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水を通して見た世界

雨水資源化システム学会 理事 多 炭 雅 博

水資源をテーマに海外の仕事をしていると、その土地ごとに独特のルールや慣習があって面白い。アメリカ西部では水利権は農家個人に属していた。この場合、広域水資源管理は水利権の売買を通して行われる。お金のある人が（あるいは水利組織や行政が）水利権を購入することで水資源の再配分が行われる。一方、スペイン南部のアンダルシア地域では、水利権は農家個人に属するものではなく、毎年地域の水利組織が集まって、話し合いによって水の配分を決定していた。最近研究で関わったタジキスタンやアフガニスタンでは、はっきりした水利権の概念自体が無いようだった。灌漑地区の水利団体や灌漑技術者は、「河に流れている水はいくら使ってもよい」「水を下流や他国に流すのはもったいないので、自分達でもっとたくさん使いたい」と言う。彼らにとって問題は、水を貯めたり、農地まで運ぶためのインフラ整備の資金欠乏にある。現在取り組んでいるイランの塩湖の水環境保全調査では、水利権は書類上・名目上のものになっているようだ。多くの農家は名目上の水利権に関わらず自由に水を使って農地拡張を行っており、水利用の持続性に問題が出ている。



これら仕事として関わる水だけではなく、観光を通してふれる世界各地の水利用も興味深い。スペイン南部、年間降水量300 mmの半乾燥地に位置するグラナダの世界遺産、アルハンブラ宮殿は、敷地内に水路が張り巡らされ、貴重な水をふんだんに使って池や噴水を贅沢に配置している。水を富と権力の象徴として捉えていた当時の様子がかうかがえて面白い。メキシコの首都、メキシコシティ近辺にある世界遺産のソチミルコでは、チナンバ農業（＝湖の上に浮島を作ることで、湖の水や養分が常に毛管上昇で自動供給される自動灌漑畑になる）の名残を見ることができる。アステカ王国時代の巨大都市の人口を支えるために工夫された、ユニークな灌漑農業だ。昔から都市の発展には灌漑技術が不可欠だったことがよくわかる。スリランカの国会議事堂は、日本の援助で人工的に作られた大きなため池の真ん中に建てられている。国の意思決定を行う場である国会議事堂を池の中心に据えることで、「水を治めるものが国を治める」という精神を具現化しているようだ。スリランカは長らく内戦が続いた時期があったので、国会議事堂が大きな池の中にあるのは、実際には議事堂の警備や国会議員の警護などの治安確保の役割も考えてのことだろう。

このように、過去から現在まで、人々のいろんな想いをのせて利用されてきた水は、今後どうなっていくのだろうか。世界的に水需要が増え続けており、化石地下水の枯渇等に代表される地域水資源のインバランスの問題はなかなか解決が難しい。また海外で灌漑水資源計画や評価の仕事に携わる上で、最近はずっかり「気候変動」が調査研究業務の一部に組み込まれた感がある。10年前は気候変動による水資源の時間空間的分布の不安定化は、気候変動の専門家が取り組むべきテーマだと認識していた。しかしこの10年間で、私のような普通の灌漑研究者が、気候変動が地域水資源に及ぼす影響評価までを含めて、灌漑水資源の計画なり評価なりを行うことを期待されるようになった。ドローンを利用したりリモートセンシングによる観測・測量技術の現場への進展も近年すさまじい。水を取り巻く自然環境や社会情勢が変化し、データの取得や処理環境も急速に変化する中、将来にわたり健全な水環境を確保するため、本学会が担う役割もますます重要になるものと考え。

