5) for conditions characteristic of an IBL developing over an agricultural surface of vegetation type V, the following equation results:

$$u_{z\ V} = u_{z\ W} \frac{\left[(1 - S_V)\ln \left(\frac{z_V - d_V}{z_{om\ V}} \right) + S_V \frac{z_V - d_V}{z_{IBL\ V}} \right]}{\left[(1 - S_W)\ln \left(\frac{z_W - d_W}{z_{om\ W}} \right) + S_W \frac{z_W - d_W}{z_{IBL\ W}} \right]} \quad (10)$$

where $u_{z\ V}$ = estimated wind speed at the z_V height over vegetation type V, given $u_{z\ W}$ measured at z_W height over weather surface W. S_V and S_W are computed following (7) as

$$S_V = \frac{\ln \left(\frac{z_{om\ R}}{z_{om\ V}} \right) \frac{z_{IBL\ V}}{z_{IBL\ V} + d_V - d_R}}{\ln \left(\frac{z_{IBL\ V}}{z_{om\ V}} \right) - 1} \quad (11)$$

and

$$S_W = \frac{\ln \left(\frac{z_{om\ R}}{z_{om\ W}} \right) \frac{z_{IBL\ W}}{z_{IBL\ W} + d_W - d_R}}{\ln \left(\frac{z_{IBL\ W}}{z_{om\ W}} \right) - 1} \quad (12)$$

Eqs. (10-12) can be used to adjust wind-speed measurements taken over surface W at the z_W height to wind speeds likely to occur at the z_V height over vegetation V. The heights of the associated IBLs for the weather and vegetated surfaces are a function of upwind fetch as discussed in the following section.

Application of (10-12) employs the assumption of continuity of both mean horizontal velocity and shear stress at the IBL interfaces.

DEVELOPMENT OF SECOND WIND-SPEED TRANSLATION ALGORITHM

If friction velocity is assumed to be constant within a developing IBL and equal in value to the friction velocity characteristic of the underlying surface (either u_{*W} or u_{*V}), then a translation algorithm can be developed for changes in both measurement height and surface roughness by applying (3) for weather, region, and vegetated surfaces. However, this approach assumes that u_* is constant within a developing IBL, thus resulting in a discontinuity where u_* interfaces with the regional IBL. As is shown in the "Application" section, this assumption does not significantly change the adjustment.

This alternative approach characterizes the velocity profiles over each surface by roughness length characteristic of that surface. Therefore, (3) can be used to extrapolate from within localized IBLs to elevations within the regional IBL and then down again to a localized IBL characteristic of a new, specific surface.

Fig. 2 depicts a simple model showing development of IBLs on both a regional (IBL_R) and field (IBL_W and IBL_V) scale. Logarithmic wind profiles over both a weather surface (W) and a cropped surface of vegetation type V (solid lines) are shown relative to the wind profile characteristic of the region (dashed line). The regional IBL supposedly integrates effects of both W, V and other surfaces. In Fig. 2, roughness length and zero plane displacement for the weather surfaces, $z_{om\ W}$ and d_W, are less than z_{om} and d for the cropped surfaces, $z_{om\ V}$ and d_V, resulting in a lower and flatter wind profile. The roughness length and d of the regional surfaces, $z_{om\ R}$ and d_R in Fig. 2, are assumed to be intermediate to those for the weather surface and for the cropped surface, i.e., the regional profile has curvature in between those for the W and V surfaces.

The elevations of the upper boundaries of the IBLs in Fig. 2 relative to ground elevation are labeled $z_{IBL\ R}$, $z_{IBL\ W}$, and $z_{IBL\ V}$ for the regional, weather station, and cropped surfaces, respectively. The internal boundary layers for the weather and cropped surfaces have zero velocity at the $d + z_{om}$ height and intersect the regional wind profile at the $z_{IBL\ W}$ and $z_{IBL\ V}$ heights.
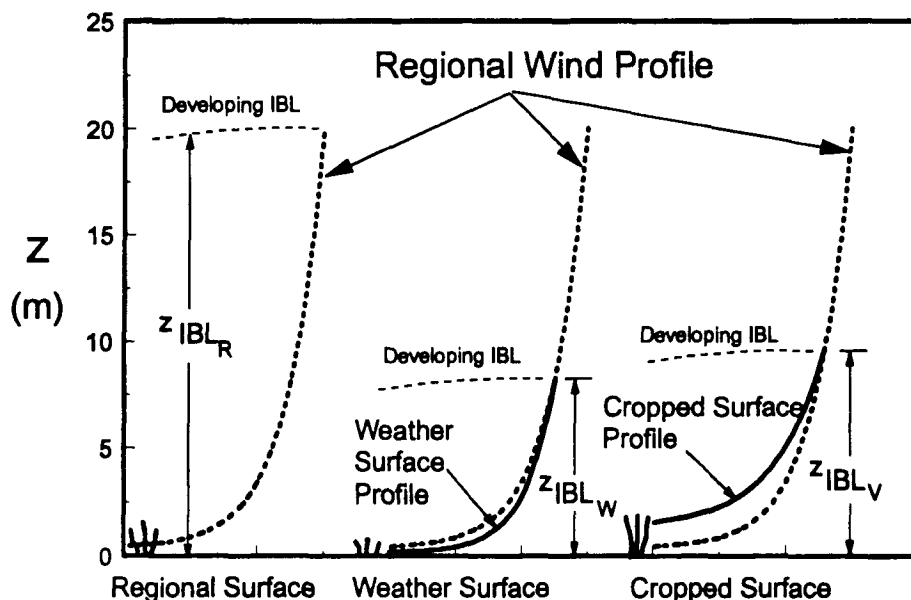

