LBA-ECO CD-03 Eddy Flux and Micrometeorological Data, Pasture Site, Para: 2001-2005

Formulae used in calculating eddy flux variables

Turbulent fluxes calculation:

Fluxes were directly calculated using:

$$u_* = \overline{w'U'} = \frac{1}{N}\sum_{i=1}^{N} w'U'$$

$$\overline{w'T'} = \frac{1}{N}\sum_{i=1}^{N} w'T'$$

$$\overline{w'x'} = \frac{1}{N}\sum_{i=1}^{N}\left(\overline{w'x'} + \frac{m_d}{m_w}\frac{\rho_x}{\rho_d}\overline{w'\rho_w'} + \rho_x\left(1+\frac{m_d}{m_w}\frac{\rho_x}{\rho_d}\right)\frac{\overline{w'T'}}{T}\right)$$

where U is the horizontal wind speed, w is the vertical wind speed, T is the air temperature, x is a scalar (in this study the specific humidity q or the CO_2 concentration *[CO2]*), m_d/m_w is the ratio of molecular weight of the dry air to that of water vapor, and ρ_d, ρ_w, and ρ_x are the densities for dry air, water vapor, and x respectively. The right hand side of $\overline{w'x'}$ has extra terms due to corrections in air density (Webb et al., 1980, Wyngaard, 1990).

Spectrum correction:

The frequency associated with a certain value of attenuation (f_{att}) is given by:

$$f_{att} = \left(\frac{-2D\ln(Tr)}{0.829 r_0^2\, t_{lag}}\right)^{1/2},$$

where D is the gas diffusion coefficient, Tr is the value of attenuation due to the tubing, r_0 is the radius of the tubing, and t_{lag} is the travel time from the sampling inlet to the IRGA. Assuming that t_{lag} corresponds to delay that yields the maximum correlation in the w-CO_2 and w-q cross-correlation, t_{lag}.= 3.9 s. To achieve an attenuation of 90% (Tr = 0.9), and D values of 0.169 and 0.269 cm^2/s (Rogers and Yau, 1989) for CO_2 and H_2O (p = 1000 mb, T = 30°C) respectively, f_{att} is about 0.25 Hz for the water vapor signal and 0.17 Hz for the CO_2 signal. According to the observed spectra, the attenuation begins at a lower frequency than that predicted by f_{att}. A lower cut-off frequency of 0.08 Hz (f_{cut}) has been used to correct both cospectral curves. The fraction of the flux lost due to the high frequency attenuation (e) is:

$$e = \frac{\sum_{f>f_{cut}} CO(wT)}{\overline{w'T'}} - \frac{\sum_{f>f_{cut}} CO(wx_{mea})}{\overline{w'x'}_{mea}},$$

where *CO()* is the cospectrum, $\overline{w'T'}$, and $\overline{w'x'_{mea}}$ are the turbulent fluxes for T and the scalar quantity x (q or CO_2) measured by the EC system. The corrected flux ($\overline{w'x'_{corr}}$) is given by:

$$\overline{w'x'}_{corr} = (1+e)\overline{w'x'}_{mea}$$

Nocturnal boundary layer budget method (NBLb)

The optimal nocturnal boundary layer (NBL) height (h_N) leads to approximate energy budget closure. Considering that the EC system height and the ground to be the sides of a box bounded by h_N, the layer energy budget is:

$$A \equiv -Q_* - G - St = H + LE + Adv \quad ,$$

where A is the available energy, Q_* is the net radiative flux (the sum of the upward and downward components of the solar and terrestrial radiative fluxes), G is the heat ground flux, St is the storage of energy in the vegetated surface and the air up to the reference level, and Adv represents horizontal thermal advection in the layer. The sign convention is such that downward fluxes are negative, and upward fluxes are positive.

