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APPLICATION OF THE ACASA MODEL AT A DRY DIPTEROCARP FOREST IN THAILAND

Srisunee Wuthiwongyothin[1], Kyaw Tha Paw U[2] and *Montri Sanwangsri[3,4]

[1] Department of Civil Engineering, Faculty of Engineering, Burapha University, Thailand;
[2] Atmospheric Science, University of California, Davis, U.S.A;
[3] Highland Agriculture and Natural Resources, Faculty of Agriculture, Chiang Mai University, Thailand;
[4] Agriculture and Forestry Climate Change Research Center, Faculty of Agriculture, Chiang Mai University, Thailand

*Corresponding Author, Received: 13 June 2023, Revised: 04 Aug. 2024, Accepted: 11 Aug. 2024

ABSTRACT: Climate change is associated with increasingly frequent disasters such as floods and droughts, and/or changes in the timing and duration of seasons. Forest ecosystems play an important role in mitigating greenhouse gas emissions to the atmosphere with their large storage of carbon (carbon sequestration). Understanding the energy balance, heat flux, and net ecosystem exchange in forests is important for developing approaches to cope with the effects of climate change via management, mitigation, and adaptation. This study utilized the Advanced Canopy–Atmosphere–Soil Algorithm (ACASA), a land surface model (LSM) which is used here to examine a dry dipterocarp tropical forest in Thailand's Phayao province. Half-hourly averaged data from 2015 were used to calibrate the model, while data from 2014 and 2016 were used to validate the model. The results showed that the ACASA model can simulate net radiation, incoming and outgoing shortwave radiation, and outgoing longwave radiation parameters very accurately, with R^2 values greater than 0.9 and root mean square errors of 4.49–38.02 W/m^2. In addition, the model can achieve reasonable estimates of sensible heat flux and latent heat flux, with R^2 values of 0.57–0.68. The results from this LSM have potential implications for developing and validating climate models as well as analyzing forest sensitivity and adaptation under a changing climate.

Keywords: Land surface model, ACASA model, Energy flux, Net ecosystem exchange, Dry dipterocarp forest

1. INTRODUCTION

Understanding the complex interactions between the land surface and the atmosphere is crucial for predicting and mitigating the impacts of climate change. Integrated models that incorporate soil–vegetation–atmosphere transfer schemes are called land surface models (LSMs). These models represent the Earth's land surface, subsurface, and hydrological processes, and their interactions with the atmosphere [1-2]. LSMs are used in climatology, hydrology, ecology, and agriculture to understand and predict land surface behavior under different environmental conditions [3]. The model incorporates mathematical equations to simulate physical, biological, and processes on the Earth's surface [4]. These interactions can help improve our understanding of climate dynamics [5] and develop effective strategies to mitigate and adapt to climate change.

Vegetation, including forests, serves as a critical factor in moderating the transfer of water, energy, and carbon fluxes between the Earth's land surface and atmosphere. Forests exert significant control on the Earth's energy balance, net radiation, and net heat fluxes with the atmosphere (e.g., sensible heat and latent heat). Forest canopies intercept and absorb solar radiation, thus affecting the amount of energy that reaches the ground surface: this leads to changes in surface temperature and the partitioning of energy into sensible heat (i.e., energy directly heating the air) and latent heat (i.e., energy associated with evaporation from leaves and soil). The structure and characteristics of forest vegetation, such as leaf area and canopy density, influence the forest's absorption, reflection, and transmission of solar radiation, thus also affecting the energy balance [2,7].

Forests influence the feedback between the land surface and atmosphere through energy and mass fluxes such as evapotranspiration, which represents the combined loss of water to the atmosphere through plant transpiration and soil evaporation. Forests, with their extensive leaf area, actively transpire large amounts of water vapor into the atmosphere, thus cooling the land surface and influencing their local microclimate. The presence of forests increases evapotranspiration rates relative to non-forested areas, thereby influencing the temperature, humidity, and atmospheric circulation patterns. Forest canopies also affect energy fluxes by exchanging heat and momentum with the atmosphere [8].

