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Long-term analysis of evapotranspiration over a diverse land use area in northern Thailand

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Abstract:

Evapotranspiration (ET) over a diverse land use area in northern Thailand was successfully estimated by long-term eddy covariance measurements. Some measurement gaps due to instrumentation problems and administrative difficulties were unavoidable. Monthly ET trends revealed a maximum of 150 ± 10 mm in June and a minimum of 60 ± 10 mm in January. The annual mean ET was estimated to be 1300 ± 140 mm. The interannual variation in ET reflects the response of the land surface to meteorological events and land use/cover changes (LUCC); however, the effect of rainfall variation on ET was greater than that of LUCC. Effective heterogeneity was evaluated using the Bowen ratio; such information will be useful for understanding the effect of land surface heterogeneity on latent and sensible heat fluxes.

KEYWORDS Bowen ratio; evapotranspiration; effective heterogeneity; land use/cover change; northern Thailand

INTRODUCTION

Land use/cover change (LUCC) that occurs as a result of various human activities could have a critical effect on regional hydrological cycles, which in turn could affect regional climate (Henderson-Sellers *et al.*, 1993; Zheng and Eltahir, 1998), particularly with regard to Asian monsoons. Previous studies have suggested that changes in evapotranspiration (ET) as a result of deforestation have diminished regional precipitation (P) in Thailand (Kanae *et al.*, 2001), and increased ET due to LUCC has decreased the runoff in the Chaophraya river basin (Kim *et al.*, 2005). Both studies indicate that ET plays a significant role in the hydrological cycle in this region; however, few verifiable ET measurements that could confirm these results are available.

Early studies to measure ET using the eddy covariance (EC) method during a period of LUCC in northern Thailand were undertaken by Kim *et al.* (2001) and Toda *et al.* (2002), and more recent results have also been reported (Kim *et al.*, 2011a, b). However, the studies undertaken by Kim *et al.* (2001) had some limitations; a single land surface model was paramaeterized using EC measurements at a paddy field, and only the general uncertainty of the EC method over various land surface types was analyzed. Toda *et al.* (2002) attempted to clarify the annual variation in ET over a diverse land use area using the bandpass covariance method. However, the period investigated was insufficient to provide a thorough understanding of consistent variation. Therefore, while the previous studies provided valuable information about ET, a long-term measurement study is required to comprehensively understand the annual and interannual variations in ET related to LUCC in Thailand.

There are various issues associated with EC measurements. Conventional methods substantially satisfy data quality control and quality assurance issues (Aubinet *et al.*, 1999; Papale *et al.*, 2006); however, the methods are premised on homogeneous land cover and therefore cannot satisfactorily estimate ET related to LUCC. Göckede *et al.* (2008) tried to estimate ET over heterogeneous conditions; however, the analysis did not include estimation uncertainty. In addition, although sensible and latent heat fluxes (H and lE) were simultaneously measured over a homogeneous vegetated surface, the uncertainty would differ between the fluxes (Andreas *et al.*, 1998; Katul *et al.*, 1999). Therefore, analysis of heterogeneity together with uncertainty based on long-term EC measurements in an area with ongoing LUCC would be valuable.

The goals of this study are to quantify and characterize ET with its uncertainty under LUCC in northern Thailand, and to challenge the estimation of annual and interannual variations in the effective heterogeneity based on long-term EC measurements.

SITE DESCRIPTION AND ET ESTIMATION

The flux measurement site, referred to as Diverse land-use in Tak, Thailand (DTT: 16°56.390'N, 99°25.793'E, 117 m asl), is located 30 km east of Tak and 40 km west of Sukhothai in northern Thailand. The climate in this region is characterized by Southeast Asian monsoons. In Thailand, the mean annual P was 1230 mm between 1981 and 2010 (Mean Annual Rainfall in Thailand 30 year by TMD: Thai Meteorological Department, 2013); 80% of P fell between May and October (Mean Monthly Rainfall in Thailand 30 year by TMD, 2013). Typically across Thailand, there are two P peaks; one in May as a pre-monsoon period, and the

