Evaluation of the GCOM-C global ET\textsubscript{index} estimation algorithm

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Abstract

This paper presents the application results of the Global Change Observation Mission-Climate (GCOM-C) global ET\textsubscript{index} estimation algorithm to the entire globe over the seven years from 2001 to 2007 using MODIS daily thermal observation data. The GCOM-C global ET\textsubscript{index} estimation algorithm was developed to automatically provide global ET\textsubscript{index} information for the Global Change Observation Mission (GCOM) of the Japan Aerospace Exploration Agency (JAXA).

The ET\textsubscript{index} maps resulting from this study were compared with global precipitation, Köppen’s climate classification, and forest distribution maps in order to investigate the general correspondence between the ET\textsubscript{index} and climate/ecosystem distributions. The estimated ET\textsubscript{index} was confirmed to be in general agreement with the distributions of climate and forest at the global and continental scales and at annual and seasonal timescales.

The resultant global evapotranspiration (ET) maps were evaluated using point-measured precipitation for 199 locations worldwide and measured ET data in Mongolia. The relationship between precipitation and ET supported the adequacy of the ET estimation method for annual timescales. A monthly comparison of the ET\textsubscript{index} with precipitation implied that the algorithm is functional in summer but nonfunctional in winter under some conditions. An accuracy assessment of the algorithm using actual ET measurement data from Mongolia indicated that the algorithm showed good performance at annual timescales. The error in the 4-year average of estimated ET was equivalent to 12% of the actual ET or 0.7% of the reference ET.

Key words: Crop coefficient, Evapotranspiration, GCOM-C, Surface temperature, Water management.

1. Introduction

To meet the demand for evapotranspiration (ET) estimations for global water-resources management, the Global Change Observation Mission-Climate (GCOM-C) ET\textsubscript{index} algorithm was developed (Tasumi et al., 2016). The goal was to provide global ET\textsubscript{index} maps using thermal observations from the GCOM-C satellite. The GCOM-C satellite is intended to provide climate monitoring within the integrated global observations of the Global Change Observation Mission (GCOM) of the Japan Aerospace Exploration Agency (JAXA), which is expected to be launched in Japan’s fiscal year 2016. The moderate-resolution imaging spectroradiometer (MODIS) MOD16 global ET estimation algorithm developed by Mu et al. (2011) is a popular algorithm used to generate global ET maps based on MODIS satellite observations. Compared to the MOD16 algorithm, the GCOM-C ET\textsubscript{index} algorithm relies more on satellite thermal observations, and the products derived focus more on agricultural water management. The ET\textsubscript{index} maps attained using the GCOM-C ET\textsubscript{index} algorithm have congruency with traditional agricultural water-management methodologies. The ET\textsubscript{index} is defined as the actual evapotranspiration (ET\textsubscript{act}) normalized by a weather parameter called the reference evapotranspiration (ET\textsubscript{r}), as described in Eq. 1.

\[ ET_{\text{index}} = \frac{ET_{\text{act}}}{ET_0}, \]  

\( ET_0 \) has been defined by the Food and Agriculture Organization of the United Nations (FAO; Allen et al., 1998) as the “ET from a hypothetical, adequately watered, extensive grass reference surface with crop height of 12 cm, surface resistance of 70 s m\textsuperscript{-1}, and an albedo of 0.23.” The ET\textsubscript{index} is equivalent to the crop coefficient, which has been applied widely in agricultural and irrigation water management throughout the world. Therefore, the ET\textsubscript{index} maps derived from this algorithm have good congruency with traditional agricultural water-management methodologies, although the application targets of the ET\textsubscript{index} are not limited to irrigation or agriculture.

The primary input data of the algorithm are satellite-observed thermal imageries provided by GCOM-C and near-surface global wind-speed data provided by a global climate model. A previous study (Tasumi et al., 2012) showed that an earlier version of the algorithm applied to a series of Landsat images successfully estimated 8-month cumulative ET data in an irrigated agricultural region in the Western United States. A standard error of the estimate was equivalent to 6.8% of ET\textsubscript{r}. A global application of the algorithm with fully automated ET estimation including the rejection of cloud impact has not been reported.