宮崎大学農学部森林緑地環境科学科 教授

Editor

Professor Noriyuki Kobayashi

CONTENTS

An optimal allocation model to release fish into a river system <i>Yuta Yaegashi, Hidekazu Yoshioka, Koichi Unami and Masayuki Fujihara</i>	1
Evaluation of GCOM-C ETindex Estimation Algorithm at a Lodgepole Pine Tree Open Forest in Idaho, USA <i>Asep Denih, Akira Maeda, Masahiro Tasumi, Yoshinori Shinohara and Shinichi Takeshita</i>	9
Freshwater Lens Conservation during Drought -Case Study of the Majuro Atoll in the Republic of Marshall Islands- <i>Kazuhiisa Koda</i>	15
The Influence of Bottom Sediment Redox State on Water Quality Dynamics under Long-term Anoxic Conditions in an Organically Polluted Reservoir <i>Tran Tuan Thach, Masayoshi Harada, Kazuaki Hiramatsu and Toshinori Tabata</i>	23
Numerical Computation of Robust Optimal Harvesting Policy in a Fish Pond under Uncertainty <i>Elizaphan Otieno Ndede, Koichi Unami and Masayuki Fujihara</i>	33
■ News & Announcements	
第 26 回日本雨水資源化システム学会大会/開催案内	37
学会誌論文投稿規定及び執筆要領	40
雨水資源化システム学会賞候補の推薦	41
雨水資源化システム学会会員募集	42
Instructions to Authors(I)	44
執筆要領(II)	46
Errata/既掲載論文の一部訂正	48

Evaluation of GCOM-C ET_{index} Estimation Algorithm at a Lodgepole Pine Tree Open Forest in Idaho, USA

Asep Denih¹, Akira Maeda², Masahiro Tasumi³, Yoshinori Shinohara⁴ and Shinichi Takeshita⁴

Abstract: This study attempted to evaluate the performance of the GCOM-C ET_{index} estimation algorithm at a lodgepole pine tree open forest in eastern Idaho, United States using a dataset provided by the Idaho EPSCoR program. As a limitation of the study, the energy balance closure problem in flux measurement, which is a typical problem in flux measurements by eddy covariance systems, prevented a robust, quantitative evaluation of the ET estimation accuracy. Under this limitation, the results indicated that the estimation algorithm overestimated ET in the conditions of the study area, especially during summer time. One possible reason for the overestimation was that the algorithm overestimated surface wetness over most of the year, except in winter. The results of this evaluation provide valuable information for future improvement of the estimation algorithm. Further investigation of the weather and flux conditions, including the use of additional data such as scintillometer-measured flux data, might reduce uncertainty in the measured flux data.

Keywords: *Evapotranspiration; GCOM-C; ET_{index} ; Eddy covariance; Forest energy balance*

1 Introduction

Evapotranspiration (ET) is one of the most important parameters in environmental water management. In recent decades, several attempts have been made to estimate ET with its spatial and temporal distribution using satellite remote sensing. The Global Change Observation Mission-Climate (GCOM-C) ET_{index} estimation algorithm, developed by Tasumi *et al.* (2016a), is a satellite-based ET estimation model that estimates ET using an automated procedure. The algorithm is applicable to any satellite image having thermal observation, although it was originally developed for application with Japan's GCOM-C satellite launched in December 2017. The observation data by GCOM-C is expected to be in public from 2019. Because it is a newly developed algorithm, limited information about its estimation accuracy has been available (e.g. Tasumi *et al.*, 2016b), and further assessments to evaluate the algorithm performance are needed.

Comparing the ET estimation results with latent heat flux measurements using eddy covariance systems has been the most popular method of evaluating satellite-based ET estimation algorithms (e.g. Mu *et al.*, 2007). Some of the flux measurement data, measured globally by several researchers, have become available to the public, for example, through flux networks such as AmeriFlux and AsiaFlux. While the rich data availability is a strong advantage of eddy covariance measurements, several cautions must be stated regarding the use of flux data for the purpose of evaluating satellite-based ET estimations. The energy balance closure problem

is a well-known problem that implies that flux measurements by eddy covariance systems have some uncertainty or fail to capture a portion of the energy flux. Theoretically, net radiation (R_n) expressed by radiation balance (Eq. 1) and by heat balance (Eq. 2) should be equal if advection is ignored.

$$R_n = (1 - \alpha)R_s + (1 - \varepsilon)R_{lin} - R_{lout} \quad (1)$$

where R_n is net radiation, α is surface albedo, R_s is solar radiation, ε is thermal emissivity of the surface, and R_{lin} and R_{lout} are incoming and outgoing longwave radiations, respectively.

$$R_n = H + LE - G \quad (2)$$

where H is sensible heat flux, LE is latent heat flux, and G is soil heat flux.

