Effects of Density Correction on Latent Heat Flux, CO_2 Flux, and Energy Balance Closure in a Winter Wheat/Summer Maize Rotation Field Postprint

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Abstract

This study employs the eddy covariance technique to measure CO2, water vapor, and energy exchange between the winter wheat/summer maize rotation field and the atmosphere at the Qingdao Agricultural University Modern Agricultural Science and Technology Demonstration Park Experimental Station during 2013-2014. Two density corrections (WPL correction and Liu correction) were applied to latent heat and CO2 fluxes, respectively, and compared, and the energy balance closure of the winter wheat/summer maize rotation field was calculated before and after the two density corrections. The results show that both WPL correction and Liu correction can increase latent heat flux: after WPL correction, the latent heat flux in the summer maize field increased by approximately 6% and by about 2% in the winter wheat field; after Liu correction, the summer maize field increased by less than 1% and the winter wheat field increased by about 2%. Therefore, the WPL correction demonstrates a significantly better correction effect on latent heat in the summer maize field compared to the Liu correction, while for the winter wheat field, both methods produce equivalent effects on latent heat correction. Both correction methods have a reducing effect on CO2 flux: after WPL correction, CO2 flux decreased by 3% and 4% in the summer maize field and winter wheat field, respectively; after Liu correction, CO2 decreased by 2% and 3% in the summer maize field and winter wheat field, respectively. It can be seen that the difference between WPL correction and Liu correction for CO2 flux is very small (the difference is only 1%). Through analysis of the energy balance closure of the winter wheat/summer maize rotation field in the Qingdao region, it was found that density correction can improve energy balance closure, but different underlying surfaces exhibit different correction effects. Under bare soil conditions, WPL correction can improve energy balance closure by approximately 2.53%-9.76%, by 4.05% in the summer maize field, and by 1.35% in the winter wheat field; whereas Liu correction improves energy balance closure by less than 2.53% for bare soil and by about 1.35% for both the summer maize field and winter wheat field. Clearly, the correction magnitude of WPL correction for energy balance closure is greater than that of Liu correction. The magnitude relationship of energy balance closure is: Bare soil I (before summer maize emergence) > Bare soil II (before winter wheat emergence) > Summer maize field > Winter wheat field.

Full Text

Influence of Density Correction on Latent Heat, CO_2 Flux and Energy Balance Closure in Winter Wheat/Summer Maize Rotation Fields*

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Abstract

Over the past two decades, the eddy covariance technique has become a standardized method for measuring exchanges of CO_2, water vapor, and heat between vegetation and the atmosphere. To understand the variation characteristics of CO_2, water vapor, and heat fluxes in a winter wheat/summer maize rotation system, an experiment was conducted from June 2013 to June 2014 at the Qingdao Modern Agricultural Demonstration Farm of Qingdao Agricultural University. The CO_2, water vapor, and heat fluxes were measured during both winter wheat and summer maize growing seasons using the eddy covariance method, and the values were corrected by two density correction methods (WPL correction and Liu correction). The differences between the two methods were compared, and energy balance closure was computed during bare soil and vegetation cover periods for both winter wheat and summer maize based on the two density correction methods.

The results showed that both correction methods increased latent heat flux. The WPL correction method increased latent heat flux by about 6% for the summer maize season and 2% for the winter wheat season, while the Liu correction method increased latent heat flux by less than 1% for the summer maize season and about 2% for the winter wheat season. The WPL correction method reduced CO_2 flux by less than 3% for summer maize and 4% for winter wheat. Similarly, the Liu correction method reduced CO_2 flux by about 2% for summer maize and 3% for winter wheat. There was little difference (about 1%) between the two correction methods for both latent heat and CO_2 flux corrections. The two correction methods had the potential to increase energy balance closure. WPL correction obviously increased energy balance closure by about 2.53%–9.76% for bare soil, by 4.05% for summer maize, and by 1.35% for winter wheat. In contrast, Liu correction increased energy balance closure by less than 2.53% for bare soil and by about 1.35% for both summer maize and winter wheat seasons. This suggested that the degree of correction by the WPL method was greater than that by the Liu method. Energy balance closure during bare soil periods was obviously higher than that during vegetation cover periods. The order of energy balance closure was: bare soil I (before maize seed emergence) > bare soil II (before winter wheat seed emergence) > summer maize vegetation period > winter wheat vegetation period.

