7.6 A RE-EXAMINATION OF DENSITY EFFECTS IN EDDY COVARIANCE MEASUREMENTS OF CO_2 FLUXES

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1 INTRODUCTION

Corrections of the density effects resulting from air-parcel expansion/compression are important in interpreting eddy covariance fluxes of water vapour and CO_2 when open-path systems are used. To correct these effects, mean vertical velocity and perturbation of dry air density are two critical parameters in treating those physical processes involved in air-parcel expansion/compression. Based on various underlying assumptions, different formula for mean vertical velocity and perturbation of dry air density in previous studies has led to a number of alternative approaches for this correction. This paper explores the fundamental differences in physical processes related to the assumptions that are made to formulate the density effects. It is suggested in this paper that the assumption of zero dry air flux in previous studies implies ignoring the contribution of water vapour to the expansion/compression of total moist air parcel. Instead, the zero moist air flux holds in the surface layer, which reflects the nature of turbulence transfer of the total moist air. We also re-examine the mixing ratio relative to dry air.

It is shown that a correction is still required even though the mixing ratio relative to dry air is obtained, which contradicts previous thought.

2. ZERO DRY AIR FLUX OR ZERO MOIST AIR FLUX IN TREATING DENSITY EFFECTS?

Under steady state and horizontal homogeneous conditions with no subsidence, it is well known that one-dimensional vertical CO_2 fluxes in the surface layer can be written as

$$F_c = \overline{w'\rho_c'} + \overline{w}\,\overline{\rho}_c , \quad (1)$$

where w is the vertical wind velocity and ρ_c is the density of CO_2. The term $\overline{w'\rho_c'}$ is directly measured by a single-tower eddy covariance system at a certain height above canopy. $\overline{\rho}_c$ is the mean density of CO_2 and $\overline{w}$ is the mean vertical velocity at the same level as the eddy covariance system. As stated in Webb et al. (1980) and Liu (2005), this mean vertical velocity is caused by air-parcel expansion/compression which then leads to concurrent density variations, i.e., the so called density effects. Obviously, this mean vertical velocity is entirely different in principle to that which may be caused by other synoptic or mesoscale atmospheric processes and local circulations.

Webb and Pearman (1977) propose to use the assumption of zero mean vertical flux of dry air as

$$\overline{w\rho_a} = 0 , \quad (2)$$

where ρ_a is the density of dry air. As a consequence, Equation (2) gives the mean vertical velocity after decomposition and rearrangements as:

$$\overline{w} = -\frac{\overline{w'\rho_a'}}{\overline{\rho}_a} . \quad (3)$$

Recently, Liu (2005) argues that using Equation (3) as a boundary constraint to close Equation (1) is actually equivalent to assuming that only the dry air part of the total moist air contributes to the air-parcel expansion/compression.

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Instead, based on the mass conservation and incompressibility of the air in the surface layer, the zero total moist air flux reasonably holds (i.e., $\overline{w\rho} = 0$) whenever there is evaporation sensed by the eddy covariance system at the interface. Again, this boundary constraint should be set in this interface to close Equation (1), rather than at the lower boundary (i.e., the surface). Therefore, the zero moist air flux yields a mean vertical velocity, $\overline{w}_m$, as

$$\overline{w}_m = -\frac{\overline{w'\rho'}}{\overline{\rho}} = -\frac{\overline{w'\rho'_v}}{\overline{\rho}} - \frac{\overline{w'\rho'_a}}{\overline{\rho}}. \qquad (4)$$

3. MIXING RATIO RELATIVE TO DRY AIR OR TO TOTAL MOIST AIR?

For a constituent, e.g., CO_2, the mixing ratio relative to dry air may be written as $s = \rho_c / \rho_a$. It is generally accepted that there is no correction required if the constituent's mixing ratio relative to dry air could be determined through an indirect way to obtain ρ_c and ρ_a concurrently. In this section, however, we will demonstrate that the use of the mixing ratio relative to dry air component still requires an appropriate correction when accounting for the effect of expansion/compression of the total moist air on CO_2 flux measurements.