However, energy flux measured by eddy covariance systems (i.e. integration of H and LE , which is also called "available energy") tends to be less than what is expected by radiation and soil heat measurements. Wilson *et al.* (2002) found that the average imbalance of available energy was approximately 20% by investigating 22 eddy covariance measurements taken in the United States and in Europe. The magnitude of the imbalance changes according to the measurement site. Significant levels of imbalance (e.g. 40% or more) occurs in some sites, while no imbalance is confirmed in some other sites.

In this research, performance of the GCOM-C ET_{index} estimation algorithm is examined using a flux dataset measured at a lodgepole pine tree open forest in Idaho, United States after the energy balance closure problem of the measurement flux data is examined. This research is the first attempt to evaluate the accuracy of the algorithm in a forest area. Thus, the results of this study will provide new and val-

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uable information regarding the performance of the algorithm in a forest area.

2 GCOM-C ET_{index} algorithm

The GCOM-C ET_{index} algorithm (Tasumi *et al.*, 2016a) estimates the ET_{index} , which is a relative index of actual evapotranspiration, by the following equation.

$$ET_{index} = C_{adj} \frac{T_s(\text{dry}) - T_s(\text{act})}{T_s(\text{dry}) - T_s(\text{wet})} \quad (3)$$

where $T_s(\text{act})$ is the instantaneous actual surface temperature from satellite thermal observation ($^{\circ}\text{C}$) at the satellite overpass time, and $T_s(\text{wet})$ and $T_s(\text{dry})$ are the hypothetical wet and dry surface temperatures ($^{\circ}\text{C}$), which are the computed instantaneous surface temperatures at the satellite overpass moment if the surface is expected to have zero sensible heat flux and zero latent heat flux, respectively. The value of $T_s(\text{act})$ can be as small as $T_s(\text{wet})$, and as large as $T_s(\text{dry})$.

In Eq. 3, the constant C_{adj} is an empirical adjustment factor employed in the algorithm determined to be 1.23. $T_s(\text{wet})$ and $T_s(\text{dry})$ are estimated by empirical equations in the algorithm, assuming that the surface temperatures of these extreme conditions are largely affected by solar radiation, with some impact by wind. The calculation equation for $T_s(\text{wet})$ is as follows:

$$T_s(\text{wet}) = C_1 R_s + C_2 - \sin\left(2\pi \frac{DoY + C_3}{365}\right) \times f_{lat} \quad (4)$$

where DoY is day of year, f_{lat} is a function of latitude calculated in Eq. 5, and C_1 to C_3 are calibration constants determined as 0.06, -30.34, and 37, respectively, for the northern hemisphere.

$$f_{lat} = -0.0021 \times Lat^2 + 0.3449 \times |Lat| - 2.9864 \quad (5)$$

where Lat is latitude in degrees (north is positive) and the value of f_{lat} should be limited to $0 \leq f_{lat} \leq 10$.

$T_s(\text{dry})$ is calculated by the following equation:

$$T_s(\text{dry}) = T_s(\text{wet}) - (0.0023u - 0.0301)R_s \quad (6)$$

where u is wind speed measured at a height of 2 m above the surface (m s^{-1}).

Note that the series of equations is applicable only for clear-sky conditions, when actual surface temperature is measured by the satellite with no disturbance from cloud. ET_{index} for cloudy or no satellite-overpass days must be estimated by a different method, such as by interpolation using the nearest available image information. For an automated application with the GCOM-C and MODIS satellite observations, Tasumi *et al.* (2016b) suggest to pick the minimum ET_{index} value for 16 consecutive days and use the value as the representative ET_{index} for the 16-day period, assuming that there is at least one cloud-free day in 16 days, and that cloud

contamination increases ET_{index} value.

ET_{index} is defined as the ratio between actual evapotranspiration (ET_{act}) and reference evapotranspiration (ET_o). Thus, ET_{act} is computed by the following equation:

$$ET_{act} = ET_{index} \times ET_o \quad (7)$$

where ET_o is daily reference evapotranspiration defined by the Food and Agricultural Organization of the United Nations (Allen *et al.*, 1998), and is calculated by daily solar radiation, air temperature, vapor pressure, and wind speed.