FIG. 2. Schematic of Velocity Profiles Characteristic of Regional, Weather, and Cropped Surfaces Following Assumption of Constant Friction Velocity, u_*, within Each IBL

The second translation algorithm uses (3) to extrapolate wind velocity profiles along the solid curves in Fig. 2 above the W and V surfaces for all heights below the fully adjusted IBLs corresponding to each surface. Velocity profiles are extrapolated along the dotted curves, which correspond to the regional, integrated surface, at heights above $z_{IBL\ W}$ or $z_{IBL\ V}$. Therefore, when translating wind-speed measurements from the z_W height over a weather station surface (where $z_W <$ $z_{IBL\ W}$) to some z_V height over a cropped surface (where $z_V <$ $z_{IBL\ V}$), the procedure extrapolates upward from z_W to $z_{IBL\ W}$ using (3), $z_{om\ W}$, and d_W and extrapolates from $z_{IBL\ W}$ to $z_{IBL\ R}$ using (3), $z_{om\ R}$, and d_R. Then, beginning at $z_{IBL\ R}$, the procedure extrapolates down from $z_{IBL\ R}$ to $z_{IBL\ V}$ using (3), $z_{om\ R}$, and d_R and from $z_{IBL\ V}$ to z_V using (3), $z_{om\ V}$, and d_V. The net combination of these extrapolations is a multiplicative combination of (3) with the following form:

$$u_{z\ V} = u_{z\ W} \frac{\ln\left(\frac{z_{IBL\ W} - d_W}{z_{om\ W}}\right) \ln\left(\frac{z_{IBL\ V} - d_R}{z_{om\ R}}\right) \ln\left(\frac{z_V - d_V}{z_{om\ V}}\right)}{\ln\left(\frac{z_W - d_W}{z_{om\ W}}\right) \ln\left(\frac{z_{IBL\ W} - d_R}{z_{om\ R}}\right) \ln\left(\frac{z_{IBL\ V} - d_V}{z_{om\ V}}\right)}$$

(13)

where $u_{z\ W}$ = wind speed measured at a weather station at z_W elevation above the ground surface; and $u_{z\ V}$ = predicted wind speed at the z_V elevation on ground covered with vegetation of type V. The combination of extrapolation functions in (13) eliminates the need for $z_{IBL\ R}$, which is the height of the complete IBL for the region. The two remaining z_{IBL}s in (13) represent the heights of the fully adjusted boundary sublayers over the weather surface and cropped surfaces. Roughness lengths and zero plane displacement heights for all three surfaces are required.

LIMITATIONS OF TWO TRANSLATION PROCEDURES

The translation algorithms (10) and (13) assume that wind speeds at z_{IBL} are driven by the horizontal velocity of an upper air mass, but that various logarithmic velocity profiles tie the regional or local air streams and momentum sinks to the underlying ground surfaces. Although not entirely true, these presumed mechanisms have some application value.

Both translation procedures [(10–12) and (13)] assume that the regional IBL lies directly above IBLs for the crop and weather surfaces, and that a third IBL has not developed directly upwind of either of these two surfaces. Both procedures also assume that the values for z_{IBL}s for the various surfaces are known or can be predicted and that neutral conditions hold. Therefore, application of this approach may only be valid for daily or longer time steps where these assumptions can be loosely applied.

APPROXIMATING z_{IBL}

The thickness of the internal boundary layer, z_{IBL}, varies with the size of area (or fields) having similar surface properties. These properties include roughness, vegetation density, and latent and sensible heat fluxes. Values for z_{IBL} may range from only 1 to 2 m for small fields 1 ha in size to more than 100 m thickness for very large fields or regions having homogeneous vegetation. On a regional scale, the thickness of $z_{IBL\ R}$ may vary from tens of meters to perhaps 2,000 m and may average about 100–400 m (Brutsaert 1982).

Downwind of a discontinuity in surface roughness, the thickness of a developing IBL increases with increasing length of horizontal fetch and follows a logarithmic relationship with distance. In regions having large expanses of homogenous surface vegetation, there may be no real height at which wind

speed is not in equilibrium with specific surface characteristics. In this situation, one should theoretically take $z_{IBL\ R} \to \infty$. However, in reality, the height of the regional IBL depends on the size of the region, the roughness of underlying vegetation, thermal stability, and wind speed. Above the adjusted IBL over large expanses of homogenous vegetation, wind velocity is affected by Coriolis forces and by the free air stream. Fortunately, the value for $z_{IBL\ R}$ is a relatively moot point with the proposed translation procedure, as the term does not directly occur in (13) and need not be estimated.