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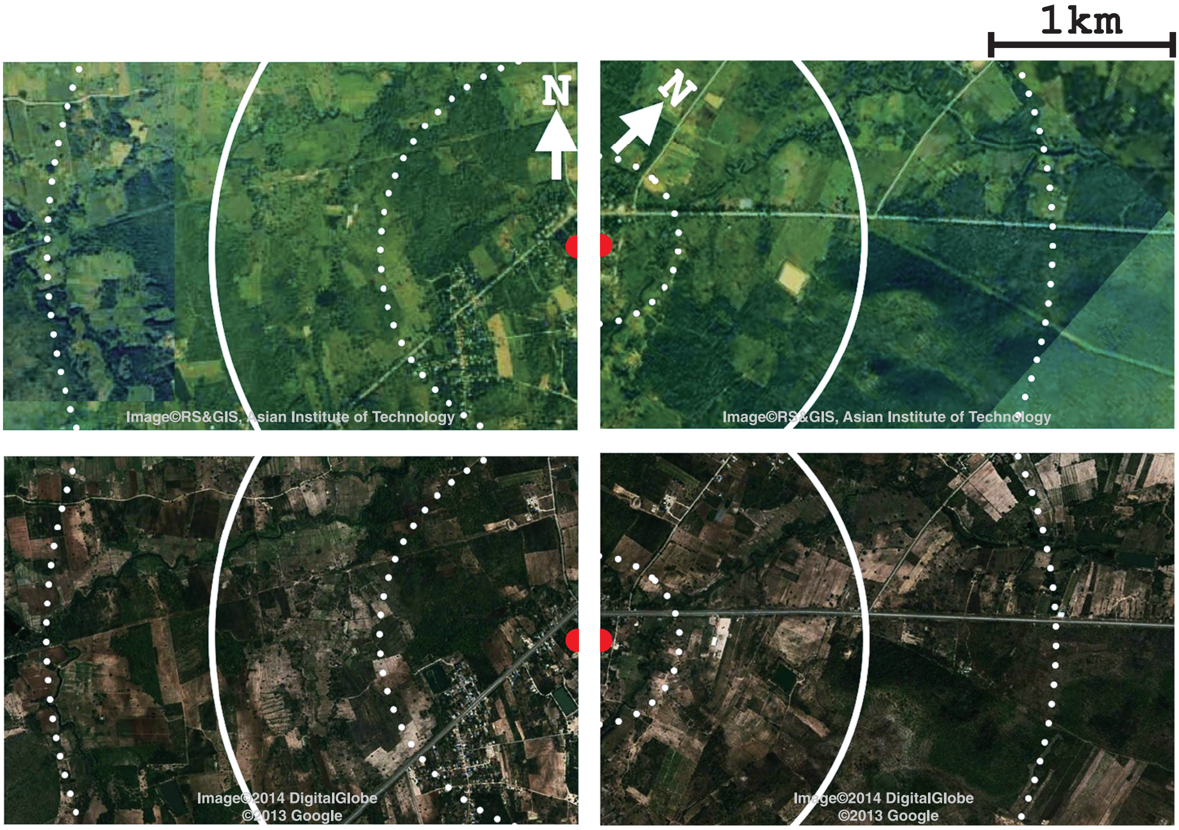

Figure 1. Land cover observed on November 23, 2002 (top panel) and April 27, 2012 (bottom panel) with micrometeorological footprint analysis (Kljun *et al.*, 2004). The red semicircle denotes the flux measurement tower. The solid line describes the mean source area that contributes 75% based on latent heat flux estimated in 2010, and the dotted lines indicate the standard deviation in the mean source area. The left images are estimated to be on the west side of the tower during the monsoon season and the right images the north-east side during the non-monsoon season. The top images were constructed from aerial photographs provided by RS&GIS at the Asian Institute of Technology, and the bottom images were obtained from *Google Earth*

other in the September monsoon period (Singhrattna *et al.*, 2005).

The wind associated with the monsoon season was in a westerly direction from February to September compared to in a northeasterly direction in January and from October to December in the non-monsoon season. With regard to wind direction, the source area, which contributed 75% of ET, was confined to 1.9 ± 0.8 km for the monsoon season and 1.4 ± 1.0 km for the non-monsoon season in our micrometeorological footprint analysis (Figure 1), which used the method developed by Kljun *et al.* (2004). Land use change (LUC) between 2002 and 2013 was evident. Over the footprint area, the major crop gradually changed from single-year crop of rice or corn to multi-year crop of cassava. While land cover change (LCC) was insignificant, the agricultural land area increased slightly due to deforestation (less than 10%). In Figure 1, an aerial photograph taken on 23 November, 2002 and a satellite image taken on 27 April, 2012, illustrate LUC and LCC, respectively.

