Application of the GCOM-C global $ET_{\text{index}}$ estimation algorithm in 40 forests located throughout Japan, North America, Australia, and the tropical region

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Abstract

Evapotranspiration estimates in forested areas are important not only for water resource management on a regional scale but also to better understand the water cycle on a global scale. The objective of this study was to evaluate the Global Change Observation Mission-Climate (GCOM-C) global Evapotranspiration-index ($ET_{\text{index}}$) estimation algorithm (GCOM-C $ET_{\text{index}}$ algorithm) applied to forested areas. $ET_{\text{index}}$, which is the ratio of the actual evapotranspiration to the reference evapotranspiration, is estimated from the actual surface temperature and hypothetical wet and dry surface temperatures, i.e., $T_s$ (wet) and $T_s$ (dry), respectively. Based on the algorithm, evapotranspiration is calculated from thermal satellite images and near-surface weather data. We compared the observed ground-based annual evapotranspiration with the estimated annual evapotranspiration obtained using the GCOM-C $ET_{\text{index}}$ algorithm and thermal images from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite for 40 forests, with 10 sites in four different areas, including Japan, North America, Australia, and the tropical region. We found that the GCOM-C $ET_{\text{index}}$ algorithm well reproduced annual evapotranspiration for most forests. The root mean square errors (RMSE) for the 40 forests was 239 mm. In Japan, North America, and Australia, the overestimation of summer evapotranspiration was offset by the underestimation of winter evapotranspiration. The accuracy of annual evapotranspiration estimates in forests with low annual mean temperatures ($<15^\circ$C) was less than that in forests with high annual mean temperatures ($\geq 15^\circ$C). Forests with a low annual mean temperature displayed low levels of evapotranspiration in winter. In these forests, the overestimation of summer evapotranspiration was not offset by the underestimation of winter evapotranspiration. The overestimation of $T_s$ (wet) is the primary reason for the overestimation of summer evapotranspiration. Redetermination of the parameters for the $T_s$ (wet) estimates must improve the evapotranspiration estimates in the forested areas, especially the ones with a low annual mean temperature.

Key words: Latent heat; MODIS; Reference evapotranspiration; Sensible heat; Surface temperature

1. Introduction

The maximum available water resources are effectively estimated as precipitation minus evapotranspiration. Forested areas generally receive larger amounts of precipitation than other areas (Sawano et al., 2005) and provide excess water that can be used for the irrigation of agricultural lands and to meet the water needs in urban areas. Thus, it is important to accurately estimate evapotranspiration in forested areas to effectively manage water resources for human activity on a regional scale. In addition, evapotranspiration from terrestrial lands greatly affects the overall water cycle on a global scale (Oki and Kanae, 2006). Understanding the global water cycle is an essential component of many methods used to predict future climate change (Jung et al., 2010). However, the wide-scale estimated evapotranspiration generally involves errors caused due to the uncertainties of the climate data and algorithms.

Several algorithms for estimating evapotranspiration based on satellite images have been developed (Allen et al., 2007; Mu et al., 2007, 2011), and these algorithms are used to estimate evapotranspiration on both the global and regional scales. Recently, Tasumi et al. (2016a) developed an algorithm to estimate the Evapotranspiration-index ($ET_{\text{index}}$), which is applicable to thermal images from the Global Change Observation Mission-Climate (GCOM-C) satellite (hereinafter, this algorithm is referred to as the GCOM-C $ET_{\text{index}}$ algorithm). The GCOM-C satellite provides thermal images with a spatial resolution of 250 m every day or every 2 days at nadir. This resolution is considerably higher than that of similar semidaily observational satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (1000 m spatial resolution at nadir) (Tasumi et al., 2019).

The $ET_{\text{index}}$ is the ratio of actual evapotranspiration to the reference evapotranspiration ($ET_o$) defined by the Food and Agriculture Organization of the United Nations (Allen et al., 1998). The $ET_o$ can be estimated using near-surface weather data such as air temperature, relative humidity, solar radiation, and wind speed. In the proposed GCOM-C $ET_{\text{index}}$ algorithm, the $ET_{\text{index}}$ can be estimated using satellite thermal images and near-surface wind speed data without adjusting parameters at each individual site. Thus, the GCOM-C $ET_{\text{index}}$ algorithm enables us to automatically estimate evapotranspiration via satellite thermal images and the near-surface weather data.

