P2.4 AN APPROACH FOR ESTIMATING KINEMATIC HEAT FLUX LOSS DUE TO AIR-PARCEL EXPANSION/COMPRESSION IN THE SURFACE LAYER

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1 INTRODUCTION

Equations are proposed to explain kinematic heat flux loss when eddy covariance measurements are used to obtain kinematic heat flux (i.e., $\overline{w'T'}$ where w' and T' are the fluctuations of vertical velocity and air temperature relative to their means, respectively).

This loss is caused by air-parcel expansion/compression as the air parcels move between the surface and the level of eddy covariance measurements. The physical derivation in this paper involves the use of the first law of thermodynamics and air-parcel expansion/compression approach developed by H. P. Liu (Boundary-Layer Meteorol., 115, 151-168). The equations are then applied to data collected over three boreal ecosystems. The results show that this lost kinematic heat flux can be up to 10-15% of the total kinematic heat flux that is sheded from the surfaces to the atmosphere. This loss may have significant implications for some situations that use the form of the kinematic heat flux.

2. THEORETICAL BACKGROUND

The turbulent surface layer consists of air parcels with different scales. These air parcels move up and down in the surface layer. As a result, expansion/compression of the air parcels occurs (Webb et al., 1980). The detailed picture about this physical process is provided in Liu (2005). As these thermal air parcels move upward in the daytime unstable surface layer, for example, some energy is consumed as work of expansion, leading to a decrease in temperature in this adiabatic system. Therefore, the measured temperatures by fast-response thermometers at a certain height above the surface may be lower than what would be expected without expansion. This means that kinematic heat flux measured by eddy covariance systems (product of w' and T') may not take into account the influence of the work of expansion.

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Based on above analysis, we attempt to estimate how much energy flux goes into air-parcel expansion and how much energy flux is gained from air-parcel compression in the surface layer.

It is assumed that these air parcels represent a closed thermodynamic system when they move from the surface to the height of eddy covariance measurements. However, this is a rough assumption as cooler ambient air is entrained into these thermal air parcels in both lateral and vertical directions during their upwards movements, and consequently heat is gradually lost from the parcels. As a consequence of this heat exchange process, the ambient air in the surface layer warms and the air temperature in the surface layer increases. This is similar to the development of thermal plumes in a convective mixed layer (Stull, 1988).

This lost heat flux due to expansion can also be estimated using the first law of thermodynamics that was discussed extensively in many textbooks (e.g. Wallace and Hobbs, 1977),

$$C_v\,dT + P\,dV = dQ\,, \qquad (1)$$

where C_v is the specific heat at constant volume, dT is temperature variation during this adiabatic process. P is the pressure that is assumed to be constant in the surface layer, dV is the specific volume change ($V = 1/\rho$ with a unit mass; ρ is the total air density) due to expansion. In Equation (1), the first term on the left-hand-side (*LHS*) denotes the internal energy variation due to the variation in the air-parcel temperature during the air-parcel movement from the surface to the measurement height. The second term on the *LHS* denotes the work of expansion performed by the air-parcel. The term dQ is the heat source or sink. If it is assumed that there is no heat exchange between the air-parcel and the ambient environment, then the term dQ is equal to zero. Actually, this is a rough assumption as aforementioned since there is a heat exchange between the air parcels and the ambient air.

The temperature perturbation T'' (T'' is used in order to avoid confusion with the temperature fluctuation (T') measured by eddy covariance systems) caused by air-parcel expansion can be obtained from Equation (1),

$$T'' = -\frac{PV'}{C_v}. \qquad (2)$$

To obtain in Equation (2), the expansion/compression approach developed in Liu (2005) is used. Firstly, following Webb et al (1980) and applying the ideal gas law to dry air, water vapor and moist air, respectively, we obtain

$$P_a = \frac{\rho_a}{m_a} RT, \qquad (3)$$

$$P_v = \frac{\rho_v}{m_v} RT, \qquad (4)$$

$$P = \frac{\rho}{m} RT, \qquad (5)$$

where P_a and P_a are partial pressures of dry air and water vapor, respectively; *P* is the total atmospheric pressure; ρ_a, ρ_v, and ρ are the respective density of dry air, density of water and the total density of moist air ($\rho = \rho_a + \rho_v$); m_a, m_v, and m are the molecular masses of dry air, water vapor, and moist air, respectively; R is the universal gas constant; and T is the absolute air temperature.

As for such a system, it is assumed that the ambient atmospheric pressure is constant in the surface layer (at least up to the height of eddy covariance measurements), and that the surface pressure fluctuation, as compared with water vapor fluctuation, is negligibly small (Webb et al., 1980; Paw U et al., 2000; Liu, 2005). We then obtain the relationship between the perturbations in the densities for dry air, water vapour, and temperature through applying the ideal gas law for dry air, water vapour, and moist air, which is the same as in Webb et al. (1980).

$$\rho_a' = -\frac{m_a}{m_v}\rho_v' - (\overline{\rho}_a + \frac{m_a}{m_v}\overline{\rho}_v)\frac{T'}{\overline{\overline{T}}}. \qquad (6)$$

Clearly, the expansion/compression in the volume of the air parcel leads to variations in the density,

$$\frac{V'}{\overline{\overline{V}}} = -\frac{1}{\overline{\overline{\rho}}}\rho', \qquad (7)$$

where V' is a perturbation in specific volume.

