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臺灣雲霧森林的蒸發散組成及特殊相對濕度日變化

Partitioning of Evapotranspiration in Taiwan Montane Cloud Forests and the Unique Diurnal Relative Humidity Characteristics

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本論文係施璟宏君（B07209013）在國立臺灣大學大氣科學學系完成之學士班學生論文，於民國 111 年 04 月 27 日承下列考試委員審查通過及口試及格，特此證明

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摘要

探討蒸發散組成有助於我們瞭解一地的能量、水文以及碳循環，然而，過去研究較少利用觀測資料探討臺灣雲霧森林的蒸發散組成。本研究利用 flux variance similarity method（FVS 方法）探討棲蘭雲霧森林的蒸發散組成，FVS 方法能藉由渦流相關法的觀測資料得到蒸發散組成，被視為是有潛力重新分析過去通量塔資料的方法，然而，本研究利用 FVS 方法得到的棲蘭雲霧森林蒸散日變化卻與陸地模式模擬或樹液流觀測的日變化不同，FVS 方法得到的植物蒸散日變化有明顯的峰值提前現象，在本研究我們提出 FVS 方法在棲蘭雲霧森林的潛在不適用性。

白天相對濕度增加是雲霧森林的特色之一，這不僅代表當地水氣在白天快速累積，也代表白天容易達到高相對濕度狀況。白天快速累積水氣可能是非本地水氣累積造成的，然而非本地的水氣來源會違背 FVS 方法的假設；高相對濕度狀況則可能造成 FVS 方法結果有不確定性。

本研究強調將 FVS 方法應用在棲蘭雲霧森林仍有很大的不確定性，未來的研究不僅需要將 FVS 方法應用在其他雲霧森林以確認其不適用性，更需要將多種探討蒸發散組成的方法應用在雲霧森林區域，以真正瞭解雲霧森林當地的蒸發散組成，進而探討該地的能量、水文以及碳循環。

關鍵字：蒸發散組成、雲霧森林、flux variance similarity method、相對濕度

ABSTRACT

Quantifying the evapotranspiration's component is essential for studying the energy, water, and carbon cycle. However, few studies used observational data to analyze the evapotranspiration partitioning in Taiwan montane cloud forests, featuring an increased relative humidity in daytime and an early peak of evapotranspiration. This study applies the flux variance similarity (FVS) method, which is known for its potential for analysis of evapotranspiration partitioning of flux tower datasets, into the Chi-Lan montane cloud forest. An early peak of transpiration derived from the FVS method is found, which is not consistent with the diurnal cycle of transpiration obtained from the Community Land Model and the sap flow velocity. It suggests the possible inapplicability of the FVS method in such humid regions. Increased relative humidity in daytime is a unique diurnal characteristic in Chi-Lan montane cloud forest, indicating rapidly increased specific humidity and high humidity conditions in daytime. The rapidly increased specific humidity may be a signal of non-local moisture accumulation, which disobeys the assumption of the FVS method. High relative humidity conditions may lead to the uncertainty of the evapotranspiration partitioning results. This study concludes that there has a large uncertainty of evapotranspiration partitioning when applying the FVS method in Chi-Lan, a region with a unique hydro-climatological cycle. Applying the FVS method in other cloud forest flux tower sites and intercomparing different evapotranspiration partitioning methods in these regions are needed for future work.

Keywords: evapotranspiration partitioning, cloud forest, flux variance similarity method, relative humidity

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Chapter 1 Introduction

Montane cloud forests, known for forests immersed in a high frequency of fog, have a great value to hydrology and ecology. Frequent fog provides extra source of moisture, which can stabilize water quality and maintain the natural flow pattern of the streams and rivers. Although taking up only approximately 0.26 percent of earth's land surface, cloud forests harbor a large number of the world's species. (Bubb et al., 2004; Bruijnzeel et al., 2010). Anthropogenic effects, such as land use and land cover change or climate change, may pose a threat to fog formation. Land use and land cover change in upwind regions of cloud forest may reduce cloud cover (Lawton et al., 2001). Climate change, including rising temperature and elevated carbon dioxide concentration, may lift the cloud base height and affect local water vapor supply (Bubb et al., 2004; Foster, 2001; Oliveria et al., 2014).

Land evapotranspiration is composed of soil evaporation, plant transpiration, and canopy evaporation (Lawrence et al., 2007). Partitioning evapotranspiration is essential for studying energy, water, and carbon cycle. For the energy cycle, evapotranspiration, which is equal to latent heat flux, may affect local energy budget and temperature. Total evapotranspiration may be changed due to the response of evapotranspiration partitioning to different atmospheric or land forcings. For the water cycle, evapotranspiration can influence local water budget and subsequently affect rainfall, runoff, and soil moisture. The local water budget may be altered due to different evapotranspiration partitioning. For the carbon cycle, plant transpiration is linked with photosynthesis, which is a carbon sink for atmosphere. Different evapotranspiration partitioning will affect local carbon budget between atmosphere and land.

As in Fig 1.1, Gu et al. (2021) used the NCAR Community Land Model and found that the diurnal pattern of evapotranspiration partitioning in Chi-Lan montane cloud forest may be a key for local fog formation and processing such a unique hydro-climatological cycle. An early peak of diurnal pattern of latent heat flux in Chi-Lan montane cloud forest may result from lots of canopy water intercepted from rainfall and fog or dew formation. A large amount of canopy water is evaporated in the morning (Fig 1.2), indicating most of the energy was used for phase change instead of heating air by sensible heat flux. This contributes to slowly increased air temperature in daytime. Moisture accumulation results from local evapotranspiration and lateral water vapor advection combined with a lower diurnal temperature change contributes to increased relative humidity, which is favorable for fog formation.

However, not many studies use observational data to partition evapotranspiration in montane cloud forests. Anderson et al. (2017) suggested that it is essential to partition evaporation and transpiration for numerous hydrological purposes, e.g., improving validation of vadose zone models. Various observation techniques have been established for partitioning evapotranspiration in recent years (Kool et al., 2014; Anderson et al., 2017; Stoy et al., 2019; Nelson et al., 2020; Zhou et al., 2016). As in Fig 1.3, Anderson et al. (2017) summarized the spatial scale and temporal scale of different evapotranspiration partitioning approaches. Flux variance similarity partitioning method (FVS method) has the advantage of analyzing various spatial and time scales of evapotranspiration partitioning. Moreover, no additional instruments are needed to install on eddy covariance measurements (Anderson et al., 2017; Sulman et al., 2016), indicating the potential for analysis of network flux tower datasets. It will be suitable to apply the FVS method in Chi-Lan montane cloud forest to reanalysis the evapotranspiration partitioning and compare the results in Gu et al. (2021).

On the contrary, the disadvantage of the FVS method is multiple sources of uncertainty in the parameterization of leaf-level water use efficiency. The possible source of uncertainty includes the uncertainty of leaf temperature and intercellular carbon dioxide (Sulman et al., 2016; Anderson et al., 2017; Skaggs et al., 2018; Scanlon et al., 2019; Wagle et al., 2021). The uncertainty of leaf-level water use efficiency will contribute to different ratios of transpiration to evapotranspiration. Moreover, Sulman et al. (2016) suggested that the assumption of the FVS method might not be violated in forest areas due to the air flow and spatial heterogeneity.

Stoy et al. (2019) and Anderson et al. (2017) suggested intercomparisons of evapotranspiration partitioning approaches at a variety of field sites are needed. Wagle et al. (2021) applied the FVS method into three C3 and two C4 grain crops. However, most of the studies applied the FVS method into irrigated regions (Skaggs et al., 2018; Wagle et al., 2020; Wagle et al., 2021) or in grass covers (Wang et al., 2016), while some studies applied the FVS method into forest regions (Sulman et al., 2016; Scanlon et al., 2019). Not many studies apply the FVS method into cloud forest regions, which is known for its moist environment and unique diurnal patterns of latent heat flux. The applicability of the FVS method in such humid regions remains unknown.

Our study aims to investigate the applicability of evapotranspiration partitioning based on the FVS method in montane cloud forests. We hypothesize that the unique diurnal relative humidity characteristic of montane cloud forests may affect the performance of the FVS method, since parameterization of leaf-level water use efficiency may be unstable in humid conditions. We will intercompare the diurnal pattern of evapotranspiration partitioning based on the simulations in Gu et al. (2021) and the sap flow measurements to analyze the applicability of the FVS method.

Chapter 2 Data and Methodology

We use the flux variance similarity method (FVS method) and the Community Land Model to explore the diurnal cycle of evapotranspiration partitioning in Chi-Lan cloud forest. To highlight the uniqueness of evapotranspiration partitioning in Chi-Lan, we apply the same methods in Lien-Hua-Chih non-cloud-fog forest to compare the results with Chi-Lan. Due to few studies applying the FVS method in such humid regions, in this study, we focus on the applicability of the FVS method, especially for the diurnal cycle of evapotranspiration partitioning. If the FVS method is inapplicable in such humid regions, we will focus on the possible limitations of the FVS method. The simulations results of the Community Land Model in Chi-Lan and Lien-Hua-Chih will be used to compare the diurnal cycle obtained from the FVS method. Moreover, we use the sap flow measurement to intercompare the diurnal cycle of transpiration derived from the FVS method as well. The following shows a detailed introduction of the data and the model we use in this study.

2.1 Site Description

2.1.1 Chi-Lan Flux Tower

Chi-Lan (CL) is a cloud forest located in northeastern Taiwan. The annual mean temperature is around 15 °C, and the annual precipitation is 3720 mm, composed of drizzles from orographic precipitation and stronger rainfall from Mei-yu or typhoon events. Chi-Lan is frequently immersed in fog with the peak time from 3 pm to 6 pm. Chi-Lan is an evergreen coniferous forest dominated by Taiwan yellow cypress (*Chamaecyparis obtusa var. formosana*) ranging from 11 to 13 meters in height, with the understory covered with lots of epiphytes. The leaf area index (LAI) ranges from 3.3 to 5.7 m^2/m^2 in a year (Chu et al., 2014; Gu, 2021).

The flux tower (24°35'N, 121°25'E) was 24 meters height on the mountain slope toward the southeastern side, built at the altitude of 1650 meters above the mean sea level. It was equipped with a closed-path eddy covariance system. The raw data, including three-dimensional velocity, sonic temperature, pressure, and water vapor and carbon dioxide concentration, was sampled at 10Hz frequency. The data was converted to half-hourly surface fluxes data by the eddy covariance method. There are also some other measurements, including air temperature, relative humidity, photosynthesis active radiation, shortwave and longwave radiation and visibility, on the tower to provide half-hourly data. Gu et al. (2021) used the above half-hourly data from 2008 to 2011 as the atmospheric forcings to drive the land surface model. We input the raw data from 2008 to 2011 in the flux variance similarity method.

2.1.2 Lien-Hua-Chih Flux Tower

Lien-Hua-Chih (LHC) is a non-cloud-fog forest situated in Central Taiwan. The annual mean temperature is around 19 ℃, and the annual precipitation is 1894 mm. Lien-Hua-Chih is an evergreen broadleaf forest, whose average canopy height is about 17 meters. The leaf area index (LAI) ranges from 2.5 to 4.5 m^2/m^2 in a year (Chen and Li, 2012; Gu, 2020).