The GCOM-C $ET_{\text{index}}$ algorithm was developed using the data in a semi-arid region (Tasumi et al., 2016a), wherein a
large amount of data related to the heat and radiation balances were available. Although the GCOM-C $ET_{\text{index}}$ algorithm is theoretically applicable to all types of terrestrial lands, the applicability to forests has not been extensively examined. Denih et al. (2018) preliminary evaluated the performance of this algorithm at a lodgepole pine forest in Idaho, USA and found that it overestimated evapotranspiration, especially in summer. Since the heat balance is considerably different among regions (Matsumoto et al., 2008), the performance of the algorithm must also be different among regions.

This study aims to evaluate the GCOM-C $ET_{\text{index}}$ algorithm in forested areas. The estimated annual evapotranspiration based on the GCOM-C $ET_{\text{index}}$ algorithm was compared with the ground-based observed annual evapotranspiration in respective 10 forested sites (i.e., a total of 40 sites) located throughout Japan, North America, Australia, and the tropical region. Thermal images for long-term periods are required for this analysis. The GCOM-C satellite was just launched on December 2017; therefore, no thermal images for long-term periods are accumulated. Herein, we have used the estimated evapotranspiration based on thermal images from the MODIS satellite with similar temporal resolution to the GCOM-C satellite. The results of this study will contribute to the further improvement and optimization of the GCOM-C $ET_{\text{index}}$ algorithm.

2. Materials and methods

2.1 GCOM-C $ET_{\text{index}}$ algorithm

Since more extensive details of the GCOM-C $ET_{\text{index}}$ algorithm were provided by Tasumi et al. (2016a), the algorithm is briefly mentioned here. In the GCOM-C $ET_{\text{index}}$ algorithm, $ET_{\text{index}}$ is estimated as follows:

$$ET_{\text{index}} = \frac{T_i(\text{dry}) - T_i(\text{act})}{T_i(\text{dry}) - T_i(\text{wet})} \quad (0 \leq ET_{\text{index}} \leq 1.23) \quad (1),$$

where $C_{\text{adj}}$ is an empirical adjustment factor ($= 1.23$), $T_i(\text{act})$ is the surface temperature obtained using satellite thermal images ($\degree C$) at the satellite overpass time, and $T_i(\text{wet})$ and $T_i(\text{dry})$ are the hypothetical wet and dry surface temperatures ($\degree C$) at that time, which are surface temperatures assuming a surface with zero sensible or latent heat fluxes, respectively.

$T_i(\text{wet})$ is estimated as follows:

$$T_i(\text{wet}) = C_1 R_s + C_2 \sin \left( \frac{2 \pi \text{DOY} + C_3}{365} \right) \times f_{\text{sat}} \quad (2),$$

where $R_s$ is solar radiation ($W m^{-2}$), DOY is the day of the year, $f_{\text{sat}}$ is a function of latitude, and $C_1 (= 0.06)$, $C_2 (= -30.34)$, and $C_3 (= 37)$ for the North Hemisphere and 220 for the Southern Hemisphere) are calibration constants. Since the surface temperature associated with particular satellite images are available only for cloud-free days, $R_s$ is calculated from $R_s$ under clear sky conditions, which can be estimated from latitude and elevation (Allen et al., 1998). $f_{\text{sat}}$ is calculated as follows:

$$f_{\text{sat}} = -0.0021 \times \text{Lat}^2 + 0.3449 \times |\text{Lat}| - 2.9864 \quad (3),$$

where $\text{Lat}$ is latitude in degrees, and the value of $f_{\text{sat}}$ should be limited to $0 \leq f_{\text{sat}} \leq 10$.