3 Materials and methods

3.1 Study area and the flux measurement data

This research uses flux data collected by a research group in Idaho, United States and distributed online via the EPSCoR (Established Program to Stimulate Competitive Research) project of the National Science Foundation. A detailed description of the site and the data can be found in Allen (2011). The key information for the study area and the data are summarized below:

The study area is Island Park, which is located near the eastern border of Idaho State (Figure 1). The coordinates of the flux measurement location are approximately 44.5°N , 111.4°W , and the elevation is approximately 1950 m. The flux measurements were primarily taken at the top of two observation towers installed in a relatively flat and uniform 50-year-old lodgepole pine forest with a mean maximum tree height of approximately 14-15 m (Figure 2). Understory vegetation was a mixture of grasses and herbs with relatively good density. The heights of the north tower and south tower were 24 m and 22 m, respectively, and the two towers were approximately 1.7 km apart.

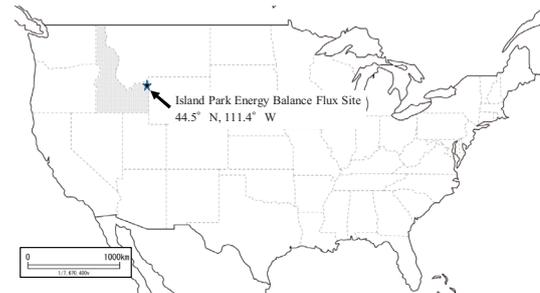


Figure 1: Location of study site.



Figure 2: Photo of the study site.

While the EPSCoR project takes multiple sets of measurements at the two tower locations and some other neighboring locations, the specific datasets summarized in Table 1 were used in this study. Eddy covariance measurements (i.e., sensible and latent heat fluxes) were taken at a 20-Hz interval and reported as a 30-min average. Other parameters were also reported as a 30-min average (or integration). In this study, the data analysis period was selected to be from March 2011 to September 2012, because this was the only period when significant missing data did not occur.

Table 1: Parameters, sensors, and the locations of the measurements taken in this study

Parameters	Sensors	Location	Height or depth
Temperature, Humidity	Vaisalla RH/T	South Tower	4 m above ground
Precipitation	Tipping bucket raingauge with antifreeze	South Tower	22.5 m above ground
4-way radiation	Kipp & Zonen CNR1	South Tower	20 m above ground
Wind speed, Sensible and Latent Heat 1	Campbell CSAT3 with LiCor 7500 Hygrometer	South Tower	20 m above ground
Sensible and Latent Heat 2	RMYoung 3D-sonic anemometer with LiCor 7500 Hygrometer	North Tower	25 m above ground
Soil heat flux (6 locations)	Rebs Soil Heat Flux Plate	Near South Tower	6 cm depth
Soil water content (6 locations)	Campbell Scientific CS616 TDT soil water content sensor	Near South Tower	0-12 cm depth

3.2 Method of data analysis

3.2.1 Quality control of the measurement data

General weather and radiation data did not show any obvious problems. However, in sensible and latent heat flux measurements, the original 30-min average data suffered some missing data and a high level of noise. Missing and noisy data were filled in by linear interpolation using adjacent values, where the flux data less than -400 W m^{-2} or more than 500 W m^{-2} in the 30-min averages were considered noisy. There were two sets of sensible and latent heat flux data. One was measured on the south tower, and the other was measured on the north tower. The dataset from the south tower was much more reliable in terms of data availability. Thus, we essentially used sensible and latent heat flux data from the south tower. The north tower data were used as supplementary data when the data from south tower were not available or contained noise.

Next, a daily dataset was prepared using the 30-min average dataset. In the daily dataset, the minimum and the maximum of both sensible and latent heat flux were limited to be equal to zero and the net radiation, respectively. Furthermore, the monthly average value was used for dates that had more than 3-hr missing data.

3.2.2 Energy balance closure assessment

The primary purpose of this study is to compare our ET estimation with the measured latent heat flux to investigate the performance of the GCOM-C ET_{index} estimation algorithm at this forest site. Therefore, understanding the quality (or uncertainty) in the measurement data before the comparison is

important. From Eq. 2, " $H + LE$ " must be theoretically balanced to " $R_n - G$ ". However, " $H + LE$ " measured by the eddy covariance system is typically smaller than measured " $R_n - G$ ", where R_n is measured by radiation measurements and G is measured by soil heat flux plates (e.g. Wilson *et al.*, 2002). This energy imbalance is an indication of failure in capturing a portion of the energy flux by the eddy-covariance system, and the problem is called "energy balance closure problem." The cause of the problem is debatable, and the methods of corrections vary widely by research, including no-correction (Matsumoto, 2016). In this study, the intensity of energy balance closure problem of the EOSCoR dataset was evaluated by comparing " $H + LE$ " measured by eddy covariance and " $R_n - G$ " measured by radiation and soil flux measurements. All data used for this energy-closure assessment, except soil heat flux, (i.e. 4-way radiation, sensible and latent heat flux) have been measured above the canopy (Table 1).