The flux tower (23°55'52"N, 120°53'59"E) was 22 meters height on the ridge in sub-watershed No.5 at LHC Research Center, built at the altitude of 780 meters above the mean sea level. It was equipped with 3-D sonic anemometer (R. M. Young 81000) and a krypton hygrometer (KH20) mounted with 30 cm separation on a mast at a height of 25 m. The raw data, including three-dimensional velocity, sonic temperature, and concentration of water vapor and carbon dioxide, was still sampled at 10Hz frequency. The data was still converted to half-hourly surface fluxes data by the eddy covariance method. There are other measurements, including air temperature, relative humidity, shortwave and longwave radiation, on the tower to provide half-hourly data. Gu, (2020) used the above half-hourly data from 2009 to 2013 as the atmospheric forcings to drive the land surface model. Due to the lack of high frequency signal of pressure, we calculate the 10Hz pressure with the assumption of constant air density in each 30 minutes interval. We then input the 10Hz data in 2013 in the flux variance similarity method.

2.2 Model Simulations

This study applies the Community Land Model (CLM, version 4) in Community Earth System Model (CESM, version 1.0.3) to analyze the evapotranspiration partitioning in Chi-Lan and Lien-Hua-Chih. The detailed setting for the simulations is shown in Table 1.

For Chi-Lan, we use the CTR simulations conducted in Gu et al., (2021) for analysis, which the canopy water may come from precipitation, dew and fog. Gu et al., (2021) input the half-hourly data from 2008 to 2011 as the atmospheric forcings to drive the land surface model. The four years forcing ran repeatedly for a total of 24 years. We use the last 4 years for analysis. The simulations can not only explain about 70% variances of observational latent heat flux but also capture the asymmetry of the diurnal cycle of latent heat flux (Gu et al., 2021).

For Lien-Hua-Chih, the land surface condition was set equivalent to that in Gu, (2020). The half-hourly data from 2009 to 2013 was input as the atmospheric forcings to drive the land surface model. The five years forcing ran repeatedly for a total of 25 years and we use the last years for analysis. The simulations can explain about 79% variance of observational latent heat flux. It can also capture the symmetry diurnal characteristic of latent heat flux (Fig 2.1).

2.3 Flux Variance Similarity Method

Since the flux variance similarity method (FVS method) have been described in some literature (Scanlon and Sahu, 2008; Scanlon and Kustas, 2010; Paletella et al., 2014; Skaggs et al., 2018), we only briefly introduce the basic concepts of this method: The carbon dioxide fluxes and water vapor fluxes measured by the eddy covariance method are composed of stomatal fluxes, including photosynthesis and transpiration, and non-stomatal fluxes, such as respiration and evaporation. Monin-Obukhov similarity theory implied that scaler, including water vapor and carbon dioxide concentration, high frequency time series will exhibit perfect correlation at the same position within a homogeneous atmospheric layer. The water vapor and carbon dioxide budgets in the lower boundary atmosphere mainly arise from stomatal fluxes and non-stomatal fluxes. If the stomatal fluxes dominate, the transpiration acts as a water vapor source and photosynthesis acts as a carbon dioxide sink. According the similarity theory, the correlation between water vapor and carbon dioxide approaches to -1. On the other hand, if the non-stomatal fluxes dominate, evaporation acts as a water vapor source and respiration acts as a carbon source. The correlation between water vapor and carbon dioxide approaches to 1. (Fig 2.2). The core concept of the FVS method is an analysis of using the degree of contamination of correlation between scalars to infer the relative amounts of stomatal fluxes and non-stomatal fluxes.

Leaf-level water use efficiency (WUE), whose definitions are shown in Eqs. 1, will be parameterized by Eqs. 2 to process the FVS method. We use const_ppm parameterization, which is the parameterization of WUE that assumes intercellular carbon dioxide as a constant, to apply the FVS method in Chi-Lan and Lien-Hua-Chih. Time periods with above-canopy friction velocity less than 0.1 m s^{-1} was excluded. The raw data were quality checked and spikes were removed (Vickers and Mahrt, 1997). Time lags between scalars and vertical velocity were corrected (Hörtnagl, L., 2021). Planer fit method was used to rotate the three-dimensional velocity into the mean streamline coordinate system in monthly temporal resolution (Wilczak et al., 2001). Webb–Pearman–Leuning correction was applied to correct the fluctuation of air density and temperature (Webb et al., 1980). For Chi-Lan and Lien-Hua-Chih, we set the plant type as C3 plant. The canopy height was set to 12 and 17 meters, respectively in Chi-Lan and Lien-Hua-Chih. The measurement height was set to 24 meters in Chi-Lan and 25 meters in Lien-Hua-Chih. More detailed data processing and preprocessing setting were shown in Table 2 and Table 3.

$$WUE = \frac{<w'c_p'>}{<w'q_t'>} \quad \text{Eqs.1}$$

$$WUE = \frac{1}{1.6}\frac{c_a - c_i}{q_a - q_i} \quad \text{Eqs. 2}$$

The 10Hz frequency data in Chi-Lan and Lien-Hua-Chih were applied in the FVS method using Fluxpart version 0.2.8 (Skaggs et al., 2018). The source code of Fluxpart is accessible at https://github.com/usda-ars-ussl/fluxpart (accessed February 21, 2020). The FVS method may fail to partition fluxes due to some reasons, including negative vapor pressure deficit error (NVPD error), incompatible frictional velocity error, lacking data error, negative latent heat flux error, incompatible WUE error, and incompatible EC data error. NVPD error often occur in high humidity conditions, in which vapor pressure deficit may be less than zero due to the simplification of vapor pressure deficit, or measurement error. Incompatible frictional velocity error occurs when friction velocity is less than 0.1 m s^{-1}. Lacking data error was because of lacking 10 % of data in 30 minutes due to quality checked. Negative latent heat flux was excluded due to the assumption of the FVS method that requires the upward latent heat flux. Incompatible EC data error occurs when the high frequency data for a given time interval does not satisfy the constraint that mentioned in Wagle et al. (2021). Incompatible WUE error occurs when WUE does not satisfy the physical admissible condition mentioned in Wagle et al. (2021).

The fraction of partitioned output of the FVS method is calculated by Eqs. 3. The fractions in Chi-Lan and Lien-Hia-Chih are shown in Table 4. A large fraction of data in Chi-Lan fail to partition fluxes due to NVPD error, mainly because of moist environment in Chi-Lan. The diurnal cycle of evapotranspiration partitioning obtained from the FVS method will neglect the prevailing weather condition in Chi-Lan, the most unique hydro-climatological characteristic in montane cloud forest.

$$fraction = \frac{(error)_i}{N_{total} - (error)_{small\ data\ frac}} \quad \text{Eqs. 3}$$

Due to the possibility of neglecting the diurnal cycle of evapotranspiration partitioning obtained from the FVS method in Chi-Lan, we developed the Modified FVS method (ModFVS method). The algorithm of the ModFVS method is similar to that of FVS method except for high humidity conditions. When the relative humidity for a given time period exceeds the maximum relative humidity threshold, the ambient water vapor is modified to make the relative humidity equal to the maximum relative humidity threshold. The detailed flow chart of the ModFVS method is shown in Fig 2.3. Due to the novel application of the ModFVS method in such humid regions, we will first analyze the sensitivity of the maximum relative humidity threshold on the partitioned fluxes in Chapter 3.

Since the gap-filled method for the FVS method (Lee et al., 2021) has not been applied in many studies, we will not apply gap-filled method in Chi-Lan and Lien-Hua-Chih. Considering the missing data due to some reasons mentioned above, we only choose the days that more than half of half-hourly data from 6 am to 6 pm success to partition evapotranspiration for analysis.

2.4 Sap Flow Measurement

The Granier system's heat dissipation method (Granier, 1985) is applied to obtain sap flow measurements from May 2020 to November 2021 in Chi-Lan. Four sample trees were installed with 2 cm Granier-type sensor at the northward side of trees. The setting of the probes basically follows the method in Chiu et al. (2016). The paired probes are two thermocouples, which are 10 cm vertically apart from each other. The upper thermocouple was constantly heated by 0.2 Watts. The raw data was converted to half-hourly sap flow velocity through the equations in Granier (1987) and Tsuruta et al. (2010).

Chapter 3 Results

3.1 Sensitivity of modified flux variance similarity method

The maximum RH threshold has high sensitivity on leaf-level water use efficiency (WUE) in Chi-Lan. The mean value of WUE varies from -40 mg/g to -300 mg/g with the interquartile range from 20 mg/g to 400 mg/g (Fig 3.1a). On the contrary, the maximum RH threshold has low sensitivity to WUE in Lien-Hua-Chih. The mean value of WUE varies from -20 mg/g to -40 mg/g with the interquartile range from 2 mg/g to 20 mg/g. (Fig 3.1b). Due to the sensitivity of WUE, the maximum RH threshold has higher sensitivity on the ratio of transpiration and evapotranspiration in Chi-Lan compared to that in Lien-Hua-Chih. The mean value of the ratio varies from 0.43 to 0.61(Fig 3.1c), indicating that the dominant source of evapotranspiration in Chi-Lan derived from the ModFVS method depends on the maximum RH threshold. In Lien-Hua-Chih, the mean value of ratio is approximately 0.64 (Fig 3.1d), showing that transpiration is the dominant source of evapotranspiration in daytime.

Although the value of transpiration in Chi-Lan depends on the maximum RH threshold, the threshold does not affect the peak time of transpiration. The peak time of transpiration occurs at 9 am no matter what the maximum RH threshold is (Fig 3.2). However, the peak time of transpiration is not consistent with the results found in Community Land Model (Fig 1.1), suggesting the peak time is around 11 am.

High RH yields lower WUE according to the parameterization of WUE. Thus, when the maximum RH threshold is larger in Chi-Lan, WUE will be lower due to a higher occurrence of RH (Fig 3.1a), then contributing to a lower ratio of transpiration and evapotranspiration (Fig 3.1c, Fig 3.2, Sulman et al., 2016).

Due to the high sensitivity of the maximum RH threshold on the value of transpiration in Chi-Lan, we will only analyze the diurnal pattern of transpiration with the maximum RH threshold = 95 %.

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3.2 Diurnal cycle of energy fluxes based on flux variance similarity method

Both the FVS method and the ModFVS method suggest an asymmetric diurnal cycle of latent heat flux in Chi-Lan and a symmetric diurnal cycle of latent heat flux in Lien-Hua-Chih, which is consistent with the observation (Gu et al., 2021). The peak time of latent heat flux occurs at 9 am in Chi-Lan, while it occurs at noon in Lien-Hua-Chih (Fig 3.3a, Fig A1a). In Chi-Lan, the diurnal cycle of latent heat flux does not follow the diurnal cycle of net radiation (Fig 3.3c, Fig A1c), indicating that the component of evapotranspiration has an asymmetric diurnal cycle.

The diurnal cycle of transpiration in Chi-Lan derived from the ModFVS method has an asymmetric diurnal cycle characteristic, while it shows a symmetric diurnal cycle in Lien-Hua-Chih (Fig 3.3b, Fig A1b). The peak time of transpiration derived from the ModFVS method in Chi-Lan occurs at 8 am, which does not follow with the diurnal cycle of net radiation. This indicates two possibilities: (a) plants in Chi-Lan does not favor photosynthesis with increased net radiation. (b) FVS method is not applicable in Chi-Lan. Therefore, we analyze the diurnal cycle of transpiration derived from the Community Land Model (Chapter 3.3) and from observed sap flow velocity (Chapter 3.5) to confirm the plant characteristic in Chi-Lan. We further analyze the diurnal cycle of meteorological variables (Chapter 3.4) to affirm the applicability of FVS method in Chi-Lan.

