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Hydroclimatological influences at multi-spatial scales on recently increased droughts in China's largest freshwater lake

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Abstract

Lake droughts are the consequences of climatic, hydrologic and anthropogenic influences. It may produce substantial impacts on local water sources, inhabitants and economy, but few studies have determined the contributions from the individual influences, especially under the changing climate, which is of highly valuable for policymakers to make effective adaption. This study proposes to use a multi-scale hydroclimatic analysis for the determination, taking Poyang Lake as an example. It is the China's largest freshwater lake, which has been undergoing drastic hydrological alterations in recent decade. Our analysis demonstrates that in the recent decade the lake droughts worsened in terms of duration, frequency, magnitude and severity, and intensified in magnitude significantly. At the lake region, water deficiency severed as the hydroclimatic foundation for the worsening droughts. Overall contribution to the lake droughts included decreased inflow (45 %), increased outflow (24 %), reduced local precipitation (23 %), and increased evapotranspiration (8 %). At the basin scale, the decreased inflow was ascribed to reduced basin-scale precipitation (82 %) and increased evapotranspiration (18 %). The increased outflow was principally controlled by the weakened blocking effects of the Yangtze River, which serves as a boundary condition of Poyang Lake. Water impoundments of the Three Gorges Dam (TGD) established upstream should not be responsible for the increased drought occurrence, but they may have enhanced the drought magnitude with a limit contribution. The findings provide an example of intensified lake droughts, and offer an insightful view into lake droughts under the changing climate and anthropogenic influences. It should be valuable for improving our understanding and for promoting effective climate adaptation and water resources management practices.

1 Introduction

A drought is a temporary lack of water caused by abnormal climate or environmental influences, among other factors (Kallis, 2008; Mishra and Singh, 2010; and references therein). There are meteorological droughts (abnormal low precipitation), hydrological droughts (abnormal low streamflow or groundwater) and agricultural droughts (abnormal low soil moisture). The drought phenomena have different temporal features and causation structures (Kallis, 2008; Mishra and Singh, 2010). Hydrological droughts occur when land water decreases significantly below its normal conditions, represented by low water levels in streams, lakes, reservoirs and groundwater as well (Nalbantis and Tsakiris, 2009; Keskin and Sorman, 2010). Streamflow droughts occur because of basin-scale precipitation deficiency and/or excessive evapotranspiration (Zelenhasic and Salvai, 1987; Tallaksen et al., 1997; Kingston et al., 2013). Besides local precipitation and evaporation, lake droughts involve additional hydrological components including inflows from streams surrounding the lake and outflows out of the lake. Since lakes are sensitive to climate-related changes occurring within their catchment (Adrian, 2009), lake droughts can be more complicated than streamflow droughts in causation structure. Furthermore, both inflows and outflows may alter with anthropogenic influences, for example, land cover change (Wilcox et al., 2010). Therefore, lake droughts are the consequences of climatic, hydrologic and anthropogenic influences. Yet, few studies have addressed the lake droughts and determined the contributions from the individual influences, especially under the changing climate, which is of highly valuable for policymakers to make effective adaption. In a disciplinary sense, in contrast to floods that have been given a great deal of attention in hydrology, droughts are not yet comprehensively understood. Therefore, place-based drought analysis is a starting point towards integrated theories of drought (Kallis, 2008).

Among numerous lakes in the world, Poyang Lake is the China's largest freshwater lake, which has been undergoing drastic hydrological alterations in recent decade

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(Jiao, 2009; Finlayson et al., 2010; Hervé et al., 2011; Liu et al., 2013). The lake is located at the south bank of the Yangtze River, which is a humid monsoon climatic region. Although the region historically experiences significant floods (Shankman and Liang, 2003), severe lake droughts have occurred frequently in the recent decade, resulting in hydrological, biological, ecological and economic consequences (Min, 2010; Environment News Service, 2012). Because the lake is the primary part of the well-known Poyang Lake Wetland and the lake region serves as an important food base for China, the frequent lake droughts have received increasing international attention (Shankman et al., 2006; Jiao, 2009; Finlayson et al., 2010; Liu et al., 2011; Environment News Service, 2012; The Ramsar Convention, 2012). On one hand, the increase in the number of lake droughts is consistent with the anticipated consequences that droughts will increase owing to global climate change (Kallis, 2008; Mishra and Singh, 2010). On the other hand, in addition to the local precipitation and the inflows of five sub-tributary river systems, Poyang Lake discharges into the Yangtze River via a narrow outlet at the Hukou (Fig. 1). If the River's blocking effect weakens, more lake water will flow out into the river (Shankman et al., 2006; Hu et al., 2007; Guo et al., 2012), thus making it more complicated to determine the controlling causes of the increased lake droughts. While the lake droughts were frequently noted in recent studies, most of them explained the decrease of low lake stage in dry season (Zhao et al., 2010; Hervé et al., 2011; Guo et al., 2012; Zhang et al., 2012) or specified lake shrinkage responses to individual drought events (Wu and Liu, 2014). Definitely, the low water level is different from the drought since the latter may occur in any season (Smakhtin, 2001); thereby the existing studies do not provide a full description of the recent drought events. More importantly, it is yet unknown how each hydroclimatic factor contributed to the lake droughts, given the combined climatic, hydrologic and anthropogenic influences. Especially for practice, it is necessary to disclose the hidden mechanism of recent increase in drought occurrence, which is essential to effective prevention of the droughts in long term.