3.2.3 ET estimation and the accuracy assessment

ET is estimated using the GCOM-C ET_{index} estimation algorithm by solving Eq. 3 to 7. Although the algorithm was developed to apply to satellite measurements of surface temperature, this study uses ground-measured surface temperature as a substitution of the satellite measurements, in order to evaluate the performance of the algorithm itself. Therefore, $T_s(\text{act})$ in Eq. 3 is actual surface temperature computed by measured longwave radiation from the surface. Upon surface temperature computation, surface emissivity was assumed to be 0.98, which was the average emissivity value of the Pinon-Juniper group reported by Arp and Phinney (1979). To make the application condition similar to the satellite-based application, the computations were performed only for the data collected under the 10:30 am in the local solar time, and clear-sky condition, and the minimum ET_{index} value for 16 consecutive days was used as the representative ET_{index} for the 16-day period, as suggested by Tasumi *et al.* (2016b). Here, 10:30 am is a typical image acquisition time by earth-observation satellites, such as Landsat, MODIS, and GCOM-C. In the calculation, clear-sky conditions were determined to be when the ratio between measured actual and computed clear-sky solar radiation was more than 0.95. Estimated daily ET is computed by multiplying daily ET_o and the corresponding 16-day representative ET_{index} , as described in Eq. 7. In future operational applications using not ground-measured but satellite-derived surface temperature, estimation accuracy of satellite-derived surface temperature products will also be involved.

There was a minor inconsistency in applying the GCOM-C ET_{index} algorithm to tall forest areas. The algorithm was designed to be used with near-surface weather parameters (e.g. wind speed as measured at 2 m above the surface of the earth), assuming that the primary application targets are bare-soil surface and surfaces with short vegetation. Detailed methods of weather data application to tall forests has not been well determined and examined. In this research, we used measured weather parameters without correction for measurement heights by accepting uncertainty in application. The estimated ET was then compared with the measured ET to evaluate the performance of the estimation algorithm.

4 Results and discussion

4.1 Description of general weather and soil water conditions in the study area

Understanding general weather conditions in the study area is important to better understand the results of flux analysis. Figure 3 shows the general weather and soil water conditions in the study area during the period of analysis from March 2011 to September 2012. The study area has a calm summer and a cold winter (Figure 3-A), and the annual average temperature from March 2011 to February 2012 was 1.9°C. Annual precipitation (from March 2011 to February 2012) was 1250 mm. The dry season is from mid-July to September (Figure 3-B). Soil moisture corresponded well to the precipitation, except in winter (when soil is freezing) and in the periods after soil water reached field capacity (about 26%).

Figure 4 shows the comparison between air temperature and surface temperature, where the surface temperature was measured as a part of four-way radiometer measurement assuming the surface emissivity as 0.98. Both temperatures were very close each other, and a strong linear relationship was confirmed between the two temperatures.

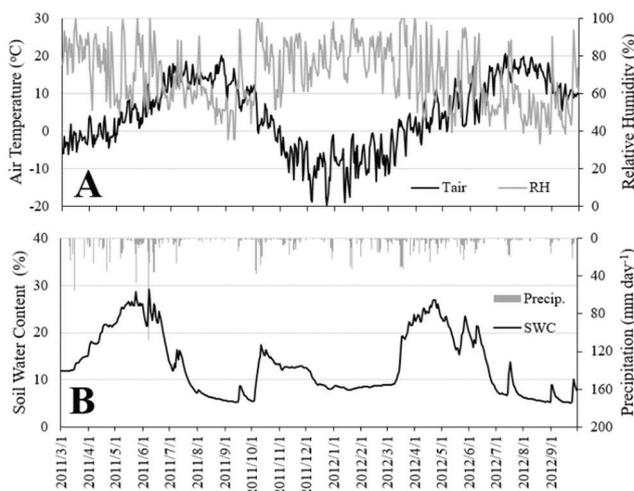


Figure 3: General weather and soil moisture conditions of the study site – A: air temperature and humidity, B: precipitation and soil water content.

