Spatio-temporal changes in evapotranspiration over China using GLEAM_V3.0a products (1980–2014)
Xiuqin Yang, Bin Yong, Yixing Yin and Yuqing Zhang

ABSTRACT
This study used land evapotranspiration (ET) values from 61 ChinaFLUX eddy covariance (EC) sites and water-balanced derived ET in ten basins to investigate the performance of Global Land Evaporation Amsterdam Model (GLEAM) V3.0a ET estimates (i.e., ETG) over China. We quantified the spatio-temporal characteristics of ETG and the impact of precipitation (P) and potential ET (ETP) on ETG. ETG was appropriate for estimating daily, seasonal, and annual ET rates. The mean annual ETG increased progressively from the northwest to southeast of China. Domain-averaged annual ETG over China was 421.90 mm year\(^{-1}\) during 1980 to 2014. The spatial patterns of ETG were in accordance with those of annual precipitation. Low ETG values occurred in the Northwestern River Basin, and relatively high ET values were found across southern China. ETG showed the highest annual variation in the Northwestern River Basin and low variation in the southwest region, which captured seasonal variations with maxima in summer and minima in winter. The inter-annual variation of annual ETG and ETP differed significantly from 1980 to 2014, yielding prominent spatial variability around –16.50 to 9.10 mm year\(^{-2}\) and –1.90 to 4.70 mm year\(^{-2}\), respectively. Annual ETG is correlated well with P and ETP at each site.

Key words | China, EC ET, ETG product, spatial and temporal variation, water-balanced ET

INTRODUCTION
Climate change alters the world’s series of complex land-atmospheric interactions and has a marked effect on global water cycles (Martens et al. 2016b), including air temperature, precipitation, runoff, and land evapotranspiration (ET). It is necessary to use long time periods with measured and uniform datasets to evaluate the response to global climate change. Most hydrological variables can be readily measured at different spatio-temporal scales, but large-scale ET measurements are difficult to obtain because water flux cannot be directly sensed via satellite. Hydrological cycles present considerable uncertainties, mainly because land water availability impacts ET (Dolman et al. 2014). Researchers have become increasingly aware of the importance of ET in terms of climatic systems, linking hydrologic and energy cycles, regulating air humidity, near surface air temperature and precipitation, and other factors (Seneviratne et al. 2010; Miralles et al. 2012). Recent years have seen numerous efforts to reliably estimate ET variability at the global scale. There has been substantial progress in this regard, especially in regularly observing evaporation at tower sites (Wang & Dickinson 2012), which can be used to obtain in-situ measurements across different global climatic regions (Baldocchi et al. 2001; Jung et al. 2009). Unfortunately, current in-situ eddy covariance (EC) observations are relatively sparse and not sufficient to research ET variability over large spatial and temporal scales (Yang et al. 2017).

In regards to hydrological, agricultural, and climatic applications, the potential of satellite retrieval has been extensively explored as it relates to ET dynamics. The
disadvantages of in-situ observations and the fact that evaporation cannot be directly detected from space-based measurement technologies have led researchers to develop several novel techniques for estimating terrestrial evaporation based on satellite remote sensing data (Martens et al. 2016a).

The spatial distribution examined by different ET methodologies are generally closely consistent with each other within a given region (Mueller et al. 2011); however, there are large apparent differences in ET products during space and time. Modeled ET products generally present uncertainty ranging from 15% to 30% (Bastiaanssen et al. 2005; Kalma et al. 2008; Senay et al. 2008). The uncertainties of large-scale ET products are approximately 50% of the mean annual ET (i.e., AET) (Mueller et al. 2011; Vinukollu et al. 2011a). The domain-averaged ET over China varies considerably across different ET models, ranging from 369.80 mm year\(^{-1}\) to 500.00 mm year\(^{-1}\) (Liu et al. 2013a; Li et al. 2014). These large uncertainties likely originate from complications in modeling ET and do not facilitate direct ET observations.

Existing models can be used to retrieve continuous, long series, and globally reliable ET products; however, the existing methodologies and input datasets for these ET models markedly differ (Mu et al. 2007; Fisher et al. 2008; Zhang et al. 2010; Miralles et al. 2011b; Martens et al. 2016b). The Global Land Evaporation Amsterdam Model (GLEAM) (Miralles et al. 2011b) is the sole global ET methodology. It has three features distinguishing it from other models. First, the model is mainly forged by satellite-based retrievals and considers soil moisture as constraints for land evaporation. Second, it provides self-sufficient and accurate parameterization of tall-canopy interception loss using Gash’s analytical model (Gash 1979). Third, it uses vegetation optical depth (VOD) as a substitute for vegetation water content (Liu et al. 2013b) to calculate evaporative stress (Miralles et al. 2011b, 2014b; Martens et al. 2016a).

Recently, GLEAM ET models have been extensively applied to diagnose spatial variations as well as trends in hydrological cycles (Jasechko et al. 2015; Greve et al. 2014; Miralles et al. 2014a; Zhang et al. 2016) and land-atmosphere interactions (Miralles et al. 2014b; Guillod et al. 2015). Several researchers have evaluated GLEAM ET products at different spatiotemporal scales (Miralles et al. 2011b; Liu et al. 2016b; Martens et al. 2016b). Multi-scale validation of the GLEAM ET products also has been performed over China, but with relatively few in-situ observations and shorter time periods (Yang et al. 2017). The third version of GLEAM products was adopted in this study because it can be readily obtained online, and because the new version of GLEAM ET/potential ET (ET\(_p\)) spans the entire globe over the time period from 1 January 1980 to 31 December 2014.

In this study, we used daily EC measurements of eight in-situ sites from the Chinese Flux Observation and Research Network (ChinaFLUX) and a comprehensive AET dataset comprising 61 EC flux sites data over China, constructed by Zheng et al. (2016), to evaluate the third version of GLEAM (GLEAM_V3.0a) at the point scale, accumulated by season and year as well as at the basin scale. We also sought to quantify the spatio-temporal changes in ET over terrestrial China from 1980 to 2014.