Forests act as both carbon sinks and sources in the carbon cycle. Through photosynthesis, forests absorb carbon dioxide (CO_2) from the atmosphere and store it in plant biomass and soils, thus contributing to carbon sequestration [9]. In contrast, forests also release CO_2 through processes such as respiration, decay, and combustion, which contribute to carbon emissions. The balance between these aspects, and thus the net carbon flux of a forest, depends on various factors. Pan et al. [9] investigated the carbon dynamics of forests and quantitatively assessed their capacity as carbon sinks, considering factors such as forest type, age, disturbance history, and management practices. It is well-known that forests play an important role in reducing the increase of greenhouse gas concentrations from anthropogenic emissions to the atmosphere in which forests have to potential for the large storage of carbon (carbon sequestration). Proper forest management, including afforestation, reforestation, and sustainable logging, can enhance carbon sequestration and reduce carbon emissions [1]. Thus, understanding factors such as CO_2 exchange, net primary production (NPP) or net ecosystem exchange (NEE), energy balance, and heat flux in forests is vital to coping with the effects of climate change via management, mitigation, and adaptation strategies.

Dry dipterocarp forests, characterized by a dominance of dipterocarp tree species and a pronounced dry season, have distinct impacts on land surface processes [10]. This forest type plays a crucial role in regulating the water balance of the land surface. During the dry season, these forests undergo water stress associated with reduced soil moisture and limited water availability. The dense canopy of dipterocarp trees helps to intercept and retain rainfall, thus facilitating water infiltration and reducing surface runoff; in turn, this helps to maintain soil moisture levels and contributes to groundwater recharge. Dipterocarp trees are also known for their large size and significant carbon storage capacity in their biomass. The slow decomposition rates in these dry forests contribute to long-term carbon storage in soils and woody debris [6].

This research utilizes the University of California, Davis (UCD) Advanced Canopy–Atmosphere–Soil Algorithm (ACASA) model developed by Pyles et al. [11] to model and simulate a dry tropical dipterocarp forest in Thailand's. ACASA is a comprehensive LSM that integrates various components of the forest ecosystem, including the canopy, atmosphere, and soil, to simulate their interactions. This model has been tested in various climates and vegetation regimes based on in-situ measurements, e.g., temperate grass, tropical pasture, deciduous forest, coniferous forest, tropical rainforest, and temperate rainforest [11]. Furthermore, this model has been applied to a range of forest ecosystems, including a Mediterranean maquis ecosystem [12], irrigated almond orchards [13], and spruce in Germany [14,15]. The main objective of this study is to apply the ACASA model and evaluate its performance when simulating the energy balance and momentum flux of a dry tropical dipterocarp forest in Thailand's Phayao province.

2. RESEARCH SIGNIFICANCE

This study is significant as it applies the ACASA model and evaluates its performance in simulating the energy balance and momentum flux of a dry dipterocarp forest in Phayao province, Thailand. By investigating the model's performance in this context, this study enhances our understanding of land–atmosphere interactions and can provide important insights for sustainable forest management, climate change mitigation, and ecosystem conservation. The findings can help to inform and guide the effective management of these vital ecosystems.

3. METHODOLOGY

3.1 Model Description

The ACASA model [11] was extensively developed based on models by Meyers and Paw U (1986, 1987) [16,17]. The model incorporates various equations and parameterizations to capture the complex processes taking place in vegetation canopies, soils, and the atmosphere. In this model, the canopy is described as multiple vertical plant layers composed of leaves at various angles. The model's key processes are summarized below.

3.1.1 Canopy processes

The solar radiation partitioning equation determines the fraction of solar radiation absorbed by the canopy and the fraction transmitted or reflected on a vertical layer by layer basis.

The photosynthesis and carbon balance equation estimates the rate of carbon assimilation by vegetation based on factors such as light availability, CO_2 concentration, leaf temperature, leaf area index (LAI), and stomatal conductance, which is a function of various factors including soil moisture and photosynthesis based on a modified Farquhar–von Caemmerer equation. Leaves are separated in nine sunlit leaf angle classes and one shaded leaf class, within each canopy layer.

The stomatal conductance equation calculates the rate at which CO_2 diffuses through the plants' stomata based on the environmental conditions.