Complicated causality of lake droughts requires robust approach for determining the contributions from the multiple influences. This study proposes to use a multi-scale analysis for the determination, taking the Poyang Lake droughts as an examination. The paper consists of the following sections: Sect. 2 introduces the approaches for drought analysis; Sect. 3 describes the study materials and data processing for multi-scale hydrocliamtic analysis; Sect. 4 describes the Poyang Lake droughts and addresses the mechanisms accounting for the recent strengthening of lake droughts; and Sect. 5 summarizes our conclusions. The findings should be valuable for improving our understanding of lake droughts under the changing climate and be useful for water resources management and local climatic adaptation.

2 Methodology

A full description of droughts includes duration, frequency, magnitude and severity, as well as spatial extent for the case of meteorological or agricultural droughts (Mishra and Singh, 2010). Notably, drought severity does not parallel to other items, but consists of both drought magnitude and drought duration (Dracup et al., 1980). For quantitative analysis, a prime variable or a derivative index is necessary. Among numerous indices, standardized precipitation index (SPI) is commonly used (Mishra and Singh, 2010). The SPI is defined as follows (McKee et al., 1993):

$$\mathrm{SPI}_{ij} = \frac{p_{ij} - \overline{p}_j}{\sigma_j}, \tag{1}$$

where p_{ij} is the normalized monthly precipitation of year i and month j ($j = 1, 2, \ldots, 12$) normalized with a gamma distribution. $\overline{p}_j$ is the multi-year mean of monthly precipitation for month j, and σ_j is the standardized deviation of monthly precipitation for month j.

SPI is uniquely related to occurrence probability. Namely, SPI = −1 denotes an occurrence probability of 15.9 %, SPI = −1.5 expresses a probability of 4.4 %, and SPI = −2 represents a probability of 2.3 % (Lloyd-Hughes and Saunders, 2002). Moreover, SPI can be either positive or negative. The positive (negative) value indicates

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precipitation higher (lower) than the normal condition for the period. The negative value quantifies the drought magnitude and is divided into four categorizes: extreme drought $(-\infty, -2.0]$, severe drought $(-2.0, -1.5]$, moderate drought $(-1.5, -1.0]$ and mild drought $(-1.0, 0.0)$ (McKee et al., 1993). Accordingly, the onset and the termination of a drought are also discernible with the SPI. Once the droughts are identified, the drought duration and the occurrence frequency for the period of interest can be determined. Drought severity, defined as the product of drought magnitude and duration, is calculated as follows (Keyantash and Dracup, 2002; Mishra and Singh, 2010):

$$\text{Severity} = \sum_{k=m}^{k=n} \text{SPI}_k, \tag{2}$$

where m denotes the onset time of a drought and n represents the termination time.

SPI is developed on a basis of monthly scale and available for use at a given aggregation time scale (McKee et al., 1993). It was initially proposed to quantify precipitation deficiency but applicable to other hydroclimatic variables relevant to drought, for example, snowpack, streamflow discharge, soil moisture, reservoir storage, and groundwater level (McKee et al., 1993; Shukla and Wood, 2008). In the case of lake drought, it can be described with lake stage, lake area or water storage. Because the time series data of lake area or water storage are generally unavailable, lake stage may be used. The present study uses the standardized lake stage index (SLI) in place of SPI to determine drought duration, frequency, magnitude and severity, with a time interval of one month as did in Keyantash and Dracup (2002). McKee et al. (1993)'s definition of SPI would be consistent with the subsequent use of the SLI approach to quantify the drought.

In addition to drought quantification, water budget analysis is essential to clarify the lake drought causes and the hydroclimatic influences. A general water balance within an entity for a period can be described as follows:

$$\Delta = P - \mathrm{ET} + I - O \tag{3}$$

where Δ is the water budget, P is the precipitation, ET is the evapotranspiration, I is the inflow and O is the outflow. For a water component X, being Δ, P, ET, I or O, its monthly anomaly is described as follows:

$$X_{\mathrm{a},ij} = X_{ij} - \overline{X}_j, \tag{4}$$

where $X_{\mathrm{a},ij}$ denotes the anomaly of the water component for year i and month j. $\overline{X}_j$ is the multi-year mean of X_{ij}. For a drought event, the total water deficiency of water budget is a combined result of the anomalies of all the water components, namely, low precipitation, high evapotranspiration, low inflow and high outflow. The contribution of each water component to the water deficiency of the water budget is quantifiable with a ratio defined as follows:

$$C_X = \frac{\sum_{k=m}^{k=n} X_{\mathrm{a},k}}{\sum_{k=m}^{k=n} \Delta_{\mathrm{a},k}}, \tag{5}$$

where C_X denotes the contribution, the numerator is the sum of the monthly anomaly of a water component, and the denominator is that of the water budget. For a drought event, $\sum_{k=m}^{k=n} \Delta_{\mathrm{a},k}$ is generally negative, but $\sum_{k=m}^{k=n} X_{\mathrm{a},k}$ varies with hydroclimatic conditions. For example, precipitation deficiency leads to a negative $\sum_{k=m}^{k=n} X_{\mathrm{a},k}$ value to produce a positive C_X. Low evapotranspitation lessens water deficiency to generate a negative C_X. Therefore, C_X can be either positive or negative.