Brutsaert (1982) provided theoretical considerations for boundary layer development that can be used to approximate z_{IBL} for the specific measurement surface. Brutsaert's Eq. (7.39), which relates boundary layer growth downwind of a discontinuity in surface roughness, may be assumed to apply to the growth of IBLs over individual fields of agricultural crops. Brutsaert's equation can be expressed as

$$z_{IBL} = d + 0.33 z_{om}^{0.125} x_f^{0.875}$$

(14)

where z_{IBL} = height of the perturbed IBL above a surface of new roughness (z_{om}) and zero plane displacement (d). Variable x_f in (14) is the horizontal distance downwind of the surface discontinuity (horizontal fetch). z_{IBL}, d, and z_{om} in (14) have the same units. x_f is in meters. z_{ESL}, the height of the fully adjusted sublayer can be approximated as $0.10 z_{IBL}$ for smooth to rough discontinuities and as $0.05 z_{IBL}$ for rough to smooth discontinuities, following Brutsaert's (1982) summary of higher-order closure models by Peterson (1969), Shiir (1972), and Rao et al. (1974). The equilibrium sublayer, z_{ESL}, is defined as the region where the shear stress (or u_*) is within 10% of its surface value and represents a region where measurements of latent and sensible heat flux, air temperature, and vapor pressure are valid in the context of K-theory.

Computations for z_{IBL} from (14) are presented in Table 1 for various vegetation heights, H, and fetch lengths, x_f. Roughness length, z_{om}, and zero plane displacement height, d, were approximated as $0.12H$ and $0.67H$ (Brutsaert 1982), representing fully developed canopies. z_{IBL} is shown to be 12 m for 0.2-m grass having a homogenous fetch of 100 m and 13 m for 0.5-m-tall alfalfa having a 100-m fetch. These two values both follow 8:1 growth ramps in IBL development. When the 0.2-m vegetation is downwind of a smoother surface, the growth in the equilibrium sublayer (ESL) is predicted to follow an 80:1 (or roughly 100:1) growth ramp $(z_{ESL}:z_{IBL} = 0.10)$, which

TABLE 1. Calculations of z_{IBL} (Height of Internal Boundary Layer) Predicted Using Eq. (14) for Various Heights of Vegetation and z_{ESL} (Height of Equilibrium Sublayer) Predicted as 0.05 or 0.10 z_{IBL}

Vegetation height (m) (1)	Fetch x_f (m) (2)	d (3)	z_{om} (m) (4)	z_{IBL} (m) (5)	z_{ESL} (m) (6)
0.1	50	0.08	0.014	6	0.32
0.2	100	0.13	0.024	12	0.6
0.2	1000	0.13	0.024	87	4.4
0.2	10000	0.13	0.024	655	32.7
0.5	100	0.34	0.060	13	1.3
0.5	1000	0.34	0.060	98	9.8
0.5	10000	0.34	0.060	734	73.4
0.7	100	0.47	0.084	14	1.4
0.7	200	0.47	0.084	25	2.5
0.7	1000	0.47	0.084	103	10.3
1.0	100	0.67	0.120	15	1.5
1.0	200	0.67	0.120	27	2.7
1.0	1000	0.67	0.120	107	10.7

Note: d and z_{om} were estimated as $0.67\ H$ and $0.12\ H$, where $H =$ vegetation height. $z_{ESL} = 0.05\ z_{IBL}$ for rough to smooth transition, and $z_{ESL} = 0.10\ z_{IBL}$ for smooth to rough transition. The upwind vegetation height was assumed to be 0.3 m.

is characteristic of fetch length recommendations common in the literature for placement of meteorological instrumentation.

Upper Limits on z_{IBL}

An upper limit on z_{IBL}, representing the height where Coriolis effects begin to significantly affect the shape of logarithmic wind profiles, can be roughly approximated using Ekman-height scales (δ_r) for neutral conditions following Brutsaert (1982) where

$$\delta_r = \frac{C_r u_*}{|f|} \quad (15)$$

where δ_r = a neutral thickness scale for the IBL; $z_{IBL\ ul}$ = upper limit for z_{IBL} and is approximated as $z_{IBL\ ul} = \delta_r$; C_r = a constant having suggested values ranging from 0.15 to 0.3 (Brutsaert, 1982); u_* = friction velocity; and f = Coriolis parameter representing the influence of the earth's rotation. Units in (15) cancel to length. The Coriolis parameter can be computed following Brutsaert (1982) as

$$f = 2\omega \sin \phi \quad (16)$$

where ω = angular speed of rotation of the earth (2π rad d^{-1}); and ϕ = latitude. For midlatitudes ($40°$ to $55°$), f has a value of approximately $9\ d^{-1}$ or $10^{-4}\ s^{-1}$.

Utilizing a mean integration equation for u_* based on (2), an approximation for the upper limit of z_{IBL} ($z_{IBL\ ul}$) can be written as

$$z_{IBL\ ul} = \frac{C_r u_z k}{\ln\left(\dfrac{z - d}{z_{om}}\right) 2\omega |\sin \phi|} \quad (17)$$

Values for z_{om} and d in (17) represent those for the underlying surface or region. u_z is the wind-speed measurement taken at the z height above the surface in m d^{-1} for ω in rad d^{-1} [or in m s^{-1} if (17) is multiplied by 86,400 s d^{-1} and ω is in rad d^{-1}]. All lengths in (17) are in the same units. Example estimates of $z_{IBL\ ul}$ using (17) are presented in Table 2 for a latitude of $45°$ ($\pi/4$) for two vegetation heights and wind speeds at 2 m. C_r was taken as 0.2. For 1-m-tall vegetation with z_{om} and d computed as $0.12\ H$ and $0.67\ H$, $z_{IBL\ ul} = 760\ u_z$, so that for u_z at 2 m equal to 1 m s^{-1}, the estimated upper limit for z_{IBL} under neutral conditions would be approximately 760 m. For u_z of 2 m s^{-1}, $z_{IBL\ ul} = 1,520$ m. Clearly, a large range exists between estimates of z_{IBL} by (14) and estimates of $z_{IBL\ ul}$ by (17). Fortunately, (10) and (13) are relatively insensitive to the value used for z_{IBL}, so that precise estimation of z_{IBL} is not essential. Both equations predict a change in the ratio of $u_{z\ v}$ to $u_{z\ w}$ of only 2% per 100% change in $z_{IBL\ v}$ or $z_{IBL\ w}$. The equations are more sensitive to the roughness values used for $z_{om\ v}$ and $z_{om\ w}$, predicting a change in the ratio of $u_{z\ v}$ to $u_{z\ w}$ of up to 25% per 100% change in the value used for roughness