3.1.2 Soil processes

The soil heat conduction equation calculates the soil's vertical temperature distribution profile based on thermal properties and heat fluxes.

The soil water balance equation tracks soil moisture content and movement within different soil layers, considering factors such as infiltration, evaporation, and plant water uptake.

3.1.3 Energy and water fluxes

The energy balance equation computes the net radiation, sensible heat flux, and latent heat flux for each leaf class in each layer and can be integrated vertically to yield energy partitioning between the land surface and the atmosphere. The leaf energy budget equation is based on Paw U and Gao (1988) [18], and the sum of all leaf classes and canopy layers will give the overall ecosystem energy budget.

The ACASA model version used here can calculate various fluxes, starting from the soil zone (i.e. beneath the soil surface) up to twice the height of the canopy. This model subdivides the root zone into four sublayers (specified as five levels), while the plant canopy is divided into 10 layers, and the overlying atmosphere is divided into 10 additional layers.

3.2 Study Area and Data

3.2.1 Dry dipterocarp forest flux Phayao site

The dry dipterocarp forest flux Phayao site (DPT) is in the University of Phayao, northern Thailand (Fig. 1). This type of forest is a dry tropical seasonal forest found only in Southeast Asia [19]. The DPT flux tower was installed in May 2013 as part of the joint JST–JICA project on hydro-meteorological prediction and adaptation to climate change in Thailand (IMPACT-T Project). The area's topography is characterized by sloping terrain, and the forest is middle-aged (around 30 years old). The DPT site was set up to monitor long-term energy flux, water, and carbon exchange between the atmosphere and dry dipterocarp forest. The observations use the eddy covariance method with an open-path CO_2/H_2O analyzer (Campbell Scientific, Inc. EC150) and three-dimensional sonic anemometer (Campbell Scientific, Inc. CSAT3) on a 42 m tower (Fig. 1). More details of the site and its sensors can be found in [20]. Some general site information is shown in Table 1.

3.2.2 Data

The data used in the ACASA model can be broadly classified into time series data and statics data, as described below.

1) Meteorology time series data: these data include weather-related variables such as temperature, humidity, precipitation, wind speed, atmospheric pressure, global radiation, incoming longwave radiation, temperature, and CO_2 concentration. These data form the boundary conditions at canopy height and above the canopy.

2) Geomorphology and physiology data: these data relate to the soil type, plant area density as a function of height, leaf optical properties, and physiological parameters.

The meteorology input data obtained from the Phayao flux's site station include high-frequency (10 Hz) measurements summarized every 30 minutes between the years 2014 and 2016. These time series data usually contain some missing or outlier values due to technical issues or weather conditions. Thus, some basic data preprocessing is required. Outliers or abnormal values were removed, while small data gaps were filled using the linear interpolation method.

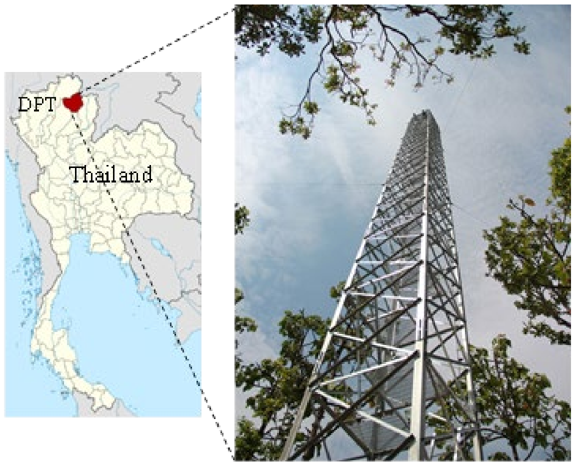

Fig.1 Map showing the generalized location of the dry dipterocarp forest flux Phayao site and its flux tower a photograph showing the site's flux tower