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3 Study materials and data processing

Poyang Lake has a maximum area of 3860 km^2 with an average depth of 8 m at the lake stage of 22 m. It is located at the northern part of the Poyang Lake Basin, a sub-basin of the Yangtze River Basin of China (Fig. 1). The lake water flows out into the Yangtze River via the Hukou outlet. The lake water principally comes from five major river systems including Xiushui, Ganjiang, Fuhe, Raohe and Xinjiang. Seven hydrological control stations are located downstream (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Dufengkeng and Shizhenjie) to measure the discharge of the five rivers. The lake region downstream from the stations is 23 089 km^2, which is 6.0 times the maximum lake size. The Poyang Lake Basin has an area of 162 225 km^2 and belongs to a humid subtropical climate zone with an annual mean surface air temperature of 17.5° C and an annual precipitation of 1635.9 mm for the years 1960–2010. Forestlands, agricultural fields, grasslands, bare-lands and water surfaces are the dominant land cover types (Liu et al., 2012).

Daily precipitation data from thirteen national weather stations within the Poyang Lake Basin are available from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/) from 1961 to 2010. Similar to previous studies (Hu et al., 2007; Guo et al., 2012; Liu et al., 2013), the precipitation data were grouped and averaged for Poyang lake region, five sub-basins and the whole basin. Daily discharge and water level data for the Hukou outlet are available from the Hydrological Bureau of the Yangtze River Water Resources Commission. Daily discharge data from seven control stations were obtained from the Hydrological Bureau of Poyang Lake. Regional evapotranspiration data were extracted from MOD16 products of the Moderate resolution Imaging Spectroradiometer (MODIS) (http://www.ntsg.umt.edu/project/mod16) (Mu et al., 2011). The datasets have a spatial resolution of 1 km at 8-day, monthly and annual intervals from 2000 to 2010, and have been applied worldwide. For the present study area, it was also evaluated with monthly precipitation and discharge data for five sub-basins of the Poyang Lake Basin, based on the principle

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of water balance. The evaluation showed an overall accuracy of 90.4 % for the basin (Wu et al., 2013). Since regional evapotranspiration data prior to 2000 was unavailable, the multi-year mean of monthly evapotranspiration was generated from the difference between that of monthly precipitation and discharge for 1961–2010. A one-month lag was applied to discharge to account for peak rainfall and peak discharge for the basin (Senay et al., 2011; Liu et al., 2013).

Furthermore, SLI was calculated with Eq. (1) to quantify lake droughts with the monthly lake stage data at the Hukou outlet from 1961 to 2010. Notably, a negative SLI indicates the lake stage is lower than the normal, but not all the negatives are classified into a drought event. Only when SLI deviates away from the normal by more than one standard deviation ($\mathrm{SLI} < -1$), a drought event can be established. Furthermore, the onset of the drought was decided when SLI became negative and the termination was determined before SLI became positive in the SLI time series. Subsequently, all the lake droughts were identified and grouped into extreme drought $(-\infty, -2.0]$, severe drought $(-2.0, -1.5]$, or moderate drought $(-1.5, -1.0]$. The drought duration, frequency, magnitude and severity were subsequently determined.

In addition to lake precipitation and evaporation, Poyang Lake water comes mainly from the inflows of five major rivers and numerous small rivers and brooks. The small rivers and brooks originate in the lake region, which is a result of local precipitation and evapotranspiration, and the five major rivers originate in the Poyang Lake Basin (Fig. 1). Therefore, drought analysis was made at three scales: Poyang Lake, the lake region and the lake basin. It should be emphasized that, for the sake of addressing water contribution at the multi-scales, the water amounts (unit in m^3) of all the water components were normalized to equivalent water height (unit in mm) of the whole basin (unit in km^2). In addition, given that Poyang Lake has remarkable surface variation, time series data of lake evaporation are unavailable for the whole lake. Because both the lake precipitation and evaporation occupy less than 2 % of the total lake discharge (Liu et al., 2012), we did not explicitly address them, but implicitly included them as a part of the water budget at the lake region. Consequently, Eqs. (3)–(5) were utilized to

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evaluate the contribution of each water component. Besides, paired F test (and T test) were used to examine the variance (and mean) difference between the statistics for 1961–2000 and that for 2001–2010.