Given the mixing ratio relative to dry air, we obtain to a close approximation

$$s' = \frac{1}{\overline{\rho}_a}\rho'_c - \frac{\overline{\rho}_c}{\overline{\rho}_a^{\,2}}\rho'_a. \qquad (5)$$

After multiplied by w' and then applying Reynolds averaging, Equation (5) then yields

$$\overline{w's'} = \frac{1}{\overline{\rho}_a}\overline{w'\rho'_c} - \frac{\overline{\rho}_c}{\overline{\rho}_a^{\,2}}\overline{w'\rho'_a}. \qquad (6)$$

In Equation (6), since $\overline{w'\rho'_a}$ is unknown, therefore, we still require one more equation or parameterization scheme to close it. Again, this new equation should be mathematically and physically reasonable for the physical processes the proposed new equation attempts to describe. The assumption of zero dry air flux gives $\overline{w'\rho'_a} = -\overline{w}_a\,\overline{\rho}_a$. Note that we add a subscript (a) to the mean vertical velocity to indicate that this mean vertical velocity is caused by the expansion/compression of the dry air only. Substitution of this expression (i.e., $\overline{w'\rho'_a} = -\overline{w}_a\,\overline{\rho}_a$) into Equation (6) yields after re-arrangement

$$\overline{\rho}_a\,\overline{w's'} = \overline{w'\rho'_c} + \overline{w}_a\,\overline{\rho}_c. \qquad (7)$$

By comparing Equation (7) with Equation (1) and keeping in mind that $\overline{w}$ in Equation (1) requires the mean vertical velocity being caused by the expansion/compression of the total moist air, we obtain $\overline{w} \neq \overline{w}_a$ without question. It clearly shows that a correction is still required even though the mixing ratio relative to dry air could be obtained through high frequency conversion from mass density.

Liu (2005) points out that the contribution of the air-parcel expansion/compression to the density variations implies the use of the mixing ratio relative to the total moist air. Together with the spectral correction issue when making high-frequency point-by-point conversions from mass density to mixing ratio (Massman, 2004), we suggest the use of density effect correction directly instead of the mixing ratio conversion.

Figure 1 shows the difference in the mean vertical velocity obtained by Equation (3) and Equation (4). The difference in magnitudes are substential, and it reflects the contribution of water vapour to the air parcel expansion/compression. This difference led to difference in CO_2 fluxes after corrections following Webb et al. (198) and Liu (2005).

4 FIELD SITES

The data used in this study were collected in three sites near Delta Junction in interior Alaska (63° 54'N, 145 °40'W). More detail site information can be found in Liu et al. (2005).

Grass

Grass and shrub in this site established after the Donnelly Flats fire that occurred in June of 1999 just south of Delta Junction (63°55'N, 145°44'W). The boles of the black spruce remained standing three years after the fire with a mean height of 4 m and a stand density of 2691 ± 778 dead trees per ha (M.C. Mack, unpublished data).

In 2002, approximately 30% of the surface was covered by bunch grasses (*Festuca altaica*) and deciduous shrubs (that had a height less than 1 m). The other 70% of the surface was not covered by vascular plants. A uniform fetch from the tower extended for more than 1 km in all directions. Moss cover expanded in each consecutive year since the burn, and consisted of *Polytrichum* and *Ceratodon* species.

Aspen

The aspen site was located southeast of Delta Junction (63°56'N, 145°37'W). The canopy developed after the Granite Creek fire occurred in 1987. In 2002, heterogeneous aspen and willow species dominated the overstory (*Populus tremuloides* and *Salix* spp.). Aspen had a mean canopy height of 5 m. The sparse understory vegetation included shrubs (*Salix* spp., *Ledum paustre*, *Rosa acicularis, Vaccinium uliginosum,* and *Vaccinium vitis-idaea*), black spruce (*Picea mariana*), and grasses (*Festuca* spp. and *Calamagrostis lapponica*), separated by patches of moss in open areas (*Polytrichum* spp.). The burn scar from the tower extended for more than 1 km to the south, west and north, and approximately 500 m to the east.

Black spruce

The black spruce site was located approximately 5 km to the south of the grass site (63°53'N, 145°44'W). The canopy overstory consisted of homogeneous stands of black spruce (*Picea mariana*) with a mean canopy height of 4 m and a mean age of 80 years based on tree ring measurements. The sparse understory consisted primarily of shrubs (*Ledum palustre*, *Vaccinium uliginosum*, and *V. vitis-idaea*).