In this study, the current ET\textsubscript{index} estimation algorithm was applied to MODIS daily global thermal observation data for the
seven years from 2001 to 2007. Although the original spatial resolution of the MODIS thermal observation is 1 km, a spatial resolution of 0.05° was adopted in this application study because of a limitation related to our hardware environment. The resultant output data throughout this study were 16-day, cloud-free global ETindex maps and daily estimated ET maps for 2001–2007. These maps were compared to weather and ET data to evaluate their adequacy and accuracy, and to investigate the performance of the algorithm.

2. Materials and Methods

2.1 Preparation of the global ETindex and ET maps

The GCOM-C ETindex algorithm (Tasumi et al., 2016) estimates the ETindex using satellite-observed actual surface temperature as a relative indicator of surface evapotranspiration by employing two hypothetical surface temperatures, the wet and the dry surface temperatures. The ETindex is computed using the following equation:

\[ ET_{\text{index}} = C_{\text{adj}} \times \frac{T_s(\text{dry}) - T_s(\text{act})}{T_s(\text{dry}) - T_s(\text{wet})}. \]  

(2)

where \( T_s(\text{act}) \) is the instantaneous actual surface temperature based on satellite thermal observation (°C), and \( T_s(\text{wet}) \) and \( T_s(\text{dry}) \) are the wet surface temperature and the dry surface temperature (°C), which are the hypothetical instantaneous surface temperatures when the surface is expected to take zero sensible heat flux and when the surface has zero latent heat flux, respectively. The constant \( C_{\text{adj}} \) is an adjustment factor employed in the algorithm and has been calibrated as 1.23.

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

(3)

\[ T_s(\text{dry}) = T_s(\text{wet}) + (-0.0023u + 0.0301) \times R_p, \]  

(4)

where \( R_s \) is instantaneous solar radiation (W m\(^{-2}\)), DoY is day of year, \( f_{\text{lat}} \) is a function of latitude, \( C_1 \) to \( C_3 \) are calibration constants, and \( u \) is near-surface wind speed (m s\(^{-1}\)).

The estimated daily ETindex data are gathered for 16 days, and 16-day cloud-free composite maps are computed by taking the minimum value of the ETindex for the 16-day period, assuming that the minimum ETindex most likely occurs on a cloud-free day. Daily actual ET maps are then obtained from the 16-day, cloud-free ETindex maps by inversely using Eq. 1 if additional daily meteorological data are available. See Tasumi et al. (2016) for additional details about the algorithm.

The GCOM-C ETindex algorithm requires two primary types of input data in order to compute the 16-day, cloud-free global ETindex: actual surface temperature as observed by satellite and global near-surface wind-speed data. The 16-day, cloud-free global ETindex maps are then converted to maps of daily estimated actual ET using additional weather data. Monthly and annual ET data are derived from simple integrations of daily ET.

The input data for the global ETindex and ET estimation are summarized in Table 1. For estimation of the ETindex, the MODIS MOD11 Land Surface Temperature (LST) product (collection 5) with a spatial resolution of 0.05° was used for the observed surface temperature as a substitute for GCOM-C thermal observation data. Instantaneous clear-sky solar radiation for the observation timing of LST was calculated as a substitute for the instantaneous actual solar radiation for the satellite data-acquisition time using a digital elevation model (DEM) and pixel-by-pixel MODIS thermal observation time/location information. The global weather dataset, which was reanalysis data originally developed as input data for a global climate model (Mabuchi, 2011), was provided by Dr. Mabuchi of Chiba University. For the ETindex estimation, only wind speed is used as the weather data. Conversion from the ETindex to ET requires daily solar radiation (including cloudy days), air temperature, and vapor pressure in addition to wind speed. In this application, a 16-day global ETindex and daily ET were calculated for the seven-year period from 2001 to 2007. Global 16-day, cloud-free ETindex maps are computed using the algorithm described by Tasumi et al. (2016). The derived ETindex maps are further converted to global daily actual ET maps, using equation 1 with global daily ETindex maps computed from a global weather dataset. The global estimation is conducted with full automation, without any decisions or modifications being made by a person.