4 Results and discussions

4.1 Poyang Lake droughts in recent decade

A quantitative description of drought occurrence is a prerequisite for insightful drought analysis. Figure 2a illustrates the SLI variation for Poyang Lake in the recent decade. According to the drought classification scale (Mckee et al., 1993), three extreme, two severe and five moderate droughts were identified. Among the ten cases, three droughts started in spring, two in early summer and five in autumn (Table 1). Drought duration varied from 1 to 10 months, with a mean of 5.1 months and one standard deviation (SD) of 2.7 months. Drought magnitude ranged from −1.14 to −3.19 with a mean of -1.81 ± 0.71. The top three lowest SLI values were −3.19, −2.76 and −2.20, corresponding to possibilities of 0.07 %, 0.29 % and 1.39 %, respectively, for each occurrence. Drought severity varied from −1.14 to −12.82 with a mean of -5.41 ± 3.54. In the category of "severe drought", the drought that ranked first in both magnitude and severity occurred from June 2006 to February 2007, lasting 9 months. The second most severe drought emerged in September 2009–January 2010, persisting 5 months. The third most severe drought took place from April to July 2007, lasting 4 months. The two droughts in the "severe drought" category occurred from June to October 2001 and from October 2007 to April 2008. Among the five droughts in the "moderate drought" category, the longest occurred from October 2003 to August 2004, lasting 10 months. Although it was classified as a moderate drought by magnitude, its drought severity was comparable to the second most severe one, producing substantial effects on local inhabitants (Min et al., 2008).

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In comparison to the years 1961–2000, the lake droughts changed in terms of duration, frequency, magnitude and severity in the most recent decade (Fig. 2b) as follows: on average, drought duration extended from 4.9 to 5.1 months; drought frequency increased from 7.0 to 10.0 events per decade; drought magnitude intensified from −1.54 to −1.81; and drought severity increased from −4.75 to −5.41. Paired F test showed that only the change in drought magnitude was significant ($p = 0.0254$), indicating that the lake droughts intensified significantly. In regard to the intensification, further analysis revealed that the number of moderate droughts increased from 3.3 to 5.0 events per decade but the number of severe droughts decreased from 2.5 to 2.0 events per decade (Fig. 2c). The number of extreme droughts, which developed from the intensification of severe droughts, increased from 1.3 to 3.0 events per decade. Overall, the lake droughts increased in duration, frequency and severity, and intensified significantly in magnitude over the last decade.

4.2 Hydroclimatic change at Poyang Lake region

It is impossible to measure all of the surface runoff downstream from the hydrological control stations into Poyang Lake. The Poyang Lake region is thus the minimum closure entity directly available for water budget analysis. Prior to the water budget analysis of drought events, clarification of the normal variation of water components is helpful in identifying drought occurrence as an abnormal change. Figure 3 shows the multi-year mean of monthly precipitation (P_R) and evapotranspiration (E_R) for the lake region, lake inflow (I) from five major rivers and outflow (O) into the Yangtze River. The monthly precipitation varied from 9.3 to 58.6 mm with a peak in June followed by a sharp decrease; inflow had a similar seasonal pattern with a peak of 139.0 mm and a base of 21.7 mm; outflow had the maximum value in June and the minimum in January; the maximum evapotranspiration appeared in August and the minimum in December (Table 2). From a perspective of water balance, the water budget was positive from January to June with a peak in June. It became negative from July to December, and the minimum value appeared in October. These results indicate a shift in water budget from a surplus phase in the first half of the year to a deficit phase in the second half of the year. On an annual scale, the equivalent water supply from the local precipitation was 324.1 mm and that from inflow was 714.4 mm. The water loss from the local evapotranspiration was 129.7 mm and that from outflow was 908.8 mm. Obviously, all the water components had seasonal variations, while the inflow and outflow were much higher than the local precipitation and evapotranspiration. This finding implies the dominant role of hydrologic components over meteorological components in Poyang Lake variation.

Lake droughts occur when abnormal change appears in the water budget. Table 2 lists the water components for the lake region during the periods of lake droughts. The water budgets ($P_R - E_R + I - O$) were −38.0, 42.4 and −73.1 mm for three extreme lake droughts, −46.6 and −66.3 mm for two severe lake droughts, and −107.9, −11.6, 49.2, 11.5 and −73.5 mm for five moderate lake droughts. The budget was negative (deficit) for seven cases and positive (surplus) for three cases. Despite the positive water budgets, the large negative anomalies of $P_R - E_R + I$ for the cases illustrate that the lake water income ($P_R - E_R + I$) was exceptionally lower than normal. The low water income resulted from largely decreased inflow and precipitation, as well as increased evapotranspiration. The positive water budgets were attributed to the water surplus period in the first half of the year. In this sense, the definition of drought is a water anomaly referenced to a normal state of either a water surplus or deficit phase. It indicated that the water deficiency (negative anomaly) of water budget was more closely related to a drought occurrence than the net water budget. For example, the water budget did not show any statistically significant relationships with drought magnitude or drought severity. On the contrary, the total water anomaly of a drought event showed a significant relationship with drought severity (x) ($y = -6.3372x^2 - 24.11x - 233.02$, $n = 10$, $R^2 = 0.6029$, $p = 0.0395$).