Keywords: Density correction; Latent heat flux; CO_2 flux; Energy balance closure; Winter wheat/summer maize rotation field

Introduction

To better understand regional and global carbon and water cycle characteristics, an increasing number of regions have established carbon and water flux observation stations that are part of the global carbon and water flux observation network (FLUXNET), monitoring regional CO_2 emission and absorption dynamics and water evapotranspiration in real time [1]. Although the eddy covariance method still has some unresolved issues, it has become an internationally recognized standard method for measuring dynamic changes in carbon and water cycles in various ecosystems [2]. Density correction is an essential process in processing eddy covariance system data. Webb et al. [3] first proposed density corrections for latent heat and carbon flux in 1980. Based on the assumption of dry air mass conservation, they calculated the mean vertical velocity and derived the calculation method for latent heat and CO_2 flux, known as the WPL correction method. For over 30 years since its proposal, the WPL correction method has maintained strong vitality and has become an indispensable part of correcting observed atmospheric boundary layer energy and material fluxes. By 2010, citations of WPL correction had reached 130 per year [4]. It is safe to say that without the WPL correction method, the development and growth of FLUXNET research would have been impossible.

In 2005, Liu [5] proposed an alternative density correction method for latent heat and CO_2 flux based on the physical theory of air parcel expansion/compression, without assuming dry air mass conservation or requiring calculation of mean vertical velocity. This method is known as the Liu correction method. Upon its publication, Kowalski [6–7] in 2006 and Leuning [8] in 2007 questioned and criticized this correction method, arguing that Liu correction was an erroneous theory. Liu [9] subsequently published his own views and opinions, and both sides engaged in intense debate regarding the two density correction methods. However, applications in cropland and grassland have shown that there are no significant differences between the two correction methods for latent heat and CO_2 flux [10-11]. Further comparison of the two methods requires more experimental validation.

This study utilized eddy covariance and meteorological data from a winter wheat/summer maize rotation field in Qingdao in 2013 to analyze the effects of two density correction methods on latent heat and CO_2 fluxes in the rotation field. Energy balance closure was calculated for different growth stages of winter wheat and summer maize to provide more experimental data for comparing WPL correction and Liu correction.

Methods

Site Description

The experiment was conducted at the Qingdao Modern Agricultural Science and Technology Demonstration Park (120.48°E, 36.26°N) of Qingdao Agricultural University. The site is located in a semi-humid, drought-prone region with an average temperature of 12.4 °C and annual sunshine duration of 2,229 hours. The average annual rainfall over the past decade was 662 mm, concentrated in late July and early August. The observation area was 150 m × 200 m. Except for fruit trees to the west, the surrounding areas had the same crop type as the observation area: a winter wheat/summer maize double-cropping rotation system. Summer maize (variety 'Zhengdan 958') was planted on June 26, 2013, using no-tillage with fertilizer application, with row spacing of 0.65 m and plant spacing of 0.22 m. Fertilizer $N\text{-}P_2O_5\text{-}K_2O$ (22-10-10) was applied at 525 $kg \cdot ha^{-1}$, with an additional 225 $kg \cdot ha^{-1}$ of urea applied at the small trumpet stage, and harvested on October 10. Winter wheat (variety 'Jimai 22') was planted on October 14, 2013, using one pass of plowing and two passes of rotary tillage with fertilizer application. $N\text{-}P_2O_5\text{-}K_2O$ fertilizer was applied at 525 $kg \cdot ha^{-1}$ with a seeding rate of 185 $kg \cdot ha^{-1}$ and row spacing of 0.20 m, and harvested on June 16, 2014. The soil at the experimental site was lime concretion black soil with pH 6.7, organic matter content of 12.65 $g \cdot kg^{-1}$, and available nitrogen, phosphorus, and potassium of 100.41 $mg \cdot kg^{-1}$, 39.80 $mg \cdot kg^{-1}$, and 135.8 $mg \cdot kg^{-1}$, respectively.

Instruments

The eddy covariance system was located in the southeastern part of the demonstration park, at the center of a 30,000 m^2 winter wheat/summer maize rotation field. Three-dimensional wind speed was measured by an ultrasonic anemometer (CAST3, Campbell, USA). Vertical fluxes of latent heat, CO_2, and H_2O were measured by an open-path infrared gas analyzer (LI-7500, Li-Cor Inc., USA).

The ultrasonic anemometer and infrared gas analyzer were installed at the same height on the flux tower (2.5 m during early and mid-maize growth, adjusted to 3.5 m during late maize season; fixed at 2.5 m throughout the winter wheat growing season) and connected to a data logger (CR3000, Campbell, USA). Raw data were collected at 10 Hz frequency and output as 30-minute averages.

