Interannual variability of regional evapotranspiration under precipitation extremes: A case study of the Youngsan River basin in Korea

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1. Introduction

Vegetation plays a key role in the regional water cycle through evapotranspiration (ET). A number of recent observations have suggested that 40–60% of precipitation (P) can be lost through ET in temperate deciduous and coniferous forests (Jassal et al., 2009; Komatsu et al., 2007; Kosugi and Katsuyama, 2007; Wilson and Baldocchi, 2000), even in drought conditions (Brümer et al., 2012; Oishi et al., 2010). In future conditions with more intensified heavy precipitation and drought events (IPCC, 2013), it is critical to understand the variations in ET in relation to extreme P, because of the implications for regional water resource management.

It is widely recognized that ET is controlled by complex processes and interactions between the atmosphere, soil, and vegetation, which are characterized by the climatic, vegetation cover, and catchment features of the region (Baldocchi et al., 2004; Marc and Robinson, 2007; Ryu et al., 2008a; Zhang et al., 2004). Climatic factors such as precipitation, solar radiation, air temperature, humidity, and wind speed are primary influences on ET (Oishi et al., 2010; Penman, 1948; Zhang et al., 2004), because the

Understanding basin-scale evapotranspiration (ET) is an important issue for the management of regional water resources, especially with the recent trend of intensified precipitation (P). This study assessed the spatial and temporal variations of regional ET in response to P extremes, for various types of land-cover across the Youngsan River basin in Korea.

The spatial distribution of monthly P and ET from 2001 to 2009 were estimated using rainfall records from 40 weather stations located across the basin and a satellite-derived, process-based ET model Breathing Earth System Simulator (BESS) (Ryu et al., 2011), respectively. The study periods were focused on the recent years with abnormally large, small and normal P, which were identified from anomalies in the z-scores of long-term (1973–2011) rainfall records. The variation of regional ET was assessed in terms of: (1) the controlling factors, using the statistics of related meteorological and geographical data, (2) a water-energy balance, using Budyko’s framework, and (3) the water balance of four selected watersheds in the region, using the partitioning of annual P into ET and riverflow discharge (Q).

The total annual ET of this region decreased in abnormally large-P year and increased in small-P year, because the ET in July to August (which accounts for more than 36% of annual ET) was limited by the available energy rather than available water due to the summer monsoon. In terms of land cover types, forests showed larger interannual variability in ET than paddy fields or cropland, with the differences in ET between large and small-P years being 108 and 82 mm yr⁻¹, respectively. The sensitivity of annual ET to P extremes was significantly related to the leaf area index (LAI), rather than soil properties, topography, or specific land-cover type (p < 0.05, generalized linear model). However, the interannual variations of ET were not large (15–18%) compared to those of annual P (51–62%) and Q (108–232%) during 2002–2009. Thus, vegetation played a consistent role in releasing water back to the regional atmosphere through ET, regardless of P extremes.

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regional vegetation is exposed to similar atmospheric conditions. Coupled with the weather conditions, variations in ET depend on surface conductance (Monteith, 1965; Wever et al., 2002; Wilson and Baldocchi, 2000), leaf area index (LAI) (Zha et al., 2010), stand age (Jassal et al., 2009; Komatsu et al., 2007; Murakami et al., 2000), and the accessibility of roots to the water table (Lafleur et al., 2005; Paço et al., 2009; Ryu et al., 2008a). Moreover, catchment characteristics affect ET because soil properties such as water storage capacity or permeability, and topographical factors such as slope or elevation, can determine the accessibility of water resources by plants (Zhang et al., 2001, 2004). However, most of these findings were made at selected sites, and therefore represent only the situation for plots in specific ecosystems, and not across the wider-scale heterogeneous landscape.