While the lake droughts were generated from a water anomaly of the water budget, it was not clear to what extent the change of each water component contributes to the anomaly. Clarification of the contribution is helpful for understanding drought causes and will be useful for preventing droughts under the changing climate. Table 3 shows the ratios of the total water anomaly of a component to that of the water budget for each event (Eq. 5). For the three extreme droughts, outflow and inflow played the most important role. For example, inflow was 55.6 mm higher, local precipitation was 26.1 mm lower and evapotranspiration was 18.5 mm higher than normal for the most severe drought (June 2006–Feburary 2007). Outflow was 30.7 mm higher making a positive contribution of 141 % to the water anomaly of $P_R - E_R + I - O$, indicating an exceptionally large amount of lake water loss. For the second most severe drought (April–July 2007), precipitation was 76.0 mm lower and evapotranspiration was 15.1 mm higher. Inflow was 192.6 mm lower, contributing to 80 % of the anomaly. For the third most severe drought (September 2009–January 2010), precipitation was 25.5 mm lower and evapotranspiration was 7.9 mm higher. The reduced inflow contributed to 27 % of the anomaly and the increased outflow contributed to 50 % for the period. In addition to the positive contribution, a water component may contribute negatively. For example, there are three negative cases of outflow occurring mainly in a water surplus period (Table 3). The negative contribution implies less outflow in reference to water income ($P_R - E_R + I$), which is consistent with the water budget ($P_R - E_R + I - O$). Overall, for all the drought cases, 45 % of the total water anomaly of the water budget came from the reduced inflow, 24 % from increased outflow, 23 % from decreased precipitation and 8 % from increased evapotranspiration at the lake region.

4.3 Hydroclimatic change at Poyang Lake basin

Because inflow reduction is the major contribution to the water anomaly in the lake region, it is important to trace how precipitation and evapotranspiration changed at the basin scale in the recent decade. Likewise, prior to performing a water budget analysis, it is valuable to clarify the normal variation of water components. Generally, precipitation (P_B) and evapotranspiration (E_B) had similar seasonal patterns in the basin as those in the lake region (Fig. 4a). Monthly precipitation varied seasonably from

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49.4 to 281.6 mm with a peak in June, followed by peaks in May and April (Table 2). Major precipitation appeared in the first half of the year. Monthly evapotranspiration was generally less than precipitation, ranging from 13.8 to 119.7 mm. The top three highest values appeared from June to August. Monthly outflow was approximately half of precipitation with a similar seasonal pattern. Consequently, the monthly water budget was positive (surplus) from December to June and negative (deficit) from July to November. The highest water surpluses appeared in March, April and May. The lowest water deficits were in July, August and September.

The water budget was 22.4, 5.1 and −37.9 mm for the three extreme lake droughts, −149.1 and −50.6 mm for the two severe lake droughts, and −115.2, 40.7, 7.2, −40.3 and −74.4 mm for the moderate lake droughts (Table 2). There were six cases with negative values and four with positive values. For the negative cases, the water budget featured less precipitation (negative anomaly) and more evapotranspiration (positive anomaly). For the three positive cases, $P_B - E_B$ had large negative anomalies over 100 mm, but the water budgets became positive due to the largely reduced outflow. For the most severe lake droughts (June 2006–Feburary 2007), $P_B - E_B$ was 46.0 mm higher than the normal, indicating that meteorological droughts did not occur at the basin scale during that period. This case, along with a similar case in October 2002, indicates that a basin-scale meteorological drought is not a necessary circumstance for a lake drought to occur.

Generally, basin-scale precipitation is an important water source to the lake, as confirmed by the high correlation between $P_B - E_B$ (x) and I (y) ($y = 0.9934x$, $R^2 = 0.9136$, $n = 10$, $p < 0.0001$) (Fig. 4b). The expected correlation is also an indirect validation of the high quality of precipitation and evapotranspiration data used. While the inflow reduction was generated from combined hydroclimatic change, precipitation and evapotranspiration may have played different roles. For example, precipitation was 88.0 mm and evapotranspiration was 41.9 mm higher than the normal, and they produced inflow 55.6 mm higher from June 2006 to Feburary 2007. In contrast, precipitation was 273.2 mm lower and evapotranspiration was 57.4 mm higher, but they

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generated inflow that was 192.6 mm lower than normal from April 2007 to Feburary 2008; there was a similar case from September 2009 to January 2010. As a whole, 82 % of meteorological deficiency ($P_B - E_B$) came from decreased precipitation and 18 % came from increased evapotranspiration for all ten drought cases (Table 3). These results demonstrate the dominant role of precipitation in reducing the inflow to Poyang Lake.

4.4 Mechanisms accounting for recent lake droughts

The above sections detail the lake droughts as abnormal phenomena and the hydroclimatic contribution to each drought event. Yet, it remains unclear why the droughts strengthened in the recent decade. Did the droughts result from a seasonal combination of hydroclimatic influences or a long-term change of these influences? To address the questions, further analysis is necessary to explain the recently strengthened droughts.