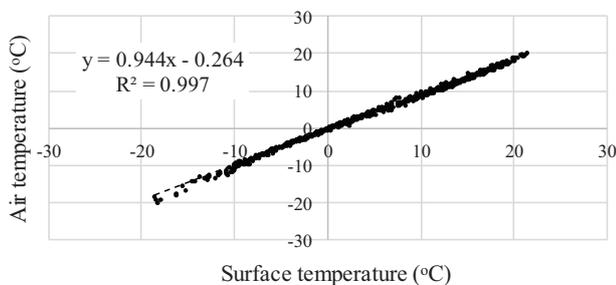


Figure 4: Comparison between daily surface and air temperatures during the period of analysis.

4.2 Results of energy balance measurements and the energy balance closure assessment

Figure 5 shows surface radiation and heat balance data for the period of the analysis. In Figure 5-A, the peak of R_{out} appears one or two months later than the peak of R_s , probably reflecting the time-lag caused by the thermal inertia of the earth. R_{out} deviates from R_{in} during the dry season (mid-July to September), which might be due to the hotter surface (relatively high R_{out}) and less cloud (relatively low R_{in}) during the dry season. G was much smaller than H and LE in the forest (Figure 5-B) due to the shadows and the understory vegetation cover of the land. The annual average for G (from March 2011 to February 2012) was $0.07 \text{ W m}^{-2} \text{ day}^{-1}$, which is close to zero. The near-zero value of annual averaged G adds some confidence to the G measurement, because G is expected to be nearly zero in annual balance (e.g. Allen *et al.*, 1998). The Bowen ratio, which is a ratio of sensible heat and latent heat defined as H/LE , is shown in Figure 5-C. The Bowen ratio becomes unstable and not useful during winter or under very dry conditions, when the denominator becomes very small. During summer time, the Bowen ratio increases in the dry season, from mid-July to September, for both 2011 and 2012. This trend successfully represented the drying condition of the soil in the forest, as seen in Figure 3-B.

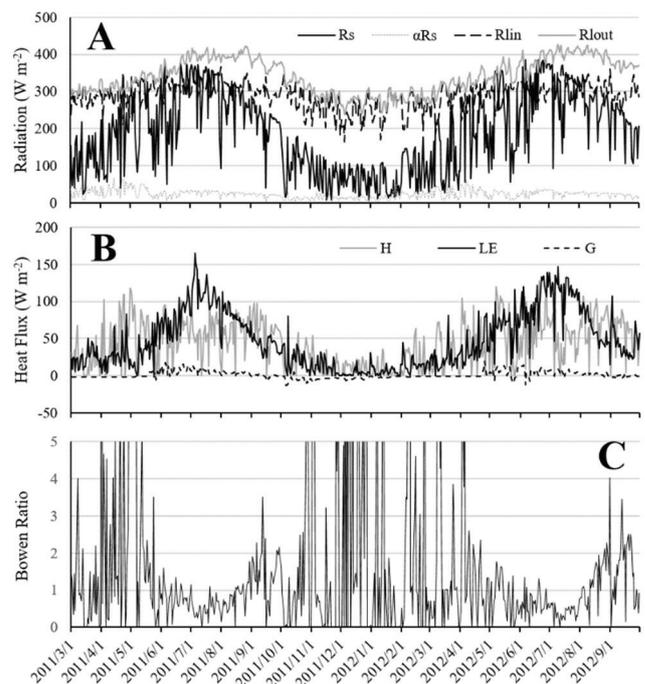


Figure 5: Surface energy measurements – A: radiation balance components, B: heat balance components; C: Bowen ratio.

Available energy calculated by radiation and soil heat measurements ($R_n - G$) and by eddy covariance flux measurements ($H + LE$) were compared on a daily basis to assess the energy balance closure (Figure 6-A). As a limitation of the measurements, latent heat of fusion, which is typically expected in snow covered conditions, is lacking in the observation data. To avoid the potential impact of snow, and to

more strictly evaluate the energy balance closure, the assessment was also made with the data from June to September only (Figure 6-B).

