Estimation of Boundary Layer Conductance, Surface Water Vapor Conductance, and Net Radiation in the Penman-Monteith Equation

We dedicate this work to John Lennox Monteith who passed away on July 20, 2012, in Edinburgh, Scotland

Mark Blonquist, Apogee Instruments, Inc., Logan, Utah (mark.blonquist@apogeeinstruments.com)
Bruce Bugbee, Dept. of Plants, Soils, and Climate, Utah State University, Logan, Utah
Robert Lascano, USDA-ARS Cropping Systems Research Laboratory, Lubbock, Texas
Acknowledgement: Steve Evett, USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas

Introduction

The Penman-Monteith (P-M) equation is widely applied to estimate evapotranspiration (ET) of crop fields. Currently, typical application of the P-M equation does not include stability effects in the calculation of the boundary layer heat/water vapor conductance term and assumes the surface water vapor conductance term is constant. Additionally, many weather-stations are not equipped with a net radiometer, thus net radiation is estimated from solar radiation measurements. The purposes of this study were to develop simple equations to estimate the conductance terms and test the new equations, and to show how improved estimates of net radiation can improve ET estimation.

The two-source surface energy balance model described in Blonquist et al. (2009), a modified form of the model of Norman et al. (1995), was used to develop equations for calculating boundary layer heat/water vapor conductance and reference surface water vapor conductance. A well-watered alfalfa canopy with height of 0.5 m and leaf area index of 4.5 m^2 m^{-2} was assumed in model calculations. A data set collected over well-watered alfalfa, where ET was measured with a weighing lysimeter, was used to verify the newly developed equations.

Penman-Monteith Equation

The P-M equation is derived from the surface energy balance and provides ET estimates from net radiation, vapor pressure deficit, and the conductance terms:

$$\lambda E = \frac{\Delta(R_n - G) + g_b C_p (e_s - e_a)}{\Delta + \gamma\left(1 + \frac{g_b}{g_s}\right)}$$

where λE is latent heat flux [W m^{-2}] (ET is calculated from λE by dividing by the latent heat of vaporization λ [J mol^{-1}] and multiplying by the molar mass of water, 0.018 kg mol^{-1}), R_n is net radiation [W m^{-2}], G is soil heat flux [W m^{-2}], C_p is heat capacity of air [J mol^{-1} C^{-1}], e_s is saturation vapor pressure of air [kPa], e_a is actual vapor pressure of air [kPa], Δ is the slope of the saturation vapor pressure-temperature relationship [kPa C^{-1}], γ is the psychrometric constant [kPa C^{-1}], g_b is canopy boundary layer conductance to heat and water vapor (often called aerodynamic conductance) [mol m^{-2} s^{-1}], and g_s is surface water vapor conductance [mol m^{-2} s^{-1}]. ET is largely driven by R_n and vapor pressure deficit ($e_s - e_a$), as shown by the P-M equation. Thus, ET estimates from the P-M equation are sensitive to R_n. The sensitivity to g_b and g_s increases as $e_s - e_a$ increases and as wind speed increases.

Boundary Layer Heat/Water Vapor Conductance Equation

Boundary layer heat/water vapor conductance (g_b) is dependent on wind speed, surface roughness, and stability in the layer of air near the surface. Calculation of g_b is based on the shape of the wind speed, temperature, and humidity profiles in the surface boundary layer:

$$g_b = \frac{u \rho_{mol} k^2}{\left[\ln\left(\frac{z_u - d}{z_m}\right) - \Psi_m\right]\left[\ln\left(\frac{z_{Ta} - d}{z_{hv}}\right) - \Psi_{hv}\right]}$$

where u is wind speed [m s^{-1}], ρ_{mol} is molar density of air [mol m^{-3}], k is the von Karman constant, z_u and z_{Ta} are wind speed and air temperature measurement heights [m], respectively, d is zero plane displacement height [m], z_m and z_{hv} are roughness lengths for momentum and heat/water vapor [m], respectively, and Ψ_m and Ψ_{hv} are stability parameters for momentum and heat/water vapor, respectively. The equation for neutral conditions, used in typical applications of the P-M equation, does not include Ψ_m and Ψ_{hv}. To derive an equation for g_b that includes the effects of stability, g_b from the two-source model, which includes the stability parameters, was divided by g_b from the equation for neutral conditions to produce the data shown in Figure 1 for stable and unstable conditions. The neutral equation was then modified by deriving empirical coefficients that produced the best fit to the data in Figure 1. ET predictions from the P-M equation, assuming neutral conditions and using the modified equations, indicate potential improvement when stability is accounted for (Figure 2; stability, stable or unstable, was determined by calculating the bulk Richardson number). However, more data at low wind speeds should be tested.