$T_i(\text{dry})$ is empirically calculated as follows:

$$T_i(\text{dry}) = T_i(\text{wet}) - (0.0023 u - 0.0301) R_s \quad (4),$$

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

Tasumi et al. (2016b) provided the global maps of daily evapotranspiration with a spatial resolution of $0.05^\circ$ for 2001–2007. In these maps, the evapotranspiration was calculated as $ET_{\text{index}} \times ET_s$. $ET_{\text{index}}$ was calculated using the MODIS MOD11 land surface temperature and $u$ of the reanalyzed global weather data (Mabuchi, 2011). Meanwhile, $ET_s$ was calculated using the reanalyzed global weather data (Mabuchi, 2011). The data of the surface temperature are not available for every day owing to the cloud contamination. Tasumi et al. (2016b) assumed that cloud contamination increases the $ET_{\text{index}}$ value and there is at least one cloud-free day every 16-days. Consequently, the minimum $ET_{\text{index}}$ for each 16-day period was used. In this study, monthly and annual evapotranspiration maps for 2001–2007, which were calculated from the daily evapotranspiration maps, were used (Tasumi et al., 2016b).

Fig. 1. Locations of the respective 10 sites in Japan (#1–#10), in Australia (#11–#20), in North America (#21–#30), and the tropical region (#31–#40).
2.2 Ground-based evapotranspiration observed data

Komatsu et al. (2012) compiled 829 ground-based observed data of forest annual evapotranspiration to develop a simple model for global estimation of annual evapotranspiration in forested areas. Among these data, the datasets from 10 respective locations in Japan, North America, Australia, and the tropical region (Fig. 1) were selected. Here, the tropical region was defined as the region where the Köppen climate classification deemed it a tropical region. The datasets from the 40 forests were selected using three criteria. First, the position of the forest and the observation period are available. Second, the targeted forests were distributed in areas that covered an area that was more than 5 km × 5 km, which corresponded to the spatial resolution of the evapotranspiration maps used in this study. Third, the target pixel(s) contained forests more than 50% both for 2001–2007 and for the observation period. The latter condition was verified using the time lapse tools on Google Earth (Google LCC, Mountain View, CA, USA).

Table 1 provides the summary of the 40 targeted forests, which are the subject of this study. The measurement periods were different among the 40 forests, with the range of 1–41 years. Although the observation periods for some forests partially overlapped with the estimated period (i.e., 2001–2007), the periods for other forests were different from the estimated one. We believe that the difference does not alter our conclusions because of two reasons. First, we verified that 40 sites had been covered by forests both in the observed and estimated periods. Second, long-term changes in annual evapotranspiration with tree growth and change in tree species, i.e., without clearcutting, was observed to be less than 200 mm (Komatsu et al., 2007; Kosugi et al., 2010).

Table 1. Annual precipitation (P), annual mean temperature (T), elevation, forest type, observed annual evapotranspiration (ET), and observed method in the 40 sites.