2.2 Evaluation methods

In this research, the derived ETindex and ET maps are evaluated comprehensively. A summary of the data used for evaluation is provided in Table 2. First, the derived ETindex map is compared with a Köppen climate classification map (Peel et al., 2007), a forest distribution map (Shimada et al., 2014), and a world pre-

| Table 1. Input data for global ETindex and ET estimation. |
|----------------------------------------------------------|
| **Data category** | **Item** | **Spatial resolution** | **Timescale** | **Use for** |
| Satellite and GIS data | MODIS MOD11 Land Surface Temperature (collection 5) | 0.05° | Instantaneous | ETindex |
| | MODIS observation time and location | 0.05° | Instantaneous | ETindex |
| | Global Digital Elevation Model (m) | 0.05° | NA | ETindex |
| Global weather data (reanalysis data) | Near-surface wind speed (m s\(^{-1}\)) | 1.875° | daily average | ETindex |
| | At-surface solar radiation (W m\(^{-2}\)) | 1.875° | daily average | Actual ET |
| | Near-surface air temperature (°C) | 1.875° | daily average | Actual ET |
| | Near-surface air vapor pressure (kPa) | 1.875° | daily average | Actual ET |
Table 2. Summary of the data for evaluation.

| Data category | Item | Spatial resolution | Evaluation target | Advantages | Disadvantages | Reference |
|---------------|------|--------------------|-------------------|------------|--------------|-----------|
| Global map data | Köppen climate classification map | NA | annual $ET_{index}$ | | | Peel et al. (2007) |
| | Global forest/non-forest maps by ALOS PALSAR (FNF100) | 100m (original); 0.05° (used) | annual $ET_{index}$ | | | Shimada et al. (2014) |
| | Global precipitation by Tropical Rainfall Measuring Mission (TRMM product 3B43 v7) | 0.25° (original/used) | monthly $ET_{index}$ | Global data | Not a measurement data | Huffman and Bolvin (2014) |
| Ground measurement data | Precipitation point data | | annual | Measurement data | Various locations in the world | Not $ET$ (indirect comparison) | National Astronomical Observatory of Japan (2010) |
| | Evapotranspiration point data | | annual $ET$ | Measured $ET$ data | (direct comparison) | Limited location | Li et al., (2007) |

Evapotranspiration (Huffman and Bolvin, 2014). The $ET_{index}$ has a good relation with the soil moisture availability (Tasumi and Kimura, 2013), and investigating the correspondence between the $ET_{index}$ and the distributions of climates and ecosystems provides an initial appraisal of the accuracy of the $ET_{index}$ estimation.

Evaluations of the $ET_{index}$ and $ET$ maps using ground measurements are also important. However, a comprehensive evaluation using ground-measured $ET$ data is difficult because the accessibility of in situ $ET$ measurement data may have uncertainty in accuracy (e.g., Wilson et al., 2002); furthermore, the footprint of the in situ measurement may not be comparable to the 0.05° estimated $ET$ pixel. In this research, we use ground-measured precipitation data to evaluate the general adequacy of the $ET$ estimation results on an annual basis. The results of the comparison will be evaluated by referring to the results reported in previous research by Kondoh et al. (1999). The advantages of using ground-measured precipitation data include the following: (1) robust data are easily obtainable because precipitation measurements are much more popular and easier to access than $ET$ measurements, and (2) the requirement for the footprint agreement in comparison with the $ET$ map is more lenient because precipitation, compared to $ET$, is much less sensitive to surface conditions. The precipitation dataset used in this study (National Astronomical Observatory of Japan, 2010) is from 199 observation sites throughout the world. The 199 sites are typically located in the capitals or major cities of their respective countries, such as Paris and Seoul, and the data are most likely from the primary meteorological stations. Of these 199 sites, 157 are from the Northern Hemisphere, and 42 are from the Southern Hemisphere. The precipitation data used in this analysis are long-term monthly average data, typically averaged over 1971–2000. The precipitation data are compared with the estimated average annual $ET$ for 2001–2007.