TABLE 2. Estimates of Upper Limit of z_{IBL} ($z_{IBL\ ul}$) Calculated Using Eq. (17)

Vegetation height (m) (1)	d (m) (2)	z_{om} (m) (3)	u_z (m/s) (4)	z (m) (5)	$z_{IBL\ ul}$ (m) (6)
0.7	0.47	0.08	1	2	630
0.7	0.47	0.08	2	2	1260
0.7	0.47	0.08	3	2	1900
1.0	0.67	0.12	1	2	760
1.0	0.67	0.12	2	2	1530

Note: d and z_{om} were estimated as $0.67\ H$ and $0.12\ H$, where H = vegetation height. z is the elevation of the wind measurement u_z above the ground surface.

of the vegetation or weather surface. Eqs. (10) and (13) are insensitive to the value for $z_{om\ R}$, changing only 2% per 100% change in $z_{om\ R}$ using typical values for roughness height, measurement height, and z_{IBL}, indicating that simple area-weighted values for $z_{om\ R}$ and d_R based on composition of regional vegetation types are appropriate.

MODIFICATION OF EQ. (13) FOR WHEN z_W OR z_V ARE GREATER THAN $z_{IBL\ W}$ OR $z_{IBL\ V}$

Eqs. (10) and (13) are valid only for $z_W < z_{IBL\ W}$ and $z_V < z_{IBL\ V}$. When these requirements do not hold, then one or both measurements happen to be above the heights of the developing IBLs and wind speeds at these heights are independent of the underlying surface characteristics. In these situations, (10) should no longer be applied, and, for $z_W > z_{IBL\ W}$ and $z_V < z_{IBL\ V}$, (13) reduces to

$$u_{z\ V} = u_{z\ W} \frac{\ln\left(\dfrac{z_{IBL\ V} - d_R}{z_{om\ R}}\right) \ln\left(\dfrac{z_V - d_V}{z_{om\ V}}\right)}{\ln\left(\dfrac{z_W - d_R}{z_{om\ R}}\right) \ln\left(\dfrac{z_{IBL\ V} - d_V}{z_{om\ V}}\right)} \quad (18)$$

For $z_W < z_{IBL\ W}$ and $z_V > z_{IBL\ V}$, (13) reduces to

$$u_{z\ V} = u_{z\ W} \frac{\ln\left(\dfrac{z_{IBL\ W} - d_W}{z_{om\ W}}\right) \ln\left(\dfrac{z_V - d_R}{z_{om\ R}}\right)}{\ln\left(\dfrac{z_W - d_W}{z_{om\ W}}\right) \ln\left(\dfrac{z_{IBL\ W} - d_R}{z_{om\ R}}\right)} \quad (19)$$

Eq. (18) is the same as that used by Allen et al. (1989) to translate wind speed over a grassed weather surface to wind speed over alfalfa (vegetation V).

When $z_W > z_{IBL\ W}$ and $z_V > z_{IBL\ V}$, both wind measurement heights are above the heights of the respective developing IBLs and profiles at the z_W and z_V heights are characteristic of the regional roughness, only. In this case, (13) reduces to

$$u_{z\ V} = u_{z\ W} \frac{\ln\left(\dfrac{z_V - d_R}{z_{om\ R}}\right)}{\ln\left(\dfrac{z_W - d_R}{z_{om\ R}}\right)} \quad (20)$$

which is a common form for adjusting wind speed for differences in measurement heights over a uniform surface (Thompson et al. 1981; Allen et al. 1989; Jensen et al. 1990), and is equivalent to (4).

Application

Eqs. (10) and (13) were tested using daily average wind data measured at two locations near the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) research center in Kimberly, Idaho during five growing seasons (1973, 1974, 1976, 1978, and 1979). One measurement site was instrumented and operated by the U.S. Weather Service (USWS) where wind speed was measured at 3.66 m over 0.12-m clipped grass. The other site was instrumented and operated by the USDA-ARS with wind measured at 2 m over snap beans during 1973 and 1974 and at 2 m over winter wheat in 1978 and spring wheat in 1979. Wind speeds were measured at 3 and 5 m over field corn at the USDA site during 1976.

The USWS site was located about 50 m south of the USDA research center office building and was surrounded by open agricultural fields, with office and outlying buildings at 100 m to the north and northwest, orchards and windbreaks at 0.5 km to the west, and roadways at 100 and 300 m to the east and north. The size of the grassed weather measurement surface

was approximately 50 × 50 m. The average vegetation height surrounding the USWS site was 0.12 m.

The USDA-ARS lysimeter site was located 0.8 km south of the USWS site in a 160 × 160 m (2.6 ha) field and was surrounded by the specific crop for at least 75–100 m in all directions and by other low-growing agricultural vegetation for over 1 km (Wright 1991). The anemometer at the USDA site was well maintained during the measurement period with bearing replacement as needed. Various instruments were occasionally paired to confirm calibration. All wind analyses were conducted using 24-h averages in order to average effects of wind direction and boundary layer stability on wind-speed profiles.

