Details for VTT correction

Extrapolation to mid-boundary layer mixing ratios will be achieved using mixed-layer similarity theory (Wyngaard and Brost, 1984). This theory states that for a well-mixed boundary where solar heating of the earth's surface drives vigorous convection, the mean vertical mixing ratio gradient is governed via the following expression:

$$\frac{\partial C}{\partial z} = -g_b\left(\frac{z}{z_i}\right)\frac{F_0^C}{w_* z_i} - g_t\left(\frac{z}{z_i}\right)\frac{F_{z_i}^C}{w_* z_i} \qquad (1)$$

where C is the scalar mixing ratio (e.g. CO_2), F_0^C and F_{zi}^C are the surface and entrainment fluxes of the scalar, z_i is the depth of the convective boundary layer, w_* is the convective velocity scale (a function of the surface buoyancy flux and z_i), z is altitude above ground (or, for a forest, above the displacement height) and g_b and g_t are dimensionless gradient functions that depend on normalized altitude within the convective layer.

The difference between surface layer and mid-boundary layer mixing ratios are computed by integrating the flux-gradient relationship across this vertical interval,

$$\Delta C = C\left(\frac{z_{ABL}}{z_i}\right) - C\left(\frac{z_0}{z_i}\right) = -\frac{F_0^C}{w_* z_i}\int_{z0}^{zABL} g_b\left(\frac{z}{z_i}\right)dz - \frac{F_{z_i}^C}{w_* z_i}\int_{z0}^{zABL} g_t\left(\frac{z}{z_i}\right)dz, \qquad (2)$$

where z_0 is the altitude of the surface layer measurement, and z_{ABL} is an altitude in the well-mixed atmospheric boundary layer. Note that the gradient varies linearly with the magnitude of the surface flux (so that in winter, if fluxes are very small, essentially no correction is required), and that the difference in mixing ratio is proportional to the integral of the gradient functions. Note also that for the lower half of the boundary layer, the top-down gradient function is quite small (Moeng and Wyngaard, 1989).

Moeng and Wyngaard (1989) simulated these gradient functions using large eddy simulations (LES). Davis et al (1998), using CO_2 flux and mixing ratio data from the WLEF tall tower for one month, calculated the bottom-up gradient function using data limited to convective conditions. Patton et al (2003) also computed the bottom-up gradient function from a nested forest-boundary layer LES, the first nested model of its kind. A leaf area density similar to a closed deciduous forest canopy was used for the forested simulation, and a no-canopy case was run as a comparison. Turbulent eddies were resolved within the canopy in the surface layer.

This combination of simulation and observation gives insight into the range of errors that will be introduced by this bias correction. The random uncertainty of the *observed bottom-up gradient function*, which includes the turbulent fluctuations in fluxes and mixing ratios, all captured in the WLEF observations and propagated through equation (2), yields a monthly mean random uncertainty in monthly mean mid-CBL mixing ratio of only 0.15 ppm for midsummer fluxes. Note that the calculations shown in Figure 3 assumed a monthly mean uncertainty of 2 ppm! The choice of gradient function is more significant, and the uncertainties are systematic. Integrated, simulated gradient functions over forested vs. non-forested surfaces differ by roughly a factor of two. The maximum reasonable error that could be made (e.g. choosing forest gradient functions if instead the LES canopy functions should be applied) is then about 50% of the total change in CO_2 mixing ratio from surface layer to mid-boundary layer.

Not all elements needed to compute the correction factor (equation 2) are routinely measured at AmeriFlux sites. The depth of the CBL and entrainment flux of CO_2 (mixing downwards from above the mixed layer) will not be known at most sites. The influence of entrainment on the difference between surface and mid-CBL mixing ratios (0.3 to 0.5 z/zi, or 300 to 800m), however, is very small. At midday the CBL depth can be estimated with sufficient accuracy by BL cloud base, nearby rawinsondes, or thermodynamic CBL growth models (Yi et al, 2001). Surface buoyancy and CO_2 flux, and the surface layer CO_2 mixing ratio will be obtained directly from the instrumented flux towers. The majority of the bottom-up vertical gradient occurs very close to the surface, so choosing a precise mid-CBL altitude for the correction is also not critical.