3.3 Diurnal cycle of energy fluxes based on model simulations

Both model simulations and the ModFVS method suggests an asymmetric diurnal characteristic in Chi-Lan and a symmetric diurnal characteristic in Lien-Hua-Chih (Fig 3.4a). The diurnal cycle of latent heat flux still does not follow the diurnal cycle of net radiation in Chi-Lan (Fig 3.4c).

Unlike the ModFVS method results, both the diurnal cycle of transpiration in Chi-Lan and Lien-Hua-Chih in CLM follow the diurnal cycle of net radiation. In Chi-Lan, the peak time of transpiration and net radiation occurs at 10-11 am. In Lien-Hua-Chih, the peak time of transpiration and net radiation occurs at noon (Fig 3.4c). This highlights that the plants in Chi-Lan and Lien-Hua-Chih favor photosynthesis with increased net radiation in the model simulations. The asymmetric diurnal cycle of evapotranspiration in Chi-Lan only results from the asymmetric diurnal cycle of canopy evaporation, which is different from the ModFVS method results.

Besides, the value of transpiration estimated by model simulations is different from that estimated by the ModFVS method in Lien-Hua-Chih (Fig 3.3b, Fig 3.4b). The maximum mean transpiration derived from model simulations is approximately 150 W/m^2, while that derived from the ModFVS method is approximately 170 W/m^2. This suggests that the ModFVS method still has uncertainty about the evapotranspiration partitioning even it can catch the diurnal cycle of transpiration. This may be due to the possible inapplicability of the FVS method in the forest (Sulman et al., 2016).

We speculate the early peak of transpiration derived from the ModFVS method is because of biased FVS method when applied in Chi-Lan based on the results in model simulations. Therefore, we will analyze the diurnal cycle of meteorological variables to see if the basic concept of FVS can be applied in Chi-Lan or not.

3.4 The unique diurnal relative humidity characteristics

Similar to the diurnal cycle of transpiration derived from the ModFVS method, the diurnal cycle of the correlation between water vapor and carbon dioxide has an asymmetric diurnal characteristic in Chi-Lan and a symmetric diurnal characteristic in Lien-Hua-Chih (Fig 3.5a). When the correlation between water vapor and carbon dioxide is close to -1, it indicates that evapotranspiration is mostly composed of transpiration according to the assumption of FVS method. The early peak of transpiration in Chi-Lan is caused by the early peak of the correlation between water vapor and carbon dioxide.

The specific humidity rises rapidly in the morning in Chi-Lan compared with that in Lien-Hua-Chih (Fig 3.5b). The rapidly increasing trend in Chi-Lan might result from local evapotranspiration and lateral moisture advection by the mountain-valley wind. However, the FVS method requires identical source/sink distribution which can translate into perfect correlations or anticorrelations of water vapor and carbon dioxide. Therefore, the extra water vapor source (e.g., from advection or canopy evaporation) might disobey the assumption of the FVS method.

The rapidly increasing specific humidity trend and slowly increasing saturated specific humidity trend in daytime (Fig 3.5c) contribute to an increased trend of relative humidity in daytime in Chi-Lan (Fig 3.5d). The hydro-climatological cycle in Chi-Lan montane cloud forests, with unique diurnal relative humidity characteristics, can be used to diagnosed whether the FVS method can be applied or not. If relative humidity increases in daytime, this area should have a rapidly increased trend of specific humidity, which may result from extra non-local water vapor sources, leading to the inapplicability of the FVS method.

Furthermore, we choose a case study in Chi-Lan from May 8th to May 12th in 2009 to analyze the inapplicability of the FVS method. Early peak of evapotranspiration (Fig

3.6a) and increased relative humidity trend (Fig 3.6f) in daytime, which is unique diurnal characteristic in Chi-Lan, can be found in these five days. In these five days, fog only occurs in the fourth day afternoon, which leads a nearly symmetric diurnal cycle of photosynthesis active radiation (PAR) in daytime (Fig 3.6b). We are able to neglect the high relative humidity problem, which will cause the instability of WUE, in these five days. However, the diurnal cycle of transpiration does not have an apparent peak in noontime, meaning that it does not follow the diurnal cycle of PAR (Fig 3.6c).

A rapidly increasing specific humidity in daytime can be found during these five days (Fig 3.6d). This may be due to the accumulation from local evapotranspiration and lateral water vapor advection. The non-local water vapor source contributes to the asymmetric diurnal cycle of relationship between water vapor and carbon dioxide (Fig 3.6e). Therefore, the peak time of transpiration in these five days does not occur at noon.

To sum up, the early peak of transpiration in Chi-Lan, derived from the FVS method, is possibly because of non-local moisture accumulation in daytime. The non-local moisture accumulation will contaminate the assumption of the FVS method that the source/sink of correlation between water vapor and carbon dioxide is only from local evapotranspiration.

To verify our speculation, we will compare the diurnal cycle of sap flow velocity with transpiration derived from the FVS method to see plant characteristic in Chi-Lan.

3.5 Diurnal cycle of sap flow measurement

The diurnal cycle of sap flow velocity from May 2020 to November 2021 in Chi-Lan suggests a nearly symmetric diurnal cycle. The sap flow velocity of the four sample trees peaks from 10 am to 12 am (Fig 3.7). The diurnal cycle of sap flow velocity has a similar pattern to the diurnal cycle of transpiration derived from model simulations (Fig 3.4b).

The above results provide more evidence that transpiration should have a symmetric diurnal cycle in the daytime in Chi-Lan. Thus, the partitioning result derived from the FVS method might be biased due to the accumulation of lateral water vapor.

Chapter 4 Discussion

4.1 Role of unique diurnal relative humidity characteristic in flux variance similarity method algorithms

The increasing relative humidity in daytime is a unique diurnal characteristic in Chi-Lan. It indicates not only a high relative humidity in daytime (Fig 3.5d) but also a rapidly increased specific humidity after sunrise (Fig 3.5c). High relative humidity in daytime will not only cause a large fraction of NVPD error (Table 3) but also cause the unstable WUE problem (Eqs. 2).

A large fraction of NVPD error will cause low successful partition in a high relative humidity condition, the most unique hydro-climatological characteristic in montane cloud forests. The diurnal cycle of evapotranspiration partitioning derived from the FVS method will neglect the prevailing weather condition in Chi-Lan. The unstable WUE problem will cause a large uncertainty in the evapotranspiration partitioning (Sulman et al., 2016; Anderson et al., 2017; Skaggs et al., 2018; Scanlon et al., 2019; Wagle et al., 2021). We apply the maximum relative humidity threshold and the ModFVS method to prevent the NVPD problem and obtain evapotranspiration partitioning in high relative humidity conditions or foggy times. However, the WUE value and the ratio of transpiration to evapotranspiration are sensitive to the maximum relative humidity. Thus, the value of evapotranspiration partitioning obtained from the FVS method in the regions with unique relative humidity characteristics has high uncertainty.

Rapidly increased specific humidity may be a signal of large lateral water vapor accumulation. The non-local moisture accumulation disobeys the assumption of the FVS method that the source/sink of water vapor and carbon dioxide originate from the local area. The correlation between water vapor and carbon dioxide is not only affected by the stomatal and non-stomatal fluxes but also the moisture advection. The early peak of correlation between water vapor and carbon dioxide then contributes to the early peak of transpiration in Chi-Lan. This problem has not been discussed in previous studies because most studies apply this method to irrigated region (Skaggs et al., 2018; Wagle et al., 2020; Wagle et al., 2021) or in grass covers (Wang et al., 2016). Some studies apply the FVS method into forest regions (Sulman et al., 2016; Scanlon et al., 2019). However, such early peak of transpiration partitioning from the FVS method is not reported. This is perhaps because of little contribution of non-local water vapor source in those areas. Although how much the contribution of non-local water vapor accumulation can affect the result derived from FVS method remain unknown, the increased relative humidity diurnal characteristics suggests a rapidly increased specific humidity in daytime, which can be used to diagnose the suitability of the FVS method.

To sum up, the increased relative humidity in daytime will not only amplify the uncertainty of results obtained from FVS method but also contribute to biased evapotranspiration partitioning. Last but not least, this unique characteristic may be a signal of non-local water vapor accumulation, which will affect the peak time of transpiration.

4.2 Limitations of flux variance similarity method

Previous study has suggested that errors in the estimation of WUE could lead to biases in FVS partitioned fluxes (Sulman et al., 2016; Anderson et al., 2017; Skaggs et al., 2018; Scanlon et al., 2019; Wagle et al., 2021). As intercellular carbon dioxide is hard to measure, it relies on parameterization to obtain WUE (Eqs. 2). Wagle et al. (2021) suggested that five WUE parameterization yield considerable differences in the FVS algorithm performance and the ratio of transpiration to evapotranspiration. In forest regions, Sulman et al. (2016) suggested that variations in WUE within the canopy could violate the assumption of the FVS method. In this study, we use the maximum relative humidity to test the sensitivity of WUE on the ratio to transpiration and evapotranspiration. The mean value of ratio varies from 0.43 to 0.61 when WUE varies from -40 mg/g to -300 mg/g (Fig 3.1a). The sensitivity can be amplified due to the high relative humidity condition. This result suggests that future work is needed to develop methods for estimating WUE within the FVS method, especially in high humidity relative conditions.

Aside from the WUE sensitivity problem, the above-ground biomass, including moss attached to the trees or soil respiration in Chi-Lan, could lead to spatial heterogeneity in non-stomatal fluxes. Klosterhalfen et al. (2019) suggested a certain degree of decorrelation of water vapor and carbon dioxide is needed to remove the impacts from soil sources and canopy sink/sources. However, how much degree of decorrelation in such a humid region remains unknown.

Both model simulations and the ModFVS method suggests an asymmetric diurnal evapotranspiration characteristic in Chi-Lan and a symmetric diurnal evapotranspiration characteristic in Lien-Hua-Chih (Fig 3.4a). However, canopy evaporation is the dominant component in evapotranspiration in Chi-Lan in the morning (Fig 1.1). Lots of canopy water evaporate in the morning, contributing to increasing correlation between water vapor and carbon dioxide. This may violet the assumption of FVS method, which will contribute to the wrong evapotranspiration partitioning results. However, most studies apply the FVS method in transpiration dominated regions, which will neglect the contribution of canopy evaporation in the correlation between water vapor and canopy water. This study suggests an estimation of the contribution of canopy evaporation to the FVS method is required to further applying the FVS method to global flux tower sites.

The FVS method may be violated due to the complex airflow and mixing below or within the canopy (Sulman et al., 2016). This study emphasizes that lateral water vapor accumulation may also violate the FVS method's assumption. Both effects highlight the source/sink of the water vapor and carbon dioxide from the local forest system and the non-local region. These effects may alter the peak time of correlation between water vapor and carbon dioxide (Fig 3.1), leading to that the diurnal cycle of the transpiration does not peak in the peak time of either the net radiation or photosynthesis active radiation (Fig 3.3, Fig 3.6).

In conclusion, the limitations of the FVS method in Chi-Lan include (a) wrong estimations of WUE, (b) spatial heterogeneity of non-stomatal fluxes due to above-ground biomass, (c) lots of canopy evaporation, and (d) complex airflow with and mixing or lateral water vapor sources. This study suggests that there still has a large uncertainty of evapotranspiration partitioning applying FVS method in Chi-Lan, a region with unique hydro-climatological cycle. Other evapotranspiration partitioning methods applying in Chi-Lan or other regions with similar hydro-climatological cycle are required to better figure out the land-atmosphere interaction in these regions.