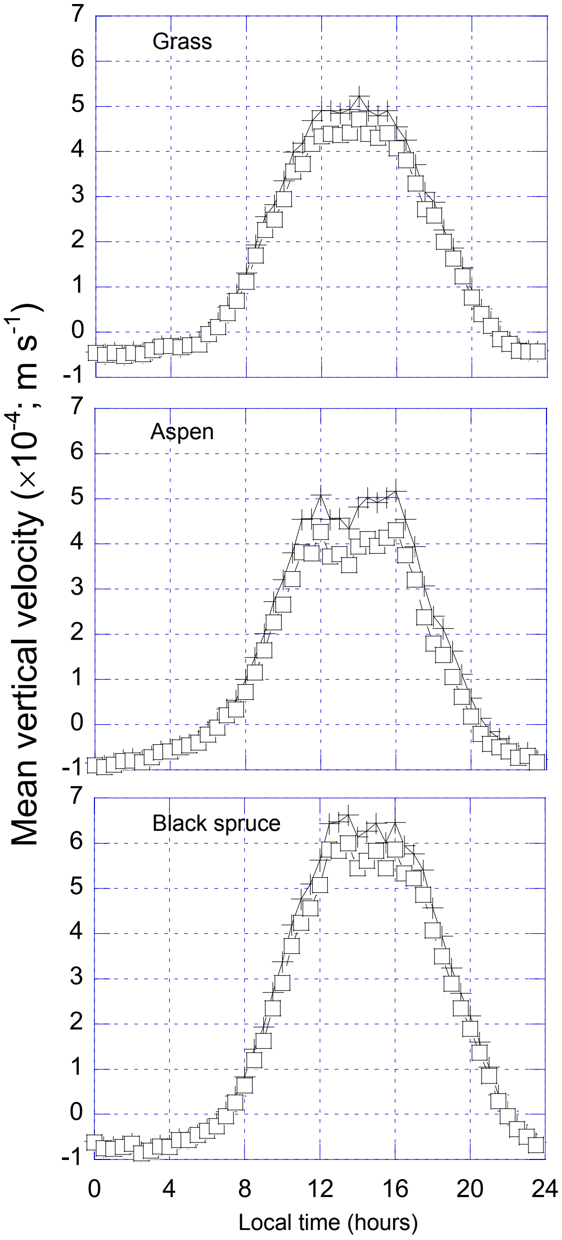

Figure 1. Comparison of diurnal variations of mean vertical velocity obtained by the assumption of zero dry air flux (crosses) and zero moist air flux (squares) over grass, aspen, and black spruce stands in interior Alaska. Data cover the period from June 17 to August 5, 2003. Total half-hour data numbers are 1,695, 1,793, and 1,895 for the grass, aspen, and black spruce sites, respectively.

The dominant ground cover species were feathermoss (*Pleurozium schreberi* and *Rhytidium rugosum*) and lichen (*Cladonia* spp. and *Stereocaulon spp.*). Moss and soil organic layers had a mean depth of approximately 11 cm to mineral soil. The site extended from the tower for more than 1 km to the south, west and north, with the shortest fetch to the east (approximately 200 m).

5 INSTRUMENTS

Turbulent fluxes of sensible heat (H), latent heat (LE), and carbon dioxide (CO_2) were measured at each site with an eddy covariance system that consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Inc.) and an open-path carbon dioxide/water vapor (CO_2/H_2O) infrared gas analyzer (IRGA; LI 7500, LI-COR, Inc.). The sonic anemometers measured fluctuations of the three components of wind velocity and fluctuations of sonic temperature of the atmosphere. IRGAs measured fluctuations of densities of water vapor and carbon dioxide. At each site, the eddy covariance system was mounted at a height approximately 2 times that of the mean canopy on an aluminum tower (Climatronics Corp.).

Sensor signals were recorded by dataloggers (CR5000, Campbell Scientific, Inc.) at a rate of 10 Hz. Vertical fluxes of sensible (H) and latent heat (LE) were obtained via 30-min mean covariance between vertical velocity (w') and the respective scalar (c') fluctuation. Turbulent fluctuations were calculated as the difference between the instantaneous and the 30-min mean quantities. Because the temperature obtained from the sonic anemometer is the sonic temperature and because the crosswind effect should be taken into account (Kaimal and Finnigan, 1994), we applied a correction following that established by Liu et al. (2001). We checked the original 10 Hz time series of temperature, H_2O, and CO_2 for spiking/noise. Data points were replaced through linear interpolation when their magnitudes exceeded 5σ of the half hour mean (where σ denotes standard deviation). Some flux data were rejected when winds were blowing through the towers and when the data did not pass a quality check (Foken and Wichura, 1996). In addition, in our analysis and site comparisons, we only included flux data from each site during periods when all three sites were simultaneously active.

Along with the turbulent fluxes, a variety of micrometeorological variables were also measured as 30-min averages of 1 s readings at our three sites. Net radiation (Rn) was measured with net radiometers (Q-7.1, Radiation and Energy Balance Systems [REBS], Inc.) at all three sites. Incoming and reflected global solar radiation were measured with Precision Spectral Pyranometers (Eppley Lab., Inc.) at the grass and black spruce sites. Air temperature and relative humidity were measured at three heights at all three sites with temperature/humidity probes (HMP45C, Vaisala, Inc.). A wind sentry unit (model 03001, RM Young, Inc.) was mounted at the top of the tower to measure wind speed and wind direction while another wind speed sensor (model 03101, RM Young, Inc.) was mounted on each tower at an intermediate height.

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