Except for 2010, no complete year-round turbulence time series could be gathered by an EC measurement system mounted at a height of 100 m during the period of our investigation (2003–2013). In the worst case, which occurred in 2011, only 30% of the series was acquired because of various difficulties with instrumentation and administrative challenges such as difficult accessibility, power failure, and inadequate human resources. For the entire period of our investigation, the mean acquisition rate was 60%.

The effective heterogeneity, i.e., the heterogeneity scale parameter for EC fluxes suggested by Kim *et al.* (2011b), for estimating land surface variability against each specific flux was obtained by

$$\eta = 1 - \frac{\omega}{\varepsilon}, \qquad (1)$$

where ω is a constant (≈ 0.07), and ε is the relative sampling error, i.e., fractional uncertainty. η ranges from 0 to 1; $\eta = 0$ denotes perfect homogeneity. For instrumentation details and the principles of ε and η refer to Kim *et al.* (2011a, b).

RESULTS AND DISCUSSION

Annual and interannual ET trend

The mean monthly ET increased gradually from a minimum of 60 ± 10 mm in January to a maximum of 150 ± 10 mm in June, and decreased to 70 ± 10 mm in December with a 120 ± 20 mm drop in August (Figure 2, top chart).

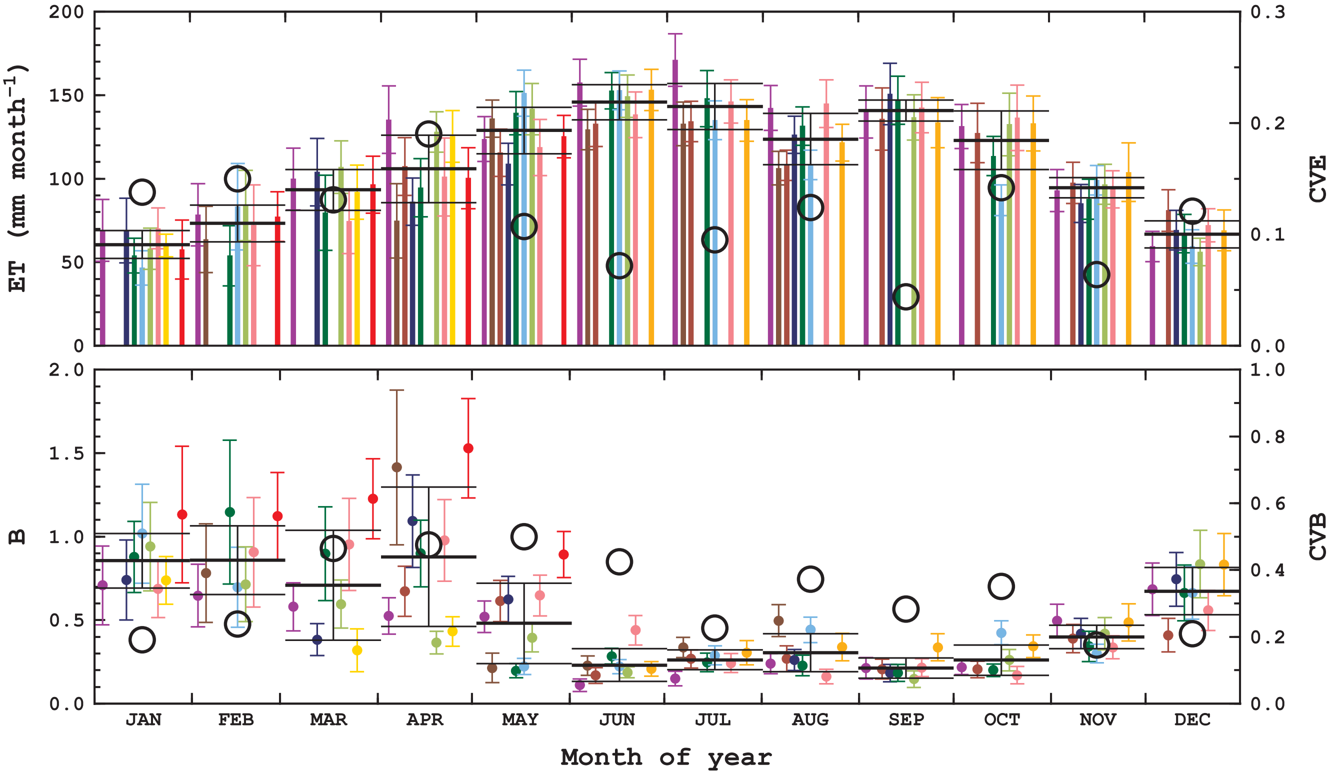

Figure 2. Annual and interannual evapotranspiration (ET: top panel) and Bowen ratio (bottom panel) for 11 years (2003 : purple–2013 : red). The hovering horizontal bar and the open circle in each panel denote the monthly mean and the coefficient of variation (CV), respectively. Tails represent the standard deviation for a month. ET averages and error bars in each month of each year denote the integrated daily mean variation in ET estimated by the hourly latent heat flux *lE* using the eddy covariance method, and the propagated uncertainty originating from the hourly uncertainty of *lE*, respectively

The mean annual ET was estimated as 1300 ± 140 mm. Compared with the normal *P* of 1230 mm in northern Thailand (Mean Annual Rainfall in Thailand 30 year by TMD, 2013), our estimation is reasonable considering that the potential ET estimated by the Turc method (Lu *et al.*, 2005) was higher than the actual year-round ET, and in turn most of the *P* would be evapotranspirated over the flat terrain at the DTT. The estimate provided by Toda *et al.* (2002) was 526 mm at the same DTT. It is important to note that specific conditions apply to this estimate, i.e., ET was measured from June 1998 to February 1999; the accumulation was zero from April to May; the *P* in 1998 was 7% lower than that of normal *P* in Thailand (Mean Annual Rainfall in Thailand Above-below Normal in Percentage by TMD, 2013); and the traditional bandpass covariance method has the potential to underestimate ET by 10–30% (Asanuma *et al.