| Site | P (mm) | T (°C) | Elevation (m) | Forest Type* | Observed ET (mm) | Methods** | Citation |
|------|--------|--------|---------------|--------------|------------------|-----------|----------|
| #1 Jozankei | 1253 | 8 | 310–441 | EC | 408 | WB | Hattori et al. (2001) |
| #2 TakaragawaHonryu | 3673 | 5 | 1391 | MM | 556 | WB | Takeda (1951) |
| #3 Hitachi-ohta | 1345 | 14 | 280–330 | EC | 546 | WB | Fujieda et al. (1996) |
| #4 Tsukuba | 1338 | 14 | 290–390 | EC | 748 | WB | Water Resources Lab. and Flood Control Lab., Forest Environmental Division (1993) |
| #5 Nutanodani | 2454 | 13 | 470–990 | MM | 807 | WB | Hattori et al. (2001) |
| #6 Shirakawatani | 2933 | 9 | 740–1140 | EC | 517 | WB | Yao et al. (1996) |
| #7 KahokuII | 2176 | 16 | 160–250 | EC | 935 | WB | Shimizu et al. (2003) |
| #8 SarakawaII | 2766 | 13 | 290 | EB | 1078 | WB | Takeshita et al. (1996) |
| #9 Minaminomijiymaya | 1785 | 22 | 145–244 | EB | 1094 | WB | Fujieda et al. (1995) |
| #10 Hedona | 2897 | 20 | 187–399 | EM | 1114 | WB | Kanna et al. (2001) |
| #11 Howard River | 1720 | 27 | *** | EB | 1110 | M, SF | Cook et al. (1998) |
| #12 Oliver Creek | 2481 | 24 | 30 | EB | 1298 | SF, I | McJannet et al. (2007) |
| #13 Mount LewisI | 3040 | 17 | 1100 | EB | 1533 | SF, I | McJannet et al. (2007) |
| #14 Babinda Creek | 5400 | 15 | 50–150 | UN | 700 | WB | Chiew and McMahon (1994) |
| #15 BellendenKer | 7471 | 14 | 1560 | EB | 971 | SF, I | McJannet et al. (2007) |
| #16 Upper Barron | 2983 | 18 | 1050 | EB | 1518 | SF, I | McJannet et al. (2007) |
| #17 Canning River at Glen Eagle | 800 | 16 | 300–400 | UN | 780 | WB | Chiew and McMahon (1994) |
| #18 Lewin North | 1100 | 16 | *** | EB | 911 | WB | Bari et al. (2005) |
| #19 April Road | 975 | 16 | 170–230 | EB | 795 | WB | Bari et al. (1996) |
| #20 March Road | 991 | 16 | 200–240 | EB | 843 | WB | Bari et al. (1996) |
| #21 Delta Junction, 15-year | 304 | 2 | *** | DB | 284 | M | Liu et al. (2005) |
| #22 Prince Albert National Park | 422 | 1 | 601 | DB | 418 | M | Barr et al. (2007) |
| #23 DF49 | 1470 | 9 | 350 | EC | 413 | M | Jassal et al. (2010) |
| #24 HDF00 | 1410 | 10 | 175 | EC | 285 | M | Jassal et al. (2010) |
| #25 HDF88 | 1610 | 9 | 170 | EC | 418 | M | Jassal et al. (2010) |
| #26 USDA Forest Service Research Natural Area | 392 | 8 | 941 | EC | 415 | M | Anthoni et al. (1999) |
| #27 HJ Andrews | 2177 | 9 | 780 | EC | 881 | WB, Model | Wachler et al. (2005) |
| #28 Duke Forest pine | 1091 | 16 | 163 | EC | 782 | M | Novick et al. (2009) |
| #29 CoweeaWS7 | 1890 | 13 | 724–1060 | DB | 830 | WB | Swank et al. (2001) |
| #30 Gainesville | 1175 | 21 | *** | EC | 1126 | M | Gholz and Clark (2002) |
| #31 La Selva | 3300 | 25 | *** | EB | 1588 | M, P+I | Loescher et al. (2005), Bigelow (2001) |
| #32 Upper Rio Orinoco | 3223 | 26 | 105 | EB | 1492 | M | Rollenbeck and Anhuf (2007) |
| #33 ReboJaru | 2200 | 25 | 145 | EB | 1359 | M | von Randow et al. (2004) |
| #34 Asu | 2621 | 26 | 45–120 | EB | 1409 | SWB | Tomassella et al. (2008) |
| #35 Aracruz experimental catchment | 1147 | 24 | *** | EB | 1108 | WB | Almeida et al. (2007) |
| #36 Nsini | 1751 | 24 | 500–700 | UN | 1371 | M | Oliveira et al. (1999) |
| #37 Mule Hole | 1156 | 27 | 820–910 | DB | 809 | SWB, Model | Ruiz et al. (2010) |
| #38 Pasoh | 1733 | 25 | 75–150 | EB | 1318 | M | Takahashi et al. (2010) |
| #39 BukitTimah | 2369 | 27 | 90–164 | EB | 1350 | WB | Chappell and Sherlock (2005) |
| #40 W855 | 2778 | 27 | 150–300 | EB | 1350 | WB | Chappell and Sherlock (2005) |

* EB: evergreen broadleaved; EC: evergreen coniferous; EM: evergreen mixed; DB: deciduous broadleaved; MM: mixed; UN: unknown
** WB: catchment water balance; SF: sap flux; I: interception; M: micrometeorological; SWB: soil water balance; Model: interpolation by models; P: porometry
*** Unavailable
and Katsuyma, 2007), which was relatively smaller than the differences in the annual evapotranspiration among sites.

