

Is surface conductance theoretically independent of reference height?

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Abstract

Many studies have compared surface conductance G_s at different observation sites when examining physiological differences between sites and/or between vegetation categories. However, a theoretical analysis confirming the robustness of such comparisons has not yet been published. It is unclear whether G_s is independent of the reference height where evaporative fluxes and meteorological factors are observed, as G_s is a conceptual parameter rather than a purely physiological parameter.

This short note shows that G_s is independent of reference height when above-canopy fluxes of evapotranspiration and available energy are independent of reference height, and when energy balance closure is complete. Thus, this note gives a theoretical basis for comparing G_s values at different observation sites. Furthermore, we make recommendations for examining the G_s dependency on reference height in field conditions. Copyright © 2005 John Wiley & Sons, Ltd.

Key Words surface conductance; Penman–Monteith equation; evapotranspiration; vegetation; reference height

Introduction

The Penman–Monteith equation (e.g. Monteith and Unsworth, 1990; Jones, 1992; Landsberg and Gower, 1997; Campbell and Norman, 1998; Waring and Running, 1998) is a useful tool for analysing evapotranspiration processes of vegetation canopies (e.g. Cienciala *et al.*, 1994, 1998; Wright *et al.*, 1995; Steduto and Hsiao, 1998a; Komatsu, 2003a, 2004; Kumagai *et al.*, 2004, 2005). When applying the Penman–Monteith equation on an ecosystem scale, physiological and aerodynamic controls of evapotranspiration are represented by surface and aerodynamic conductance respectively (e.g. Monteith and Unsworth, 1990; Landsberg and Gower, 1997; Komatsu, 2003a,b, 2004, 2005). Thus, the significance of physiological and aerodynamic controls of evapotranspiration can be evaluated separately.

As the surface conductance G_s affects evapotranspiration rates of vegetation canopies greatly, many observational studies (e.g. Lindroth, 1985a,b; Verma *et al.*, 1986; Dunin *et al.*, 1991; Stewart and Verma, 1992; Wilson and Baldocchi, 2000) include calculations of G_s for each site. Such G_s calculations are performed by substituting evapotranspiration rate, aerodynamic conductance, and meteorological factors observed above the canopy into the Penman–Monteith equation. In principle, G_s can be calculated from direct measurements of surface temperature

using the flux/gradient equation. However, few studies have calculated G_s using this method. The value of G_s calculated using this method is unreliable because of differences in the projection area of surface temperature and evaporative flux measurements, and because of the horizontal heterogeneity of surface temperature (Sugita *et al.*, 2001).

Summarizing G_s values for various observation sites, many studies (Shuttleworth, 1989; Jones, 1992; Kelliher *et al.*, 1993, 1995; Schulze *et al.*, 1994, 1995; Granier *et al.*, 1996; Baldocchi *et al.*, 1997, 2000; Dolman *et al.*, 1998; Komatsu, 2003a,b) have compared these G_s values when examining physiological differences, on an ecosystem scale, between sites and/or between vegetation categories. The results of these comparison studies are especially useful for parameterizing a G_s sub-model incorporated in hydrological, meteorological, and ecological models (e.g. Running and Coughlan, 1988; McMurtrie *et al.*, 1990a, 1992; Running and Gower, 1991; Whitehead and Kelliher, 1991; Sellers *et al.*, 1996, 1997; Mauser and Schadlich, 1998; Merz and Bardossy, 1998; Soares and Almeida, 2001). For example, Komatsu (2003b) summarized published G_s data for different coniferous forests and subsequently developed a G_s parameterization (Komatsu, 2004) that reproduces variations in evapotranspiration for different coniferous forests.

Comparisons of G_s from different observation sites are common, but a theoretical analysis confirming the robustness of such comparisons has not yet been published. Therefore, it is unclear whether G_s is independent of the reference height where evaporative fluxes and meteorological variables are observed. Actually, G_s may depend on reference height for the following two reasons. First, air temperature and vapour pressure measured at reference height depend on reference height (e.g. Monteith and Unsworth, 1990; Jones, 1992; Campbell and Norman, 1998; Arya, 2001). As G_s is calculated based on the air temperature and vapour pressure measured at reference height, G_s may depend on reference height. If so, G_s comparisons from different observation sites should be invalid, due to differences in reference height between sites. Second, G_s is not a purely physiological parameter. If G_s were a purely physiological parameter, then G_s would be independent of reference height, as is the case for stomatal conductance (Raupach and Finnigan, 1988; Raupach, 1995). However,