As a result, in both cases, the slope of the linear regression lines was 0.81–0.83 and the intercept was very small, indicating that only about 81–83% of the available energy was captured by the eddy covariance system, and nearly 20% of the energy was missing, which agreed with the average value of missing energy reported by Wilson *et al.* (2002).

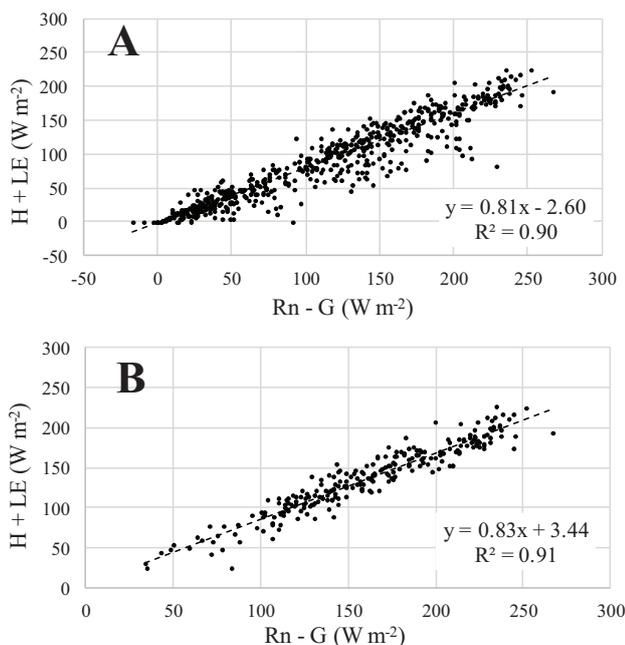


Figure 6: Comparison of available energy measured by radiometer and soil heat flux plates ($R_n - G$) and by eddy covariance system ($H + LE$), A: all periods, including winter, B: June to September only.

4.3 Results of ET estimation and the accuracy assessment

Figure 7 shows comparison of estimated monthly ET with two sets of measured ET; one is measured ET without any correction for energy balance closure (meas1), and the other accounts for all missing energy as latent heat (meas2). ET(meas2) is thus expressed as; $ET(\text{meas2}) = (R_n - G - H)/L$, where “ $R_n - G$ ” is available energy measured by radiometer and soil heat flux plates, H is measured by eddy covariance system without any correction for energy balance closure, and L is latent heat of vaporization.

Actual ET is expected to be somewhere between “meas1” (no correction for energy balance closure) and “meas2” (maximum correction to make the energy balanced). Estimated ET was close to the “meas2” during October to May. However, estimated values were significantly overestimated for the months of June, July, and August (and in September, 2012). The results shown in Figure 7 are also summarized as Table 2. In the table, values for January and February are for 2012, values for March to September are an average of both years, and values for October to December are for 2011. If the maximum correction of measurement value (meas2) is assumed as actual ET, annual estimation error is 30%, and

most of the error occurs during June to September. During October to May, the cumulative difference between “meas2” and the estimated value is 18 mm and is equivalent to 5% of the measured ET. In the case that the non-corrected values (meas1) are assumed as actual ET, annual estimation error is 96%, which is very large. Under this assumption, the significant overestimations occurred in most months except some winter months.

Making a quantitative conclusion of the estimation accuracy was difficult due to the energy balance closure problem in the actual ET measurement. However, the results of this comparison at least indicated that (1) the GCOM-C ET_{index} algorithm overestimated ET in the evaluated forest site, and (2) overestimation primarily occurred not in winter but in summer.

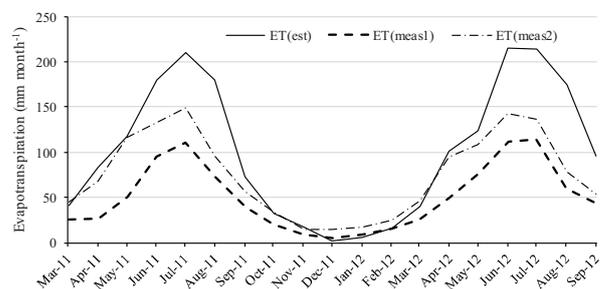


Figure 7: Estimated actual ET compared with measured ET without any correction (ET(meas1)), and by accounting for all missing energy as latent heat (ET(meas2)).