Figure 5a shows the accumulated anomalies of water components from 2001 to 2010. At the lake region, the water budget ($P_R - E_R + I - O$) declined from mid-2002 to a low value in September 2009, then increased. The decrease in the water budget is a hydroclimatic setting for the recent drought increase. The water deficits reflect local precipitation and evapotranspiration, lake inflow and outflow, but each of these components has different influences. For instance, the accumulated P_R showed a decreasing trend after mid-2003 while the E_R increased gradually but steadily. The accumulated E_R even exceeded the P_R after April 2010, exhibiting an increasing influence on the water deficit. Comparatively, the accumulated inflow or outflow had a relatively large variation, consistent with their dominance over P_R and E_R at the seasonal scale, as they displayed similar behaviors with a peak in Spring 2003, and then declined by the end of 2009. In the entire period, precipitation decreased by 5 %, evapotranspiration increased by 19 %, inflow declined by 5 % and outflow declined by 4 % for the lake region. The decrease in inflow was attributed to the precipitation decrease (–2 %) and evapotranspiration increase (8 %) at the basin scale.

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The water deficit served as the hydroclimatic foundation for the increased drought occurrence. However, the hydroclimatic circumstances do not require that all of the water components be abnormally low to produce a lake drought. For example, the P_B was 9.4 mm higher in October 2002 and 88.0 mm higher from June 2006 to Feburary 2007, and the E_B was slightly higher for the two periods. The increased precipitation and the normal evapotranspiration generated an increased inflow, which was also higher from September 2010 to December 2010. Furthermore, the P_R and E_R were normal for two of the three cases. Even with the sufficient inflow and precipitation, the lake droughts occurred because of substantially increased outflows. This observation demonstrates that the lake droughts can occur from exceptional outflows, despite the fact that the $P_R - E_R$ and inflow ($= P_B - E_B$) are sufficient. Since the Yangtze River serves as a boundary condition of Poyang Lake and its blocking effects of principally control outflow, more lake water will flow out into the river if the effects weaken (Guo et al., 2012). While the water impoundment of the TGD could lower the downstream stage, it is natural to discuss whether the impoundments have generated more droughts. Routinely, the TGD impoundment begins in mid-September and spans one to two months. Among all the drought events, none occurred during exactly the same span; accordingly, the TGD impoundments should not be responsible for the increased drought occurrence. Principally, the increased occurrence resulted from the regional hydroclimatic change, in which the total precipitation decreased 22 %, the evapotranspiration increased 19 %, the inflow reduced 20 % and the outflow decreased 18 % in the recent decade. The total inflow decrease came from a precipitation decrease (−14 %) and evapotranspiration increase (8 %) at the basin scale for the period.

In addition to the increased drought occurrence, the drought intensification requires explanations, properly at monthly scale. In comparison to 1961–2000, during 2001–2010 the water surplus reduced for the first half of the year, and the water deficit increased for the second half of the year except for August and November (Fig. 5b). The large surplus reduction includes March and June, and the enhanced deficit includes

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July and September. The reduced surplus and the enhanced deficit would increase the possibility of drought occurrence and intensify the drought magnitude. Notably, two of the three extreme lake droughts appeared in October. This can be explained by the enhanced total water deficits in September and October. For September, the $P_R - E_R$ and $I - O$ contributed to 43 and 57 % of the enlarged water deficit, respectively. In the $I - O$ deficit, inflow decreased but outflow increased. Usually, the outflow decreases with reduced inflow and $P_R - E_R$. Therefore, the increased outflow should be a result of weakened blocking effects of the lake-Yangtze River interactions. In addition to climate change in the upper reaches of the Yangtze River, the weakened effects also include the TGD water impoundments (Guo et al., 2012). The impoundments may have lowered the lake stage at the Hukou outlet by 1 ~ 2 m for September–October in 2003–2008 (Guo et al., 2012). Accordingly, the lowered lake stage would have intensified the lake droughts. For example, the TGD may have increased the drought magnitude from severe to extreme, which is a reasonable explanation for the decrease in the number of severe droughts but increase in the number of extreme droughts (Fig. 2c). Because of highly nonlinear relationships between the lake stage and the TGD operation, it is yet very uncertain to determine a convincible lake change for clarifying the TGD operation on an individual drought event, which requires further studies.

In general, the recently increased droughts were principally ascribed to decreased inflow, increased outflow, and reduced local precipitation and increased evapotranspiration at the lake region. The TGD water impoundments may have contributed to the lake droughts but played a limit role, because it should be within the contribution of the increased outflow from the lake (24 %), in which combined the effects of both the TGD operation and climatic change in the upper reaches of the Yangtze River (Guo et al., 2012). Therefore, the recently increased lake droughts were basically the hydroclimatic consequences, with less important contribution from the anthropogenic influences.

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5 Conclusions

This paper proposed to use a multi-scale approach for identifying the contributions of multiple influences on lake droughts, which demonstrated with the case in Poyang Lake. It determined whether the droughts have occurred more frequently in the recent decade, and clarified the reasons for these changes, if any. Our analysis discloses that the lake droughts strengthened in terms of duration, frequency, magnitude and severity, and intensified in magnitude significantly. In the lake region, the water budget had a seasonal variation, shifting from a surplus in the first half of the year to a deficit in the second half of the year. The hydrologic components generally play a more important role than the meteorological components in the water budget, and the water anomaly is more closely related to a drought occurrence than the net water budget. Furthermore, a water component may positively or negatively contribute to the total water anomaly. The overall contribution came from decreased inflow (45 %), increased outflow (24 %), reduced precipitation (23 %) and increased evapotranspiration (8 %). 82 % of the decreased inflow resulted from basin-scale precipitation and 18 % resulted from basin-scale evapotranspiration.