Given that $\rho' = \rho_a' + \rho_v'$, combination of Equations (6) and (7) yields,

$$\frac{V'}{\overline{\overline{V}}} = -\frac{1}{\overline{\overline{\rho}}}\{(1 - \frac{m_a}{m_v})\rho_v' - (\overline{\rho}_a + \frac{m_a}{m_v}\overline{\rho}_v)\frac{T'}{\overline{\overline{T}}}\}. \qquad (8)$$

To be consistent with the assumption used in Equation (1), Equation (8) may be rewritten when a unit of mass is considered.

$$V' = -\frac{1}{\overline{\rho}^2}\{(1 - \frac{m_a}{m_v})\rho_v' - (\overline{\rho}_a + \frac{m_a}{m_v}\overline{\rho}_v)\frac{T'}{\overline{\overline{T}}}\}. \qquad (9)$$

Therefore, the temperature perturbation that is used for air-parcel expansion may be obtained after combination of Equation (2) and (9).

$$T'' = \frac{P}{C_V\overline{\overline{\rho}}^2}\{(1 - \frac{m_a}{m_v})\rho_v' - (\overline{\rho}_a + \frac{m_a}{m_v}\overline{\rho}_v)\frac{T'}{\overline{\overline{T}}}\}. \qquad (10)$$

The kinematic heat flux needed for expansion is then obtained after multiplying Equation (10) by w' and taking Reynolds average,

$$W_{\exp ansion} = \overline{w'T''}$$
$$= \frac{P}{C_V\overline{\overline{\rho}}^2}\{(1 - \frac{m_a}{m_v})\overline{w'\rho_v'} - (\overline{\rho}_a + \frac{m_a}{m_v}\overline{\rho}_v)\frac{\overline{w'T'}}{\overline{\overline{T}}}\} \qquad (11)$$

2 FIELD SITES

The data used in this study were collected in three sites near Delta Junction in interior Alaska (63^{o} 54'N, 145 ^{o}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^{o}55'N, 145^{o}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 3-year 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*). 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).

3. 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.

At three sites within 2 to 4 m of the tower base we measured soil temperature profiles. In each profile, thermocouples were placed at 0, 2.5, 5, 10, and 20 cm depths below the surface. In 2 of the 3 profiles at each site we also measured the soil heat flux (G_{10}) at a depth of 10 cm using soil heat flux plates (model HFT3, REBS, Inc.). Precipitation totals were measured at half-hourly intervals at both the grass and aspen sites with an automated tipping-bucket rain gauge (model TE525, Campbell Scientific, Inc.). More detail information about the towers can be found in Liu et al. (2005).

5. RESULTS

Using the data measured over three boreal ecosystems (i.e., grass and shrub, aspen, and black spruce stands), we obtained the kinematic heat flux directly measured by eddy covariance systems ($\overline{w'T'}$) and the lost kinematic heat flux as results of expansion/compression of air parcels using Equation (11). According to Equation (11), the magnitudes of lost kinematic heat flux depend to great extent upon the kinamatic heat flux ($\overline{w'T'}$). In general, the lost kinematic heat flux is about 10-15% of the kinematic heat flux measured by eddy covariance systems over these three ecosystems (Figure 1).

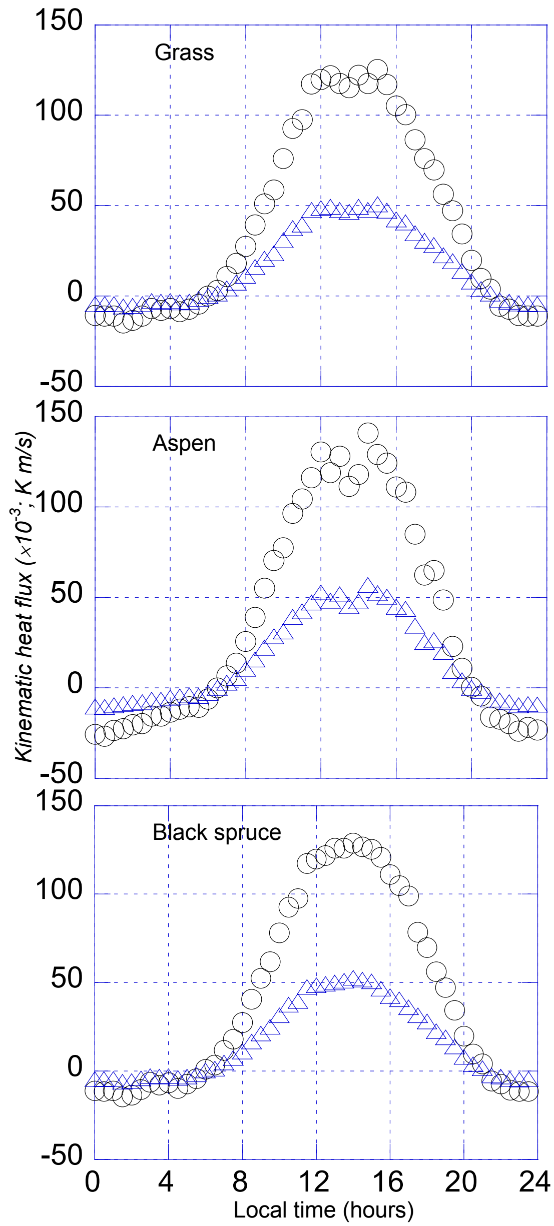

Fig. 1. Comparison of kinematic heat flux measured by eddy covariance systems (circle) and the lost kinematic heat flux as results of expansion/compression (triangle) over grass, aspen, and black spruce stands in interior Alaska. Data cover the period from June 17 to August 5, 2003. Total half-hour data numbers are 1,695, 1,793, and 1,895 for the grass, aspen, and black spruce sites, respectively.

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