Table 1. General DPT site details

Site name	Dry dipterocarp forest flux Phayao site (DPT)
Location	Phayao, Thailand
Position	19º02'14.38"N, 99º54'10.96"E
Elevation	512 m asl
Climate	Tropical monsoon
Minimum and maximum temperature (1998–2007)	16.94 °C and 35.72 °C
Mean annual precipitation (1998–2007)	1,262 mm
Vegetation type	Dry dipterocarp forest
Canopy height (2014)	16 m
Stand density	2,150 trees/ha
Flux tower height	42 m

The meteorology input was prepared in a text file format, with each column representing the following information:

(1) Date/time: date and time of the data
(2) Rain: amount of rainfall (mm)
(3) Specific humidity or relative humidity (%)
(4) Wind speed (m/s)
(5) Global radiation (Rg) (W/m^2)
(6) Incoming longwave radiation (optional) (W/m^2)
(7) Air temperature (Kelvin)
(8) Atmospheric pressure (hPa)
(9) CO_2: carbon dioxide concentration (ppm)

The morphology input data for the ACASA model for a specific area comprise numerous parameters including the location coordinates (latitude), soil types, number of soil layers and their thicknesses, initial temperature in the soil layers, initial soil moisture content, LAI, canopy architecture index based on forest type, canopy height, height of the measurement flux instrument, wilting point soil moisture, maximum rate of Rubisco carboxylase activity (V_{cmax}), leaf/canopy drag coefficient, photosynthetically active radiation, background near-infrared (NIR) reflectivity, leaf thermal emissivity, etc. Some of these parameters were defined based on literature reviews, some by observations, and some by calibrating the model.

3.3 Energy Balance Closure

The Earth's energy balance represents the balance between energy inputs, energy outputs, and any changes in energy storage within the system, as expressed in Eq. (1) for net radiation (R_n), and Eq. (2) for the general energy budget.

$$R_n = SW_{in} - SW_{out} + LW_{in} - LW_{out} \tag{1}$$

where SW_{in} is incoming shortwave radiation
SW_{out} is outgoing shortwave radiation
LW_{in} is incoming longwave radiation
LW_{out} is outgoing longwave radiation

$$R_n = LE + H + G + (S) \tag{2}$$

The energy balance closure technique can be used to assess the accuracy and reliability of measured radiation and energy flux data in environmental studies. The net radiation received by the Earth can be partitioned into heat fluxes, including latent heat (LE), sensible heat (H), ground heat storage (G), and vegetation/canopy heat storage (S) (Eq. 2). To verify the measurement accuracy of the different heat fluxes, the Eq. (2) is rearranged as follows:

$$R_n - G - (S) = LE + H \tag{3}$$

Fluxes measured from eddy covariance (LE and H) should equal the other energy balance terms as measured by other sensors, which are collectively called the available energy terms (Rn, G, and S). If the available energy terms are accurately measured, but the sum of the eddy covariance terms does not match the available energy, this may indicate errors in the eddy covariance measurement. When there is a large discrepancy indicated by a severe energy budget closure misfit, the data for these points may be omitted and the gaps filled. This evaluation step is crucial to ensure the quality of the measured data before they are used in subsequent modeling and analysis steps.

4. MODEL CALIBRATION AND VALIDATION

This study simulated the energy and momentum flux using the ACASA model. Data from 2015 were used to calibrate the model, while data from 2014 and 2016 were used to validate the model. To evaluate the model's performance, modeled data (m) can be compared with the measured values (o) using the following statistical measures.

1) The coefficient of determination (R^2) is used to measure the fit between datasets. R^2 values range from 0–1: the closer R^2 is to 1, the better the agreement between the calculated and observed data.

$$R^2 = \left(\frac{\sum_{i=1}^{n}\left(o_i - \bar{o}\right)\left(m_i - \bar{m}\right)}{\sum_{i=1}^{i=n}\left(o_i - \bar{o}\right)^2 \sum_{i=1}^{i=n}\left(m_i - \bar{m}\right)^2} \right)^2 \tag{4}$$

2) The root mean square error (RMSE) is a common method used to evaluate the accuracy of modeled values compared to measured data by quantifying the magnitude of differences between the two series. The RMSE can range from 0 to infinity: a lower RMSE value indicates a smaller average difference between the datasets and vice versa.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(o_i - m_i\right)^2}{n}} \tag{5}$$