Spatially continuous maps of ET at a regional scale have been produced by incorporating satellite remote sensing imagery (Jung et al., 2010; Ryu et al., 2011). The methodology for deriving an “ET map” is still being advanced, from empirical/statistical approach using vegetation indices (Jin et al., 2011; Lu and Zhuang, 2010; Nagler et al., 2005) which would be limited in site-specific and incomplete understanding of biophysical process, to the process-based models (Miralles et al., 2010; Mu et al., 2011; Ryu et al., 2011) which would be possible for the geospatial analysis of controlling factors across atmosphere, soil and vegetation. Advances in the spatial and temporal resolution of the regional ET estimates can be accomplished by using Moderate-resolution Imaging Spectroradiometer (MODIS) satellite data. The MODIS imagery from Terra or Aqua platforms, provided with less than 1-km spatial resolution and 1–8 daily revisit frequency since 2000 (Masuoka et al., 1998), is a potential data resource for the monitoring of inter- and intra-annual variability of regional ET (Jin et al., 2011; Lu and Zhuang, 2010; Mu et al., 2011). Thus, these advantages of process-based ET estimation using MODIS data should be highlighted in the regional water cycle assessment at monthly to yearly time scales, in relation to P extremes.

The goal of this study was to assess the seasonal and interannual variability of ET at a basin scale, in extremely large and small-P years. Using the remote sensing and process-based model for regional ET estimation, we attempted to identify the temporal and spatial characteristics of variations in ET in response to abnormal P. The driving factors resulting in changes to ET were analyzed in terms of various climatic, vegetation and catchment features. Furthermore, the implications of the variability in ET for the regional water-energy balance are discussed.

2. Materials and methods

2.1. Study site

The Youngsan River is one of the four major rivers in South Korea, and its river basin (3469 km²) was selected for this study because of its importance for regional water-resource management (Fig. 1). This region is under the East Asian Monsoon climate, characterized by intensive, long periods of rainfall during the summer season (Hong and Kim, 2011; Kang et al., 2009). Coniferous, deciduous and mixed forests dominate the landscape (45% of the land cover) and cultivated areas—including paddy fields and crop land—occupy 37% of the region (Fig. 1), emphasizing the role of ET in the regional water cycle. To analyze the regional water balance (Section 2.6), we selected four watersheds in the upper basin (2154 km²) according to the riverflow discharge (Q) monitoring sites in Fig. 2: Gwangju (Watershed A, 493 km²), Seonam (Watershed B, 564 km²), Nampyong (Watershed C, 664 km²), and Youngsan-po (Grand upper basin, 2154 km²). The annual Q at each watershed was estimated from daily flow-rate records (WAMIS, 2013).

2.2. Study periods and annual precipitation (P) anomalies

To identify “normal” and “extreme” P periods, we computed the standard scores (i.e., \( z = (x - μ)/σ \); where \( μ \) and \( σ \) are the mean and standard deviation of the population) (see Fig. 3) of annual P, from long-term (1973–2011) annual P records at nine meteorological monitoring stations within the Youngsan River basin. In the recent period (2002–2009), which was covered by the Breathing Earth System Simulator (BESS, see Section 2.4) output using MODIS, we selected the following periods as a benchmark of abnormal weather conditions: 2003 as an abnormally large-P year (1879 mm, \( z = 1.8 \)), 2008 as an abnormally small-P year (958 mm, \( z = -1.4 \)), and the average of 2005, 2006 and 2009 as a normal P year (1282, 1411, and 1330 mm; the \( z \)-values were close to 0 at \(-0.3, 0.2, \) and \(-0.1, \) respectively). The study periods included not only the selected extreme P years but also continuous trends in P from 2002 to 2009, for the analysis of interannual ET variation and water balance (Section 2.6).

2.3. Meteorological dataset

An annual P distribution map was derived from the P data recorded at the 40 locations in the study area (Fig. 1) (Korea Meteorological Administration, 2012), by interpolating the point-based observations using an inverse distance weighted technique (Watson and Philip, 1985). Additionally, we used the daily records of solar radiation, rainfall, wind speed, air temperature and vapor pressure measured at the nine meteorological monitoring stations (Korea Meteorological Administration, 2012) to identify the climatic characteristics of P extremes (Section 2.6).