G_s is a conceptual parameter that represents physiological control of evapotranspiration. Therefore, G_s can be affected by non-physiological processes (Raupach and Finnigan, 1988; Baldocchi *et al.*, 1991; Rochette *et al.*, 1991; Watanabe, 1994; Monteith, 1995), implying that G_s might depend on reference height. For example, G_s calculated from measurements 5 m above the canopy might differ from G_s calculated from measurements 10 m above the canopy. Model-based studies (e.g. Kelliher *et al.*, 1995; Raupach, 1995; Baldocchi and Meyers, 1998; Lai *et al.*, 2000) have shown a clear relationship between G_s and stomatal conductance, a purely physiological parameter. However, these model-based studies show that G_s is an approximately physiological parameter, not a purely physiological parameter (e.g. Raupach, 1995).

For establishing a basis for comparing G_s values for each observation site, this short note theoretically shows G_s independence with reference height. Our focus here is to show that G_s is independent of reference height when fluxes of above-canopy evapotranspiration and available energy are independent of reference height (i.e. when fluxes of evapotranspiration and available energy are vertically constant above the canopy), and when energy balance closure is complete. These are also the assumptions made in deriving the Penman–Monteith equation (e.g. Monteith and Unsworth, 1990; Jones, 1992; Campbell and Norman, 1998; Arya, 2001). It is beyond our scope to consider G_s dependence with reference height when fluxes of above-canopy evapotranspiration and/or available energy vary with reference height, and when energy balance closure is incomplete.

The G_s independence with reference height might be implicitly recognized by researchers who specialize in vegetation evapotranspiration processes. Even so, explicitly showing the G_s independence is valuable for the following three reasons.

First, users of the Penman–Monteith equation include researchers who do not specialize in vegetation evapotranspiration processes. For example, Running and Coughlan (1988), Band (1993), Band *et al.* (1993), and Vertessy *et al.* (1993) studied runoff processes in a vegetated catchment using hydrological and ecological models that incorporated the Penman–Monteith equation. Nobre *et al.* (1991) and da Rocha *et al.* (1996) studied climate formation processes using meteorological models that

incorporated the Penman–Monteith equation. Woodward (1987), McMurtrie *et al.* (1990a,b, 1992), Running and Gower (1991), and Hingston and Galbraith (1998) studied vegetation growth and dynamics using ecological models that incorporated the Penman–Monteith equation, because water availability can be an important limiting factor in photosynthesis (e.g. Baldocchi, 1997; Steduto and Hsiao, 1998b; Komatsu and Hashimoto, 2002). As researchers in other fields use the Penman–Monteith equation, understanding its theoretical basis is important.

Second, to establish a basis for comparing G_s values at different observation sites is critical when examining differences in photosynthetic properties between sites and/or between vegetation categories. G_s can represent photosynthetic properties in vegetation canopies (Schulze *et al.*, 1994, 1995), because G_s correlates highly with the photosynthetic rate at canopy scale (Schulze *et al.*, 1994; Law *et al.*, 2001). Therefore, to establish a basis for comparing G_s values at different observation sites is critical in ecological and physiological senses.

Third, G_s comparisons by researchers in other fields will be accelerated from now on. Data on evaporative flux (and also CO_2 flux) from many observation sites are now easily available on Websites (e.g. Baldocchi *et al.*, 2001) and are thus accessible to researchers in other fields. Therefore, to establish a basis for comparing G_s values at different observation sites is becoming more important.

This paper will be useful even for researchers who recognize the G_s independence with reference height, because it makes recommendations for examining the G_s dependency on reference height under field conditions. By theoretically showing the G_s independence, we will confirm which assumptions are needed. In practice, these assumptions might be violated by field conditions that indicate G_s may be dependent on reference height. We aim to identify cases where the G_s dependency is likely to be observed, and field studies are to be recommended.

Materials and Methods

This section describes G_s calculations based on the Penman–Monteith equation and then describes the methods of analysis.