Evapotranspiration for the 40 forests was observed using a single method or a combination of methods, including catchment water balance, micrometeorology, soil water balance, sap flux, interception, and porometry (Table 1). Wilson et al. (2001) reported that the observed evapotranspiration was different based on the measurement method. Because Komatsu et al. (2012) did not detect systematic trends in the annual evapotranspiration depend on the type of measurement method, so the data used in this study was not classified according to the measurement method used to obtain it.

3. Results

3.1 Annual evapotranspiration

Table 2 provides observed and estimated annual evapotranspiration (ET), coefficient of variation (CV) of the estimated annual evapotranspiration, and relative error in the 40 sites.

| Site                        | Observed ET (mm) | Estimated ET (mm) | CV (%) | Relative error (%) |
|-----------------------------|------------------|-------------------|--------|-------------------|
| #1 Jozankei I               | 408              | 601               | 7      | 47                |
| #2 Takaragawa honryu       | 556              | 736               | 8      | 32                |
| #3 Hitachi-ohta             | 546              | 760               | 7      | 39                |
| #4 Tsukuba                  | 748              | 686               | 5      | 8                 |
| #5 Nutanodani               | 807              | 979               | 5      | 21                |
| #6 Shirakawatani            | 517              | 964               | 7      | 87                |
| #7 Kahoku III               | 935              | 874               | 4      | 7                 |
| #8 Sarukawa II              | 1078             | 931               | 6      | 14                |
| #9 Minamiminejiyama         | 1094             | 1078              | 5      | 1                 |
| #10 Hedona                  | 1114             | 1153              | 7      | 4                 |
| #11 Howard River            | 1110             | 1062              | 7      | 4                 |
| #12 Oliver Creek            | 1298             | 1228              | 6      | 5                 |
| #13 Mount Lewis I           | 1533             | 1596              | 8      | 4                 |
| #14 Babinda Creek           | 700              | 1307              | 3      | 87                |
| #15 Bellenden Ker           | 971              | 1336              | 6      | 38                |
| #16 Upper Barron            | 1518             | 1327              | 4      | 13                |
| #17 Canning River at Glen Eagle| 780          | 724               | 7      | 7                 |
| #18 Lewin North             | 911              | 900               | 5      | 1                 |
| #19 April Road              | 795              | 841               | 3      | 6                 |
| #20 March Road              | 843              | 844               | 4      | 0                 |
| #21 Delta Junction, 15-year | 284              | 184               | 3      | 32                |
| #22 Prince Albert National Park | 418          | 989               | 23     | 137               |
| #23 DF49                    | 413              | 708               | 7      | 72                |
| #24 HDF00                   | 285              | 659               | 18     | 131               |
| #25 HDF88                   | 418              | 724               | 5      | 73                |
| #26 USDA Forest Service Research Natural Area | 415      | 778               | 10     | 88                |
| #27 HJ Andrews              | 881              | 1062              | 7      | 21                |
| #28 Duke Forest pine        | 782              | 883               | 7      | 13                |
| #29 Coweeta WS7             | 830              | 1059              | 5      | 28                |
| #30 Gainesville             | 1126             | 1047              | 5      | 7                 |
| #31 La Selva                | 1588             | 1394              | 5      | 12                |
| #32 Upper Rio Orinoco       | 1492             | 1503              | 9      | 1                 |
| #33 Rebio Jaru              | 1359             | 1645              | 5      | 21                |
| #34 Asu                      | 1409             | 1855              | 10     | 32                |
| #35 Araucruz experimental catchment | 1108     | 927               | 5      | 16                |
| #36 Nsimi                   | 1371             | 1527              | 4      | 11                |
| #37 Mule Hole               | 809              | 983               | 6      | 21                |
| #38 Pasoh                   | 1318             | 1216              | 3      | 9                 |
| #39 Bukit Timah             | 1350             | 1143              | 3      | 15                |
| #40 W8S5                    | 1350             | 1445              | 4      | 7                 |

Table 2. Observed and estimated annual evapotranspiration (ET), coefficient of variation (CV) of the estimated annual evapotranspiration, and relative error in the 40 sites.