*, 2005). Taking these caveats into consideration, our partial estimation of 1070 ± 110 mm rainfall, excluding April and May, was comparable to the results of Toda *et al.* (2002). Kim *et al.* (2005) simulated positive ET for a dry season, and attributed the result to contributions from vegetated areas having leaf area indexes greater than 0.5 despite a non-growing season for natural vegetation. This simulated ET is almost in accordance with our results in terms of trend and value.

An increase in *P* (Mann-Kendall trend test: $\tau = 0.56$, $p < 0.05$) was observed in Thailand for the past decade (2003–2012; Mean Annual Rainfall in Thailand by TMD, 2013). An increase in ET was also recorded in April and August (Figure 2, top; 2004–2012: $\tau = 0.52$, $p = 0.13$; ET in 2003 was eliminated during trend analysis to avoid a historical storage effect of soil water content due to approximately 10% higher rainfall during 1999–2002 compared to the mean of 2003–2012). Considering ET reflects *P* in a month and the 40% higher potential ET than the actual ET estimated with the Turc method, it suggests that one reason for the annual *P* increase in Thailand over the last decade may be the earlier than normal onset of the pre-monsoon season in April and a cessation of the monsoon break in August. Unfortunately, we could not directly evaluate the results with rainfall data at the DTT; however, Kuraji and Arthorn (2011) measurements in a mountainous area support our result.

The Bowen ratio (B) is one parameter for describing land surface conditions, represented by the ratio of *H* to *lE*. The mean monthly B was 0.83 ± 0.28 for January–April and 0.25 ± 0.08 for June–October (bottom panel in Figure 2). The interannual variation in B during December to May demonstrates larger variation than the other months, with a larger individual monthly uncertainty. These results indicate the following: (1) In the wet season, the soil moisture nears saturation, and the difference in surface temperature is not significantly greater than the dry season; (2) In the dry season, the temperature difference accelerated by multi-year crops or irrigation in mosaic land use area is greater than the wet season. In cases of interannual variation in seasonality in ET and B, it is possible that the variation in ET more or less describes that of the land surface in this region because the coefficient of variation of the Bowen ratio (CVB) correlates with the coefficient of variation of the evapotranspiration (CVE) as $r = 0.61$ and $p < 0.05$.