The Penman–Monteith equation (e.g. Monteith and Unsworth, 1990; Jones, 1992; Landsberg and Gower, 1997; Campbell and Norman, 1998; Waring and Running, 1998) is given as follows:

$$\lambda E = \frac{\Delta A + \rho c_p G_a(z_r)[e_s(T(z_r)) - e(z_r)]}{\Delta + \gamma(1 + G_a(z_r)/G_s(z_r))} \quad (1)$$

where λ is the latent heat of water vaporization, E is the evapotranspiration rate, Δ is the slope of the saturation vapour pressure function, A is the available energy, ρ is the air density, c_p is the specific heat of air, $G_a(z_r)$ is the aerodynamic conductance at the reference height z_r , $e_s(T(z_r))$ is the saturation vapour pressure at the reference height air temperature $T(z_r)$, $e(z_r)$ is the air vapour pressure at the reference height, γ is the psychrometer constant, and $G_s(z_r)$ is the surface conductance calculated from measurements at the reference height z_r . From Equation (1), $G_s(z_r)$ can be written as (e.g. Granier and Loustau, 1994; Kelliher *et al.*, 1997, 1998; Granier *et al.*, 2000)

$$G_s(z_r) = \frac{G_a(z_r)\gamma\lambda E}{\Delta A + \rho c_p G_a(z_r)[e_s(T(z_r)) - e(z_r)] - (\Delta + \gamma)\lambda E} \quad (2)$$

By substituting $G_a(z_r)$, E , A , $T(z_r)$, and $e(z_r)$ observed at a reference height above the canopy into Equation (2), previous observational studies have calculated G_s values for each observation site.

To determine whether $G_s(z_r)$ is independent of reference height, consider a situation in which the reference height moves from $z_r = z_{r1}$ to $z_r = z_{r2}$ (Figure 1), where A , E , and profiles of the air temperature and vapour pressure above the surface are given. Does $G_s(z_{r2}) = G_s(z_{r1})$? If so, then G_s is independent of reference height. Here, $G_s(z_{r1})$ and $G_s(z_{r2})$ are given by

$$G_s(z_{r1}) = \frac{G_a(z_{r1})\gamma\lambda E}{\Delta A + \rho c_p G_a(z_{r1})[e_s(T(z_{r1})) - e(z_{r1})] - (\Delta + \gamma)\lambda E} \quad (3)$$

$$G_s(z_{r2}) = \frac{G_a(z_{r2})\gamma\lambda E}{\Delta A + \rho c_p G_a(z_{r2})[e_s(T(z_{r2})) - e(z_{r2})] - (\Delta + \gamma)\lambda E} \quad (4)$$

The present analysis assumes vertically constant A and E , complete energy balance closure (sensible heat flux is equal to $A - \lambda E$), and $z_{r1} < z_{r2}$ (Figure 1). Note that vertically constant sensible heat flux is

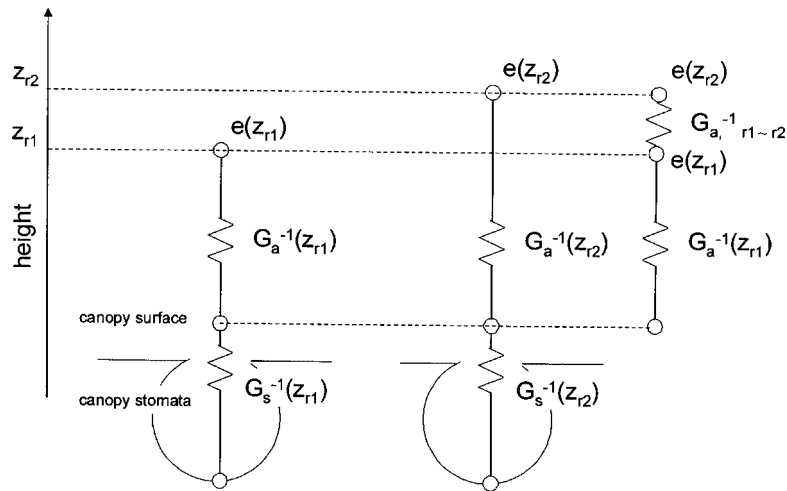


Figure 1. Schematic drawing of water transport processes from the inner space of the canopy stomata to the reference height. Surface conductance G_s conceptually represents physiological control of evapotranspiration from the surface. Thus, G_s independence with reference height is not apparent

implicitly assumed because of sensible heat flux equalling $A - \lambda E$ and because of vertically constant A and E . Vertically constant A and E and complete energy balance closure are assumptions that were also made in deriving the Penman–Monteith equation (e.g. Monteith and Unsworth, 1990; Jones, 1992; Campbell and Norman, 1998). We assume $z_{r1} < z_{r2}$ does not alter the generality of the analysis.