4.3 Regions with unique diurnal relative humidity characteristics

Lee et al. (2021) have started developing gap-filled measurements by combining the FVS partitioned fluxes and artificial neutral networks. It is important to highlight regions that are not suitable for the FVS method. As the unique diurnal relative humidity characteristic can be used to diagnosed whether the FVS method can be applied or not, we use this criterion to find the regions with unique diurnal relative humidity characteristics.

FLUXNET2015 has 206 flux tower sites globally (Fig 4.1). Approximately half of the flux tower sites are forest type land covers, including evergreen broadleaf forest, deciduous broadleaf, mixed forest and evergreen needleleaf forest. Most of the flux sites situated at North America and Europe. Only a few flux tower sites are situated in tropical regions (Pastorello et al., 2020). We analyze diurnal cycle of 194 flux tower sites in FLUXNET2015, which provide variables including relative humidity, temperature, and surface fluxes. All forests sites do not have increasing diurnal relative humidity characteristics. Only two open shrubland flux tower sites in Spain have increased diurnal relative humidity characteristics (Fig A2, Fig A3). However, these two sites do not have rapidly increasing specific humidity in daytime. It suggests most of the flux tower sites in FLUXNET2015 have a large probability of applying the FVS method successfully.

The unique diurnal humidity characteristic is likely to occur in montane cloud forests regions. Most of tropical montane cloud regions are over Maritime Continent, north of Indochina, Central America and The Andes (Fig 4.2). However, none of FLUXNET2015 sites are situated in these regions. Only a few flux tower sites registered in AmeriFlux and AsiaFlux are situated at tropical montane cloud forests regions. These flux tower sites may have a similar hydro-climatological cycle in Chi-Lan. Due to the inapplicability of the FVS method in Chi-Lan, it is essential to apply the FVS method in these tropical montane cloud forests to verify the inapplicability of recent the FVS method discussed in Chapter 4.2.

4.4 The prospect of partitioning evapotranspiration in montane cloud forests

Although the correlation between water vapor and carbon dioxide suggests that the inapplicability of FVS method in Chi-Lan is probably because of moisture advection, the contribution of moisture advection to water vapor accumulation remains unknown. The partitioned fluxes obtained from the FVS method are biased mostly because of moisture advection; therefore, we can obtain the non-local effect of water vapor accumulation if we have reasonable transpiration obtained from other methods.

Different evapotranspiration partitioning methods have been developed in recent years (Fig 1.3, Stoy et al., 2019). It is essential to apply different methods to intercompare the applicability of each method. Subsequently, a future study may use the reasonable transpiration and bias transpiration obtained from the FVS method to obtain the contribution of non-local effect in Chi-Lan or other similar hydro-climatological regions. We will be able to distinguish local and advection water supply in the flux tower field scale. Moreover, it will be able to explore how different local and non-local atmospheric forcings may change the hydro-climatological cycle in montane cloud forests.

Chapter 5 Conclusions and Future Work

The FVS method has the potential for analysis of flux tower datasets; however, not many studies applied it to montane cloud forests, whose unique hydro-climatological cycle features an early peak of evapotranspiration and increased relative humidity in daytime. This study shows an early peak of transpiration derived from the FVS method in Chi-Lan montane cloud forest. Such an early peak of transpiration is not consistent with the diurnal cycle of transpiration obtained from the Community Land Model and sap flow velocity. This may result from an asymmetric diurnal cycle of correlation between carbon dioxide and water vapor in Chi-Lan montane cloud forest due to the effect of non-local water vapor sources.

Increased relative humidity in daytime, which is favorable for fog formation, is a unique diurnal characteristic in montane cloud forests. This diurnal characteristic implies a rapidly increased specific humidity and high relative humidity conditions in daytime. A rapidly increased specific humidity may result from local evapotranspiration and moisture advection. The non-local effects may disobey the assumption of the FVS method. Moreover, high relative humidity conditions may lead to negative vapor pressure deficit or unstable leaf-level water use efficiency, leading to the diurnal cycle obtained from the FVS method not be able to represent the diurnal characteristic in montane cloud forests.

This study concludes that there has a large uncertainty of evapotranspiration partitioning when applying the FVS method in Chi-Lan, a region with a unique hydro-climatological cycle. As few flux tower sites have similar diurnal characteristics to Chi-Lan montane cloud forest, it is essential to not only apply the FVS method in other cloud forest flux tower sites but also intercompare different evapotranspiration partitioning methods in these regions. Even though the partitioning results from the FVS method are biased mostly because of horizontal moisture advection, we can obtain the non-local effect of water vapor accumulation if we have reasonable transpiration obtained from other methods. A future study may combine the FVS method and other evapotranspiration partitioning methods to distinguish local and advection water supply in the flux tower field scale. It will be able to explore how different local and non-local atmospheric forcings may change the hydro-climatological cycle in montane cloud forests and the land-atmosphere interaction in these regions.

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FIGURES

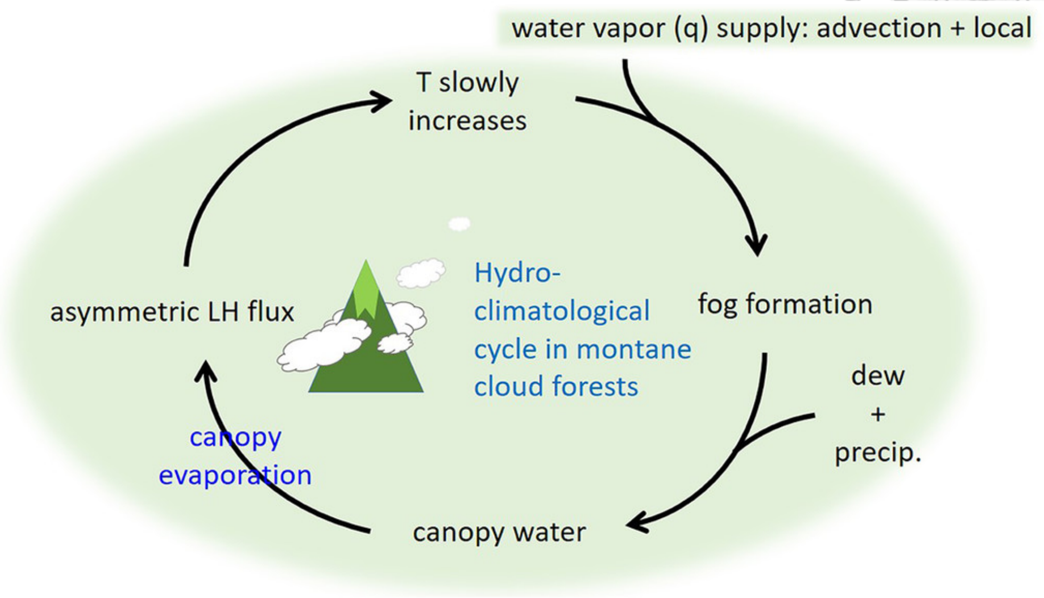

Fig 1.1 Hydro-climatological cycle in montane cloud forests (Reference: Fig. 6. in Gu et al., 2021)

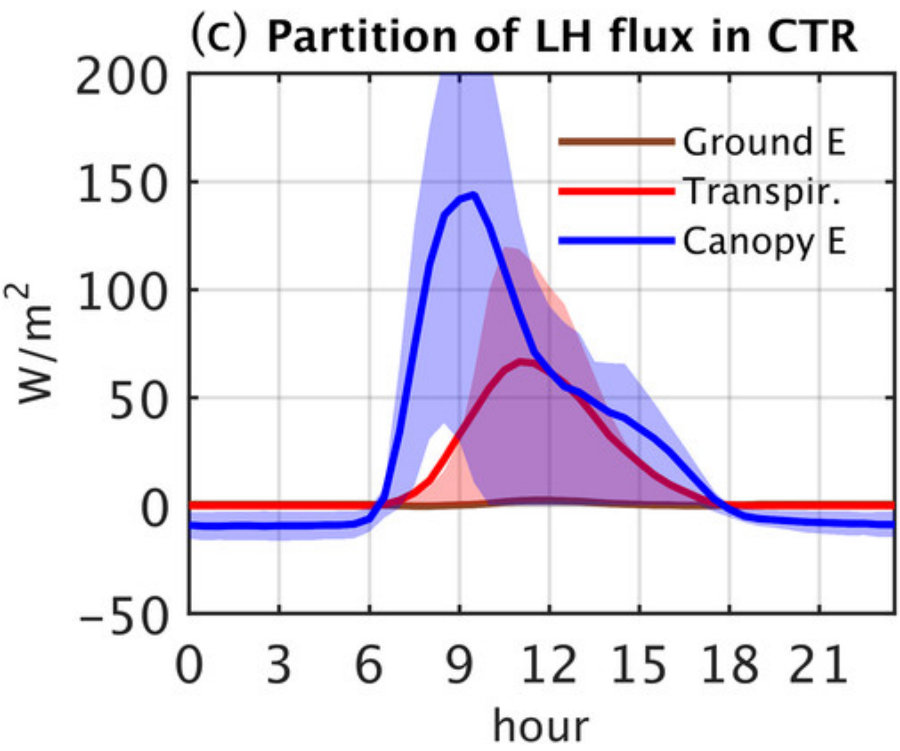

Fig 1.2 The diurnal cycle of the partitions of the latent heat flux [ground evaporation (W m−2; brown lines), transpiration (W m−2; red lines), and canopy evaporation (W m−2; blue lines)] for simulations conducted using the Community Land Model version 4. The shadings represent the variations of the energy fluxes between the first quartile and the third quartile from the last eight years of the simulations. (Reference: Fig. 5. (c) in Gu et al., 2021)

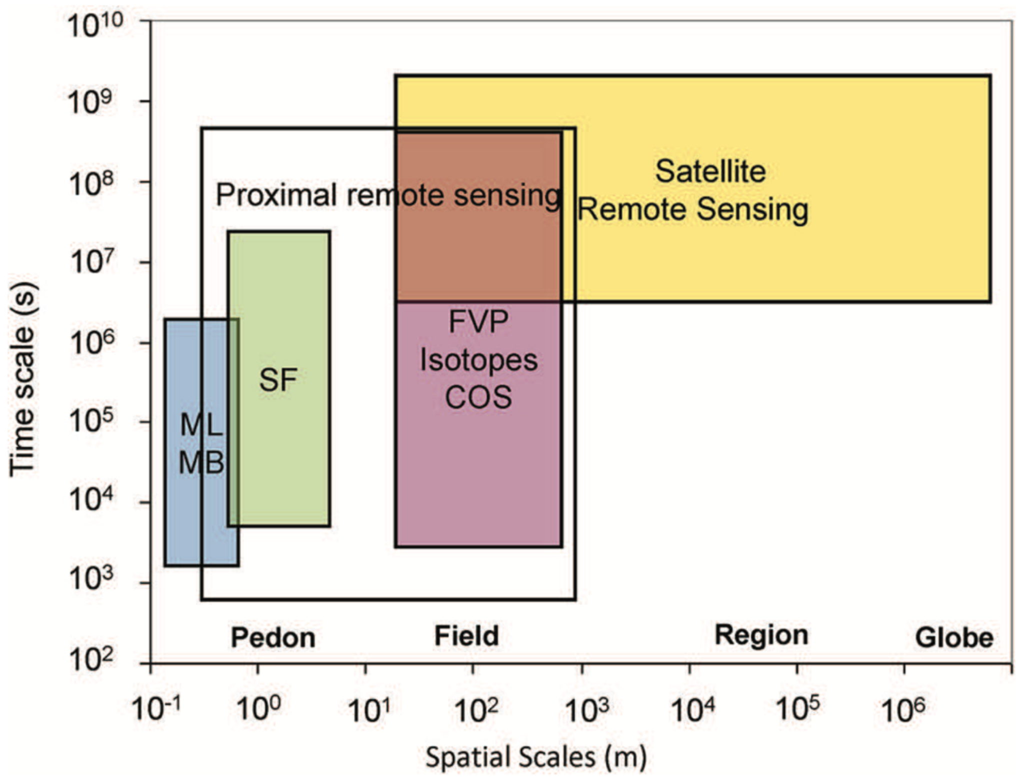

Fig 1.3 Spatial and temporal scales of different evapotranspiration partitioning approaches: microlysimeter (ML), micro-Bowen ratio (MB), sap flow (SF), flux variance partitioning (SVP), isotopes, and carbonyl sulfide (COS). All three of the atmospheric methods have approximately the same temporal and spatial scales. (Reference: Fig. 1. in Anderson et al., 2017)