To understand the seasonal characteristics of the estimated $ET$, the monthly $ET_{index}$ is compared with monthly precipitation at 84 locations in the Northern Hemisphere that are expected to have distinct spring, summer, autumn, and winter seasons (latitude > 30°N). For monthly comparisons, the $ET_{index}$, rather than $ET$, is a better parameter to compare with precipitation because it normalizes the monthly differences in energy conditions.

In an effort to evaluate the accuracy of the derived $ET$ map, the estimated $ET$ is compared with the actual $ET$ measured over a uniform natural grassland in Mongolia (Kherlenbayan Ulaan; 47°12'50.3"N, 108°44'14.4"E) (Li et al., 2007), using data provided by the AsiaFlux database (www.asiaflux.net). The evaluation period is from 2004 to 2007, which are overlapping years of the flux measurement and our ET estimation. Kherlenbayan Ulaan was the only site that was surrounded by homogeneous land cover and had four years of observation during the 2001–2007 period of the $ET_{index}$ estimation, without significant periods that lacked data. The timestamp of the original flux dataset was shifted by analyzing the southing time of the sun, and the observation data were quality-controlled for periods lacking data and for some extreme values either by interpolation or by replacing them with data from periods with similar weather conditions. The overall percentage of missing or extreme data that required adjustment was 1–3% of the total data.

3. Results and Discussions

3.1 Estimated $ET_{index}$ and $ET$ maps

The annual $ET_{index}$ and $ET$ maps estimated by the GCOM-C $ET_{index}$ algorithm for the year 2001 are shown in Fig. 1 as an example. Note that the $ET_{index}$ is defined as the ratio of $ET$ to reference $ET$. The $ET_{index}$ is zero when $ET$ is zero and one when $ET$ from the surface is equivalent to $ET$ from the reference surface, which was determined by the FAO to be an adequately watered, healthy grassland (Allen et al., 1998). An $ET_{index}$ of 1.23 indicates that the $ET$ from the surface is 23% higher than the $ET$ from the reference surface. In Fig. 1, boreal forest spreads in high latitudes
of the Northern Hemisphere appear to have high $ET_{index}$ values but low $ET$ values. Large $ET_{index}$ values indicate that the $ET$ of the area is high “for the climate.” However, $ET$ itself is small because the cold climate and weaker solar radiation at high latitudes sharply limits $ET$.

### 3.2 Initial accuracy appraisal of the estimated $ET_{index}$

Figure 2 compares the Köppen climate classification map with the estimated $ET_{index}$ map for Oceania. In the figure, Af, Am, and Aw in the classification map denote tropical rainforest, monsoon, and savannah climates, respectively. Bw and Bs (including Bsh and Bsk) denote arid desert and steppe climates, respectively. Cs, Cw, and Cf (including Cfa, Cfb, and Cfc) indicate temperate climates.

![Fig. 1. Annual $ET_{index}$ and actual $ET$ for the year 2001.](image1)

![Fig. 2. Köppen-Geiger climate classification map (left) with estimated annual $ET_{index}$ of 2001 (right) for Oceania.](image2)

![Fig. 3. Comparison between monthly average precipitation for 2001-2007 (left) and the estimated monthly average $ET_{index}$ for 2001-2007 (right).](image3)
climates with dry summers, dry winters, and lacking a dry season, respectively. The estimated ET index was higher in the “wetter” regions and lower in the “drier” regions. The representative ranges of the ET index were 1.00 – 1.23 for tropical rainforests, 0.50 – 1.00 for temperate climates, and 0.00 – 0.25 for arid climates. Similar trends were observed in other regions of the world. Thus, the ET index map represented the general wetness of the world.