Evapotranspiration data for the 40 forests was observed and estimated for comparison. The observed and estimated evapotranspiration were the averaged value over the analyzed period and that for 2001–2007, respectively. The solid and dotted lines indicate the 1:1 and the regression lines, respectively.

3.1 Annual evapotranspiration

Table 2 provides observed and estimated annual evapotranspiration (ET), coefficient of variation (CV) of the estimated annual evapotranspiration, and relative error in the 40 sites.
Table 3. The coefficient of determination ($R^2$), root mean square errors (RMSE), and the bias for the 40 sites based on the GCOM-C $ET_{index}$ algorithm, Zhang et al. (2001)'s model, and Komatsu et al. (2012)'s model.

| Area            | GCOM-C $ET_{index}$ algorithm | Zhang et al. (2001)'s model | Komatsu et al. (2012)'s model |
|-----------------|-------------------------------|-----------------------------|-------------------------------|
|                 | $R^2$ | RMSE (mm) | Bias (mm) | $R^2$ | RMSE (mm) | Bias (mm) | $R^2$ | RMSE (mm) | Bias (mm) |
| Japan           | 0.56  | 194       | 66        | 0.12  | 545       | 482       | 0.80  | 157       | 101       |
| Australia       | 0.46  | 235       | 70        | 0.26  | 325       | 130       | 0.52  | 221       | -88       |
| North America   | 0.53  | 299       | 224       | 0.21  | 441       | 288       | 0.47  | 211       | 47        |
| Tropical region | 0.44  | 216       | 48        | 0.78  | 112       | -58       | 0.68  | 128       | -40       |
| All region      | 0.69  | 239       | 110       | 0.31  | 390       | 210       | 0.77  | 183       | 5         |

1:1 line (Fig. 3b), and the absolute value of relative errors of the data from these eight forests were less than 15% (Table 2). Meanwhile, two forests in Australia (#14 and #15) had relative errors that exceeded 35% (Table 2). In North America (#21–#30), except for two sites with the maximum and minimum observed evapotranspiration, the estimated evapotranspiration was larger than the observed evapotranspiration (Fig. 3c, Table 2). In the tropical region (#31–#40), the absolute value of relative errors for all 10 forests was less than 35% (Table 2).

3.2 Seasonal change in evapotranspiration

Fig. 4 presents the estimated monthly $ET_{index}$ values. In 28 of the 30 forests in Japan, Australia, and North America, the maximum $ET_{index}$ was more than 1.0, and in 25 of the 30 forests, the minimum $ET_{index}$ was less than 0.2. Thus, there were large differences between the maximum and minimum $ET_{index}$ values in most of the forests in Japan, Australia, and North America. Fig. 5 presents the estimated monthly evapotranspiration, which is $ET_{index} \times ET_o$ in each region. The trend for the monthly evapotranspiration was similar to that for monthly $ET_{index}$. In the tropical region, no clear seasonal trends were identified. In Japan, Australia, and North America, evapotranspiration during summer was larger than during winter.

4. Discussion

Many algorithms have been developed to estimate evapotranspiration from the satellite data (Mu et al., 2007; Miralles et al., 2011; Senay et al., 2013; Yao et al., 2017).
Fig. 4. Estimated monthly ET_index in Japan (a), Australia (b), North America (c), and the tropical region (d). Gray lines and black lines with open circles indicate data for each site and data averaged over the 10 sites, respectively.

Fig. 5. Estimated monthly evapotranspiration in Japan (a), Australia (b), North America (c), and the tropical region (d). Gray lines and black lines with open circles indicate data for each site and data averaged over the 10 sites, respectively.
Among these studies, the observed and estimated annual evapotranspiration are available in Mu et al. (2007). Mu et al. (2007) developed an algorithm for evapotranspiration estimates based on the Penman–Monteith equation (Monteith, 1964) and MODIS satellite and global meteorology data (i.e., MODIS ET algorithm). They compared the observed and estimated annual mean latent heat flux at 19 sites. Note that the 19 sites included 12 forested sites and seven sites with other types of land cover. 