2.4. Mapping ET based on BESS

The spatial distribution of daily based ET from canopy and soil surfaces was estimated at a 1-km × 1-km spatial resolution using BESS (Hendrix et al., 2013; Ryu et al., 2011). This model is designed...
to compute canopy ET, potential ET and soil evaporation, by using the diverse MODIS Atmosphere and Land product as model input data. Instantaneous ET estimates for each day over an 8-day interval were obtained when the MODIS sensor overpassed the study area, and these ET estimates were then converted to 8-day mean daily sum values using a temporal ET upscaling algorithm (Ryu et al., 2012). Canopy ET was calculated using the Penman–Monteith equation (Monteith, 1965). Canopy conductance, the key input data for the Penman–Monteith equation, was computed using the Ball–Berry model (Ball, 1988; Collatz et al., 1991) with a canopy photosynthesis model (Farquhar et al., 1980). Potential ET was estimated using the Priestley and Taylor model (Priestley and Taylor, 1972). Soil evaporation was computed using the available energy in the soil surface constrained by soil dryness. BESS agreed well with direct ET measurements from 33 eddy flux towers across arctic to tropical climate zones. A detailed description and evaluation of BESS can be found in Ryu et al. (2011). Based on this performance, BESS-derived ET estimates could be applied to various types of land-cover across the Youngsan River basin.

2.5. Ancillary data

For the evaluation of BESS-derived ET, we used in situ ET data measured in 2008 (Kang et al., 2009), by an eddy covariance system installed 20 m above ground level at the Haenam flux tower site (34°33′17.70″N, 126°34′7.11″E) (Ryu et al., 2008b). This site is located ~20 km south of the southwest part of Youngsan River basin and has similar climatic conditions and vegetation cover to our study site. The flux tower is located in the flat terrain of heterogeneous farmland that is used for cultivating crops. A detailed description of the flux data acquisition and processing is provided in Kang et al. (2009).

To verify the influence of geospatial characteristics on ET variation, we used a land cover, slope, and soil property dataset for the Youngsan River basin with 30-m spatial resolution (Korea Ministry of Environment, 2013) and satellite-based LAI images. The current land cover map (Fig. 1) acquired in 2007, was considered to be representative of our study period (2002–2009). Permeability and effective soil depth were given in five categories (<20, 20–50, 50–100, 100–150, and >150 cm) and six ranks (very good, good, quite good, not that good, bad, and very bad), respectively (Korea Rural Development Agency, 2012). The regional vegetation structure was assessed using the 1-km-spatial-resolution MODIS LAI product (MOD15A2) (Myneni et al., 2002). Annual and per-pixel maximum values of LAI were obtained to describe the state of the canopy during the fully leaved season. These values were averaged from 2001 to 2009, to exclude probable outliers. This LAI image was regarded to represent the characteristics of the regional vegetation structure. In this process, we used only pixels with “good” or “marginal” reliability, as classified in the MOD15A2 quality control flag.
2.6. Analysis framework

First, we evaluated the reliability of BESS-derived ET in the study area, at both annual and monthly time scales. Long-term average values of annual ET from 2002 to 2009, estimated from the differences between P and Q at the four selected watersheds (Section 2.1), were compared with the mean values of BESS-derived annual ET for the same period and areas. The monthly averages of BESS-derived daily ET estimates were evaluated against the monthly averaged daily ET by eddy covariance measurements, at the pixel where the Haenam flux tower (Section 2.5) was located.

Temporal and spatial ET variations were then illustrated in response to annual P anomalies, depending on the type of landcover at the grand basin scale. Factors that controlled seasonal and annual ET variations were assessed using meteorological statistics (Section 2.3), a water-energy balance analysis and a generalized linear model. Water and energy controls on regional ET were analyzed using Budyko’s framework (Budyko, 1974; Li et al., 2013; Williams et al., 2012). This framework determines if the limiting factor in the ET of a region is due to available water or available energy, by plotting the scatter of the dryness index (ratio of potential ET to P) and evaporative index (ratio of ET to P). Moreover, deviations on the dryness and evaporative indices imply a change in the climatic conditions and in the partitioning between ET and Q, respectively. A more detailed description of this is given in the results (Sections 3.3.3 and 4.2).

We then attempted to clarify the influences of the other geographical and vegetation cover factors on the spatial variation of abnormal-P-driven ET changes. We used the generalized linear model, because the tested factors included both discrete and categorical data (Section 2.5). Five variables; i.e., LAI, sub-category land cover, slope, soil permeability and effective soil depth, were used to explain the changes in ET under P extremes.