Analysis of land surface condition using η

The effective heterogeneities of latent heat flux (η_{lE}) and of sensible heat flux (η_H) seasonally decrease from 0.74 ± 0.06 (February) to 0.19 ± 0.10 (June) and from 0.72 ± 0.04 (September) to 0.45 ± 0.10 (April), respectively (Figure 3). These results indicate that η has a different seasonal pattern: the source area of lE in the wet season is less heterogeneous than the dry season according to the land surface moisture content, and almost reaches saturation under frequent rainfall conditions; the source area of H in the dry season is less heterogeneous than in the wet season according to surface temperature, and reaches nearly the same temperature under peak dry season conditions. Therefore, it is possible to discern η values which are sensitive to each land surface source condition for a given H and lE, and each surface temperature and soil surface wetness condition displays independent seasonality against the landscape heterogeneity. Consequently, we suggest that η might be useful parameter for understanding the effect of land surface heterogeneity on H and lE.

The interannual variation in seasonality of η_{lE} (CVL) and η_H (CVH), the monthly coefficient of variation (CV) for η was highest in June (0.56) and April (0.42) at maximum lE (365 ± 28 MJ m^{-2} = E: 146 ± 11 mm) and H (213 ± 78 MJ m^{-2}), respectively (Figure 2 and 3). The largest CV values indicate the month in which the highest interannual variation in η occurred due to the significant differences in temperature or land surface moisture which are controlled by natural meteorological events and LUCC resulting from human activities. Meanwhile, if the CV was primarily controlled only by LUC, the CV would be unchanged based on identical land use within a single year because agricultural management is maintained on an annual or multi-annual basis. Even though the foot print areas differ between the dry and wet seasons (Figure 1), the CV is nearly the same each season. Considering the seasonality of η together with the relationship between P and ET, η might more effectively represent the response of land surface to meteorological events than LUC in this region. Considering that LCC is less than 10% (see SITE DESCRIPTION AND ET ESTIMATION and Figure 1) the results imply that, in northern Thailand, lE and H are affected by meteorological events, particularly rainfall, rather than LUCC that occurs as a result of human activity. Interestingly, the sum of CVL and CVH can explain a significant proportion of the variation in CVB (Figure 4: $r = 0.82$, $p < 0.001$). The result suggests that the interannual variation in land surface conditions can be explained by η_{lE} and η_H instead of B. Thus, η can be used as a scale parameter to define land surface heterogeneity effecting lE and H, while additional studies to directly validate η with spatial variations in surface temperature and wetness are required.