## DATASETS AND METHODOLOGY

**GLEAM_V3.0a land ET datasets**

GLEAM was designed to create ET products only based on satellite-derived data (Miralles et al. 2011a, 2011b). The GLEAM model has been regularly improved in order to incorporate new satellite-based retrievals and to provide a more realistic understanding of physical processes linked to evaporation since its original establishment in 2011. The third version (V3.0) of the GLEAM model was released in August 2016. This version features three main changes from the previous version: a modified evaporative stress function, optimized precipitation drainage algorithm, and a new soil moisture data assimilation system.

GLEAM V3.0 has reproduced three new ET datasets, including a 35-year dataset ranging from 1 January 1980 to 31 December 2014 (i.e., GLEAM_V3.0a), and two solely satellite-derived datasets (GLEAM_V3.0b and GLEAM_V3.0c). These three datasets were further detailed by Martens et al. (2016b), and evaluated using EC observations at 64 FLUXNET sites spanning a wide range of land cover types. The revised Priestley–Taylor model (Priestley et al. 1972) can be used to estimate potential evapotranspiration (ET\(_p\)) based
on observations of near-surface air temperature and surface net radiation in the model; ET\textsubscript{P} can then be transformed into ET by multiplying so-called evaporative stress factors. GLEAM outputs several intermediate products including ET\textsubscript{P}, root-zone soil moisture (SM\textsubscript{roost}), surface soil moisture (SM\textsubscript{surf}), and evaporative stress (S).

The dataset used in this study (GLEAM\_V3.0a) is based on remotely sensed observations (including soil moisture, VOD, and snow water equivalents), reanalysis air temperature and net radiation, and satellite and gauge-based precipitation products. It comprises global high temporal resolution ET and ET\textsubscript{P} products with resolution of daily/0.25° x 0.25° spanning the period from 1 January 1980 to 31 December 2014, and can be freely obtained online via www.GLEAM.eu.

Validation datasets

There are several networks which use the EC technique to directly and continuously measure ET, including the global network FLUXNET, CarboEuroFLUX, Ameriflux, and ChinaFLUX, which have been functioning for several years and contribute crucial measurements related to spatial variations in ET (Baldocchi et al. 2001). Latent heat flux data from EC sites were used as the benchmark to evaluate the GLEAM\_V3.0a ET data in this study, which was obtained from two sources. The first source includes daily observations from eight typical EC sites from the ChinaFLUX website (http://www.chinaflux.org/), ChinaFLUX has carried successive latent heat flux measurement at said eight sites since 2002 (Yu et al. 2006): four forest sites, three grassland sites, and one cropland site. We also obtained ready-made AET products from other ChinaFLUX in-situ sites over China that are available in the literature (Zheng et al. 2016), including 15 forest sites, 15 grassland sites, 15 cropland sites, and eight wetland sites. Details of these 61 sites can be found in our references (Yu et al. 2006; Zheng et al. 2016).

In practice, ET data tower-measured by EC techniques are typically processed by the corresponding site researchers. Only sites with at least one year of successive latent heat flux measurements were used to build our dataset. EC observations were not possible at ten sites located in cold climate types during winter, including Aro (No. 20), Changling (No. 21), and Siziwang (No. 30, 31). Sites located in these land cover types representing a unique ecoregion were also selected in this study, as they are very important for accurate spatial distribution analysis. Compared to the actual ET, the cold-season EC observations are relatively sparse in these ecosystems, so the EC data observed in warm seasons (or longer-term) were used to replace the actual ET. By incorporating the two above-mentioned data sources, Zheng et al. (2016) constituted the most integrated annual actual ET dataset from EC sites in China to date.

These 61 observation sites encompass a large range of latitudes (21.57° N to 47.58° N), altitudes (3.8 m to 4,333.0 m), climates, and eight major typical ecosystem types: evergreen needleleaf forest (ENF), evergreen broad-leaf forest (EBF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF), mixed forest (MF), grasslands (GRA), croplands (CRO), and wetlands (WET) (Figure 1, Table 1). Table 1 provides a simple description for all 61 sites (Zheng et al. 2016). More detailed information of each site is available in the references, and also listed in Table 1. The measured accumulated annual ET from EC sites with at least one year of measurements were directly used for evaluation in this study; for sites with more than two years of ET measurements, the mean annual ET during observational periods were adopted to remove temporal variability. We also used the mean climatic factors (precipitation) during identical measuring periods.

In summary, we used daily EC data from eight ChinaFLUX sites and mean annual ET data from other ChinaFLUX sites via Zheng (2016) for GLEAM\_V3.0a ET data validation.

Precipitation and runoff data in ten river basins

GLEAM\_V3.0a ET products were further evaluated at basin scales over China. The Chinese mainland is divided into ten major river basins by the Ministry of Water Resources (MWR): Songhua, Liao, Hai, Yellow, Huai, Yangtze, Southeast, Pearl, Southwest, and Northwest river basins (Liu et al. 2013a) (Figure 1, Table 2). The boundaries of these ten river basins are defined based on topographic river basin divides.

The GLEAM\_V3.0a ET estimates were also evaluated across ten river basins over China based on water balance principle. The annual total precipitation (hereafter denoted as P) and runoff (R) data series for the ten river basins

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[Refer to the original paper for complete citations and further details.]
ranging from 2003 to 2011 were publicly obtained from ‘China water resources bulletin’ of the MWR online (http://www.mwr.gov.cn/zwzc/hygb/szygb/qgszygb/). Songhua and Liao river basins were combined into a single basin (i.e., Song-Liao river basin) in the ‘China water resources bulletin’ before 2003. Thus, the annual P and R of Songhua and Liao river basins were only accessible post-2003. We assumed that the changes in water storage over more than one year can be ignored in a closed river basin (Vinukollu et al. 2014), therefore, water balanced annual ET was computed as a residual of annual P minus annual runoff (P/R) (hereafter denoted as ETw) at basin scale, and referenced as the true value of actual ET.