Further analysis reveals that the reduction in the water budget produced the hydroclimatic foundation for strengthened droughts in the last decade. The increased drought occurrence principally resulted from hydroclimatic change with decreased precipitation, increased evapotranspiration and reduced inflow. The TGD impoundments should not be responsible for the increased occurrence, but they may have enhanced the drought magnitude with a limit contribution. Overall, the findings provide an example of intensified lake droughts, and offer an insightful analysis of the droughts in the changing climate and anthropogenic influences. It should be valuable for improving our understanding of droughts, thus benefiting to develop integrated theories on the subject. This study is also useful for the effective promotion of water resource management and climate adaptation.

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Table 1. Drought events occurring during the 2001–2010 time period.

No.	period	duration (month)	magnitude (possibility)	severity	drought classification
1	Jun 2001–Oct 2001	5	−1.70 (0.0446)	−4.04	severe
2	Oct 2002–Oct 2002	1	−1.14 (0.1271)	−1.14	moderate
3	Oct 2003–Aug 2004	10	−1.49 (0.0681)	−7.95	moderate
4	Jun 2006–Feb 2007	9	−3.19 (0.0007)	−12.82	extreme
5	Apr 2007–Jul 2007	4	−2.20 (0.0139)	−6.00	extreme
6	Oct 2007–Feb 2008	5	−1.93 (0.0268)	−6.66	severe
7	Apr 2008–Aug 2008	5	−1.42 (0.0778)	−4.13	moderate
8	Apr 2009–Jul 2009	4	−1.17 (0.1210)	−2.58	moderate
9	Sep 2009–Jan 2010	5	−2.76 (0.0029)	−7.32	extreme
10	Sep 2010–Dec 2010	3	−1.13 (0.1292)	−1.41	moderate
overall		5.1 ± 2.7	-1.81 ± 0.71	-5.41 ± 3.54	

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Table 2. Water components (unit in mm) of the Poyang Lake region and of the basin for the drought periods. The values in parenthesis are the anomaly of a component against the multi-year mean in 1961–2010. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.

	Lake region						Lake basin			
	P_R	E_R	I	O	$P_R - E_R + I$	$P_R - E_R + I - O$	P_B	E_B	$P_B - E_B$	$P_B - E_B - O$
maximum of multi-year monthly mean	58.6	21.0	139.0	136.8	–	44.3	281.6	119.7	–	65.4
minimum of multi-year monthly mean	9.3	2.8	21.7	29.9	–	−35.6	49.4	13.8	–	−74.8
Jun 2001–Oct 2001	158.6 (−26.8)	106.6 (16.9)	333.9 (−19.6)	432.5 (−58.6)	385.9 (−63.3)	−46.6 (−4.8)	821.4 (−120.7)	538.0 (27.6)	283.4 (−148.3)	−149.1 (−89.7)
Oct 2002–Oct 2002	21.4 (−2.6)	19.3 (2.2)	49.9 (13.7)	159.9 (100.4)	52.0 (8.9)	−107.9 (−91.5)	133.7 (9.4)	88.9 (−6.0)	44.8 (15.4)	−115.2 (−85.0)
Oct 2003–Aug 2004	100.8 (−49.4)	52.7 (7.9)	221.9 (−164.0)	281.6 (−184.2)	270.0 (−221.3)	−11.6 (−37.1)	584.5 (−175.9)	262.3 (24.2)	322.2 (−200.1)	40.7 (−15.9)
Jun 2006–Feb 2007	242.6 (−26.1)	132.4 (18.5)	603.5 (55.6)	751.6 (30.7)	713.7 (11.1)	−38.0 (−19.6)	1444.6 (88.0)	670.6 (41.9)	774.0 (46.0)	22.4 (15.4)
Apr 2007–Jul 2007	112.4 (−76.0)	76.6 (15.1)	245.4 (−192.6)	238.7 (−240.2)	281.1 (−283.7)	42.4 (−43.5)	650.9 (−273.2)	407.0 (57.4)	243.8 (−330.6)	5.1 (−90.4)
Oct 2007–Feb 2008	47.4 (−14.6)	28.5 (4.3)	83.1 (−47.0)	168.3 (−45.8)	102.0 (−65.9)	−66.3 (−20.2)	256.1 (−82.4)	138.4 (7.0)	117.7 (−89.5)	−50.6 (−43.7)
Apr 2008–Aug 2008	198.0 (−19.3)	99.4 (16.9)	418.4 (−65.2)	467.8 (−92.5)	516.9 (−101.4)	49.2 (−8.9)	965.1 (−103.7)	490.1 (25.0)	474.9 (−128.7)	7.2 (−36.2)
Apr 2009–Jul 2009	99.6 (−54.2)	60.9 (9.1)	199.5 (−136.5)	226.7 (−139.2)	238.2 (−199.8)	11.5 (−60.7)	497.7 (−251.4)	311.2 (24.3)	186.4 (−275.7)	−40.3 (−136.6)
Sep 2009–Jan 2010	46.1 (−25.5)	45.1 (7.9)	93.4 (−39.6)	167.5 (−68.6)	94.4 (−73.1)	−73.1 (−4.5)	349.0 (−40.8)	219.4 (17.9)	129.6 (−58.8)	−37.9 (9.9)
Sep 2010–Dec 2010	38.7 (0.4)	20.9 (3.9)	79.7 (6.0)	170.9 (24.2)	97.4 (2.5)	−73.5 (−21.7)	194.4 (−21.7)	98.0 (7.2)	96.5 (−28.9)	−74.4 (−53.1)
Overalls	1065.6 (−294.1)	642.4 (102.7)	2328.7 (−589.2)	3065.5 (−673.8)	2751.6 (−986.0)	−313.9 (−312.5)	5897.4 (−972.4)	3223.9 (226.5)	2673.3 (−1199.2)	−392.1 (−525.3)