The region surrounding the Kimberly Research Station comprises a mixture of irrigated cropland and associated farmsteads having trees and shrubs characteristic of southern Idaho.

The predominant crops are wheat, dry beans, sugar beets, alfalfa, and pasture. The average height for regional vegetation (H_R) was estimated as an average of these five crops. The first four crops listed generally range from less than 0.1 m in height in early spring to about 1 m height during mid- and late summer. Pasture grass averages about 0.2 m. The height of snap beans ranged from 0.01 m at the beginning of the measurement periods to 0.7 m at maturity, height of the wheat crops ranged from 0.05 m at the beginning of the measurement periods to 1.0 m at maturity, and height of the field corn crop ranged from 0.02 m at the beginning of the measurement period to 2.2 m at maturity. The snap bean crops lodged permanently to about 0.4 m mean plant height toward the end of each growing season due to winds associated with thunderstorms. These height reductions were accounted for in the H_V calculations. The approximation for H_R increased during the growing season
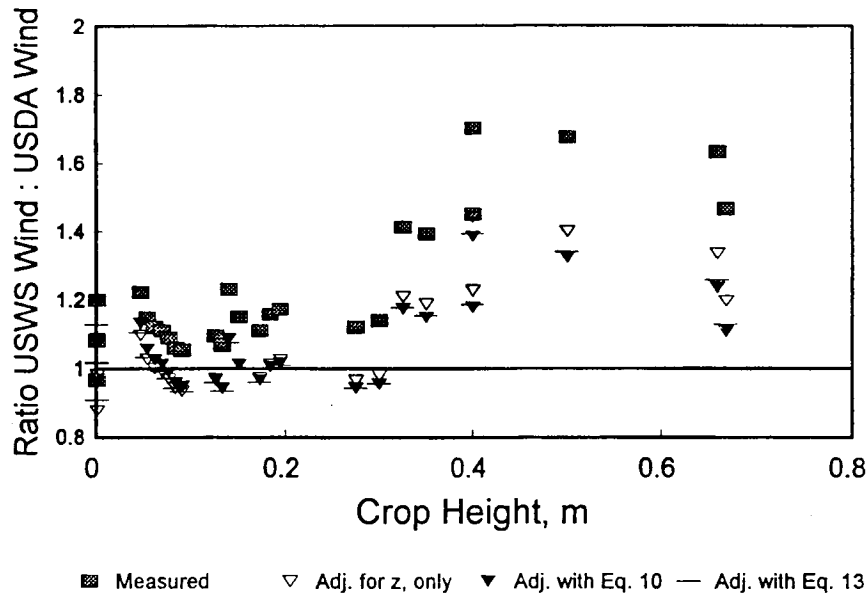
Beans, 1973

FIG. 3. Ratios of USWS Wind Measurements at 3.66 m over Grass to USDA Wind Measurements at 2 m over Snap Beans versus Crop Height at Kimberly, Idaho, during 1973 Showing Measured Ratios and Ratios Translated Using Eqs. (4), (10), and (13)
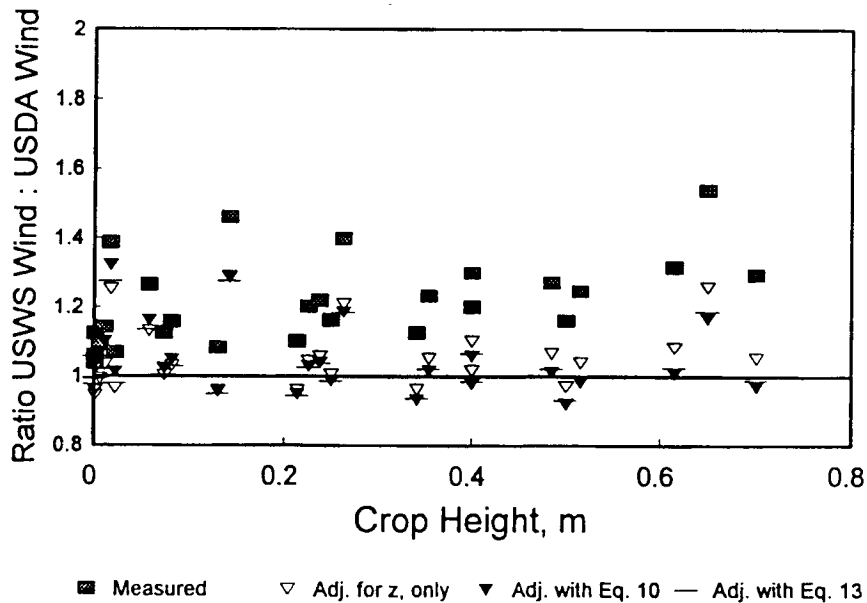
Beans, 1974

FIG. 4. Ratios of USWS Wind Measurements at 3.66 m over Grass to USDA Wind Measurements at 2 m over Snap Beans versus Crop Height at Kimberly, Idaho, during 1974 Showing Measured Ratios and Ratios Translated Using Eqs. (4), (10), and (13)

