Estimation of Maximum Water-Use Efficiency in Paddy Field by Using Eddy Covariance Method

Tohoku University Member ○ Pimsiri SUWANNAPAT
Tohoku University Member Daisuke KOMORI
National Institute for Agro-Environmental Sciences Wonsik KIM

1. INTRODUCTION

Measurements of water vapor (q) and carbon dioxide (c) concentrations in the atmospheric surface layer are now widely collected with application of eddy covariance principle. Normally, this high-frequency measurement is used to quantify carbon dioxide flux (Fc) and latent heat flux (lE) in the ecosystem scale. Therefore, understanding of water-use efficiency (WUE) is a key linking q and c from the fact that transpiration and c uptake occur simultaneously in opposite direction via the stomatal aperture (Cowan and Farquhar, 1977).

In this study, q-c correlation ($\rho_{q,c}$) in daytime was analyzed to investigate function of stomatal flux within the context of flux variance similarity principle (Scanlon and Sahu, 2008). Orthonormal wavelet transform was applied to the time series, in order to determine WUE, transfer efficiencies of q and c in across scales of turbulent eddies. Although WUE derived from ratio of Fc (with components of respiration and photosynthesis) to lE (with components direct evaporation and transpiration) as the ecosystem water-use efficiency (WUE_e), we attempted to define WUE as the stomatal function by using the maximum WUE, which exhibited a strong stomatal flux-expression.

2. STUDY FIELD AND DATA

The time series of eddy covariance data were collected over a rain-fed paddy field located on Sukhothai, Thailand (at 17°03'51"N, 99°42'17"E, 50 m asl.). WUE was investigated in a no-rain condition on 12 and 15 September, 2006 at 8:00 am to 17:00 pm. The high-frequency data (10 Hz) were corrected by 3D-sonic anemometer (CSAT3, Campbell Scientific inc.) and infrared gas analyzer (LI7500, LI-COR inc.). Detail of flux monitoring system was described in Kim *et al.* (2015).

3. METHODOLOGY

Orthonormal wavelet analysis was performed on 54.61 minute-time series (containing 2^{15} measurements) to sort level information out and provides wavelet coefficients, which are analogous to the fluctuating part of the Reynold's decomposition. Wavelet analysis depends on similarity degree between any two square integral functions $\int_{-\infty}^{+\infty} f(x)g(x)dx$, containing a signal function $f(x)$ and basis function $g(x)$.

This study, we applied discrete Haar wavelet transform for calculating the correlation of atmospheric fluxes (Scanlon and Sahu, 2008). Wavelet transform started from the original time series into level to be obtained by the translation and dilation of one unique function in the coarsest level that referred as $\Psi^0(x)$ (eq. 1). The scalar-time series of vertical wind velocity (w), q and c was decomposed by wavelet filtering (eq. 2), starting with the

$$\Psi^0(x) = \begin{cases} +1, & -\frac{1}{2} \le x \le 0 \\ -1, & 0 \le x \le \frac{1}{2} \\ 0, & otherwise \end{cases} \tag{1}$$

original time series $f(\tau)$ at the first m level ($m = 1, 2, 3, \dots, log_2(2^{15})$), when j was the centered position of data length. This step wavelet coefficients $W\,(j, m)$ were progressively generated by

$$W(j,m) = \int_{-\infty}^{+\infty} f(\tau)\Psi^m(\tau - j)d\tau \tag{2}$$

Then derived wavelet coefficients of q and c were applied to calculate correlation $\rho_{q,c}^m$ as

$$\rho_{q,c}^m = \frac{\overline{W_q^{m\prime} W_c^{m\prime}}}{\sigma_{W_q^m}\sigma_{W_c^m}} \tag{3}$$

In addition, WUE_e was calculated (eq. 4) from the ratio of lE to Fc, which were in the covariance form for vertical wind velocity as $\overline{W_w^{m\prime} W_q^{m\prime}}$ and $\overline{W_w^{m\prime} W_c^{m\prime}}$, respectively. According to water layer in submerged paddy field strictly suppressed c emission from soil (Nishimura *et al.*, 2014), the net Fc should be belongs to the photosynthesis flux $\overline{W_w^{m\prime} W_{c_p}^{m\prime}}$.

$$WUE_e^m = \frac{\overline{W_w^{m\prime} W_{c_p}^{m\prime}}}{\overline{W_w^{m\prime} W_q^{m\prime}}} = \frac{\rho_{W_w W_{c_p}}^m \cdot \sigma_{W_{c_p}^m}}{\rho_{W_w W_q}^m \cdot \sigma_{W_q^m}} \tag{4}$$

Flux variance similarity was confirmed by the ratio of q and c transport efficiencies (Scanlon *et al.*, 2008) as equation 5.

$$\frac{\rho_{W_w W_{c_p}}^m}{\rho_{W_w W_{q_t}}^m} = WUE_e^m \frac{\sigma_{W_q^m}}{\sigma_{W_{c_p}^m}} \tag{5}$$

The impact of q-c correlation, WUE, and transfer efficiencies of q and c on the various scale of eddy turbulent was identified by converting the wavelet-derived frequency to eddy diameter (D_e) within Taylor's frozen turbulence hypothesis as the following relationship:

$$D_e = \frac{2\pi}{K_m} = \frac{2\pi}{2\pi f_s / 2^m w^*} = \frac{2^m w^*}{f_s} \tag{6}$$

where K_m is wavenumber (radians·m^{-1}), f_s is the measurement frequency (10 Hz), 2^m is data length for m wavelet level, and w^* is convective velocity (m·s^{-1}).