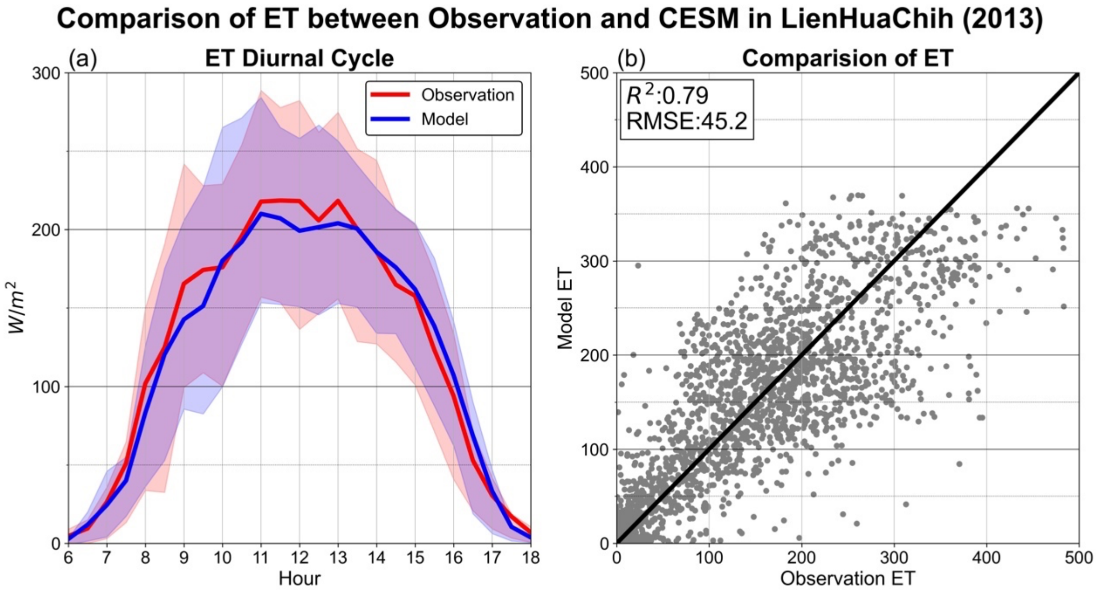

Fig 2.1 The comparison of the observation and the Community Land Model (CLM) output in Gu, 2020 in LHC: (a) the diurnal cycle of latent heat flux [observation (W m−2; red line) and CLM (W m−2; blue line)], and (b) scatter plot of latent heat flux. The shadings represent the variations of the energy fluxes between the first quartile and the third quartile. The RMSE means the root-mean-square error. (Reference: Gu, 2020 under revision)

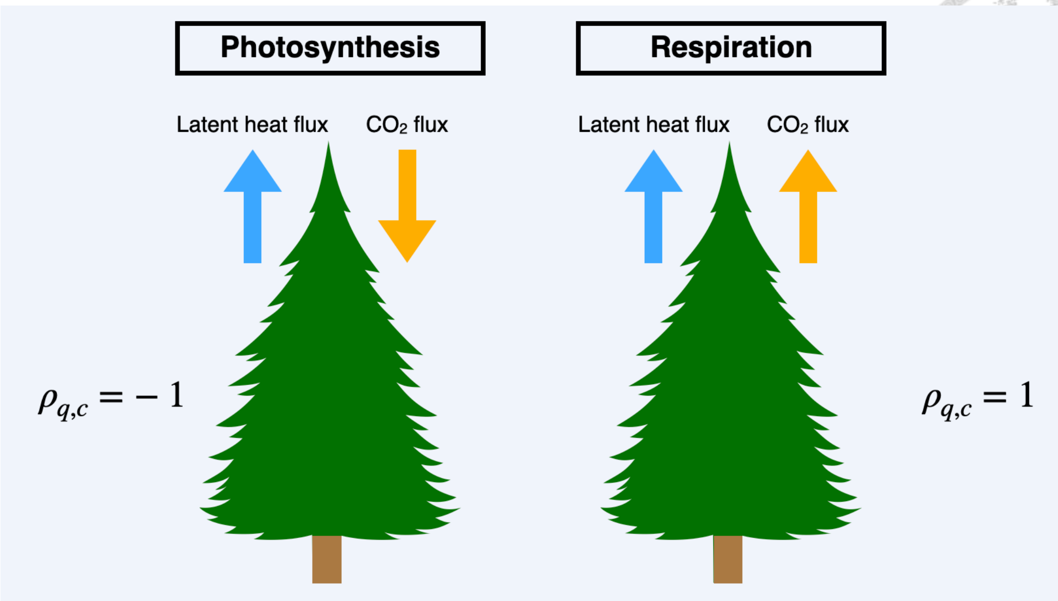

Fig 2.2 The schematic plot of the core concept of the flux variance similarity method.

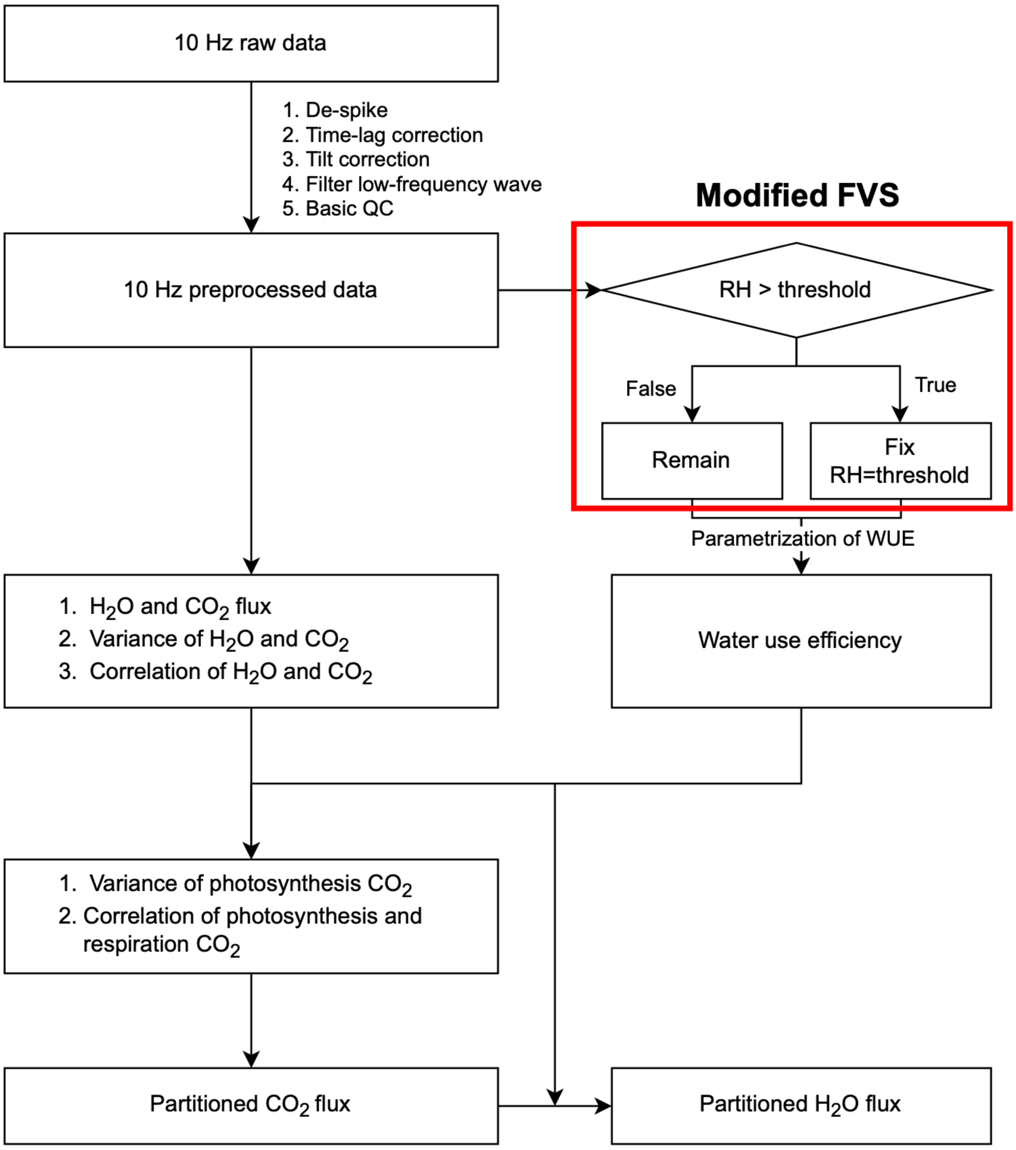

Fig 2.3 Flow chart of the ModFVS algorithms.

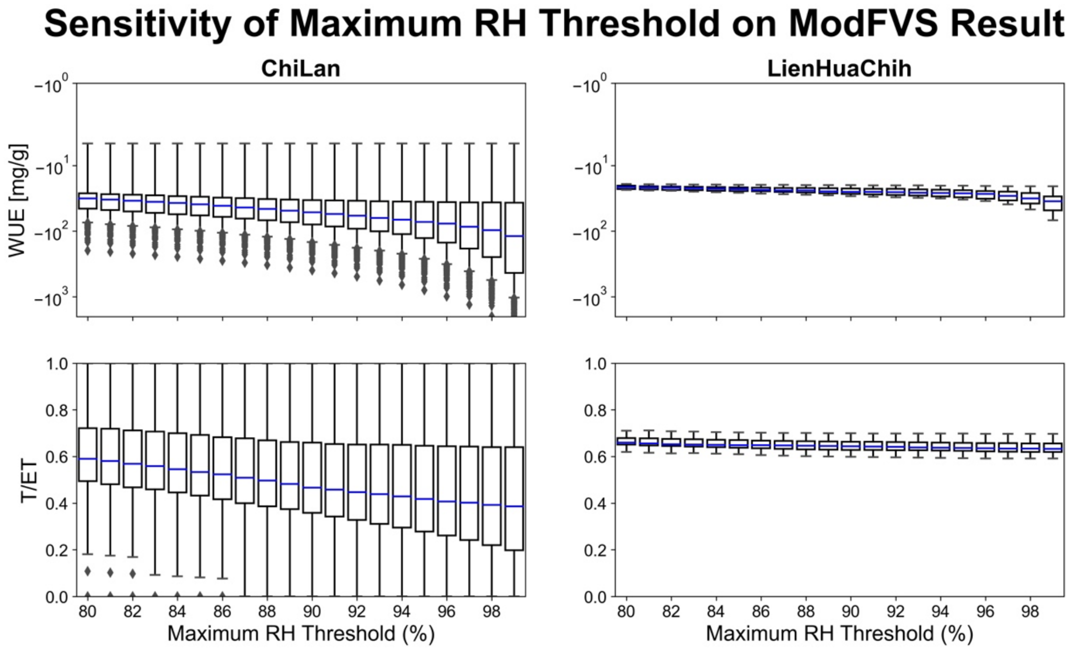

Fig 3.1 Sensitivity test of the maximum RH threshold on leaf-level water use efficiency and ratio of transpiration to evapotranspiration in daytime: (a) and (b) are sensitivity test on leaf-level water use efficiency in CL and LHC, respectively. (c) and (d) sensitivity test on ratio of transpiration to evapotranspiration in CL and LHC, respectively. The blue thick line represents the median of the distribution, and the edges of the box the 25% and 75% quantiles.