Next, the ET index was compared to a forest distribution map. The result of the comparison for a randomly selected 2,227 pixels from all over the world is summarized in Table 3 for the year 2007. As shown in the table, the average annual ET index increased almost linearly as forest coverage increased, indicating a good agreement between the ET index and the forest distribution. This likely resulted from the fact that the distributions of the forests and the ET index are positively correlated with soil moisture. Note that these two data sources are independent. The ET index estimation depends primarily on daily thermal observations by the MODIS satellite, whereas the forest coverage estimation depends on microwave observations by the Advanced Land Observing Satellite (ALOS)/Phased Array Type L-band Synthetic Aperture Radar (PALSAR).

Figure 3 shows the result of the comparison between monthly precipitation and the monthly ET index for the African continent. A clear gap in the ET index maps that appears at the equator may be caused by the coarse resolution of the input weather data (1.875°, see Table 1). As shown in the figure, regions that receive more precipitation tend to have higher ET index values. To confirm the correlation of spatial distributions between precipitation and the ET index quantitatively, the ET index was averaged for each precipitation category (Fig. 4). The figure shows the general correlation of spatial distribution between precipitation and the ET index in January. Most of the areas with precipitation less than 20 mm per month had an ET index smaller than 0.15, and the areas receiving more than 100 mm precipitation per month had an ET index greater than 0.75.

### 3.3 Evaluation using ground-measured precipitation data

A comparison between the ground-measured annual precipitation data (point data) and the ET is shown in Fig. 5. The annual ET exceeded precipitation at 20 of the 199 locations. Most of the

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**Table 3.** Average annual ET index of each forest coverage class for the randomly selected 2,227 pixels throughout the world.

| Forest coverage in 2007 (%) | 0   | 1-20 | 21-40 | 41-60 | 61-80 | 81-100 |
|---------------------------|-----|------|-------|-------|-------|--------|
| Number of sample pixels   | 1,023 | 354 | 158 | 172 | 216 | 304 |
| Average annual ET index in 2007 by GCOM-C ET index algorithm | 0.20 | 0.47 | 0.54 | 0.65 | 0.72 | 0.83 |
| Standard deviation of ET index | 0.26 | 0.28 | 0.32 | 0.27 | 0.26 | 0.25 |

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**Fig. 4.** Estimated average ET index of the African Continent for each precipitation categories in January, 2001-2007. Line indicates distribution of ET index in one standard deviation.

**Fig. 5.** Comparison between long-term annual precipitation and estimated 7-year average annual ET for the 199 locations of the world. Points indicated as “P < ET (irrigation or ocean)” are the locations where the 5 km×5 km ET pixel contains either irrigated agricultural lands or large water bodies such as oceans.
locations with an obvious exceedance of ET were either in irrigated agricultural regions, where ET can exceed precipitation because the water supply for the region comes from both precipitation and irrigation or where the 0.05° ET pixels are partially covered by large bodies of water such as oceans. The relationship between precipitation and ET for the remaining 179 locations was similar to the annual ET vs. precipitation distribution pattern reported by Kondoh et al. (1999) based on an independent water-budget study of several locations throughout the world. The agreement of the two independently derived world ET vs. precipitation distribution patterns supports the adequacy of our ET estimation at the annual timescale.

The monthly scatter plots of precipitation vs. ET\textsubscript{index} are shown in Fig. 6. Although precipitation is not the only factor that controls the ET\textsubscript{index}, an overall positive relationship between precipitation and the ET\textsubscript{index} is expected because more precipitation results in higher soil moisture and thus a higher ET\textsubscript{index}. From Fig. 6, positive relationships between precipitation and the ET\textsubscript{index} were confirmed during April to September, implying that the algorithm functions as expected in summer. However, no clear relationship was confirmed for the winter months. In winter, the ET\textsubscript{index} tends to be low even for locations with high precipitation, both in the lower latitude (30°–35°) and higher latitude (> 35°) areas. This result is contradictory to the nature of the ET\textsubscript{index}, especially at lower-latitude locations where precipitation during winter is expected to fall as rain rather than snow. The result implies that the estimation algorithm may not have functioned as expected for winter in some locations. The degraded estimation accuracy in winter might be caused by the following two reasons: (1) the algorithm was designed to achieve higher accuracy in summer than winter, considering the importance of summertime ET in natural and agricultural water-resources management (Tasumi et al., 2016); and (2) the ET\textsubscript{index} estimation is technically more difficult in winter because both the numerator and denominator in equation 2 tend to be small numbers (thus, more sensitive to observation/estimation errors) due to lower heat and energy status in winter. The impact of the malfunction of the ET\textsubscript{index} estimation in winter may not be large for locations that are dry in winter or for locations that are covered by snow, where most of the latent heat would be consumed by snowmelt rather than by evapotranspiration. Additionally, energy availability is much lower in winter than in summer, so the wintertime failure of the ET\textsubscript{index} estimation does not obviously affect the annual estimation.