3) The mean bias error (MBE) calculates the average difference or bias between the modeled values and measured data. It provides a measure of the systematic deviation between the two datasets.

$$MBE = \frac{\sum_{i=1}^{n}\left(m_i - o_i\right)}{n} \tag{6}$$

4) The index of agreement (d), developed by Willmott (1981) [21], is a standardized measure to quantify the goodness-of-fit and assess the agreement between modeled and measured datasets. This index ranges between 0 and 1, where values close to 1 indicate a high level of agreement between the datasets and values close to 0 suggest significant differences.

$$d = 1 - \frac{\sum_{i=1}^{n}\left(m_i - o_i\right)^2}{\sum_{i=1}^{n}\left(\left|m_i - \bar{o}\right| + \left|o_i + \bar{o}\right|\right)^2} \tag{7}$$

5. RESULTS AND DISCUSSION

5.1 Energy Closure Balance of the Measured DPT Data

The energy closure balance of the DPT data is plotted in Figs. 2–4. As shown, there are discrepancies in the energy balance: the observed slopes (black lines) ranged from 0.61 to 0.67, whereas the ideal slope value should be equal to 1 (red lines). The linear regression equation for the 2015 data had a corresponding R^2 value of 0.82, while the data from 2014 and 2016 had R^2 values of 0.79 and 0.83, respectively. Typically, flux measurements obtained using the eddy covariance method often result in flux values lower than the true values, as confirmed by many reviews and studies [22-24]. Some of this could be from mean advective divergence not directly measured by eddy covariance, related to fetch issues [25,26]. This discrepancy is known as energy imbalance. Thus, this dataset also contains some inaccuracies that eventually will affect the model results.

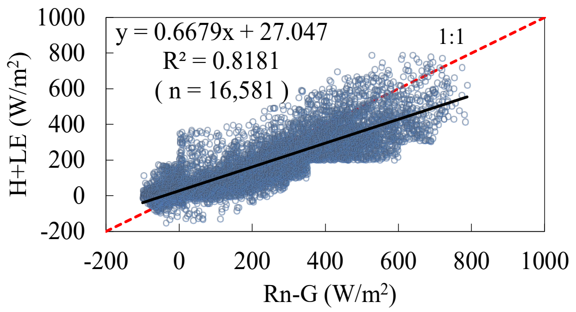

Fig.2 Energy balance closure of measured DPT data from the year 2015 (for calibration)

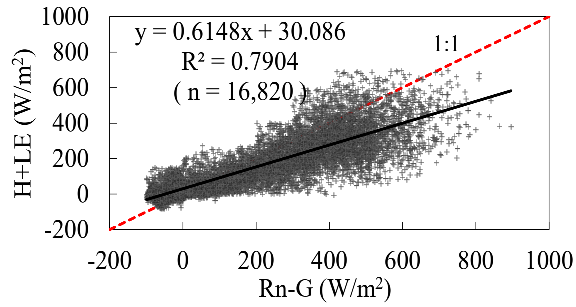

Fig.3 Energy balance closure of measured DPT data from the year 2014 (for validation)

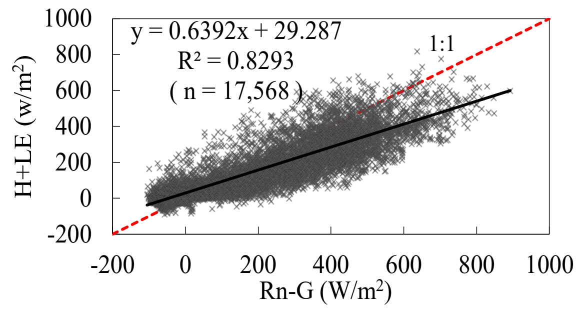

Fig.4 Energy balance closure of measured DPT data from the year 2016 (for validation)

5.2 Model Calibration and Validation Results

Results from the ACASA model calibration, validation, and assessment are presented in Tables 2–4. The ACASA model results (y-axis) plotted against the observed data (x-axis) should correspond to a linear equation (y = mx + c) whose slope (m) is close to 1. However, some deviations are expected due to the energy balance closure issue in the measured data discussed above. In Tables 2–4, n represents the total number of available data points.