Auxiliary data

The land cover map of ‘WESTDC_Land_Cover_Products 2.0’ over China at the same spatial resolution as GLEAM_V3.0a was taken from the Western Environmental and Ecological Science Data Center of China online (http://westdc.westgis.ac.cn) (Figure 1). China ground daily precipitation products (V2.0) at spatial resolution of 0.25° × 0.25° were used to study the effect on actual ET and for linear trend analysis over 1980 to 2014; they were interpolated based on high-density stations (2,472 national meteorological observational stations) over China from the National Meteorological Information Center, China Meteorological Administration (CMA). The precipitation products can be freely obtained online (http://data.cma.cn/) and show high quality after cross-validation and error analysis.

Evaluation methodology

The spatial resolution of the 0.25° × 0.25° grid-size GLEAM_V3.0a ET estimates do not agree well with the point scale ChinaFLUX EC measurements. In this study, we directly perform the grid-site validation analysis between the two ET data sources. Thus, we chose the grid based on EC site situation information across China for the purposes of this comparison. Many previous studies have used the grid-based comparison method (Adler et al. 2003; Choknagwong & Chiu 2008; Yong et al. 2010; Yang et al. 2016, 2017). Based on the 61 selected grids, the validation is implemented during identical measuring periods for each EC site, respectively. The daily values of GLEAM_V3.0a ET estimates and EC measurements were accumulated to operate the seasonal and annual scale validation.

We focused on analyzing the performance of GLEAM_V3.0a ET across different climate and land covers, as well as evaluating the effect of annual precipitation (P) and ETp on the spatial variability in actual ET. The GLEAM_V3.0a ET estimates were regarded as actual ET.
Table 1 | Attributes of the 61 EC flux sites used for GLEAM_V3.0a ET validation at point scale