Fig. 6. Comparison between long-term monthly precipitation and the estimated 7-year average monthly ET\textsubscript{index} for 84 locations in the Northern Hemisphere having a latitude greater than 30 degrees.
Improving estimation accuracy in shorter timescales is a primary issue that must be resolved in the future.

4. Conclusions

To meet the demand for evapotranspiration (ET) estimations for global water-resources management, the GCOM-C ET index algorithm was developed to provide global ET index maps using thermal observations of the GCOM-C satellite (Tasumi et al., 2016). The algorithm was applied using MODIS thermal observation data as a substitute for GCOM-C thermal observation data to the entire globe for the seven years from 2001 to 2007. The resultant ET index maps were compared with global precipitation, Köppen climate classification, and forest distribution maps to investigate the general correlation between the ET index and climate/ecosystem distributions and to appraise the general accuracy of the method. As a result of the comparison, the estimated ET index was confirmed to have general agreement with the distributions of climate and forest at the global and continental scales and at annual and seasonal timescales.

The resultant global ET maps were evaluated using point-measured precipitation for 199 locations around the world and with ET measurement data provided by the AsiaFlux database. The correlation between precipitation and ET showed good congruency with the correlation reported in a study by Kondoh et al. (1999), which supports the adequacy of our ET estimation method at the annual timescale. A monthly comparison of the ET index with precipitation implied that the algorithm is functional for summer but nonfunctional for winter periods in some conditions. An accuracy assessment of the estimated ET map using actual ET point-measurement data from a grassland ecosystem in Mongolia was attempted but failed because the spatial resolution of the global ET map was too coarse to compare with the point-measurement data. However, estimated ET from the ET index estimation algorithm using ground-measured surface temperature and other weather data indicated that the algorithm itself showed good performance at the annual timescale. The annual estimation error of ET varied from ~15 mm to +40 mm, with an average of +8 mm. In the 4-year average, the estimation error was equivalent to 12% of the actual ET or 0.7% of the ET index, indicating that the algorithm performed well at the annual timescale for the location. A series of large estimation errors were identified at the 16-day timescale. Improving estimation accuracy in shorter timescales is a primary issue that must be resolved in the future.

Table 4. Annual ET values read from the global ET map (Estimated ET1) and estimated ET from the GCOM-C ET index algorithm applied with actual ground measurements of surface temperature and other weather data (Estimated ET2) listed along with measured ET, precipitation, and ET index at Kherlenbayan Ulaan in Mongolia.

| Year | Estimated ET1 (mm) | Estimated ET2 (mm) | Measured ET (mm) | Precipitation (mm) | ET index (mm) |
|------|--------------------|--------------------|------------------|--------------------|---------------|
| 2004 | 185                | 122                | 116              | 234                | 1,039         |
| 2005 | 230                | 95                 | 110              | 136                | 1,072         |
| 2006 | 225                | 109                | 69               | 247                | 1,107         |
| 2007 | 143                | 104                | 105              | 83                 | 1,178         |
| 4-year average | 196                | 108                | 100              | 175                | 1,099         |
issue in the future.

Acknowledgements

This study was supported by a research grant for the Global Change Observation Mission of the Japan Aerospace Exploration Agency (JAXA). This work used eddy covariance data acquired by the FLUXNET community and in particular by Kherlenbayan Ulaan site of AsiaFlux, operated by Dr. J. Asanuma, Dr. S.-G. Li, and Dr. G. Davaa.

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