\[ R^2, \text{RMSE, and the bias of the MODIS ET algorithm were 0.74, 241 mm, and } -74 \text{ mm, respectively. Note that we assumed the annual air temperature of } 20^\circ \text{C when converting latent heat flux into evapotranspiration. Although the bias for the MODIS ET algorithm was better than that for the GCOM-C } ET_{\text{index}} \text{ algorithm, } R^2 \text{ and RMSE for the MODIS ET algorithm were comparable to those for the GCOM-C } ET_{\text{index}} \text{ algorithm. It is important to note that the GCOM-C } ET_{\text{index}} \text{ algorithm requires less input data than the MODIS ET algorithm. Regardless, the accuracy of the GCOM-C } ET_{\text{index}} \text{ algorithm for forested areas was close to that of the MODIS ET algorithm.}

In addition to methods based on satellite data, Zhang’s model (Zhang et al., 2001) has been widely used to predict the spatial variation in annual evapotranspiration in forests. Zhang’s model estimates evapotranspiration from annual precipitation and constant annual potential evaporation and a coefficient representing plant water availability. When Zhang’s model was applied to the data from the 40 forests in this study, \( R^2 \), RMSE, and the bias were 0.31, 390 mm, and 210 mm, respectively, which were worse than those associated with the GCOM-C \( ET_{\text{index}} \) algorithm (Table 2). Komatsu et al. (2012) improved Zhang’s model by adding the annual mean air temperature as an input. The constant annual potential evaporation for Zhang’s model was suitable for climate conditions in tropical regions (Komatsu et al., 2012). Komatsu’s model changes the annual potential evapotranspiration due to the annual mean air temperature. When Komatsu’s model was applied to the data for the 40 forests, \( R^2 \), RMSE, and the bias were 0.77, 183 mm, and 5 mm, respectively, which were better than those associated with the GCOM-C \( ET_{\text{index}} \) algorithm (Table 2). High accuracy of Komatsu’s model might be because the data for the 40 sites that we analyzed were included in the training data for developing Komatsu’s model.

Monthly evapotranspiration was not available for most of the 40 sites analyzed in this study. Suzuki (1991) reported monthly observed evapotranspiration based on the short-term water balance method for totally 22 periods in nine forested catchments of Japan. Some of the catchments and periods overlapped with the 10 sites located in Japan that were analyzed as part of this study. Fig. 6 compares the 22 monthly evapotranspiration observations with the estimated monthly evapotranspiration averaged over the 10 sites of Japan. In summer, the estimated evapotranspiration tended to be larger than the observed evapotranspiration. In winter, the estimated evapotranspiration tended to be less than the observed evapotranspiration. Thus, low estimation errors for annual evapotranspiration in the forests of Japan, North America, and Australia were likely due to the overestimation of summer evapotranspiration being offset by the underestimation of winter evapotranspiration.

In many forests of Japan, North America, and Australia, \( ET_{\text{index}} \) in summer was close to the maximum value (=1.23), suggesting that \( T_s(\text{act}) \) was close to or smaller than \( T_s(\text{wet}) \). Denh et al. (2018) also reported that \( T(\text{act}) \) in summer was close to \( T(\text{wet}) \) in the lodgepole pine tree forest in eastern Idaho, USA. To reduce the overestimation of summer evapotranspiration, a small \( T(\text{wet}) \) is required. \( T(\text{wet}) \) was basically estimated from the relation between \( R \) and \( T(\text{wet}) \), i.e., Equation (2). The empirical parameters in Equation (2) were determined using the data in a grassland of Shenmu, China, with semi-arid climate condition. Use of the two parameters \( C1 \) and \( C2 \) of Equation (2) determined in the forests could improve the accuracy of summer evapotranspiration in forests.

In these forests, \( ET_{\text{index}} \) in winter was close to 0, suggesting that \( T(\text{act}) \) was close to (or larger than) \( T(\text{dry}) \). \( T(\text{dry}) \) was calculated from \( T(\text{wet}) \) and the difference between \( T(\text{wet}) \) and \( T(\text{dry}) \). The difference was estimated from \( R \) and \( u \) (i.e., Equation (4)). The empirical parameters in Equation (4) were also determined using the data in Shenmu, China. The use of the two parameters \( C1 \) and \( C2 \) determined in Equation (4) determined in forests might improve the accuracy of winter evapotranspiration estimates for these forests.