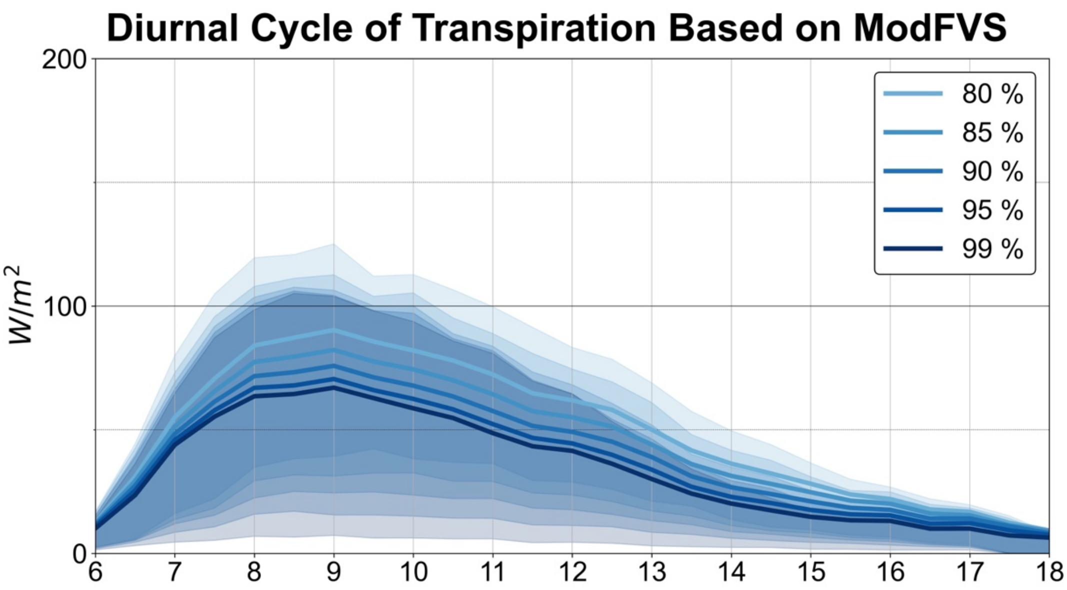

Fig 3.2 Sensitivity test of the maximum RH threshold on the diurnal cycle of transpiration in CL. Each line correspond different maximum RH threshold applied in the ModFVS method. The shadings represent the range of variation of transpiration between the first and the third quartiles of data.

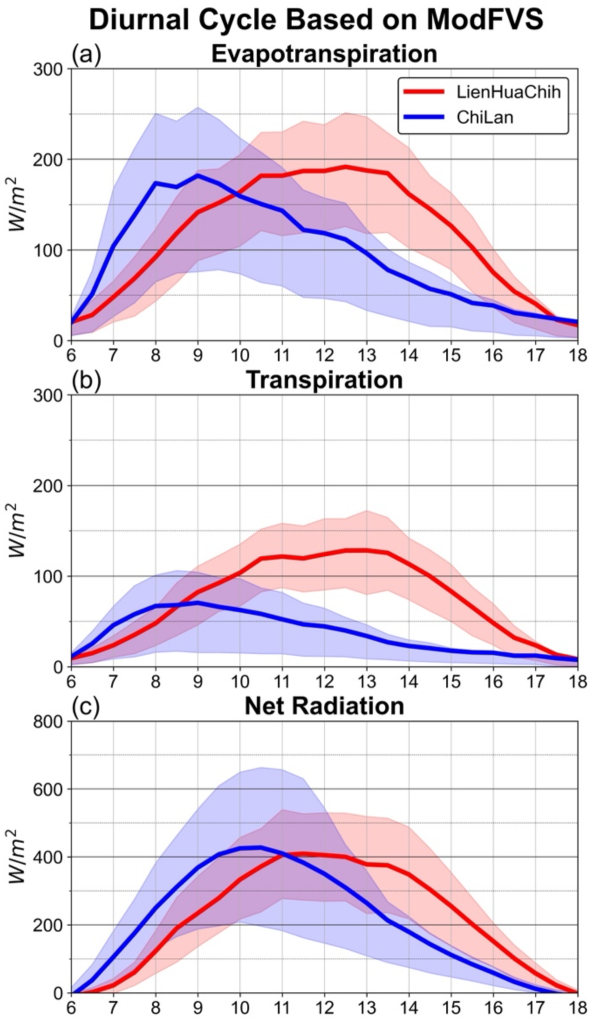

Fig 3.3 The comparison of diurnal cycle of energy flux derived from the ModFVS method and observed from in-situ flux tower between the CL (blue lines) and LHC (red lines) forest: (a) evapotranspiration (W m−2) derived from the ModFVS method, (b) transpiration (W m−2) derived from the ModFVS method, and (c) net radiation (W m−2) observed from flux tower. The shadings represent the range of variation of each meteorological variables between the first and the third quartiles of data in CL and LHC.

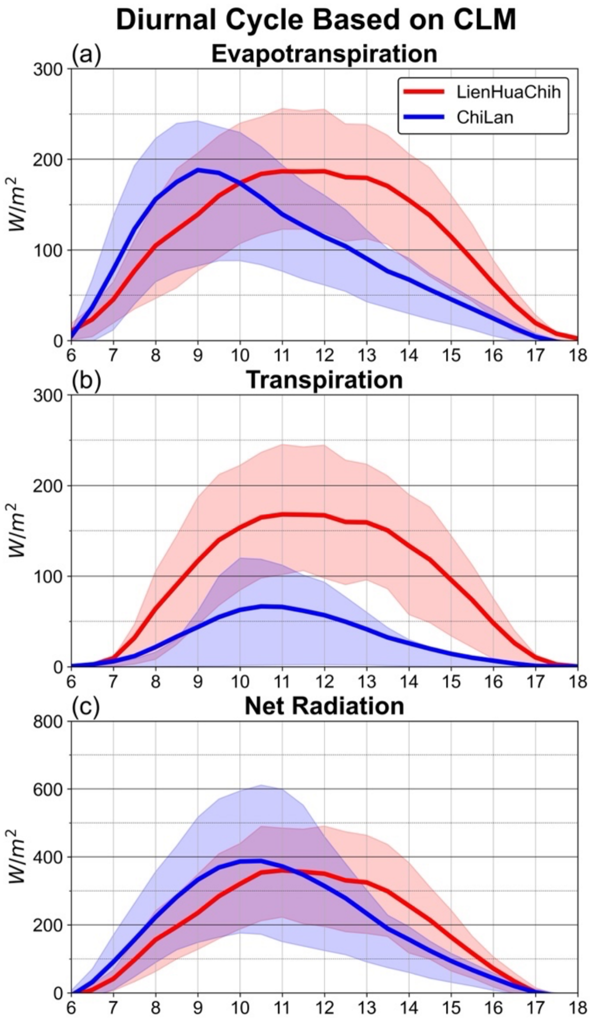

Fig 3.4 The comparison of diurnal cycle of energy flux derived from the Community Land Model (CLM) between the CL (blue lines) and LHC (red lines) forest: (a) evapotranspiration (W m−2), (b) transpiration (W m−2), and (c) net radiation (W m−2). The shadings represent the range of variation of each meteorological variable between the first and the third quartiles of data in CL and LHC.

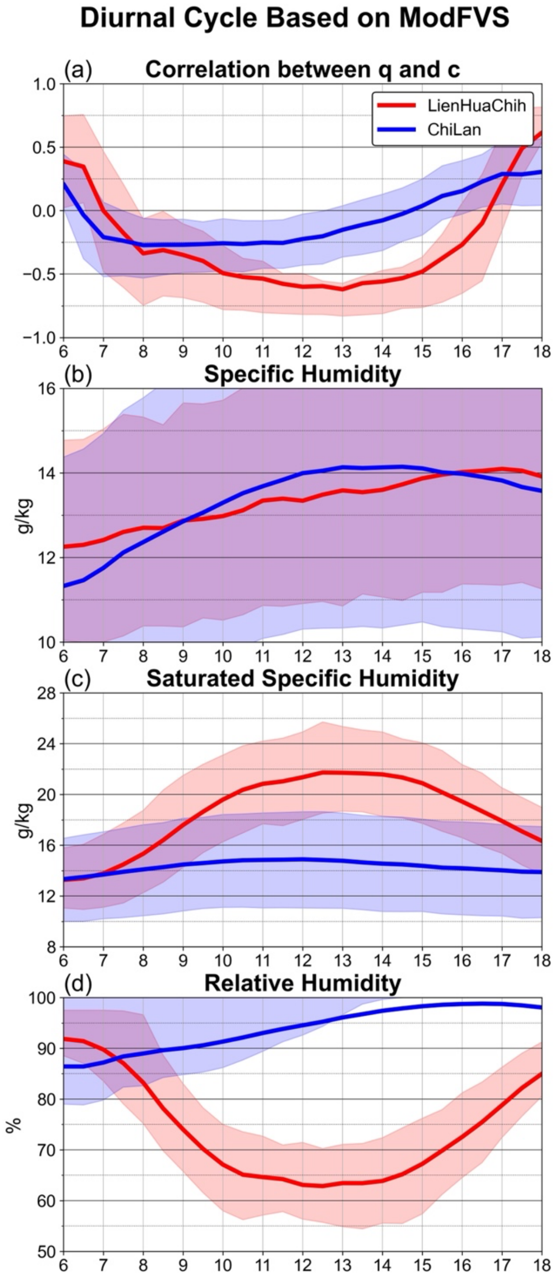

Fig 3.5 The comparison of five meteorological variables between the CL (blue lines) and LHC (red lines) forest: (a) correlation between water vapor and carbon dioxide derived from ModFVS method, (b) specific humidity (g/kg) observed from flux tower, (c) saturated specific humidity (g/kg) observed from flux tower, (c) relative humidity (%) observed from flux tower. The shadings represent the range of variation of each meteorological variable between the first and the third quartiles of data in CL and LHC.