<table>
<thead>
<tr>
<th>No.</th>
<th>Sites</th>
<th>Latitude, longitude</th>
<th>Land cover type</th>
<th>MAP (mm year$^{-1}$)</th>
<th>AET (mm year$^{-1}$)</th>
<th>Observational periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ailaoshan</td>
<td>24.53°N, 101.02°E</td>
<td>EBF</td>
<td>1,364.1</td>
<td>803.0</td>
<td>2010</td>
</tr>
<tr>
<td>2</td>
<td>Changbaishan</td>
<td>42.40°N, 128.10°E</td>
<td>MF</td>
<td>736.5</td>
<td>524.4</td>
<td>2003–2010</td>
</tr>
<tr>
<td>3</td>
<td>Changping</td>
<td>40.17°N, 116.13°E</td>
<td>DBF</td>
<td>473.5</td>
<td>790.6</td>
<td>2011</td>
</tr>
<tr>
<td>4</td>
<td>Dinghushan</td>
<td>23.17°N, 112.53°E</td>
<td>EBF</td>
<td>1,702.0</td>
<td>733.2</td>
<td>2003–2010</td>
</tr>
<tr>
<td>6</td>
<td>Gonggashan</td>
<td>29.58°N, 102.00°E</td>
<td>ENF</td>
<td>1,940.0</td>
<td>598.0</td>
<td>2009</td>
</tr>
<tr>
<td>7</td>
<td>Guantan</td>
<td>38.53°N, 100.25°E</td>
<td>ENF</td>
<td>428.0</td>
<td>417.0</td>
<td>2011</td>
</tr>
<tr>
<td>8</td>
<td>Hualing</td>
<td>33.00°N, 117.00°E</td>
<td>EBF</td>
<td>1,500.0</td>
<td>965.8</td>
<td>2005–2006</td>
</tr>
<tr>
<td>9</td>
<td>Huitong</td>
<td>26.83°N, 109.75°E</td>
<td>ENF</td>
<td>1,107.0</td>
<td>709.4</td>
<td>2009</td>
</tr>
<tr>
<td>10</td>
<td>Kubuqi</td>
<td>40.54°N, 108.69°E</td>
<td>DBF</td>
<td>318.0</td>
<td>351.6</td>
<td>2006</td>
</tr>
<tr>
<td>11</td>
<td>Laoshan</td>
<td>45.33°N, 127.57°E</td>
<td>DNF</td>
<td>700.0</td>
<td>325.4</td>
<td>2004–2006</td>
</tr>
<tr>
<td>12</td>
<td>Menglun</td>
<td>21.93°N, 101.27°E</td>
<td>EBF</td>
<td>1,504.0</td>
<td>1125.0</td>
<td>2008</td>
</tr>
<tr>
<td>13</td>
<td>Miyun</td>
<td>40.63°N, 117.32°E</td>
<td>DBF</td>
<td>589.2</td>
<td>603.6</td>
<td>2008–2010</td>
</tr>
<tr>
<td>14</td>
<td>Qianyanzhou</td>
<td>26.74°N, 115.06°E</td>
<td>ENF</td>
<td>1,379.6</td>
<td>809.6</td>
<td>2003–2011</td>
</tr>
<tr>
<td>15</td>
<td>Taihuyuan</td>
<td>30.18°N, 119.34°E</td>
<td>EBF</td>
<td>1,201.7</td>
<td>669.8</td>
<td>2011</td>
</tr>
<tr>
<td>16</td>
<td>Xiaolangdi</td>
<td>33.02°N, 112.47°E</td>
<td>MF</td>
<td>641.7</td>
<td>556.7</td>
<td>2007–2009</td>
</tr>
<tr>
<td>17</td>
<td>Xishuangbanna</td>
<td>21.93°N, 101.27°E</td>
<td>EBF</td>
<td>1,321.8</td>
<td>1028.8</td>
<td>2003–2006</td>
</tr>
<tr>
<td>18</td>
<td>Yueyang</td>
<td>29.31°N, 112.51°E</td>
<td>DBF</td>
<td>1,500.6</td>
<td>727.1</td>
<td>2006</td>
</tr>
<tr>
<td>19</td>
<td>Zhaoxian County</td>
<td>37.80°N, 114.95°E</td>
<td>DBF</td>
<td>507.0</td>
<td>759.0</td>
<td>2011</td>
</tr>
<tr>
<td>20</td>
<td>Aro</td>
<td>38.04°N, 100.46°E</td>
<td>GRA</td>
<td>403.0</td>
<td>334.3</td>
<td>2008</td>
</tr>
<tr>
<td>21</td>
<td>Changling</td>
<td>44.58°N, 123.50°E</td>
<td>GRA</td>
<td>296.1</td>
<td>315.7</td>
<td>2007–2008</td>
</tr>
<tr>
<td>22</td>
<td>Duolun County</td>
<td>42.05°N, 116.28°E</td>
<td>GRA</td>
<td>424.0</td>
<td>433.5</td>
<td>2006</td>
</tr>
<tr>
<td>23</td>
<td>Dangxiang</td>
<td>30.85°N, 91.08°E</td>
<td>GRA</td>
<td>451.2</td>
<td>529.2</td>
<td>2004–2010</td>
</tr>
<tr>
<td>24</td>
<td>Fukang</td>
<td>44.28°N, 87.93°E</td>
<td>GRA</td>
<td>175.2</td>
<td>205.0</td>
<td>2004</td>
</tr>
<tr>
<td>25</td>
<td>Haibei</td>
<td>37.60°N, 101.30°E</td>
<td>GRA</td>
<td>641.9</td>
<td>391.3</td>
<td>2002–2004</td>
</tr>
<tr>
<td>26</td>
<td>Haibe, shrubland meadow</td>
<td>37.66°N, 101.33°E</td>
<td>GRA</td>
<td>497.6</td>
<td>536.4</td>
<td>2003–2011</td>
</tr>
<tr>
<td>27</td>
<td>Kubuqi, shrubland</td>
<td>40.38°N, 108.55°E</td>
<td>GRA</td>
<td>318.0</td>
<td>329.8</td>
<td>2006</td>
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<td>28</td>
<td>Sanjiangyuan</td>
<td>34.35°N, 100.50°E</td>
<td>GRA</td>
<td>479.0</td>
<td>462.0</td>
<td>2006–2008</td>
</tr>
<tr>
<td>29</td>
<td>Sunitezuo</td>
<td>44.08°N, 113.57°E</td>
<td>GRA</td>
<td>175.6</td>
<td>206.9</td>
<td>2008–2009</td>
</tr>
<tr>
<td>30</td>
<td>Siziwang Banner, fenced</td>
<td>41.79°N, 111.89°E</td>
<td>GRA</td>
<td>325.0</td>
<td>71.8</td>
<td>2010</td>
</tr>
<tr>
<td>31</td>
<td>Siziwang Banner, grazed</td>
<td>41.79°N, 111.90°E</td>
<td>GRA</td>
<td>325.0</td>
<td>116.5</td>
<td>2010</td>
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<tr>
<td>32</td>
<td>Tianjun</td>
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<td>GRA</td>
<td>388.2</td>
<td>236.1</td>
<td>2011</td>
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<tr>
<td>33</td>
<td>Tongyu</td>
<td>44.59°N, 122.52°E</td>
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<td>296.0</td>
<td>291.5</td>
<td>2003–2008</td>
</tr>
<tr>
<td>34</td>
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<td>GRA</td>
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<td>287.1</td>
<td>2004–2006</td>
</tr>
<tr>
<td>35</td>
<td>Xilin Gol</td>
<td>43.55°N, 116.68°E</td>
<td>GRA</td>
<td>289.3</td>
<td>347.5</td>
<td>2004–2011</td>
</tr>
<tr>
<td>36</td>
<td>Xilinhot, grazed</td>
<td>43.55°N, 116.67°E</td>
<td>GRA</td>
<td>447.5</td>
<td>301.4</td>
<td>2006</td>
</tr>
<tr>
<td>37</td>
<td>Xilinhot, fenced</td>
<td>43.55°N, 116.68°E</td>
<td>GRA</td>
<td>371.6</td>
<td>352.6</td>
<td>2006</td>
</tr>
<tr>
<td>38</td>
<td>Duolun County</td>
<td>42.05°N, 116.67°E</td>
<td>CRO</td>
<td>424.0</td>
<td>394.8</td>
<td>2006</td>
</tr>
<tr>
<td>39</td>
<td>Daxing</td>
<td>39.62°N, 116.43°E</td>
<td>CRO</td>
<td>446.4</td>
<td>664.7</td>
<td>2008–2010</td>
</tr>
<tr>
<td>40</td>
<td>Dingxi</td>
<td>35.55°N, 104.58°E</td>
<td>CRO</td>
<td>382.3</td>
<td>252.4</td>
<td>2010</td>
</tr>
</tbody>
</table>

(continued)
and defined as ET_G. Four validation statistics indices were employed to validate the performance of GLEAM_V3.0a ET products against in-situ EC observations: relative bias (RB), correlation coefficient (CC), root mean square error (RMSE), and mean absolute error (MAE) (Yang et al. 2016):

\[
RB = \frac{\sum_{i=1}^{n} (y_i - x_i)}{\sum_{i=1}^{n} x_i} \times 100\% 
\]

\[
CC = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} 
\]
ETG is the mean value of annual Hydrology Research | 49.5 | 2018

where $n$ represents number of samples including $ET_G$, $ET_P$, and $P$; $x_i$; and $y_i$ are observed EC ET rates from in-situ EC sites and $ET_G$ rates extracted from GLEAM_V3.0a ET products based on the $i$th site location, respectively, while $\bar{x}$ and $\bar{y}$ are the variables' respective mean values. CC is the fraction of the variation in EC measurements that can be accounted by the GLEAM_V3.0a ET products. RB, RMSE, and MAE were used to quantify the biases between the modeled ET products and the EC observations.