Finally, the implications of the variations in ET for regional water management were discussed by considering the annual water balance. At the four selected watersheds (Fig. 2), we derived an annual water balance (i.e., annual P minus annual ET and Q) (Senay et al., 2011) and examined the partitioning of P into ET and Q. The continuous trend from 2002 to 2009 was interpreted at each watershed.

3. Results

3.1. Evaluation of BESS-derived ET estimates

Fig. 4 indicates that the BESS-derived ET in the study area can be used at pixel to watershed spatial scales and at both annual and

![Fig. 4](image-url)

**Fig. 4.** Evaluation of the BESS-derived evapotranspiration (ET) estimates at the (a) yearly and (b) monthly time scales. (a) Comparison of 8-year mean (2002–2009) estimates of yearly sum ET obtained from BESS and water balance (i.e. precipitation minus discharge) at the four selected watersheds (Fig. 2 and Section 2.1); (b) Comparison of monthly mean estimates of daily sum ET obtained from BESS and eddy covariance flux tower in Haenam (Section 2.5). Dashed lines indicate 95% CI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

![Fig. 5](image-url)

**Fig. 5.** (a) Inter- and (b) intra-annual variations of evapotranspiration (ET) in the whole basin under different precipitation (P) conditions.
monthly temporal scales. The BESS-derived ET presented a linear relationship with the annual ET derived from the watershed water balance ($R^2 = 0.99$; Fig. 4(a)) and with the monthly averaged ET estimated from the flux tower measurements ($R^2 = 0.92$; Fig. 4(b)). BESS-derived ET also had a smaller root mean square error and bias against flux-tower ET than against water-balance-derived ET.

3.2. Inter-annual, intra-annual and spatial variations of the regional ET in the abnormal P years

The annual ET of this basin decreased when the P was abnormally large (2003) and increased when the P was abnormally small (2008), compared to the normal ET in normal P years (Fig. 5(a)). These variations resulted largely from the difference in ET in summer (June–September). In the other months there were few changes in ET between normal and abnormal P years (Fig. 5(b)).

This inter-annual variation of ET is illustrated spatially in Fig. 6. For example, in the large-P year, forests in the southwest part of the basin decreased their ET compared to the normal P year (shown as orange-colored pixels in Fig. 6(a)). In the small-P year, an increase in ET remarked in the forests of the eastern part of the basin (shown as blue-colored pixels in Fig. 6(b)).

Table 1 summarizes the characteristics of ET variations in terms of the type of land cover. In this region, ET in forests presented a larger response to the abnormal P than cultivated areas at the significance level of $p < 0.01$ (Cumming et al., 2007). In forests, ET decreased more in deciduous forest in the large-P year and increased more in the small-P year than the corresponding ET values in coniferous forest ($p < 0.05$, Cumming et al. (2007)). For the cultivated areas, there were no significant differences ($p > 0.05$ by Cumming et al. (2007)) in the changes of annual average ET in abnormal P years, between paddy fields and cropland.

3.3. Factors controlling regional ET in the extreme precipitation years

3.3.1. Climatic factors

Fig. 7 shows that the climatic characteristics related to ET differed among large, small and normal P years. In the large-P year, the annual weather conditions were characterized by more rainy days (i.e., longer periods of high humidity), less solar radiation, lower wind speed, cooler air temperature and a lower vapor pressure deficit (VPD) than in normal P years, especially in the summer monsoon season of July–August. The meteorological data indicated that regional ET decreased in the large-P year (Fig. 5). In contrast, in the small-P year there were fewer rainy days (i.e., shorter periods of high humidity), more solar radiation and a higher VPD during summer than in normal P years, which drove the increase in the regional ET (Fig. 5).