Results

When considering water vapour transport between the surface and z_{r1} and between z_{r1} and z_{r2} separately, $G_a(z_{r2})$ relates to $G_a(z_{r1})$ by (Figure 1)

$$G_a^{-1}(z_{r2}) = G_a^{-1}(z_{r1}) + G_{a,r1\sim r2}^{-1} \quad (5)$$

where $G_{a,r1\sim r2}^{-1}$ is the aerodynamic conductance between z_{r1} and z_{r2} . $T(z_{r2})$ and $e(z_{r2})$ relate to $T(z_{r1})$ and $e(z_{r1})$ by

$$\rho c_p G_{a,r1\sim r2} (T(z_{r1}) - T(z_{r2})) = A - \lambda E \quad (6)$$

$$\rho G_{a,r1\sim r2} \frac{\varepsilon(e(z_{r1}) - e(z_{r2}))}{p} = E \quad (7)$$

where ε is the ratio of molecular weights of water vapour and air, and p is the total air pressure. In Equation (6), complete energy balance closure (i.e.

sensible heat flux is equal to $A - \lambda E$) is assumed. Equations (6) and (7) are rewritten as follows:

$$T(z_{r2}) = T(z_{r1}) - \frac{A - \lambda E}{\rho c_p G_{a,r1\sim r2}} \quad (8)$$

$$e(z_{r2}) = e(z_{r1}) - \frac{pE}{\rho \varepsilon G_{a,r1\sim r2}} \quad (9)$$

If Equations (5), (8), and (9) are substituted into Equation (4), $G_s(z_{r2})$ can be shown to be equal to $G_s(z_{r1})$ in the following way. Below, we try to detail transformation between equations, because the audience of this paper would include researchers who do not specialize in vegetation evapotranspiration processes.

The numerator of Equation (4) is rewritten, using Equation (5), as follows:

$$\begin{aligned} G_a(z_{r2}) \gamma \lambda E &= (G_a^{-1}(z_{r1}) + G_{a,r1\sim r2}^{-1})^{-1} \gamma \lambda E \quad (10) \\ &= (G_a^{-1}(z_{r1}) + G_{a,r1\sim r2}^{-1})^{-1} \\ &\quad \times G_a^{-1}(z_{r1}) G_a(z_{r1}) \gamma \lambda E \quad (11) \end{aligned}$$

The denominator of Equation (4) is rewritten, using Equations (5), (8), and (9), as follows:

$$\begin{aligned} \Delta A + \rho c_p G_a(z_{r2}) [e_s(T(z_{r2})) - e(z_{r2})] - (\Delta + \gamma) \lambda E \\ = \Delta A + \rho c_p (G_a^{-1}(z_{r1}) + G_{a,r1\sim r2}^{-1})^{-1} \end{aligned}$$

$$\times \left[e_s \left(T(z_{r1}) - \frac{A - \lambda E}{\rho c_p G_{a,r1 \sim r2}} \right) - \left(e(z_{r1}) - \frac{pE}{\rho \varepsilon G_{a,r1 \sim r2}} \right) \right] - (\Delta + \gamma)\lambda E \quad (12)$$

$$= \Delta A + \rho c_p (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} \times \left\{ \left[e_s(T(z_{r1})) - \Delta \frac{A - \lambda E}{\rho c_p G_{a,r1 \sim r2}} \right] - \left(e(z_{r1}) - \frac{pE}{\rho \varepsilon G_{a,r1 \sim r2}} \right) \right\} - (\Delta + \gamma)\lambda E \quad (13)$$

$$= \Delta A + \rho c_p (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} [e_s(T(z_{r1})) - e(z_{r1})] - (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} \times \left(\Delta \frac{A - \lambda E}{G_{a,r1 \sim r2}} - \frac{\gamma \lambda E}{G_{a,r1 \sim r2}} \right) - (\Delta + \gamma)\lambda E \quad (14)$$

$$= \Delta A [1 - (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} G_{a,r1 \sim r2}^{-1}] + \rho c_p (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} \times [e_s(T(z_{r1})) - e(z_{r1})] - (\Delta + \gamma)\lambda E [1 - (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} G_{a,r1 \sim r2}^{-1}] \quad (15)$$

$$= \Delta A (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} G_a^{-1}(z_{r1}) + \rho c_p (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} \times [e_s(T(z_{r1})) - e(z_{r1})] - (\Delta + \gamma)\lambda E (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} G_a^{-1}(z_{r1}) \quad (16)$$

$$= (G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} G_a^{-1}(z_{r1}) \times \{ \Delta A + \rho c_p G_a(z_{r1}) [e_s(T(z_{r1})) - e(z_{r1})] - (\Delta + \gamma)\lambda E \} \quad (17)$$