Winter Wheat, 1978

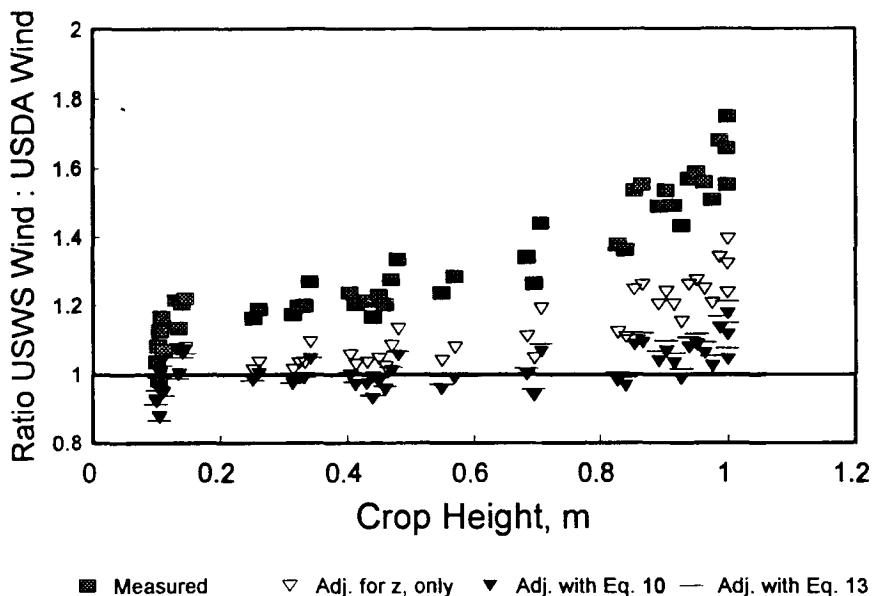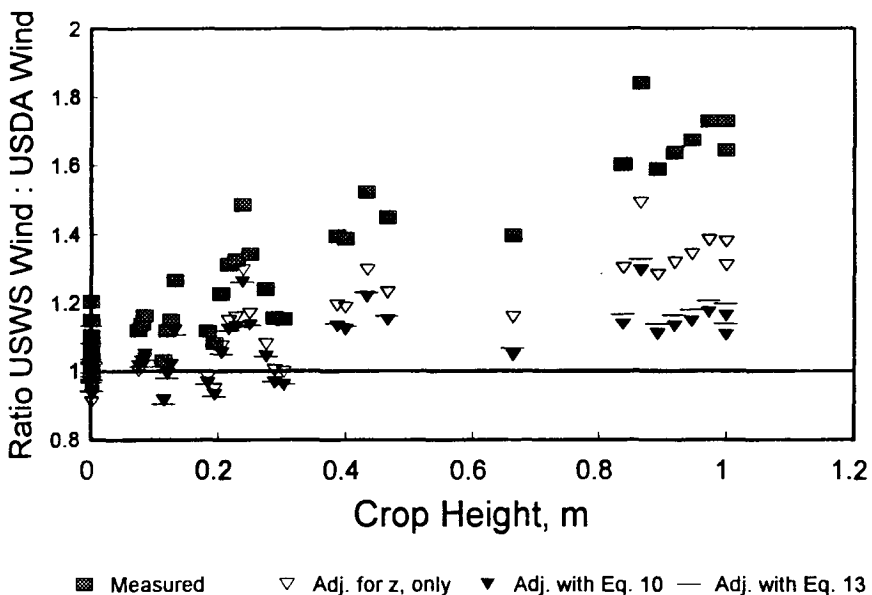Measured ■   ▽ Adj. for z, only   ▼ Adj. with Eq. 10   — Adj. with Eq. 13

FIG. 5.   Ratios of USWS Wind Measurements at 3.66 m over Grass to USDA Wind Measurements at 2 m over Winter Wheat versus Crop Height at Kimberly, Idaho, during 1978 Showing Measured Ratios and Ratios Translated Using Eqs. (4), (10), and (13)

Spring Wheat, 1979

Measured ■   ▽ Adj. for z, only   ▼ Adj. with Eq. 10   — Adj. with Eq. 13

FIG. 6.   Ratios of USWS Wind Measurements at 3.66 m over Grass to USDA Wind Measurements at 2 m over Spring Wheat versus Crop Height at Kimberly, Idaho, during 1979 Showing Measured Ratios and Ratios Translated Using Eqs. (4), (10), and (13)

as the height of various agricultural vegetation increased. As indicated previously, the calculations by the translation equations were not very sensitive to the value for H_R (and $z_{om\ R}$).

Ratios of USWS wind speeds to USDA wind speeds are plotted in Figs. 3–6 for a 2-m anemometer height over the snap bean and wheat crops during the 1973, 1974, 1978, and 1979 growing seasons and in Figs. 7 and 8 for 3 and 5 m anemometer heights over the field corn crop during 1976. Ratios of USWS to USDA wind-speed measurements increased during all five growing seasons as crop heights at the USDA site increased relative to the 0.12-m grass height surrounding the USWS station. Ratios of 3.66-m USWS wind speed to 2-m USDA wind speed reached maximum values of approximately 1.4–1.6 for the snap beans and 1.6–1.8 for the winter and spring wheat crops. Ratios of 3.66-m USWS wind speed to 3-m USDA wind over field corn reached 1.8. The large

increases in ratios resulted from increasing roughness and zero plane displacement heights of the crops at the USDA site. The increases in z_{om} and d decreased both the slopes (dU/dz) and velocities of wind profiles over the agricultural crops relative to those for the weather station. The use of the higher wind velocities at the USWS site to estimate aerodynamic resistances for the vegetation at the USDA site (snap beans, wheat, and corn) caused underestimation of aerodynamic resistances in a Penman-Monteith evapotranspiration equation by 10–40% and, depending on levels of net radiation, vapor pressure deficit, and bulk surface resistance, caused overprediction of evapotranspiration of the agricultural crops by 5–20%.