A linear regression equation (Zhang et al. 2009) was adopted to examine the regional linear trends of annual variables from 1980 to 2014. Statistical significances of CC and linear trends were calculated using a $t$-test:

$$y = ax + b$$

(5)

$$a = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$

(6)

where $n$ represents the number of years ($n = 35$ in our study); $x_i$ is the serial number of years ($x_i = 1, 2, 3, \ldots, 35$); $y_i$ is the annual ET$_G$, ET$_P$, and P in the $i$th year. If $a > 0$, the variable has an increasing trend (and vice versa). Given the significance level of $\alpha = 0.05$, we obtained the correlation coefficient (CC) critical value $CC_0(n-2)$ by calculation or using a look-up table, where $CC_0(n-2) = CC_{0.05,35} = 0.33$. The critical value for 95% confidence level in this study was $\pm 0.33$. If $|CC| > 0.33$, the variable change trend was considered statistically significant (Jiang et al. 2015; Liu et al. 2016a).

We also used the coefficient of variation ($C_V$) to evaluate the spatial pattern of annual ET$_G$ (Milich & Weiss 2000). $C_V$ is a statistic describing the extent of dispersion of a random variable:

$$C_V = \frac{\sigma_{ET_G}}{ET_G}$$

(7)

where $C_V$ is the coefficient of variation of annual ET$_G$ at each grid, $\sigma_{ET_G}$ is the standardized deviation of annual ET$_G$ at each grid, and ET$_G$ is the mean value of annual ET$_G$ from 1980 to 2014 at each grid. $C_V$ was computed at each grid to analyze the stability of ET$_G$ over the 35-year study period. A higher $C_V$ value indicates more discreteness and temporal instability in the ET$_G$ time series, and vice versa. The values of $C_V$ at each grid were placed into five levels (Table 3).

### RESULTS AND ANALYSIS

#### ET$_G$ estimates validation at point scales and basin scales

Gridded GLEAM_V3.0a ET estimates were extracted based on the eight ChinaFLUX EC sites and validated against the EC measurements at the daily time scale. The daily GLEAM_V3.0a ET products were evaluated against EC measurements at four forest sites (Changbaishan, Qianyanzhou, Dinghushan, and Xishuangbanna), three grassland sites (Haibei, Xilinhot, and Dangxiong), and one cropland site (Yucheng). The GLEAM_V3.0a and EC measured daily ET rates were closely correlated, with CC above 0.68, except at Dinghushan and Xishuangbanna forest sites (CCs of 0.58 and 0.49, respectively, and RMSEs of 1.23 and 1.19 mm d$^{-1}$) (Figure 2(a)–2(h)). However, the modeled ET products tended to overestimate daily ET rates at the four forest sites and Xilinhot grassland site while underestimating them at Haibei and Dangxiong grassland sites and the Yucheng cropland site. These results are in accordance with Mo et al. (2015), who reported CC of 0.78 and RMSE of 1.03 mm d$^{-1}$ against daily EC measurements at the

<table>
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<tr>
<th>$C_V$ of ET$_G$</th>
<th>Volatility degree</th>
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<tr>
<td>$C_V \leq 0.05$</td>
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</tr>
<tr>
<td>$0.05 &lt; C_V \leq 0.10$</td>
<td>Relatively low volatility degree</td>
</tr>
<tr>
<td>$0.10 &lt; C_V \leq 0.15$</td>
<td>Middle volatility degree</td>
</tr>
<tr>
<td>$0.15 &lt; C_V \leq 0.20$</td>
<td>Relatively high degree</td>
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<td>$C_V &gt; 0.20$</td>
<td>High volatility degree</td>
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Table 3 | Statistics of coefficient of variation ($C_V$) of ET$_G$ over China
Yucheng cropland site. Overall, we concluded that the daily GLEAM_V3.0a ET estimates are quite close to EC measurements with poor performance only at Dinghushan and Xishuangbanna forest sites.

We further validated GLEAM_V3.0a ET estimates using mean annual EC measurements from 61 flux sites as a benchmark at the annual scale. The GLEAM_V3.0a ET estimates performed well in reflecting annual ET variations, with CC of 0.77 and RB of $-13.46\%$ (Figure 3). Overall, the GLEAM_V3.0a ET performed relatively well with RMSE of 174.20 mm year$^{-1}$ and MAE of 132.98 mm year$^{-1}$, which is in accordance with previous studies. Zheng et al. (2016), for example, reported five ET products with RMSE values ranging from 103.50 to 226.50 mm year$^{-1}$ and MAE ranging from 105.12 to 153.98 mm year$^{-1}$. GLEAM_V3.0a ET estimates (456.90 mm year$^{-1}$) underestimated the average annual ET rates compared to the EC technique (534.90 mm year$^{-1}$) during identical measuring periods for all 61 sites.