Transformation of Equation (12) into Equation (13) is accomplished using the following approximation:

$$e_s \left(T(z_{r1}) - \frac{A - \lambda E}{\rho c_p G_{a,r1 \sim r2}} \right) = e_s(T(z_{r1})) - \Delta \frac{A - \lambda E}{\rho c_p G_{a,r1 \sim r2}} \quad (18)$$

A similar approximation is made to derive the Penman–Monteith equation (e.g. Monteith and Unsworth, 1990; Jones, 1992; Campbell and Norman, 1998). Transformation of Equation (13) into Equation (14) is accomplished using the following

relationship (e.g. Monteith and Unsworth, 1990; Arya, 2001):

$$\gamma = \frac{c_p P}{\lambda \varepsilon} \quad (19)$$

$G_s(z_{r2})$ is rewritten from Equations (11) and (17) as

$$G_s(z_{r2}) = \frac{(G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} \times G_a^{-1}(z_{r1}) G_a(z_{r1}) \gamma \lambda E}{(G_a^{-1}(z_{r1}) + G_{a,r1 \sim r2}^{-1})^{-1} G_a^{-1}(z_{r1}) \times \{ \Delta A + \rho c_p G_a(z_{r1}) [e_s(T(z_{r1})) - e(z_{r1})] - (\Delta + \gamma)\lambda E \}} \quad (20)$$

$$= \frac{G_a(z_{r1}) \gamma \lambda E}{\Delta A + \rho c_p G_a(z_{r1}) [e_s(T(z_{r1})) - e(z_{r1})] - (\Delta + \gamma)\lambda E} \quad (21)$$

$$= G_s(z_{r1}) \quad (22)$$

Thus, $G_s(z_{r2})$ is equal to $G_s(z_{r1})$, and G_s is shown to be independent of reference height.

Conclusions and Recommendations

This note shows that G_s is independent of reference height when above-canopy fluxes of evapotranspiration and available energy are independent of reference height, and when energy balance closure is complete. The G_s independence shown here gives a theoretical basis for G_s comparisons using data from different observation sites.

Some researchers might already have recognized the G_s independence implicitly, as described in the Introduction. However, no theoretical analysis confirming this independence has been published. This paper is the first to show the G_s independence with reference height, thus confirming the robustness of comparing G_s from different observation sites.

Subsequent studies should examine G_s dependence with reference height under field conditions, where the assumptions given in this paper may be violated.

The analysis in this note implicitly assumes an accurate G_a estimation. The analysis gives E and the air vapour pressure profile above the surface. This is equivalent to assuming an accurate G_a estimation, because G_a is uniquely determined when E and the air vapour pressure profile are given. Therefore, an inaccurate G_a estimation could violate the theoretical relationship between reference height and G_s obtained in the present analysis.

In fact, many observational studies have used simplified methods to estimate G_a , which might result in inaccurate G_a estimates. For example, Shuttleworth *et al.* (1984), Lee and Black (1993), and Kumagai *et al.* (2004, 2005) assumed that turbulent heat diffusion is as effective as turbulent momentum diffusion for their G_a estimates. In reality, the efficiency of turbulent heat diffusion differs from that of turbulent momentum diffusion (e.g. Thom, 1975; Kondo and Watanabe, 1992; Watanabe, 1994; Hall, 2002). How the use of such simplified methods affects the relationship between reference height and G_s should be examined.

The analysis given in this note assumes constant fluxes of evapotranspiration and available energy above the canopy and complete energy balance closure. In fact, these assumptions can be violated under field conditions, especially for vegetation on sloping planes or for patchy vegetation. If vegetation stands on sloping planes, advective scalar transport (e.g. Lee, 1998; Yi *et al.*, 2000; Aubinet *et al.*, 2003; Davis *et al.*, 2003) might be significant because of gravitational acceleration (e.g. Aubinet *et al.*, 2003; Komatsu *et al.*, 2003, 2005; Turnipseed *et al.*, 2003). Such transports could cause vertical variation in evaporative flux and, therefore, incomplete energy balance closure. If vegetation has a patchy structure, then the projection area of evaporative and radiative flux measurements could vary with reference height, which could result in vertical variation in evaporative and radiative fluxes and, therefore, incomplete energy balance closure (e.g. Schmid and Oke, 1990; Horst and Weil, 1992; Lloyd, 1995). Thus, examining G_s dependence with reference height is especially necessary for vegetation on sloping planes and for patchy vegetation.

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