Some of the increase in wind speed at the 3.66-m anemometer height at the USWS site relative to wind speed at the 2-m anemometer height at the USDA location (Figs. 3–6) was due to differences in anemometer positioning height, only.

Field Corn, 3m, 1976

Measured   ▽ Adj. for z, only   ▼ Adj. with Eq. 10   — Adj. with Eq. 13
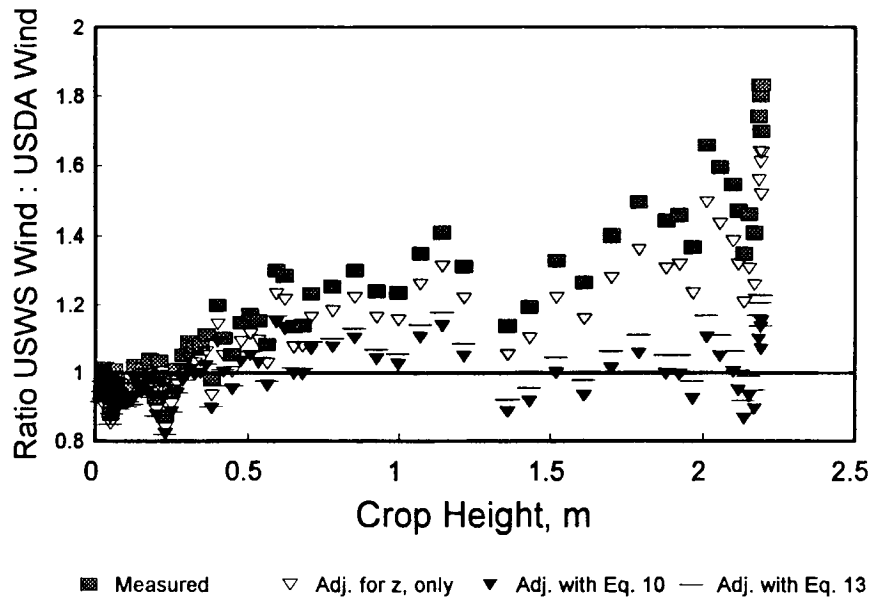
FIG. 7. Ratios of USWS Wind Measurements at 3.66 m over Grass to USDA Wind Measurements at 3 m over Field Corn versus Crop Height at Kimberly, Idaho, during 1976 Showing Measured Ratios and Ratios Translated Using Eqs. (4), (10), and (13)

Field Corn, 5m, 1976

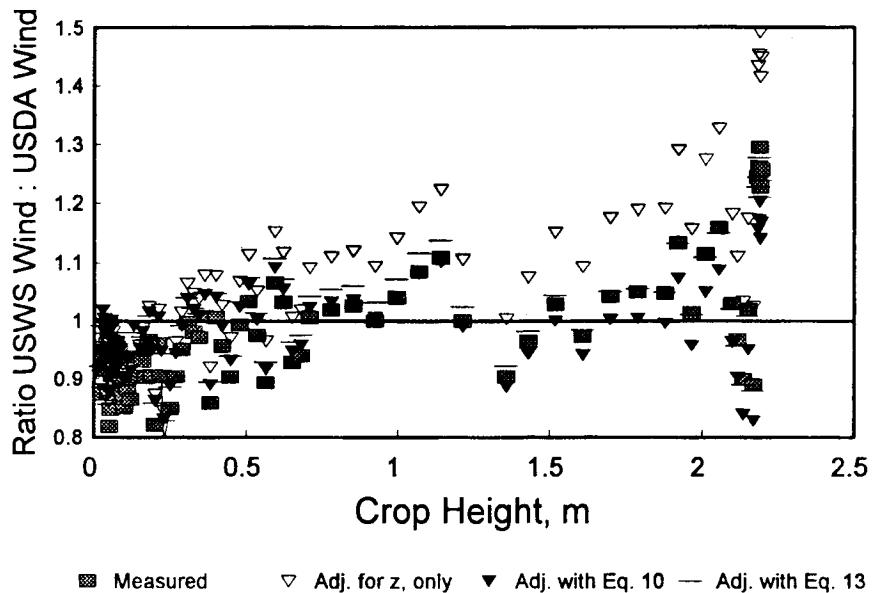**Measured**   ▽ Adj. for z, only   ▼ Adj. with Eq. 10   — Adj. with Eq. 13

FIG. 8. Ratios of USWS Wind Measurements at 3.66 m over to USDA Wind Measurements at 5 m over Field Corn versus Crop Height at Kimberly, Idaho, during 1976 Showing Measured Ratios and Ratios Translated Using Eqs. (4), (10), and (13)

Wind-speed ratios between the USWS and USDA sites could be adjusted back to nearly 1.0 when H_V was less than about 0.3 to 0.7 m by adjusting for anemometer height, only, using (4) with z_{om} and d set equal to $z_{om\ V}$ and d_V. As expected, the adjustment of wind data using only (4) was adequate during the early portions of the growing seasons when heights of the agricultural crops were similar to those of clipped grass. When crop height became greater than about 0.7 m, however, the correction for anemometer elevation alone was not sufficient to adjust USWS wind speeds to values measured over the agricultural crops, and (10) or (13) were necessary to accomplish the adjustments. The need for the translation equations is especially apparent for the wheat crops (Figs. 5 and 6) and field corn crop (Figs. 7 and 8) when $H > 0.7$ m.