Table 2 ACASA model calibration results for 2015

Var	y = mx + c			Model Evaluation			
	m	c	R^2	RMSE	MBE	d	n
R_n	0.98	15.75	1.00	15.43	-13.39	1.00	17,520
SW_{in}	0.98	7.64	0.98	38.02	-3.86	1.00	17,520
SW_{out}	0.87	-0.98	0.98	7.44	4.19	0.99	17,520
LW_{out}	0.99	0.00	1.00	4.50	4.49	0.99	17,520
Ts	0.89	32.18	0.98	0.87	0.57	0.99	17,520
H	1.20	-33.06	0.67	81.70	28.45	0.84	16,581
LE	0.97	57.15	0.59	115.67	-55.13	0.87	16,581
NEE	0.88	-3.25	0.56	7.55	3.08	0.83	17,472

Table 3 ACASA model validation results for 2014

Var	y = mx + c			Model Evaluation			
	m	c	R^2	RMSE	MBE	d	n
R_n	0.97	15.92	1.00	16.51	-12.61	1.00	17,520
SWin	0.97	4.06	0.99	27.04	0.87	1.00	17,520
SW_{out}	0.84	-0.55	0.96	8.84	4.37	0.98	17,520
LW_{out}	0.99	0.00	1.00	4.49	4.48	0.99	17,520
T_s	0.94	18.92	0.98	0.63	0.35	0.99	17,520
H	1.34	-20.51	0.68	73.17	11.98	0.84	16,820
LE	0.96	45.14	0.63	89.95	-42.44	0.84	16,820
NEE	0.88	-3.00	0.62	7.15	2.74	0.86	17,478

Table 4 ACASA model validation results for 2016

Var	y = mx + c			Model Evaluation			
	m	c	R^2	RMSE	MBE	d	n
R_n	0.98	15.72	1.00	15.34	-12.97	1.00	17,568
SW_{in}	0.97	7.49	0.98	36.27	-2.69	1.00	17,568
SW_{out}	0.87	-1.06	0.98	7.04	4.08	0.99	17,568
LW_{out}	0.99	0.00	1.00	4.52	4.51	0.99	17,568
T_s	0.93	20.20	0.99	0.75	0.47	0.99	17,568
H	1.12	-29.98	0.59	78.81	26.42	0.82	17,568
LE	0.97	60.04	0.57	93.83	-58.19	0.77	17,568
NEE	0.79	-3.24	0.53	7.81	3.00	0.82	17,502

The validation results for 2014 and 2016 confirm the model's capability of calculating R_n, SW_{in}, SW_{out}, LW_{out}, and T_s very accurately. In terms of calculating of H, LE, and NEE, the model performed relatively well (Tables 3–4) given that the measured H and LE values had some energy balance closure issues. For example, the flux footprint of the single point tower site may have some mismatches to the larger area or ecosystem. Eddy covariance measurements also require careful processing to account for instrumental noise and time lag, in addition to corrections for various sources of errors.

Diurnal plots comparing the half-hour observations with model output show Rn is well modeled by ACASA, while there is some underestimation of reflected shortwave radiation originating in the calibration run, that propagates to the validation runs (Fig. 5). Future research may involve increasing the leaf reflectivities during calibration to better match the outgoing shortwave radiation. Outgoing longwave radiation was consistently offset lower by ACASA, in the calibration runs propagating into the validation results (Fig. 5). Although this might imply that the model leaf temperatures may be underestimated.

Fig. 6 shows ACASA and observed surface temperatures match well thoughout the day and night. This implies the longwave radiation emissivity may need modification in the calibration phase to improve the consistency of accurate surface temperature simulation coupled with accurate outgoing longwave radiation simulation. The diurnal variation of H and LE show some discrepancies between model resutls and observations, conssitent with the results from Table 2–4. The simulated sensible heat flux (H) magnitude is higher than observed sensible heat in the calibration phase as well as the validation runs, more positive in the day and more negative at night. This implies that the sensible heat observations may underestimate actual H from advective and fetch challenges; these connected factors are discussed in Park and Paw U (2004) [25] and Kochendorfer and Paw U (2011) [26]. Similarly, the simulated latent energy flux (LE) is higher than observations, in a similar fashion to sensible heat H and potentially for the same reasons (Fig. 6). The possibility that observed H and LE are underreported is consistent with the lack of observed energy budget closure. Simulated NEE, which is the balance between ecosystem respiration (Re) and gross primary productivity (GPP), is also of higher magnitude than observations, also consistent with possible underreporting of the eddy covariance measurements of NEE associated with advection and fetch.