In the tropical region, the absolute value of relative error was \( \leq 35\% \) for all forests. In the other three regions, the absolute value of relative error was \( >35\% \) in 10 of the 30 forests. In all the forests wherein the absolute value of relative error is \( >35\% \), the estimated annual evapotranspiration was larger than the observed annual evapotranspiration (Fig. 2). Fig. 7 classified the relationship between the observed and estimated annual evapotranspiration according to the annual mean temperature. In the forests with an annual mean temperature of \( <15^\circ \text{C} \), the estimated annual evapotranspiration was larger than the observed annual evapotranspiration in 14 out of 17 forests evaluated. This trend was not found in the forests with an annual mean temperature of \( \geq 15^\circ \text{C} \). Furthermore, a significant negative
relation exists between the annual mean temperature and relative error \( P < 0.05 \), when we used the data for 16 of the 17 forests with the annual mean temperatures of \(<15^\circ C\) (Fig. 8). The forests with low temperatures are covered by snow in winter. In these forests, winter evapotranspiration could be close to zero, which was comparable to the estimated winter evapotranspiration. Therefore, in these forests, the overestimation of summer evapotranspiration was not offset by the underestimation of winter evapotranspiration. Therefore, redetermination of \( C_1 \) and \( C_2 \) of Equation (2) would remarkably improve the annual evapotranspiration estimates for the forests with low temperatures (i.e., the annual mean temperatures of \(<15^\circ C\)).

Except for the forested sites with low temperatures, the estimated evapotranspiration was considerably larger than the observed evapotranspiration in Shirakawatani of Japan (\#6) and Babinda Creek (\#14) and Bellenden Ker (\#15) of Australia. Although the seasonal trend in Shirakawatani’s \( ET_{\text{index}} \) was similar to those in other forests of Japan, the observed annual evapotranspiration in Shirakawatani was less than that in other forests of Japan. The spatial resolution in weather data used for estimation was low, and the altitude of Shirakawatani was higher than the surrounding areas. Therefore, the air temperature in a grid within Shirakawatani would be higher than the air temperature in Shirakawatani. This suggests that the overestimation of annual evapotranspiration in Shirakawatani may be due to its complex topography. Babinda Creek and Bellenden Ker had large amounts of annual precipitation (5,400 mm and 7,471 mm, respectively) and are classified as cloud forests. The GCOM-C \( ET_{\text{index}} \) algorithm assumes there is at least one cloud-free day every 16 days and the \( ET_{\text{index}} \) was set to the minimum value of 16 days. Annual evapotranspiration at these two sites might have been overestimated because this particular assumption was not applicable to these two forests.

The GCOM-C \( ET_{\text{index}} \) algorithm requires only thermal images and fundamental weather data and provides evapotranspiration without adjusting the parameters at each individual site. Nevertheless, the accuracy of annual evapotranspiration was similar to that for the MODIS \( ET \) algorithm with more complex structures. The GCOM-C \( ET_{\text{index}} \) algorithm accurately represented the spatial variations in annual evapotranspiration due to climate conditions. Meanwhile, this algorithm did not represent well the evapotranspiration seasonality. In addition, whether the algorithm can detect the evapotranspiration changes due to the changes in forest structures remains unknown. Further studies clarifying this could expand the applicability of the GCOM-C \( ET_{\text{index}} \) algorithm.

5. Conclusions

This study examined the accuracy of annual evapotranspiration in forests based on GCOM-C \( ET_{\text{index}} \) algorithm, which enabled us to estimate evapotranspiration from thermal satellite images and near-surface whether data. We found that the GCOM-C \( ET_{\text{index}} \) algorithm well reproduced annual evapotranspiration for most forests. Conversely, the accuracy in forests with low annual mean temperature was lower than that in forests with high annual mean temperature. In addition, in most forests, the GCOM-C \( ET_{\text{index}} \) algorithm overestimated summer evapotranspiration and underestimated winter evapotranspiration. Redetermination of the two parameters in the function estimating the hypothetical dry surface temperature must improve the evapotranspiration estimates in the forested areas, especially the ones with a low annual mean temperature.

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