Eq. (10), with S_W and S_V estimated using (11) and (12) and

z_{IBL} estimated using (14), was generally effective in adjusting measurements at 3.66 m over the USWS surface to represent wind-speed measurements at 2 m over the USDA surface for beans and wheat (Figs. 3–6) and at 3 and 5 m over the field corn (Figs. 7 and 8). Adequacy of adjustments was judged by the proximity of adjusted USWS:USDA ratios to 1.0. Fetch lengths, x_f, for the weather measurement surface (W) and cropped surface (V) were set equal to 50 and 150 m, respectively.

Eq. (13), with z_{IBL} estimated using (14), translated USWS speeds similar to (10). This was especially true for crops shorter than 1 m. For field corn, where H_V exceeded 1 m, (10) produced larger adjustments than did (13) (Figs. 7 and 8). However, differences were small. When S_V and S_W in (11) and (12) were estimated by ignoring zero plane displacements (d_W

and $d_V = 0$), (10) produced adjustments that were exactly equal to those computed using (13). These results indicate that the assumption in (13) of constant u_* within a developing IBL is valid for translating and extrapolating wind-speed profiles within and above the local IBL. Wind-speed translations by (13) were excellent throughout the 1974, 1976, and 1978 seasons and adjusted for about 80% of observed differences during the 1979 season. Some "undertranslation" occurred for the snap bean crop during 1973 when crop height was greater than 0.35 m (Fig. 3). The cause of difficulty could not be explained, but could have been due to a faulty anemometer bearing or other problem.

Eq. (4), which accounts for wind-speed differences stemming only from differences in anemometer height, provided adequate adjustment to wind speed when crop height was less than about six times the weather vegetation height. Eq. (4) yielded unsatisfactory adjustment over the tall corn crop and even adjusted in the wrong direction for the 5-m anemometer (Fig. 8). In this situation, (4) (using z_{om} and d for grass) predicted wind speed at the 5-m height over corn to be greater than at 3.66 m over grass. However, (10) and (13) correctly predicted wind speeds at 5 m above ground surface over the corn crop to be essentially the same as at 3.66 m above ground surface over grass. These results indicate that it is important to use the more sophisticated translation equations [(10) and (13)] when aerodynamic roughness is more than about six times that of the weather station surface.

CONCLUSIONS

Wind measurements taken at two sites 0.8 km apart confirm that height and roughness of vegetation beneath and upwind of an anemometer significantly affect wind speed. A translation algorithm based on linearly varying friction velocity and shear stress within a developing internal boundary layer and a second logarithmic-based translation algorithm that assumes constant friction velocity and shear stress within a developing internal boundary layer were developed and tested. These algorithms are recommended for translating wind measurements from weather measurement locations to agricultural crops. Both algorithms provided similar results. Eq. (13) is recommended over (10–12) for general application due to its simplicity. When anemometer heights are above the developing IBL, (18)–(20) should be used.

ACKNOWLEDGMENTS

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APPENDIX II.   NOTATION

The following symbols are used in this paper:

C_r = constant;
d = zero plane displacement height;
d_R = average zero plane displacement for the region;
d_V = zero plane displacement height for surface "V";
d_W = zero plane displacement height for "weather" surface "W";
f = Coriolis parameter representing the influence of the earth's rotation;
H = vegetation height;
H_R = average height of vegetation affecting the mean wind velocity profile over the region;
H_V = height of the specific crop over surface "V";
H_W = height of vegetation over the weather surface;
IBL = internal boundary layer;
IBL_V = internal boundary layer over surface "V";
k = von Karman constant (0.41);
r_a = aerodynamic resistance;
S = relative change in friction velocities between two surfaces;
S_V = relative change in friction velocities between the regional surface and surface "V";
S_W = relative change in friction velocities between surface "W" and the regional surface;
u = mean horizontal wind speed;
u_* = friction velocity;
u_{*R} = friction velocity characteristic of the upwind, regional surface;
u_{*V} = friction velocity in the ESL over surface "V";
$u_{z\,W}$ = wind speed measured at z_W elevation above the ground surface "W";
$u_{z\,V}$ = wind speed predicted to occur at z_V elevation if the ground were covered with vegetation "V";
u_1 = mean horizontal wind speed at elevation z_1 above the ground surface;
u_2 = mean horizontal wind speed at elevation z_2 above the ground surface;
x_f = horizontal distance downwind of the surface discontinuity (horizontal fetch) (m);
z = elevation above the ground surface;
z_{ESL} = height of the fully adjusted sublayer;

z_{IBL} = height of the IBL;

$z_{IBL\ R}$ = height of the IBL for the region;

$z_{IBL\ V}$ = height of the IBL over surface "V";

$z_{IBL\ W}$ = height of the IBL over surface "W" (weather measurement surface);

$z_{IBL\ ul}$ = upper limit for z_{IBL};

z_{om} = surface roughness length for momentum transfer;

$z_{om\ R}$ = average roughness length for momentum transfer for the region;

$z_{om\ V}$ = surface roughness length for momentum transfer for surface "V";

z_V = desired measurement elevation over surface "V";

z_W = wind measurement elevation over "weather" surface "W";

δ_r = Ekman-height scale;

τ = shear stress;

ϕ = latitude (rad); and

ω = angular speed of rotation of the earth (2π rad d^{-1}).