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, 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 Hinston 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 CO2 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:

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

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

$$G_s(z_t) = \frac{G_s(z_1)\lambda E}{\Delta A + \rho c_p G_s(z_1)[e_s(T(z_1))] - e(z_1)}$$

By substituting $G_s(z_t)$, $E$, $A$, $T(z_t)$, and $e(z_t)$ 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 $G_s(z_t)$ is independent of reference height, consider a situation in which the reference height moves from $z_t = z_{t1}$ to $z_t = z_{t2}$ (Figure 1), where $A$, $E$, and profiles of the air temperature and vapour pressure above the surface are given. Does $G_s(z_{t2}) = G_s(z_{t1})$? If so, then $G_s$ is independent of reference height. Here, $G_s(z_{t1})$ and $G_s(z_{t2})$ are given by

$$G_s(z_{t1}) = \frac{G_s(z_1)\lambda E}{\Delta A + \rho c_p G_s(z_1)[e_s(T(z_{t1}))] - e(z_{t1})}$$

$$G_s(z_{t2}) = \frac{G_s(z_2)\lambda E}{\Delta A + \rho c_p G_s(z_2)[e_s(T(z_{t2}))] - e(z_{t2})}$$

The present analysis assumes vertically constant $A$ and $E$, complete energy balance closure (sensible heat flux is equal to $A - \lambda E$), and $z_{t1} < z_{t2}$ (Figure 1). Note that vertically constant sensible heat flux is...
implicitly assumed because of sensible heat flux equaling $A - \lambda E$ 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)

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

where $G_{a,r1\rightarrow r2}^{-1}$ 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

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

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

where $\varepsilon$ 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:

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

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

If Equations (5), (8), and (9) are substituted into Equation (4), $G_a(z_{r2})$ can be shown to be equal to $G_a(z_{r1})$ 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:

$$ G_a(z_{r2})\gamma \lambda E = (G_a^{-1}(z_{r1}) + G_{a,r1\rightarrow r2}^{-1})^{-1} \lambda E \quad (10) $$

$$ = (G_a^{-1}(z_{r1}) + G_{a,r1\rightarrow r2}^{-1})^{-1} \times G_{a}(z_{r2})G_a(z_{r1})\gamma \lambda E \quad (11) $$

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

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

$$ = \Delta A + \rho c_p (G_a^{-1}(z_{r1}) + G_{a,r1\rightarrow r2}^{-1})^{-1} $$
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× \left[ e_s (T(z_{t1}) - \frac{A - \lambda E}{\rho_c p G_{a,t1-t2}}) \right. \\
- \left( e(z_{t1}) - \frac{pE}{\rho_c G_{a,t1-t2}} \right) - (\Delta + \gamma)\lambda E \right] (12)

= \Delta A + \rho c_p (G_{a}^{-1}(z_{t1}) + G_{a,t1-t2}^{-1})^{-1} \times \left[ e_s (T(z_{t1})) - e(z_{t1}) \right] - (\Delta + \gamma)\lambda E \times \left[ \frac{A - \lambda E}{\rho_c G_{a,t1-t2}} \right]

= \Delta A [1 - (G_{a}^{-1}(z_{t1}) + G_{a,t1-t2}^{-1})^{-1}] + \rho c_p (G_{a}^{-1}(z_{t1}) + G_{a,t1-t2}^{-1})^{-1} \times \left[ e_s (T(z_{t1})) - e(z_{t1}) \right] - (\Delta + \gamma)\lambda E \times \left[ \frac{A - \lambda E}{\rho_c G_{a,t1-t2}} \right]

= \Delta A (G_{a}^{-1}(z_{t1}) + G_{a,t1-t2}^{-1})^{-1} - (\Delta + \gamma)\lambda E \times \left[ \frac{A - \lambda E}{\rho_c G_{a,t1-t2}} \right] (15)

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

\begin{equation}
\begin{aligned}
e_s (T(z_{t1}) - \frac{A - \lambda E}{\rho c_p G_{a,t1-t2}}) &= e_s (T(z_{t1})) \\
- \frac{A - \lambda E}{\rho c_p G_{a,t1-t2}} \end{aligned}
\end{equation}

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):

\begin{equation}
\begin{aligned}
\gamma &= \frac{c_p p}{\lambda E} 
\end{aligned}
\end{equation}

\( G_a(z_{t2}) \) is rewritten from Equations (11) and (17) as

\begin{equation}
\begin{aligned}
G_a(z_{t2}) &= \frac{G_{a}^{-1}(z_{t1}) + G_{a,t1-t2}^{-1}}{(G_{a}^{-1}(z_{t1}) + G_{a,t1-t2}^{-1})^{-1} G_{a}^{-1}(z_{t1})} \times \left[ \Delta A + \rho c_p G_a(z_{t1}) e_s (T(z_{t1})) \right] - e(z_{t1}) \right] - (\Delta + \gamma)\lambda E
\end{aligned}
\end{equation}

Thus, \( G_a(z_{t2}) \) is equal to \( G_a(z_{t1}) \), and \( G_a \) is shown to be independent of reference height.

Conclusions and Recommendations

This note shows that \( G_a \) 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 \( G_a \) independence shown here gives a theoretical basis for \( G_a \) comparisons using data from different observation sites.

Some researchers might already have recognized the \( G_a \) 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 \( G_a \) independence with reference height, thus confirming the robustness of comparing \( G_a \) from different observation sites.

Subsequent studies should examine \( G_a \) 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 \( G_a \) obtained in the present analysis.
In fact, many observational studies have used simplified methods to estimate \( G_s \), which might result in inaccurate \( G_s \) 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 \( G_s \) 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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