6. CONCLUSION

This study applied the ACASA model to simulate and investigate the fluxes and micrometeorology of a dry dipterocarp forest in Phayao province, Thailand. The data measured at 30-minute intervals during the year 2015 were used to calibrate the model, while data from the years 2014 and 2016 were used for validation. ACASA model can accurately calculate energy fluxes such as R_n, SW_{in}, SW_{out}, LW_{out}, and surface temperature T_s, with observed R^2 values exceeding 0.9. The RMSE of these variables displayed a narrow range. However, the model simulated sensible heat flux (H) and latent heat flux (LE) overestimated the magnitude of the oservations and with more scatter than for the radiative fluxes, as

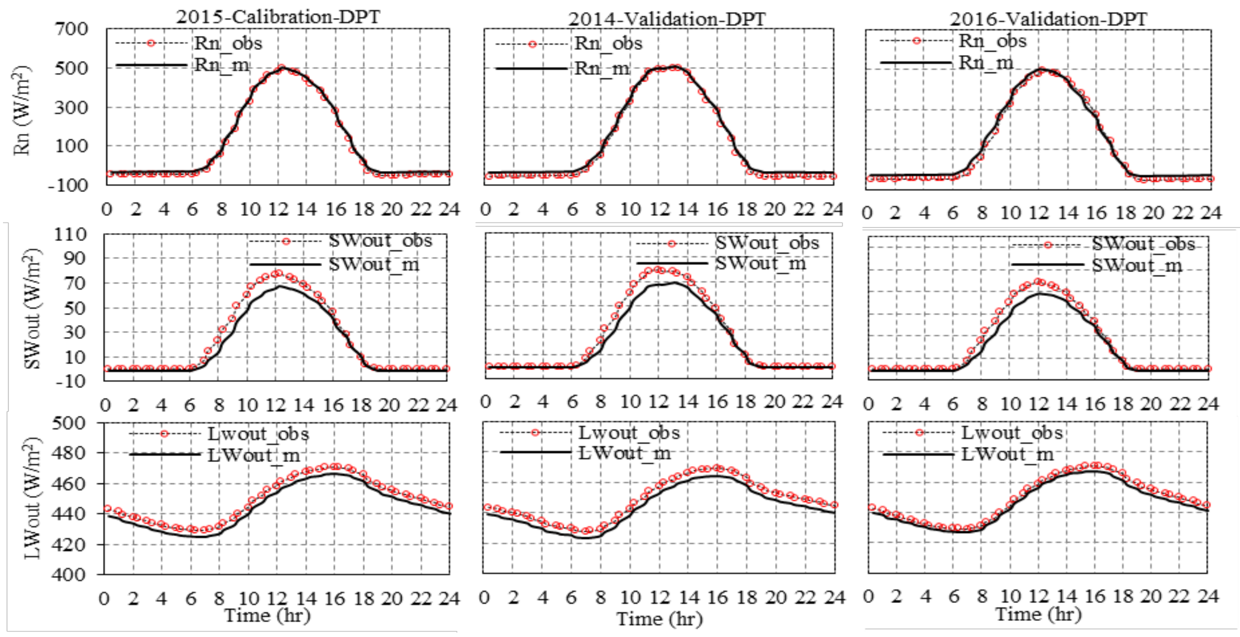