Radiation components were measured by a net radiometer (CNR1, Kipp and Zonen, Netherlands). Three soil heat flux plates (HFP01SC, Hukseflux, Netherlands) were installed at 5 mm depth to measure soil heat flux. Wind speed and direction were measured by a switch anemometer (A100R, Rhyl, Vector, UK) and wind vane (W200P, Vector, UK) installed at 5 m height. Air temperature and humidity were measured by a temperature and humidity sensor (HMP45C, Campbell, USA). Rainfall was measured by a rain gauge (52202, Young, USA). These instruments were connected to the data logger and output 30-minute averages.

Research Methods

The theoretical foundation of eddy covariance technology (Reynolds decomposition) was established by Reynolds [12] in 1895, but the technique was not developed and applied at the time due to lack of appropriate observation instruments. With the development of fast-response instruments and computers, eddy covariance technology has since advanced [13]. When the underlying surface is uniform, latent heat and CO_2 flux densities (referred to as fluxes) can be expressed by the following formulas [14]:

Latent heat flux (LE): $LE = \lambda\overline{w'\rho_v'}$

CO_2 flux (F_c): $F_c = \overline{w'\rho_c'}$

where w is vertical wind speed, λ is latent heat of vaporization, ρ_v is water vapor density, ρ_c is CO_2 density, the prime symbol ( ) denotes fluctuation values, and the overbar denotes average values.

Density Correction When using equations (1) and (2) to calculate latent heat and carbon dioxide fluxes, the time-averaged value of vertical wind speed is typically assumed to be zero ($\overline{w} = 0$). However, Webb et al. [3] pointed out that if air density fluctuates, the situation differs. Since the w value is very small and difficult to measure, Webb et al. calculated w using the dry air mass conservation equation, thereby deriving the correction results for latent heat and CO_2 flux—the WPL correction.

The WPL correction terms involve parameters including: T (air temperature), ρ_d (dry air density), μ (ratio of molecular weight of dry air to water vapor, 1.608), and other density terms. The correction accounts for density effects due to heat and water vapor transfer.

Energy Balance Closure Analysis Energy balance closure analysis is an important aspect of studying water, carbon, and heat cycles in any ecosystem and serves as an important indicator for judging data quality [15-16]. Internationally common methods for evaluating energy balance closure include ordinary least squares, orthogonal regression, energy balance ratio, and energy balance residual δ frequency distribution [17]. This study used ordinary least squares for analysis. Energy balance closure (energy balance ratio) is defined as the percentage of available energy $(\overline{H+LE})$ relative to usable energy $(R_n - G)$ over a period, where R_n is net radiation $(\mathrm{W \cdot m^{-2}})$, G is surface soil heat flux $(\mathrm{W \cdot m^{-2}})$, H is sensible heat flux $(\mathrm{W \cdot m^{-2}})$, and LE is latent heat flux $(\mathrm{W \cdot m^{-2}})$. Under ideal conditions, energy balance closure is 100%, but in reality it is always less than 100%. Many studies have shown that energy imbalance exists [18-20], with a closure deficit of about 10%-30% [2,21-22]. When calculating energy balance closure, the ratio of effective energy to available energy was calculated based on 30-minute average data, and then statistically averaged to obtain energy balance closure. Data processing software used OriginPro 8.5 and Excel 2007.

Results and Discussion

Effects of Density Correction on Latent Heat Flux and CO_2 Flux

Latent heat flux and CO_2 flux from the winter wheat/summer maize rotation field in Qingdao during 2013-2014 were subjected to WPL correction and Liu correction, and linear fitting was performed with uncorrected latent heat flux and CO_2 flux. The results are shown in [Figure 1: see original paper] and [Figure 2: see original paper].

Analysis of latent heat flux density correction (Figure 1) revealed that WPL-corrected latent heat flux was higher than before correction, with an increase of about 6% in the summer maize field and about 2% in the winter wheat field. Liu correction also increased latent heat flux, but the increase was smaller than that of WPL correction—less than 1% in the summer maize field and less than 2% in the winter wheat field. Linear fitting correlation coefficients were all above 99%. Therefore, WPL correction showed a slightly greater correction magnitude for latent heat flux than Liu correction.

Comparative analysis of CO_2 flux (Figure 2) showed that both WPL correction and Liu correction reduced CO_2 flux compared with uncorrected values. WPL correction reduced CO_2 flux by about 3% in the summer maize field and about 4% in the winter wheat field. Liu correction reduced CO_2 flux by about 2% in the summer maize field and about 3% in the winter wheat field. Linear fitting correlation coefficients were all greater than 98%. For both summer maize and winter wheat crops, the difference between WPL correction and Liu correction for CO_2 flux was less than 1%, consistent with the research results of Wang et al. [10] and Liu et al. [11].