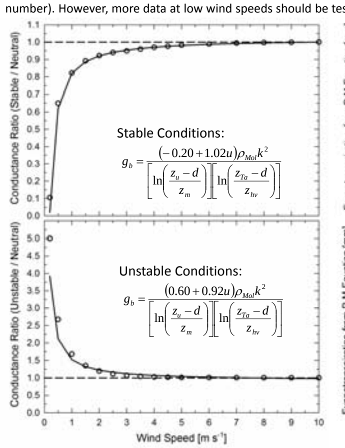

Fig. 1: Stable or unstable g_b divided neutral g_b as a function of wind speed.

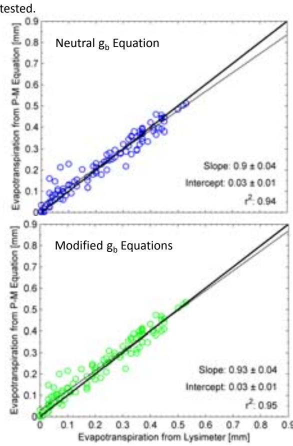

Fig. 2: ET from the P-M equation compared to measured ET.

Surface Water Vapor Conductance Equation

For vegetated surfaces, surface water vapor conductance (g_s) is highly dependent on plant water status. Typical applications of the P-M equation assume a constant reference g_s. However, g_s for well-watered plants should vary with light level and leaf area index (LAI). To derive an equation for reference g_s, canopy stomatal conductance from the two-source model was plotted versus incoming shortwave radiation (SW_i) at four different levels of cloudiness (Figure 3), characterized by the ratio of SW_i to clear sky SW_i (SW_{ic}). Cloudiness is an indirect indicator of direct versus diffuse radiation, which influences the slope of the relationship between canopy stomatal conductance and SW_i. The slopes of the lines were then plotted versus SW_i / SW_{ic} to allow derivation of an equation to predict g_s / SW_i, and subsequently g_s (Figure 3). ET predictions from the P-M equation, assuming constant g_s and using the modified equations, indicate improvement when g_s varies with light and leaf area (Figure 4).

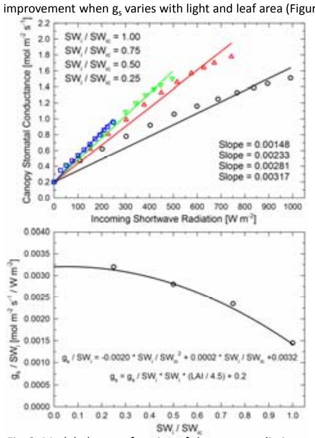

Fig. 3: Modeled g_s as a function of shortwave radiation and slope (g_s / SW_i) as function of cloudiness (SW_i / SW_{ic}).

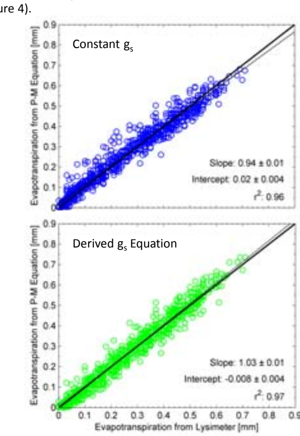

Fig. 4: ET from the P-M equation compared to measured ET.

Net Radiation Estimation

Ideally, net radiation (R_n) is a measured variable, but many ET weatherstations are not equipped with a net radiometer, in which case R_n is predicted from pyranometer measurements of SW_i, an assumed albedo, and modeled value of net longwave radiation. To improve R_n estimates, outgoing longwave radiation (LW_o) can be determined with an infrared radiometer measurement of surface temperature. Then, incoming longwave radiation (LW_i) is the only variable that must be modeled in order to determine R_n. Estimates of R_n, and subsequently ET, were more accurate when LW_o was measured along with SW_i (Figures 5 and 6).

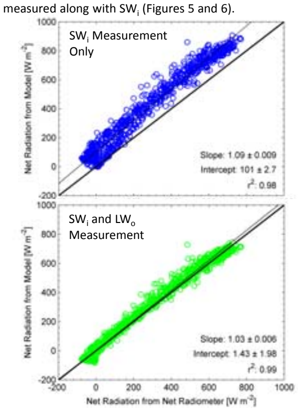

Fig. 5: Comparison of measured and modeled R_n.

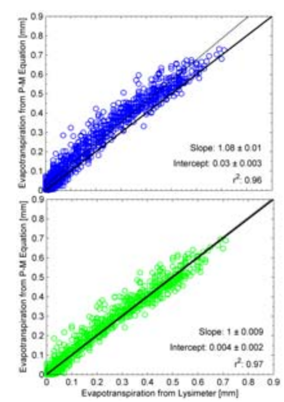

Fig. 6: Comparison of measured and modeled ET.

Summary

- Modified conductance equations and inclusion of surface temperature measurements for R_n calculation improved ET estimates with the P-M equation when compared to ET measurements from a weighing lysimeter.
- The conductance equations are easy to apply and can be used in routine applications of the P-M equation, or in recursive calculations of ET, recently suggested as an alternative to the P-M equation.