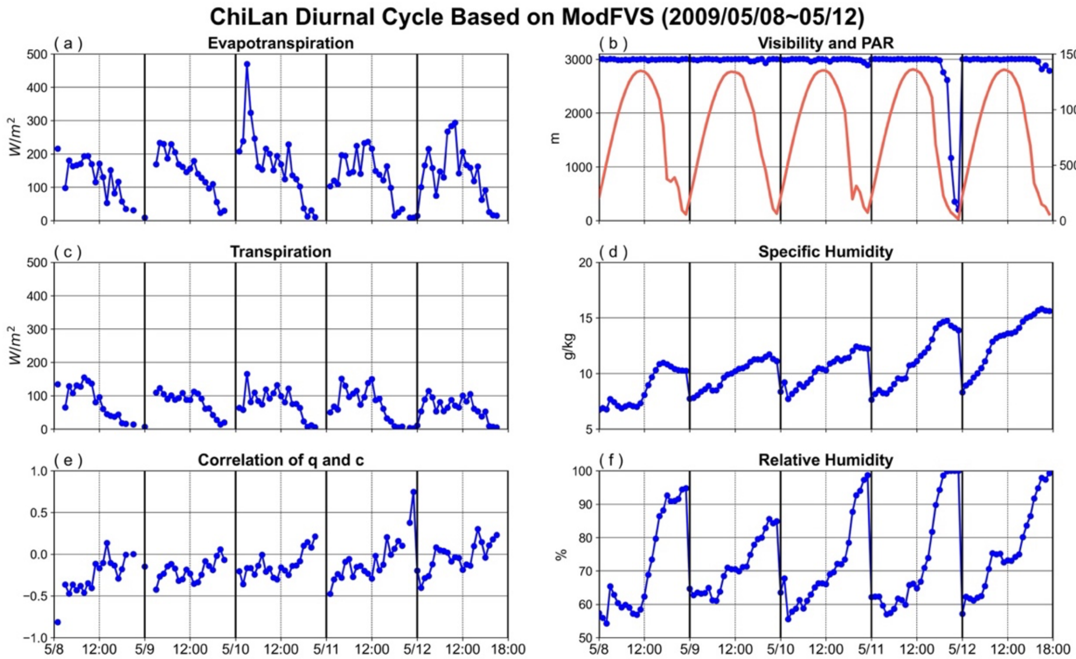

Fig 3.6 The diurnal cycle of CL forests from May 8th to May 12th in 2009: (a) evapotranspiration (W m−2) derived from the ModFVS method, (b) visibility (m, blue line) and PAR (uE/s/m^2, orange line) observed from flux tower, (c) transpiration (W m−2) derived from the ModFVS method, (d) specific humidity (g/kg) observed from flux tower, (e) correlation between water vapor and carbon dioxide derived from the ModFVS method, and (f) relative humidity (%) observed from flux tower.

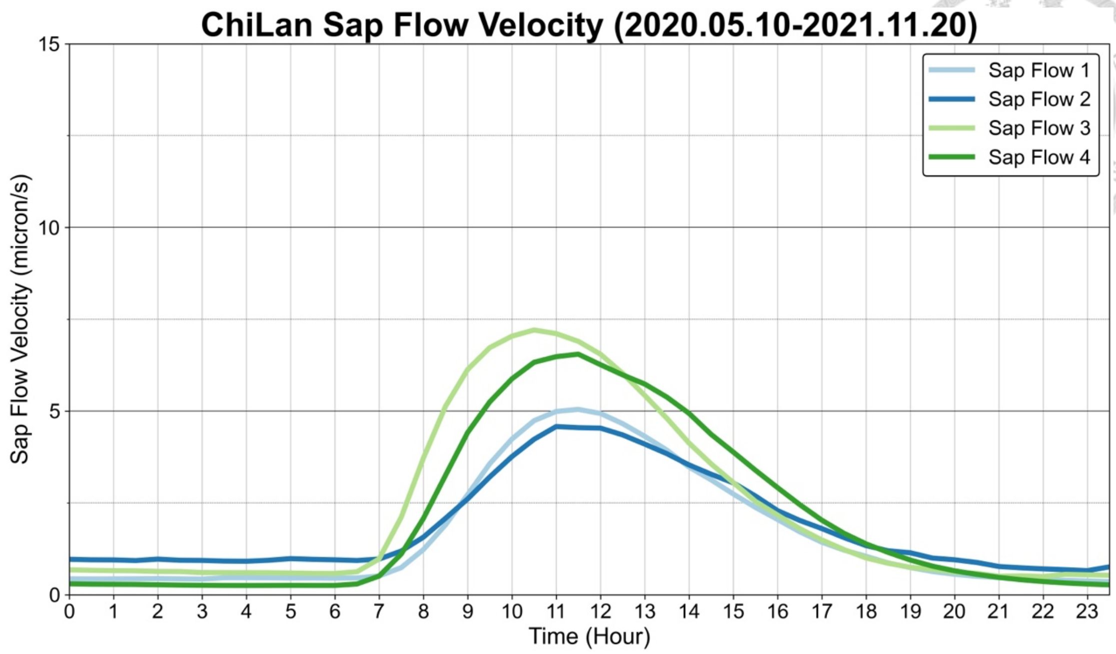

Fig 3.7 The diurnal cycle of sap flow velocity [micron/s] in CL forests from May in 2020 to November in 2021. The mean diurnal cycles of 4 sample trees are shown in the figure.

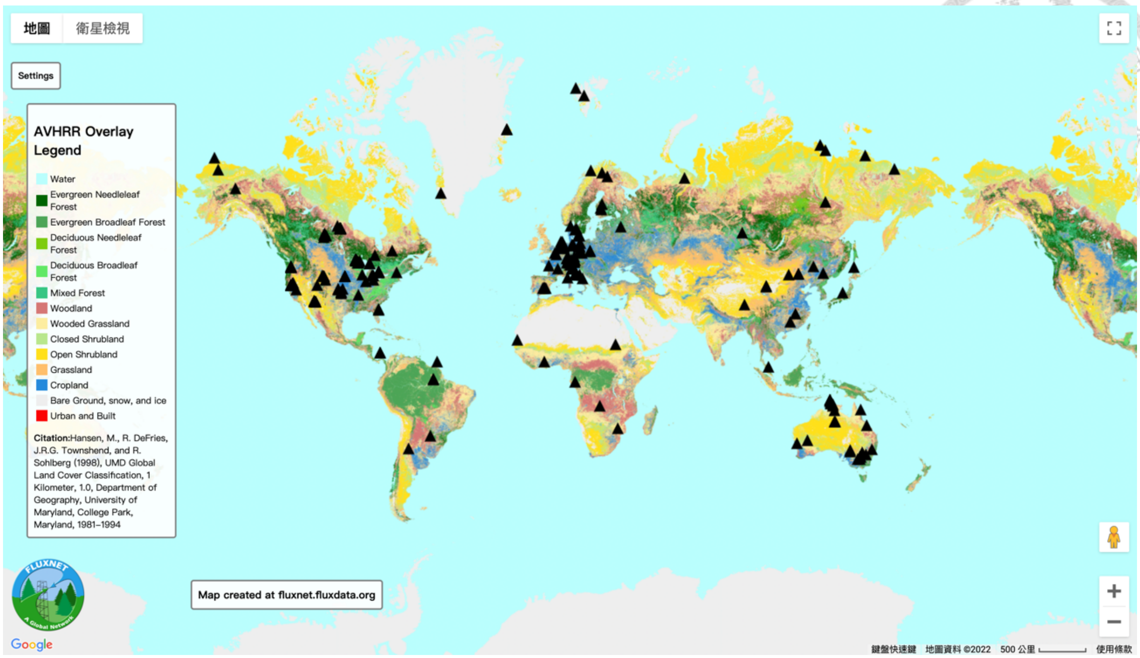

Fig 4.1 The distribution of flux tower sites registered in FLUXNET2015. The black triangles are flux tower sites registered in FLUXNET2015. The shaded is AVHRR 1km landcover data from 1981 to 1994. The map is created at fluxnet.fluxdata.org.

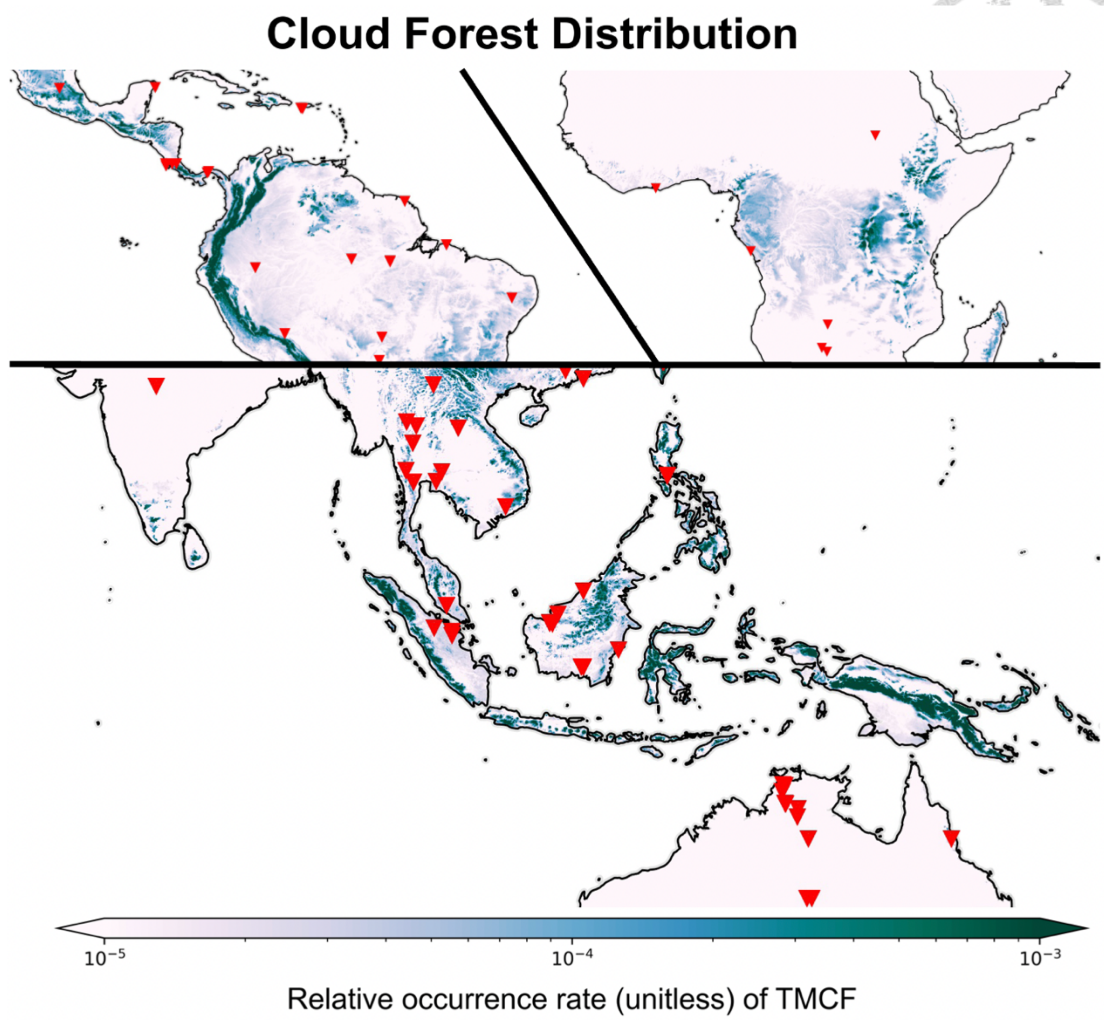

Fig 4.2 Tropical montane cloud forest distribution. The red triangles are flux tower sites registered in Fluxnet, AmeriFlux, and AsiaFlux. (Reference: Wilson et al., 2016 under revision)

TABLES

Table 1 CLM experiment design for two flux tower sites.

Sites	Land surface condition	Atmospheric forcing	Source of canopy water
Chi-Lan	100% needleleaf evergreen tree, Annual mean LAI=4.6, Coefficient of maximum allowed dew = 0.2533	Chi-Lan 2008-2011 half-hourly observational data Precip. is added by 0.2mm per 30 mins when visibility <1km	precip. dew fog
Lien-Hua-Chih	42.2% needleleaf evergreen tree, 38.6% broadleaf evergreen tree, 19.2% broadleaf evergreen shrub, Annual mean LAI=3.9519	Lien-Hua-Chih 2009-2013 half-hourly observational data	precip.