Although WPL correction and Liu correction approach from different theoretical perspectives, their correction effects on latent heat and CO_2 flux are almost identical. Therefore, both density correction methods can be used in eddy covariance data analysis.

Analysis of Energy Balance Closure Under Different Density Correction Methods

To understand the energy balance closure of the winter wheat/summer maize rotation field in Qingdao, this study analyzed energy balance closure under different underlying surface conditions. According to crop growth conditions in the rotation field, four periods were defined: 1) bare soil I (after wheat harvest to before maize emergence); 2) summer maize (from maize emergence to harvest); 3) bare soil II (after maize harvest to before wheat emergence); and 4) winter wheat (from wheat emergence to harvest). For each condition, closure analysis was performed only for daytime conditions ($R_n > 0$) [23], with results shown in .

Table 1 shows that: 1) Comparing energy balance closure before and after WPL correction revealed that WPL correction increased energy balance closure for all conditions—by 2.53% and 9.76% during bare soil periods, 4.05% during the maize growing season, and a smaller increase of 1.35% during the wheat growing season. Liu correction had a smaller effect on energy balance closure than WPL correction, with no change during bare soil I, an increase of 2.53% during bare soil II, and about 1.35% during both maize and wheat growing seasons. The all-day energy balance closure (after WPL correction) was 0.80 for the entire maize season and 0.77 for the wheat season. The average energy balance closure of ChinaFLUX sites is 0.73 [24]. Although the energy balance closure of both winter wheat and summer maize fields was slightly higher than the average level, it was lower than the results of Liu et al. [25] (1.15) and Shen et al. [26] (0.90-0.95), while the maize season result fell between Liu et al. [25] (0.78) and Li et al. [27] (0.85). 2) Analysis of different underlying surfaces showed the energy balance closure ranking was: bare soil I > bare soil II > summer maize > winter wheat. Although both were bare soil periods, the better energy balance closure of bare soil I compared to bare soil II may be due to more straw residue remaining after maize harvest (bare soil II) than after wheat harvest, thus having a greater impact on energy balance closure. Energy balance closure was higher during bare soil periods than during vegetation cover periods because many energy terms (such as canopy heat storage) were neglected during vegetation cover periods, leading to reduced energy balance closure. Additionally, different vegetation covers have different surface albedos, affecting energy balance closure. The result that energy balance closure was higher for summer maize than for winter wheat differs from Liu et al. [28] but is consistent with Li et al. [24], who found that winter energy balance closure was lower than summer energy balance closure. Further verification is needed for definitive conclusions.

Conclusion

Through comparative analysis of WPL correction and Liu correction for latent heat and CO_2 fluxes in the winter wheat/summer maize rotation field at the Qingdao Modern Agricultural Science and Technology Demonstration Park, it was concluded that both density correction methods can increase latent heat flux. WPL correction increased latent heat flux by 6% for summer maize and 2% for winter wheat, while Liu correction increased it by less than 1% for summer maize and 2% for winter wheat. Therefore, WPL correction showed a slightly greater correction magnitude than Liu correction for summer maize latent heat flux.

Both WPL correction and Liu correction reduced CO_2 flux. WPL correction reduced CO_2 flux by 3% and 4% for summer maize and winter wheat fields, respectively, while Liu correction reduced it by 2% and 3%, respectively. The difference between the two density correction methods was only about 1% for both crops. Thus, WPL correction and Liu correction show minimal differences in their correction effects on latent heat flux and CO_2 flux.

Analysis of energy balance closure for the winter wheat/summer maize rotation field in Qingdao revealed that both WPL correction and Liu correction can improve energy balance closure, with different correction effects for different underlying surfaces. WPL correction increased energy balance closure by 2.53%-9.76% during bare soil periods, and by about 4.05% and 1.35% during maize and wheat growing seasons, respectively. Liu correction increased energy balance closure by less than 3% during bare soil periods and by about 1.35% during both maize and wheat growing seasons. Comparison showed that WPL correction had a greater impact on energy balance closure than Liu correction, with varying improvement magnitudes for different underlying surfaces—greatest during bare soil I and smallest during the wheat growing season (only 1%). The ranking of energy balance closure for different underlying surfaces was: bare soil I > bare soil II > summer maize > winter wheat.

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