3.3.2. Contribution of canopy ET and soil evaporation to the variations in total ET

Regional variations in ET due to P extremes resulted mainly from the change in canopy ET rather than soil evaporation (Fig. 8). Canopy ET decreased by 15.2% in the large-P year and increased by 3.5% in the small-P year, compared to a normal P year. Soil evaporation only decreased by 4.5% and increased by 2.7% in the large and small-P years, respectively. There was little change in the inter-annual LAI, even in extreme P years (data not shown). The annual maximum LAI, which was 4.33 on average across the basin, decreased by 0.10 ($\pm 0.01$ with 95% CI) in the large-P year and increased by 0.15 ($\pm 0.01$) in the small-P year, compared to the normal P years. Based on this trend in canopy ET and soil evaporation in extreme P years, and the small magnitude of the inter-annual changes in LAI, the main reason for the variations in regional ET was not changes in vegetation factors (e.g., LAI) but changes in energy and climatic factors (e.g., solar radiation or VPD) (Section 3.3.3).

Table 1

<table>
<thead>
<tr>
<th>Land cover type</th>
<th>Annual ET (mean ± 95% CI) (mm yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-category</td>
<td>Normal P year</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
</tr>
<tr>
<td>Coniferous</td>
<td>583.1 ± 8.0</td>
</tr>
<tr>
<td>Deciduous</td>
<td>595.8 ± 12.6</td>
</tr>
<tr>
<td>Mixed</td>
<td>596.4 ± 12.9</td>
</tr>
<tr>
<td>Cultivated area</td>
<td></td>
</tr>
<tr>
<td>Paddy</td>
<td>514.4 ± 8.7</td>
</tr>
<tr>
<td>Crop</td>
<td>531.4 ± 11.9</td>
</tr>
</tbody>
</table>
3.3.3. Water and energy limitation

Fig. 9 shows a clear trend of energy-limited ET in the large-P year and water-limited ET in the small-P year. In the large-P year, ET in most of the study area (99.9%) was limited by the available energy, as shown in the region where the dryness index (the values on the x axis) is <1. In contrast, in the small-P year, ET in 92.8% of the cultivated area and 89.2% of the forests was limited by the available water, as shown where the dryness index is >1. The difference between water and energy limitations in the sub-category of land cover types (i.e., among deciduous, coniferous, and mixed forest or between paddy fields and cropland) was unclear, even for the normal annual P condition (Fig. 9(b) and (e)).

3.3.4. Geographic and vegetation factors

Table 2 shows that LAI was the most significant variable (p < 0.05) that explained the spatial distribution of the changes in ET under the P extremes described in Fig. 6. The spatial distribution of other geographic characteristics, such as soil permeability, effective soil depth, slope, or the type of land cover, was not significantly related to the variation of ET (p > 0.05), except for the changes in ET in cultivated areas in a small-P year.

3.4. Variation of ET in the regional annual water balance

The P, ET, and Q components of the annual water balance in this region were estimated for the watersheds of the upper basin from 2002 to 2009. As shown in Table 3, the interannual variation of regional P was large, changing by 51–62% depending on the watershed; but ET varied only from 15% to 18%, which was relatively stable compared to the fluctuations in P. P extremes had a substantial influence on the interannual variation of regional ET during 2002–2009, with ET being largest in the driest year (2008) and smallest in the wettest year (2003).

The P fluctuations directly influenced the variation in annual Q, rather than ET. The largest annual Q in Table 3 was recorded in the large-P year (2003), at all the watersheds. Q in the small-P year (2008) was smallest in watersheds A and B, and second smallest at C and the grand upper basin (Fig. 10). The variations in Q were greater than the fluctuation in P with differences of 108–232%, depending on the watershed.

4. Discussion

4.1. The response of ET to annual P extremes according to land-cover type

In this study site, the response of annual ET to the abnormal P conditions was larger in forests than in paddy fields or cropland (Table 1). ET in grasslands or pasture that experienced seasonally
dry climate conditions has been shown to be affected by variations in P (Paço et al., 2009; Zha et al., 2010); whereas forests sustain high levels of ET under dry weather conditions (Zhang et al., 2001). This may be because trees can maintain transpiration by using deep roots to access groundwater, while the transpiration of grass depends strongly on the occurrence of rainfall or top soil water (Paço et al., 2009). However, the annual ET of our study area is usually limited by the available energy rather than by water (Fig. 9(b) and (e)), especially during summer (Fig. 5) under the East Asian monsoon climate (Hong and Kim, 2011; Kang et al., 2009), which was the fundamentally different climate factor from the previous studies (Paço et al., 2009; Zha et al., 2010; Zhang et al., 2001). Accordingly, the magnitude of the regional ET response to P extremes has a positive relationship with LAI (Section 3.3.4); i.e., a trend towards larger changes in ET in locations where vegetation has a larger LAI. This could explain why ET varied more \( (p < 0.01, \text{Section 3.2}) \) in forests (the average LAI was 4.96) than in paddy fields or cropland (average LAI, 3.49) in this study.