4. RESULTS AND DISCUSSION

The trend of daily lE illustrated that paddy ecosystem became provided more of q in the morning and

Keyword: Water-use efficiency, Eddy covariance, Paddy field, Orthonormal wavelet analysis
Tohoku University, 6-6-20, Aoba Aramaki, Aoba-ku, Sendai-shi 980-8579, Japan. Tel & Fax: +81-22-795-7455

continuously decreased in the afternoon, while Fc trends showed the opposite results (Fig.1(a)). These results indicated that q and c exchanges over the paddy rice field had opposite direction. To tentatively estimate how stomatal flux express during the day-time, we firstly use the fluctuating part of q and c (q' and c') to calculated the correlation ($\rho_{q',c'}$). The results revealed that there was strong correlation (close to -1) during the mid-day period. (Fig. 1(b)). Therefore, the stomata mechanism most expressed in the midday.

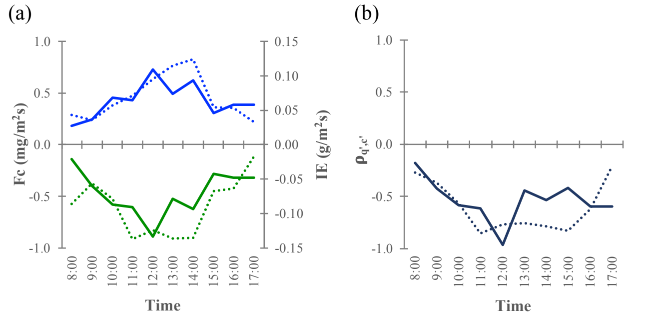

Fig. 1 (a) Daily latent heat flux; IE (Blue) and carbon dioxide flux; Fc (Green) and (b) Correlation between water vapor and carbon dioxide; $\rho_{q',c'}$, during the daytime over the paddy field. Solid lines and dotted lines illustrate the data on September 12 and 15, respectively.

The correlation coefficient ($\rho_{Wq,Wc}$) was analyzed over the rang of eddy diameter (Fig. 2(a)) to consider the relation of the scalar concentrations in atmosphere. The results showed that the smallest scale eddies had the weakest correlation, while 600 to 4000 m were closest to -1. Moreover, we found that $\rho_{Wq,Wc}$ were dominated by nearly perfectly negative correlations during mid-day periods, conform with $\rho_{q,c}$ which appeared on Fig.1(b).

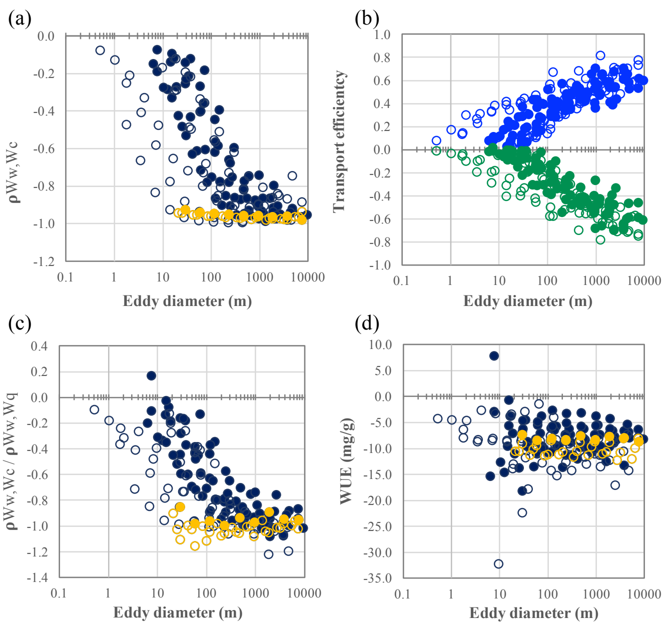

Fig. 2 (a) Correlation coefficient of q-c; $\rho W_q, W_c$, (b) transport efficiency of q (Blue) and c (Green), (c) Ratio of transport efficiency, and (d) WUE were illustrated over the range of eddy scale. Filled circles and empty circles are the data on September, 12 and 15, respectively. The yellow circles are the mid-day data (12:00 pm for September, 12 and 11:00 am to 13:00 pm for September, 15).

According to flux similarity principle, the scalar within a homogenous surface layer are governed by the same properties of turbulence in the same time and measured at the same position should exhibit correlation perfectly. In our study, the q and c exchanges between stomata and atmosphere were indicated by analyzing q and c transports in various D_e using the wavelet analysis. We noted that wavelet level 1 preformed too small D_e (0.25 to 2.94 m), while wavelet level 11 to 14 preformed large D_e (30.12 to 118.64 km) and most of the correlation results, obtaining from these D_e, were the outliers. Thus we did not show those results here.

Transformation of q and c disclosed through the transport efficiencies as Fig. 2(b). The correlation between w and the both of q and c were closed to zero at the smallest D_e, while at the larger D_e of q and c became increased and decreased, respectively.

The ratio of q and c transport efficiencies were analyzed to test the variance similarity of the stomatal flux and the mid-day data provided the best correlation (Fig. 2(c)).

As the demonstrated results, transpiration and photosynthesis most effected on IE and Fc during the mid-day period, which also were the peaks of source and sink period. Therefore, the estimated WUE_e from the midday could be assumed as the maximum WUE, belonging to the stomatal function (Transpiration and Photosynthesis). WUE were in the range of -7 to -11 mg·g^{-1} (Fig. 2(d)).

5. CONCLUSIONS

The maximum WUE, which belongs to the stomatal function, was able to analyze from eddy covariance-data by using the correlation approach. However, this method has still not developed for another complex sites.

ACKNOWLEDGMENTS

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 2015-2017 (15K20858, Daisuke Komori).

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