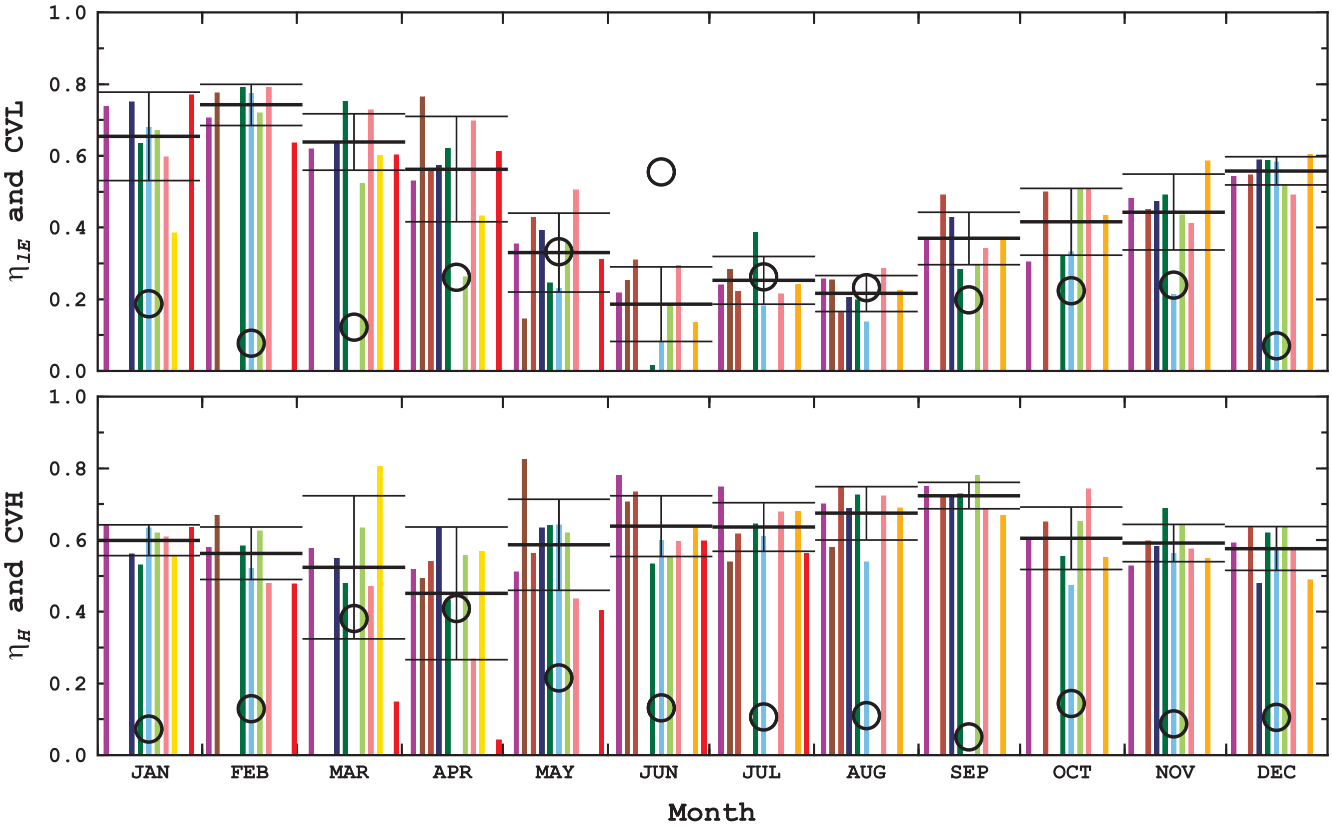

Figure 3. Same as the top panel in Figure 2 except for the effective hererogeneity of latent heat flux (η_{lE}: top panel) and of sensible heat flux (η_H: bottom panel)

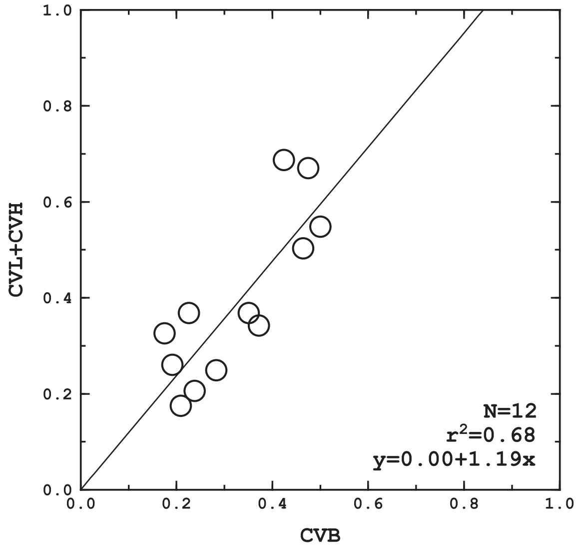

Figure 4. Relationship between the coefficient of variation of Bowen ratio (CVB) and the sum of the coefficient of variation of effective heterogeneity for latent heat flux and sensible heat flux (CVL + CVH)

CONCLUSIONS

1) The annual ET over a diverse land use area in northern Thailand is 1300 ± 140 mm, with a minimum of 60 ± 10 mm in January and a maximum of 150 ± 10 mm in June.
2) The effective heterogeneity η is an appropriate parameter for understanding the effect of land surface heterogeneity on lE and H.
3) The ET estimated in northern Thailand is primarily affected by meteorological events, particularly rainfall, rather than LUCC.
4) The sum of interannual variations in η_{lE} and η_H (CVL + CVH) explain the interannual variations in the Bowen ratio CVB. This supports Conclusion 2.

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