**Table 2**

Explanatory variables that significantly influenced the spatial distribution of abnormal-P-driven changes in ET shown in Fig. 6 \( (p < 0.05) \). To apply the generalized linear model, we assumed normally distributed dependent variables linked with an identity link function. The significance level was based on a likelihood ratio chi-square distribution.

<table>
<thead>
<tr>
<th>Landcover category</th>
<th>Independent variable</th>
<th>Effective dependent variable(s) ( (p &lt; 0.05) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest (deciduous, coniferous, mixed)</td>
<td>ET variation in large-P year (Fig. 6(a))</td>
<td>LAI</td>
</tr>
<tr>
<td></td>
<td>ET variation in small-P year (Fig. 6(b))</td>
<td>LAI</td>
</tr>
<tr>
<td>Cultivated area (paddy field, crop land)</td>
<td>ET variation in large-P year (Fig. 6(a))</td>
<td>LAI</td>
</tr>
<tr>
<td></td>
<td>ET variation in small-P year (Fig. 6(b))</td>
<td>LAI, effective soil depth, soil permeability, slope</td>
</tr>
</tbody>
</table>

**Table 3**

Variations in annual precipitation (P), evapotranspiration (ET), and discharge (Q) at four different watersheds during 2002–2009. Variation (%) indicates the percentage value of \((\max - \min)/\text{average}\).

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Component</th>
<th>Min</th>
<th>Max</th>
<th>Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Gwangju)</td>
<td>P (mm yr(^{-1}))</td>
<td>1238.3</td>
<td>2261.5</td>
<td>60.4</td>
</tr>
<tr>
<td></td>
<td>ET (mm yr(^{-1}))</td>
<td>459.9</td>
<td>547.5</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>Q (m(^3) s(^{-1}))</td>
<td>5.3</td>
<td>35.2</td>
<td>194.4</td>
</tr>
<tr>
<td>B (Seonam)</td>
<td>P (mm yr(^{-1}))</td>
<td>1137.1</td>
<td>2097.0</td>
<td>62.0</td>
</tr>
<tr>
<td></td>
<td>ET (mm yr(^{-1}))</td>
<td>504.1</td>
<td>608.4</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Q (m(^3) s(^{-1}))</td>
<td>7.9</td>
<td>50.2</td>
<td>231.6</td>
</tr>
<tr>
<td>C (Nampyong)</td>
<td>P (mm yr(^{-1}))</td>
<td>1033.2</td>
<td>1746.6</td>
<td>50.8</td>
</tr>
<tr>
<td></td>
<td>ET (mm yr(^{-1}))</td>
<td>519.9</td>
<td>605.4</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>Q (m(^3) s(^{-1}))</td>
<td>6.7</td>
<td>22.2</td>
<td>112.6</td>
</tr>
<tr>
<td>Grand upper basin</td>
<td>P (mm yr(^{-1}))</td>
<td>1116.5</td>
<td>2011.0</td>
<td>58.6</td>
</tr>
<tr>
<td></td>
<td>ET (mm yr(^{-1}))</td>
<td>469.0</td>
<td>555.4</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>Q (m(^3) s(^{-1}))</td>
<td>23.4</td>
<td>85.1</td>
<td>107.8</td>
</tr>
</tbody>
</table>

**Fig. 9.** Water and energy limitations for the evapotranspiration (ET) in cultivated areas (a–c) and forests (d–f), in large (a and d), normal (b and e), and small (c and f) precipitation (P) years, according to Budyko’s framework.
Another explanation for the differences in the variations of ET according to land-cover type is that paddy fields or cropland do not correspond to grassland or pasture where ET sensitively responds to P. In cultivated areas, the water environment is “managed” by irrigation or drainage to mitigate the effects of unexpected P extremes. Therefore, ET is more stable than in a forest (Table 1, Section 3.2).