Figure 4(a) shows the mean annual ETG rates and EC measurements during identical measurement periods for each EC site, and Figure 4(b) shows the relative bias (RB) of annual ETG compared to annual EC ET at each EC site. There were considerable deviations in estimating each in-site annual EC ET rate, with RBs mostly falling between $-40\%$ and $40\%$, which is superior to the previous report.
by Zheng et al. (2016). In forest sites, only the RB of Kubuqi (No. 10 in Table 1) and Zhaoxian County (No. 19) forest sites slightly exceeded −40%, reaching −49% and −46%, respectively. The highest RB was 258% for the Siziwang Banner fenced grassland site (No. 30, Figure 4(b)), which has low vegetation coverage; this was followed by an RB of 121% at the Siziwang Banner grazed grassland site (No. 31, Figure 4). In cropland sites, the absolute RB values of Dingxi (No. 40), Shiyang River (No. 47), Wulanwusu (No. 49), Wuwei (No. 51), and Yingke (No. 53) were above 40%, but all were relatively small without exceeding 40% at the wetland sites.

EC measurements certainly present some uncertainty, although they are commonly used as a benchmark to validate modeled ET products. Many studies have confirmed an energy imbalance at EC sites which has been computed ranging from 10% to 30% and found to indirectly result in underestimating latent heat flux (LE) (Twine et al. 2000; Baldocchi et al. 2001; Wilson et al. 2002; Yu et al. 2006; Tang et al. 2011, 2013; Mo et al. 2015). Li et al. (2005) used statistical regression between EC-measured turbulent heat fluxes (H) and surface available energy to evaluate the energy balance of ChinaFLUX, and reported that lack of energy closure was widespread at all EC sites – hence, the EC observations may contain some errors.

GLEAM_V3.0a ET estimates were also validated using water balance-derived annual ET (denoted as ETw) in ten river basins over China from 2003 to 2011 (Figure 5) at the annual scale. Annual ETG values were closely correlated with ETw at the basin scale, with CC of 0.91, RB of 25.9%, and RMSE of 171.80 mm year$^{-1}$ in the ten basins (Figure 5(a)). Zhang et al. (2010) reported an RMSE of 186.30 mm year$^{-1}$ and CC of 0.89 against water-balanced ET products for 261 basins covering 61% of the globe’s vegetated areas. Liu et al. (2016b) evaluated GLEAM V2.0 ET data at the Yangtze river basin with RMSE of 142.03 mm year$^{-1}$. Annual ETG performed higher than the ETw values in almost all years of the nine-year study period for each river basin (Figure 5(a)). However, the differences between annual ETG and ETw were relatively high except at Liao, Yellow, and Huai river basins (Figure 5(b)); ETG was overestimated in almost all regions during 2003 to 2011.

**Spatial distribution of ETp, P, and ETG at annual scale during 1980–2014**

Solar radiation and P are the two key factors controlling long-term terrestrial ET rates at the local scale, and the available energy can be represented by ETp. Figure 6(a) shows that there were substantial differences in the spatial patterns of annual mean ETG values over China from 1980 to 2014; they increased progressively from northwest to southeast China, and were significantly linked with precipitation and
land cover type (Figure 1). Previous studies have yielded similar results (Liu et al. 2008; Chen et al. 2014; Mo et al. 2015). The spatial distribution of annual ETG varied between 0 and 1,535.00 mm year$^{-1}$, and the mean annual ETG over mainland China was 421.90 mm year$^{-1}$ during the study period; these values are also in accordance with previously reported Chinese and global ET values. Liu et al. (2013a) and Li et al. (2014) reported annual ET values that varied from 369.80 to 500.00 mm year$^{-1}$ over China. Dirn Meyer et al. (2006), for example, found average global ET ranging from 272.00 to 441.00 mm year$^{-1}$. Fisher et al. (2008) calculated a global mean ET value of about 444.00 mm year$^{-1}$ for 1986 to 1993; Yuan et al. (2010) reported a global mean ET of about 417.00 mm year$^{-1}$ for 2000 to 2003. Much higher global mean ET values were predicted by Ryu et al. (2011) (500.00 mm year$^{-1}$), Zhang et al. (2010) (539.00 mm year$^{-1}$).
year\(^{-1}\), and Jung et al. (2010) (550.00 mm year\(^{-1}\)). Mueller et al. (2011) confirmed that annual global ET values are dependent on the types of models used to calculate them. In all, the mean annual ET\(_G\) in China was lower than several recently reported global ET values.

We used corresponding ET\(_P\) estimates from GLEAM V3.0a products to analyze the spatial distribution of potential evaporation. As shown in Figure 6(b), the spatial distribution of ET\(_P\) presented significant spatial heterogeneity accompanied with latitude and terrain elevation. Low ET\(_P\) values from 196.00 to 500.00 mm year\(^{-1}\) were mainly observed in the Northwest and Liao river basins. High ET\(_P\) values from 800.00 to 1,593.00 mm year\(^{-1}\) were found in the Pearl river basin and Taiwan province.

Overall, the mean annual ET\(_G\) was higher in humid tropics and sub-tropics with a wide distribution of EBF and ENF (e.g., Pearl and Southeast river basins) (Figures 1 and 6(a)). It was lower in cold and arid areas of the Northwest river basin. The ET\(_G\) spatial distribution is approximately in agreement with that of annual P (Figure 6(c)), which showed that annual ET\(_G\) is controlled by P at the region scale.

Averaged over the basin scale, the Pearl river basin showed the highest mean annual ET\(_G\) at 980.80 mm year\(^{-1}\), followed by that in the Southeast (962.60 mm year\(^{-1}\)), Yangtze (658.80 mm year\(^{-1}\)), and Huai river basins (617.20 mm year\(^{-1}\)). Average ET\(_G\) was the lowest in the Northwest river basin (171.10 mm year\(^{-1}\)) followed by that in the Yellow river basin (371.80 mm year\(^{-1}\)). In Songhua and Liao river basins, mean annual ET\(_G\) ranged from 500.00 to 600.00 mm year\(^{-1}\) under forest land covers and ranged from 300.00 to 500.00 mm year\(^{-1}\) under cropland and grassland land covers. Mean annual ET\(_G\) was about 588.70 mm year\(^{-1}\) in the Hai river basin, which is mainly covered by croplands. In the arid Northwest river basin, mean annual ET\(_G\) was less than 200.00 mm year\(^{-1}\) due to sparse precipitation and vegetation. In the Southwest river basin, mean annual ET\(_G\) was about 537.40 mm year\(^{-1}\) and had significant spatial variation; it was lower than 400.00 mm year\(^{-1}\) in the northern parts of the basin and ranged from 700.00 to 1,200.00 mm year\(^{-1}\) in southern parts of the basin. In a word, we confirmed that the mean annual ET\(_G\) in the terrestrial ecosystems of China is slightly lower than the global ET due to the widely distributed semiarid and arid regions in northwestern and northern regions of the country and the large area of the frigid Tibetan Plateau, in which ET is very low (Figure 6(a)).