Assuming no sources or sinks of heat or moisture occur within the considered layer, the rate of change of the air temperature (T) and humidity (q) are given by:

$$\frac{\partial \overline{x}}{\partial t} = -U\frac{\partial \overline{x}}{\partial y} - w\frac{\partial \overline{x}}{\partial z} - \frac{\partial \overline{U'x'}}{\partial y} - \frac{\partial \overline{w'x'}}{\partial z} \quad ,$$

where x is a scalar (T, q, or CO_2), y is the horizontal axis, z the vertical, U, w are the horizontal and vertical wind speeds respectively, and $\overline{U'x'}$, *and* $\overline{w'x'}$, are the horizontal and vertical turbulent fluxes, respectively. In subsequent analysis, we assume that the mean advection and the horizontal flux divergence term are negligible ($U\,\partial \overline{x}/\partial y \approx w\,\partial \overline{x}/\partial y \approx \partial \overline{U'x'}/\partial y \approx 0$ However, we recognize that this uncertainty must be addressed observationally in the future using 'microkinematic' techniques presented in Staebler and Fitzjarrald (2004). Applying this simplification, and integrating to a characteristic height, h_N, the top of NBL where turbulent fluxes are assumed to be zero, the surface heat and water vapor fluxes are:

$$H \approx \rho C_p \frac{\partial}{\partial t}\int_0^{h_N} T\,dz \approx \rho C_p h_N \frac{\partial T_z}{\partial t} \qquad (4a)$$

$$LE \approx \rho L \frac{\partial}{\partial t}\int_0^{h_N} q\,dz \approx \rho L\, h_N \frac{\partial q_z}{\partial t} \quad , \qquad (4b)$$

where T is the air temperature, q is the specific humidity, T_z and q_z are the mean temperature and mean humidity of the NBL layer, ρ is air density, C_p is the specific heat at constant pressure, and L is the latent heat of vaporization of water.

The analogous for CO2 flux is given by:

$$\left[\overline{wCO_2'}\right] \approx h_{NCO2} \frac{\partial [CO_2]_{z,night}}{\partial t} \quad , \qquad (5)$$

where $[CO_2]_{z,night}$ is the height-averaged CO_2 concentration at night

Daytime gap filling for wco2.

This formula is given by:

$$\overline{w'CO_2'} = \frac{A_{\max}\, PAR_{dw}}{K + PAR_{dw}} + \left(a0 + a1(e - es)\right)$$

where A_{max} (the maximum rate of photosynthetic assimilation), K (the Michaelis-Menten constant), a_0 (the intercept), and a_1 (the slope) are the parameters to be determined, PAR_{dw} is the downward PAR, e, and e_s are the water vapor pressure, and water vapor pressure of saturation respectively. The correction term for the water vapor pressure deficit (e-e_s) is small ($a_0 \approx a_1 \approx 0$), but it was retained in the gap filling procedure.

Big leaf model for H and LE gap filling:

The big leaf model is a parameterization for the water exchange over dry canopies. It makes an analogy between turbulent exchanges of water vapor with an electronic circuit. The analogous resistances are the canopy resistance (r_c), and the aerodynamic resistance (r_a). They are given by:

$$r_c = \frac{\rho Cp\, \delta e}{\gamma\, LE} + \left(\frac{\beta s}{\gamma} - 1\right) r_a$$

$$r_a = \frac{U}{u_*^2}$$

where ρ is the air density, C_p the is specific heat at constant pressure, δe is the water vapor pressure deficit, $\gamma = (p\, C_p/(0.622\, L))$ is the psychrometric constant, s is the slope of the saturation vapor pressure vs. temperature given by the differential form of the Clausius-Clapeyron equation, p is atmospheric pressure, L is the latent heat of evaporization, β is the Bowen ratio, u_* is the friction velocity, and U is the wind speed. Equation (1) can be rearranged to:

$$LE = \Omega\left(\frac{s}{s+\gamma}\right) A + (1-\Omega)\frac{\rho L \gamma\, \delta e}{r_c}$$

$$H = \beta\, LE$$

$$\Omega = \frac{s/\gamma + 1}{s/\gamma + 1 + r_c/r_a}$$

where A is the available energy.

References:

Rogers RR, Yau MK (1989) A Short Course in Cloud Physics, 3rd edn. Pergamon Press, New York.

Staebler RM, Fitzjarrald DR (2004) Observing subcanopy CO2 advection. Agricultural and Forest Meteorology, 122, 139–156.

Webb E, Pearman G, Leuning R (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society, 106, 85–100.

Wyngaard JC (1990) Scalar fluxes in the planetary boundary layer – theory, modeling and measurement. Boundary Layer Meteorology, 50, 49–75.