Within forests, the changes in ET agreed with Zha et al. (2010) and Komatsu et al. (2007), with ET decreasing more in deciduous broadleaf forest in the large-P year and increasing more in the small-P year than in coniferous forest ($p < 0.05$, Section 3.2). This result could also be explained by the difference in LAI (Section 3.3.4) (Nagler et al., 2005; Zha et al., 2010), with broadleaved forests having larger average LAI values (5.43) than coniferous forests (4.75), and the other climatic or geographical factors were not significantly different.

4.2. Implication of Budyko’s framework on the factors controlling regional ET

We successfully identified the water and energy limitations of the regional ET using Budyko’s framework. By considering the deviations in the dryness index (i.e., the values of the x axis in Fig. 9) and the evaporative index (y axis) according to the implication of this analyzing frame (Section 2.6.) (Williams et al., 2012), the scatter in ET values in the small-P year (Fig. 9(c) and (f)) could be a consequence of the warmer, drier weather conditions and lower runoff (see Sections 3.3.1 and 3.4, respectively) because the data points are located largely on the upper-right side of the plot. In contrast, cooler, wetter weather and a larger river-flow discharge in the large-P year can explain the scatter of data points in the lower-left side of Fig 9(a) and (d). These characteristics, in terms of factors controlling ET, are described spatially in Fig. 6.

The blue pixels in Fig. 6(a) and orange pixels in Fig. 6(b) may represent water-limited areas, because ET is increased by high levels of P and decreased by low levels of P. Likewise, the ET of the orange pixels in Fig. 6(a) and blue pixels in Fig. 6(b) would be limited by the available energy at the land surface.

4.3. Less variability of interannual ET than P in regional water balances

Much smaller changes in annual ET than annual P were acquired at the study site over the 8 years, which agreed well with the invariability of ET reported in previous studies, e.g., Kosugi and Katsuyama (2007), Oishi et al. (2010), Paço et al. (2009). Oishi et al. (2010) demonstrated that this was due to the P-driven change of canopy transpiration and soil evaporation being compensated for by canopy rainfall interception losses. We were unable to test the influence of canopy interception loss on ET because it was not explicitly modeled in BESS (Ryu et al., 2011). But we found that both of soil evaporation and canopy ET including the interception loss decreased in the large P year and increased in the small P year (Fig. 8). This relative invariability of ET has important implications for regional water management. The changes in annual P lead to similar changes in the amount of water that flows from forests to streams and reservoirs (Section 3.4) (Oishi et al., 2010). Vegetation plays an established role in the regional water cycle due to the consistent water release through ET, which is largely unaffected by P extremes.

5. Conclusion

Spatial and temporal variations of regional ET under abnormal P conditions were analyzed at the basin scale across several types of land-cover, based on ET estimated by satellite remote sensing and
a process-based model (BESS). The total ET of the region decreased in the abnormally large-P year, because ET was limited by the available energy, especially during the cooler and wetter summer season when large P was experienced due to the East Asian monsoon climate. In contrast, during the small-P year the regional ET increased because the drier and hotter summer than usual (i.e., more solar radiation) provided sufficient available energy for ET, rather than limiting the available water. Not only climatic factors but also the type of vegetation cover and LAI significantly influenced on the variation of ET. There was a tendency for forest to release more water through ET than paddy fields or crop lands in the small-P year, whereas in the large-P year the forest ET was more limited than the cultivated areas. The most important reason for these different responses in ET was differences in the LAI, rather than geographic characteristics such as soil properties or topography.

The variation of ET under P extremes was not large in comparison with the annual fluctuations in P. From the less variability of ET, we demonstrate that vegetation plays a regular role in the regional water cycle by the consistent release of water through ET, regardless of abnormal P. Thus, the changes in the water balance of this region are dependent on P and Q, which were quantified in this study and can be referred to for future water management. Further studies should be linked to scenarios of climate and land-use change, with further water resource data and an enhanced model for estimating ET.

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