Table 2: Monthly ET (mm) and the difference between estimation and measurements

Month	ET(est)	Measured ET		Difference	
		meas1	meas2	meas1	meas2
Jan	6	9	17	-3	-12
Feb	15	15	25	0	-9
Mar	41	26	46	15	-5
Apr	92	38	82	54	10
May	121	64	113	57	8
Jun	198	103	138	94	60
Jul	212	113	142	99	69
Aug	177	66	87	111	90
Sep	84	41	55	43	29
Oct	33	20	33	13	0
Nov	17	9	15	8	2
Dec	2	6	15	-3	-13
Annual	997	509	768	488	230

The overestimation of ET indicates that the ET_{index} estimation equation (Eq. 3) did not function in this site, especially in summer. To investigate the problem, computed $T_s(\text{wet})$ and $T_s(\text{dry})$ were plotted with measured actual surface temperatures ($T_s(\text{act})$) for measurements taken at around 10:30 am on clear-sky days (Figure 8). The figure showed that $T_s(\text{act})$ was similar or even lower than $T_s(\text{wet})$ for most peri-

ods, except winter. $T_s(\text{wet})$ is a hypothetical wet surface temperature, and the estimation algorithm assumed that the forest was under very wet conditions during most of the study period, except winter. Thus, the algorithm estimated ET to be near the maximum potential level for most of the year. However, in actual conditions, ET was much smaller than the maximum potential level, which appears as the good amount of H in Figure 5-B (e.g. easily find 50 to 100 W m^{-2} of H in most of the period except winter).

In addition to the uncertainty of measured ET caused by the energy closure problem, there is a question regarding the measured energy flux. Aerodynamically, H should be zero when the difference between surface and air temperatures is zero. In the study site, air temperature was always similar to surface temperature (Figure 4), implying that the H was small in the study area. However, observed H was not small (Figure 5-B), which is inconsistent. This phenomenon might be explained by the large roughness of the forest or strong winds, or by the impact of shadows to the surface temperature. Further investigation of the weather and flux conditions of the study site using independent sensible heat flux data, such as scintillometer-measurement data, might help reduce the uncertainty in measured flux data.

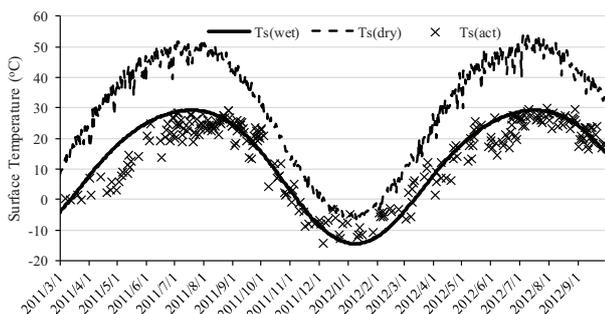


Figure 8: Computed $T_s(\text{wet})$, $T_s(\text{dry})$, and observed $T_s(\text{act})$ for data collected at around 10:30 am on clear-sky days.

5 Conclusion

This study attempted to evaluate the performance of the GCOM-C ET_{index} estimation algorithm at a lodgepole pine tree open forest in eastern Idaho, United States using a dataset provided by the Idaho EPSCoR program. The dataset includes radiation and flux measurements in addition to general weather data, where flux was measured by the eddy covariance system. The flux measurement data were examined for quality before the ET estimation by GCOM-C ET_{index} estimation algorithm was evaluated for accuracy. The evaluation of energy balance closure indicated that the flux measurement had nearly 20% uncertainty or failure in capturing available energy. The energy balance closure problem prevented a robust, quantitative evaluation of the ET estimation accuracy, which is a limitation of this study.

Estimated ET was compared with two sets of measured ET data; one is measured ET with no correction for the en-

ergy balance closure, and the other is measured ET corrected for the energy balance closure by accounting for all missing energy as latent heat. Both cases suggested that the ET_{index} estimation algorithm overestimated ET in the study area, especially during summer time. In the study area, measured surface temperature was close to the computed wet surface temperature for most of the study period except winter, which resulted in high ET estimation. This information is valuable when considering future refinement of the algorithm. Further investigation of the weather and flux conditions, including the use of additional data such as scintillometer-measured flux data, might help reduce the uncertainty in measured flux data.

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