Table 2 Detailed data preprocessing setting used for the FVS method in two flux tower sites.

Method	Data preprocessing setting
Despike (Vickers and Mahrt, 1997)	Statical outlier (vertical wind: beyond 5 std., others: beyond 3.5 std.) is screened
Time lag correction (Hörtnagl, L., 2021)	Time lags between scalars and vertical velocity was corrected for monthly time scale
Tilt correction (Wilczak et al., 2001)	Planar fit method was applied for monthly time scale

Table 3 Detailed setting in Fluxpart version 0.2.8 in two flux tower sites.

		Chi-Lan	Lien-Hua-Chih
Quality check	Water Vapor (g m^{-3})	0 ~ 23.4	0 ~ 23.4
	Carbon Dioxide (mg m^{-3})	400 ~ 700	400 ~ 900
	Horizontal wind (m s^{-1})	-30 ~ 30	-30 ~ 30
	Vertical wind (m s^{-1})	-5 ~ 5	-5 ~ 5
	Temperature (^{o}C)	-15 ~ 35	-15 ~ 35
	Pressure (hPa)	800 ~ 900	850 ~ 950
Minimum friction velocity (m s^{-1})		0.1	0.1
Plant type		C3	C3
WUE parameterization		Const_ppm	Const_ppm
Canopy height (m)		12	17
Measurement height (m)		24	25

Table 4 Fractions of partitioned outputs (%) based on the FVS method using const_ppm leaf-level water use efficiency parameterization in two flux tower sites.

	NVPD incompatible	EC data incompatible	WUE incompatible	Successful partition
ChiLan (CL)	10.13	2.63	6.64	53.78
LienHuaChih (LHC)	0.94	8.39	16.90	65.95

APPENDIX

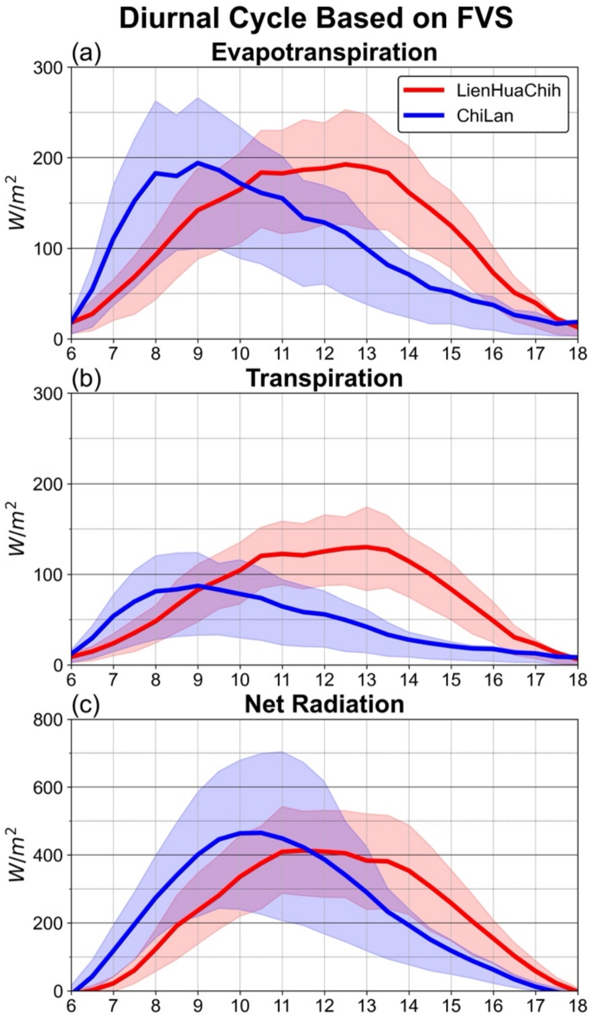

Fig A1 The comparison of diurnal cycle of energy flux derived from the FVS method and observed from in-situ flux tower between the CL (blue lines) and LHC (red lines) forest: (a) evapotranspiration (W m−2) derived from the FVS method, (b) transpiration (W m−2) derived from FVS method, and (c) net radiation (W m−2) observed from flux tower. The shadings represent the range of variation of each meteorological variables between the first and the third quartiles of data in CL and LHC.

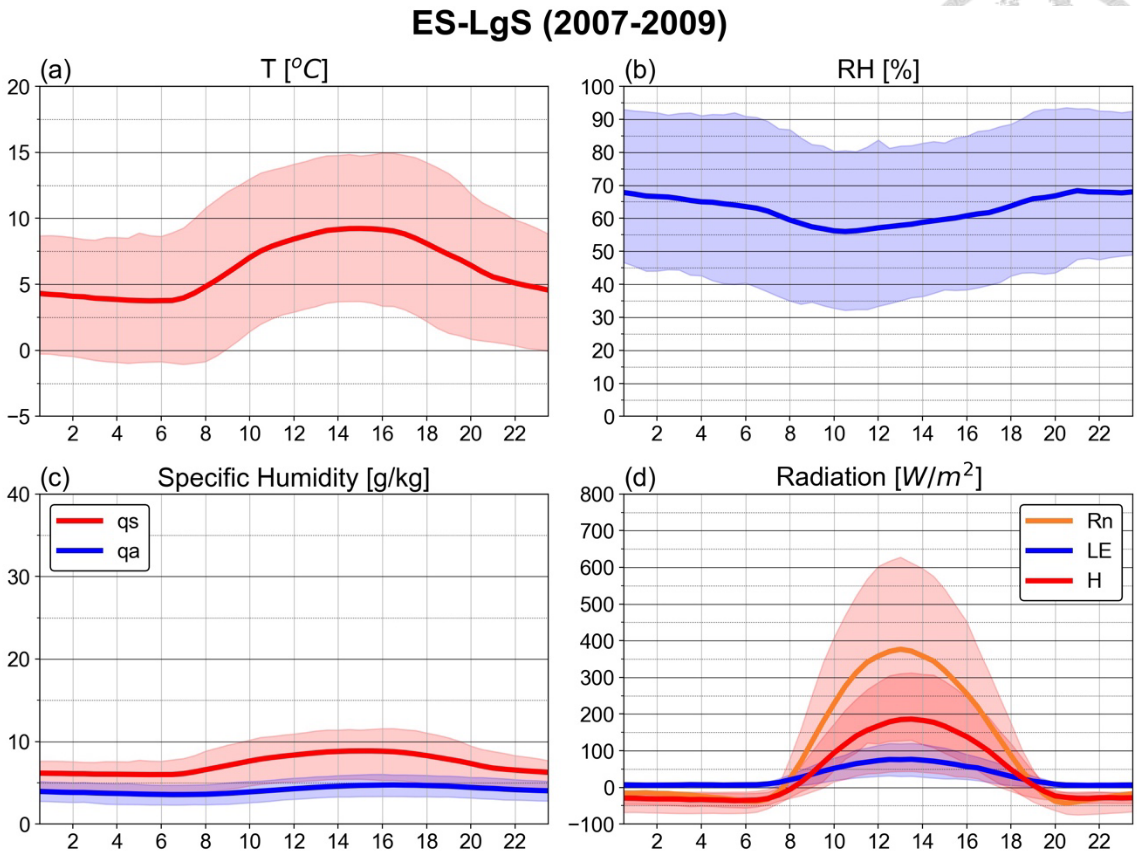

Fig A2 Diurnal cycle of meteorological measurements in ES-LgS flux tower sites from 2007 to 2009: (a) temperature (^{o}C), (b) relative humidity (%), (c) specific humidity (blue line, g/kg) and saturated specific humidity (red line, g/kg), and (d) net radiation (orange line, W m-2), latent heat flux (blue line, W m-2) and sensible heat flux (red line, W m-2). The shadings represent the range of variation of each meteorological variable between the first and the third quartiles of data.

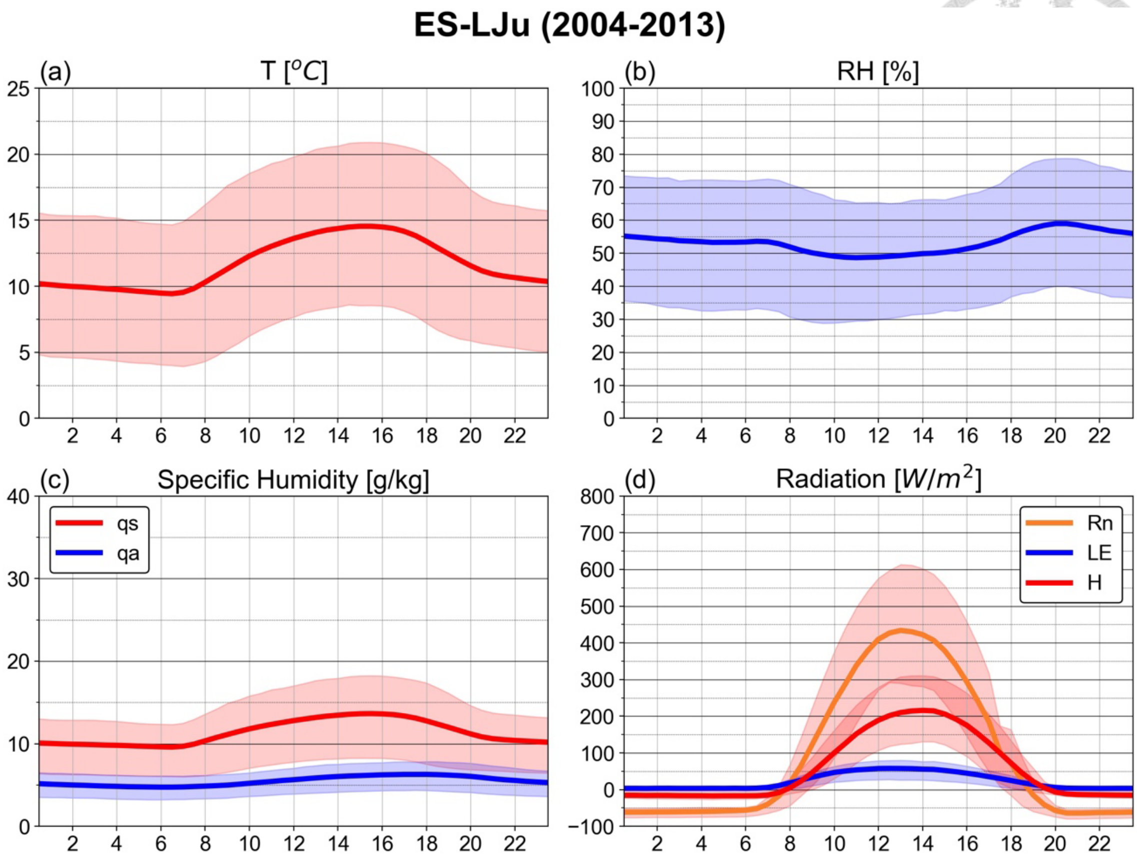

Fig A3 Diurnal cycle of meteorological measurements in ES-LJu flux tower sites from 2007 to 2009: (a) temperature (°C), (b) relative humidity (%), (c) specific humidity (blue line, g/kg) and saturated specific humidity (red line, g/kg), and (d) net radiation (orange line, W m-2), latent heat flux (blue line, W m-2) and sensible heat flux (red line, W m-2). The shadings represent the range of variation of each meteorological variable between the first and the third quartiles of data.