Figure 6(d) shows the spatial heterogeneity of ET\(_G\) over China using \(C_V\) values for all grids. The \(C_V\) of ET\(_G\) showed the highest variation in the Northwest river basin (\(C_V > 0.20\)), which is a typical high-altitude and arid, ecologically fragile area. There was little variation in the \(C_V\) of ET\(_G\) over the southwest reaches of China.

### Seasonal variation of ET\(_G\)

As shown in Figure 7, the spatial distribution of multi-year averaged seasonal ET using GLEAM V3.0a ET estimates over China from 1980 to 2014 were very distinct from the seasonal variations. The climate conditions appeared to be the main controlling factor in the seasonal distributions and spatial variations of ET. The spatial distributions of ET\(_G\) differed from east to west and from north to south in China due to the country’s diverse climatic areas and land cover types.

Figure 7(a) shows that ET\(_G\) is relatively high in southeastern regions in spring (March, April, and May) due to abundant precipitation and solar radiation increasing the air temperature. The ET\(_G\) in Hainan and Taiwan reached 300.00–461.00 mm season\(^{-1}\) under mostly forest land cover, which comes with sufficient heat and water resources during the springtime. ET\(_G\) was relatively low in northern China due to low air temperature and precipitation. In summer (June, July, and August), ET\(_G\) increased continuously to a maximum of 547.00 mm season\(^{-1}\) in Taiwan due to surplus precipitation accompanied with the maritime monsoon. Northwestern China, inclusive of the Inner Mongolian grasslands and Tibetan Plateau, still showed low ET rates due to scarce vegetation and rainfall apart from one oasis (dependent on irrigation water input during crop growing season). Northeastern China, which is dominated by DBF and warm temperate steppes, displayed relatively high ET rates in summer compared to spring.

In autumn (September, October, and November), the ET rates decreased over southeastern China compared to summer. ET\(_G\) decreased significantly in the vegetative eastern regions, where rainfall and air temperature gradually decreased. The maximum seasonal ET\(_G\) still exceeded
300.00 mm in the furthest southern subtropical regions including Hainan and Taiwan province. In the cold and dry winter (December, January, and February), ETG was no more than 100.00 mm season$^{-1}$ over most regions of China due to inactive canopies, low temperature, and precipitation.

In conclusion, the spatial distributions of seasonal ETG differed considerably. Water transferred from land to the atmosphere by ET primarily appeared in summer across highly vegetated areas. GLEAM_V3.0a displayed significant ET seasonality (Figure 7), encompassing the seasonal variations in average ET for the years from 1980 to 2014 with maxima in summer and minima in winter.

**Temporal trends of annual ETG, ETp, and P**

The temporal trends spatial patterns of annual ETG, ETp, and P over China from 1980 to 2014 were vastly different (Figure 8). Trends in P and ETp were generally completely opposite across northeast, south, and southwest China. Decline in P resulted in atmospheric vapor deficit and increase in evaporative ability causing ETp to increase.

ETG rates increased across most of the Chinese mainland. The high increasing rates of annual ETG occurred in the cropland areas of southeast Yangtze and south Huai river basins, even exceeding 2.00 mm year$^{-2}$. Annual ETG rates also increased from 0 to 2.00 mm year$^{-2}$ in the forest regions of Songhua and Yellow river basins, possibly due to agricultural development having caused more irrigation water input. The increasing trends of annual ETG were slight, only about 2.00 mm year$^{-2}$ in the Northwest river basin (including Inner Mongolia and the Tibetan Plateau). Annual ETG rates decreased in the southwestern Songhua, Northwest, Southwest, and western Pearl river basins. The decrease in ETG was most significant in the eastern Tibetan Plateau, the south of Yunnan province, Hainan province, and Taiwan, ranging from $-5.00$ to $-2.50$ mm year$^{-2}$.

ETG rates were on the decline in most southern areas due to decreases in P. Over the western part of the Qinghai-Tibetan Plateau, P and ETG increased alongside a slight decrease in ETp (Figure 8(a)). Figure 8(b) shows the temporal trends of ETp during the same study period. ETp mainly decreased in the Northwest river basin, upstream of the Yangtze river basin, and southwest parts of the Western river basin. Figure 8(c) shows the temporal trends of annual P during the 35-year study period, where P decreased in northeastern, northwestern, and southern China, including the southern Huai river basin, Songhua and Yangtze river basins, southern Southwest river basin, northwestern and eastern Northwest river basins, Pearl river basin, and
Taiwan. In some parts of these regions, the decreasing rates of annual P even exceeded 5.00 mm year\(^{-2}\).

Figure 9 shows the spatial distribution of significance (t-test) of annual \(ET_G\), \(ET_P\), and P trends under the significance level of \(\alpha = 0.05\) (95% confidence level). \(ET_G\) significantly increased in the eastern Yangtze river basin and western areas, while significantly decreasing trends were relatively sparse in only the western Songhua river basin and Taiwan (Figure 9(a)). The significant increase (2.50 mm year\(^{-2}\)) in annual \(ET_G\) in the southern Northwest river basin (Figure 9(a) and 9(c)) may have resulted from the large increase in annual P in these areas.