Fig. 5 Half–hourly average plots of R_n, SW_{out} and LW_{out}

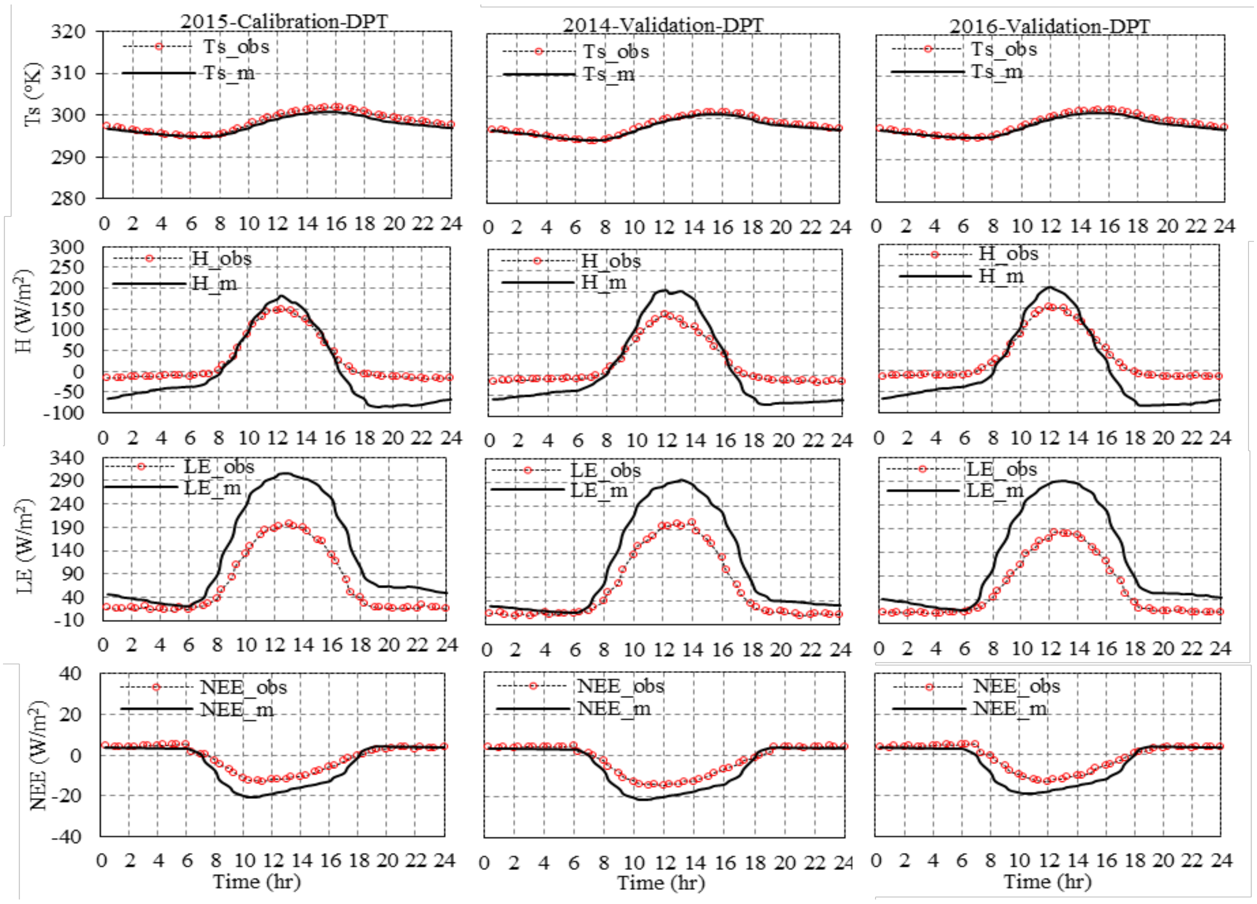

Fig. 6 Half–hourly averaged plots of Ts, H, LE and NEE

evidenced by R^2 values ranging from 0.57 to 0.68 and larger RMSE errors. This issue may relate to the quality of measured eddy covariance data, which exhibited a lack of energy balance closure and may contain some noise and other errors including advective and fetch effects, and underestimation of fluxes during low turbulence conditions. Overall, our study demonstrates that the ACASA model can effectively capture the complex processes of soil–vegetation–atmosphere transfer schemes in a dry dipterocarp forest in Thailand's Phayao province.

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