\(ET_P\) significantly increased in most parts of the Pearl, Southeast, Huai, central and eastern Yangtze, eastern
Yellow, northern Songhua, and Northwest river basins, which cover approximately half of China. Marked decreasing trends appeared in the western Southwest river basin, northwestern Yangtze river basin, Northwest river basin, and southern Taiwan (Figure 9(b)). P did not change significantly in most regions of China, but decreased significantly in a few areas in the Yangtze river basin and Southwest river basin. There were also increasing trends distributed in the southern part of the Tibetan Plateau of the Northwest river basin (Figure 9(c)).

**Variation of mean annual ETG during recent 35 years across different land covers**

The mean annual ETG, ETp, and P from 1980 to 2014 differed significantly among different land cover types at each EC site (Figure 10). The highest mean annual ETG was observed in wetlands (No. 57, No. 61) and forests (No. 12, No. 17), and the lowest ET values in croplands and grasslands.

Figure 11 shows the CC values of annual ETG with annual ETp and P from 1980 to 2014 over all land cover types (all EC sites), respectively. Annual ETG appears to be positively correlated with annual ETp (CC = 0.91) and P (CC = 0.95), which suggests that annual ETG is primarily dominated by P and ETp.

Table 4 shows that among all land covers, almost 63% (Nos. 1 to 19) of the forest sites, 55% (Nos. 20 to 37) of the grassland sites, 81% (Nos. 38 to 53) of the cropland sites, and 40% (Nos. 54 to 61) of the wetland sites experienced increasing trends. Only the annual ETG at five forest sites, one grassland site, five cropland sites, and one
Table 4 | Trends and significance test of annual ETG at each EC site in the vegetation types

<table>
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<tr>
<th>No.</th>
<th>Change rates of ETG mm 10 year⁻¹</th>
<th>CC</th>
<th>Significance</th>
<th>No.</th>
<th>Change rates of ETG mm 10 year⁻¹</th>
<th>CC</th>
<th>Significance</th>
<th>No.</th>
<th>Change rates of ETG mm 10 year⁻¹</th>
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<th>Significance</th>
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Note: Site numbers from 1 to 19 are forest sites; 20 to 37 are grassland sites; 38 to 53 are cropland sites; 54 to 61 are wetland sites.
wetland site showed significant ET increases from 1980 to 2014 (Table 4). Although the grasslands are mainly located in northern, drier areas, elevated ET rates may result in more severe droughts in those locations due to increases in soil moisture loss.

CONCLUSIONS

This study employed GLEAM_V3.0a ET products with resolution of 1 d/0.25° × 0.25° from 1980 to 2014 to make a series of analyses. The performance of the daily ET estimates was first evaluated against daily and annual EC measurements at 61 ChinaFLUX eddy-covariance flux sites. The annual ET rates were also validated with annual water-balanced derived ET in ten river basins across China. We also used the ET products to analyze the spatio-temporal variations of ET over mainland China. Our conclusions can be summarized as follows:

- There was no evident systematic error in the ET products, which can be used to estimate daily and annual ET rates effectively at point and basin scales. The products explained 68% and 77% variations of daily and annual EC measurements at the selected flux sites, as well as 91% of the variations in water-balanced annual ET values in all ten river basins. The annual ET estimates were larger than the ETw values in almost all years for each river basin.

- ETG showed obvious spatial patterns over the study period. The annual mean ETG increased from northwest to southeast China ranging from 0 to 1,535.00 mm year$^{-1}$, which agrees with trends in annual precipitation. This suggests that precipitation is the main controlling factor of ET at the regional scale. The national mean annual ETG over China was 421.90 mm year$^{-1}$. There were relatively low ET values distributed in the sparsely vegetated and deserted areas of the Northwest river basin; the greatest annual variation in ET products was found in the Northwest river basin and the least variation in southwestern regions. In short, the seasonal changes in mean ET during the study period were accurately represented with maxima in summer and minima in winter.

- The temporal trends of $ET_P$ and $ET_G$ with grid-based GLEAM_V3.0a products differed significantly across China, with a prominent spatial variability ranging from −1.90 to 4.70 mm year$^{-2}$ and −16.50 to 9.10 mm year$^{-2}$, respectively. $ET_G$ increased significantly in the eastern Yangtze river basin (maximum >5.00 mm year$^{-2}$) and western parts of the country. Decreasing trends were relatively sparse but did appear in the western Songhua river basin and Taiwan.

- The mean annual $ET_G$, $ET_P$, and $P$ were apparently controlled by land cover types at all selected EC sites. The highest ET values appeared at wetland and forest sites, while the lowest ET values were attributable to cropland and grassland sites. Annual $ET_G$ was primarily controlled by $P$ and $ET_P$. Almost 63% of the forest sites, 55% of the grassland sites, 81% of the cropland sites, and 40% of the wetland sites showed increasing trends. Only the annual $ET_G$ at five forest sites, one grassland site, five cropland sites, and one wetland site increased significantly.

The results of this study may be very useful in further researching the interactions among energy and water cycles, and also for water resource managers in China. There were uncertainties in our research worth mentioning. For instance, although GLEAM_V3.0a ET datasets were retrieved based on ground observations and remotely sensed data, there was some restricted access to meteorological observations and errors in the remote sensing vegetation parameters. These shortcomings may have introduced errors into the ET estimates. Further, the GLEAM_V3.0a ET model was only evaluated at a limited number of EC flux sites and ten largest basins over China. These issues could be rectified by further, more comprehensive and more detailed research. The $ET_G$ trends that are potentially attributable to global climate change and anthropogenic activity also merit further research. In the future, we plan to conduct continued research mainly focused on using the GLEAM_V3.0a ET to analyze concurrent events of drought and heatwaves over different ecosystem types in China.

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