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Table 3. Contribution of water components (unit in 100 %) to a water anomaly of the water budget at the lake region and lake basin for ten lake drought events.

Lake droughts	Lake region				Lake basin to I	
	P_R	E_R	I	O	P_B	E_B
Jun 2001–Oct 2001	0.24	0.15	0.18	0.42	0.81	0.19
Oct 2002–Oct 2002	0.03	0.02	−0.14	1.09	−0.61	−0.39
Oct 2003–Aug 2004	0.21	0.03	0.70	0.05	0.88	0.12
Jun 2006–Feb 2007	0.97	0.69	−2.07	1.41	−1.91	0.91
Apr 2007–Jul 2007	0.31	0.06	0.80	−0.18	0.83	0.17
Oct 2007–Feb 2008	0.11	0.03	0.36	0.50	0.92	0.08
Apr 2008–Aug 2008	0.37	0.32	1.25	−0.94	0.81	0.19
Apr 2009–Jul 2009	0.29	0.05	0.72	−0.06	0.91	0.09
Sep 2009–Jan 2010	0.17	0.05	0.27	0.50	0.69	0.30
Sep 2010–Dec 2010	−0.01	0.05	−0.08	1.04	−0.75	−0.25
overalls	0.23	0.08	0.45	0.24	0.82	0.18

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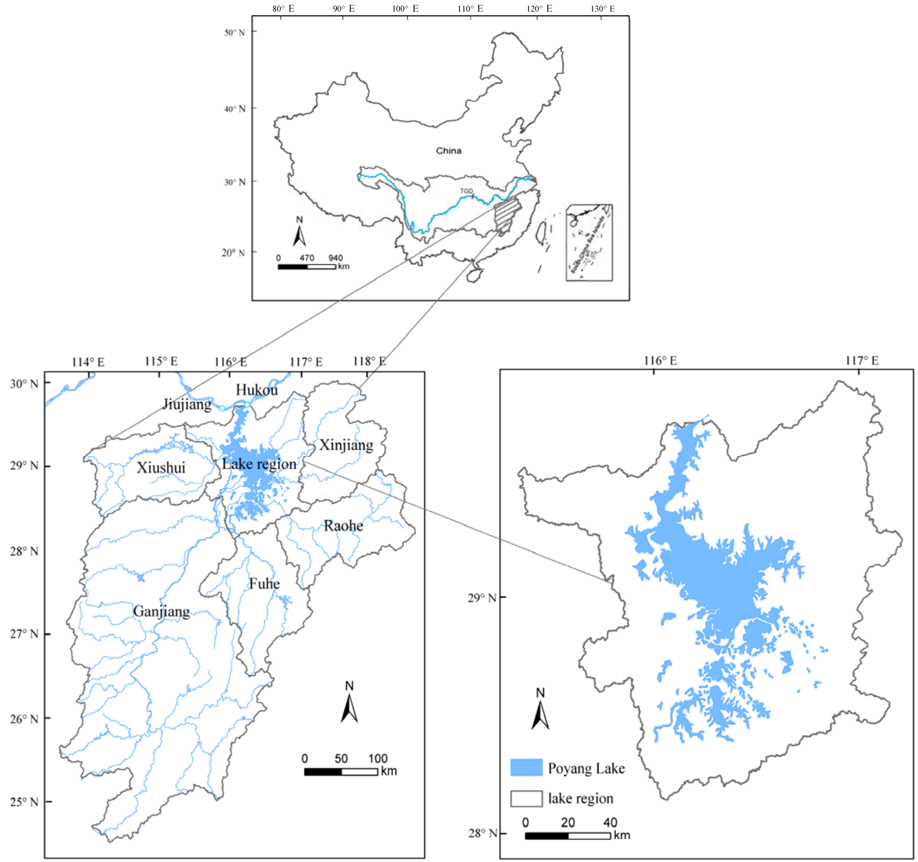

Figure 1. Geographic location of Poyang Lake, China. The lake is principally fed by a five river systems of the Poyang Lake Basin. Lake water flows into the Yangtze River via a sole outlet at the Hukou. Jiujiang is located 25 km upstream of the Hukou on the Yangtze River. The Three Gorges Dam (TGD) is upstream of the river.

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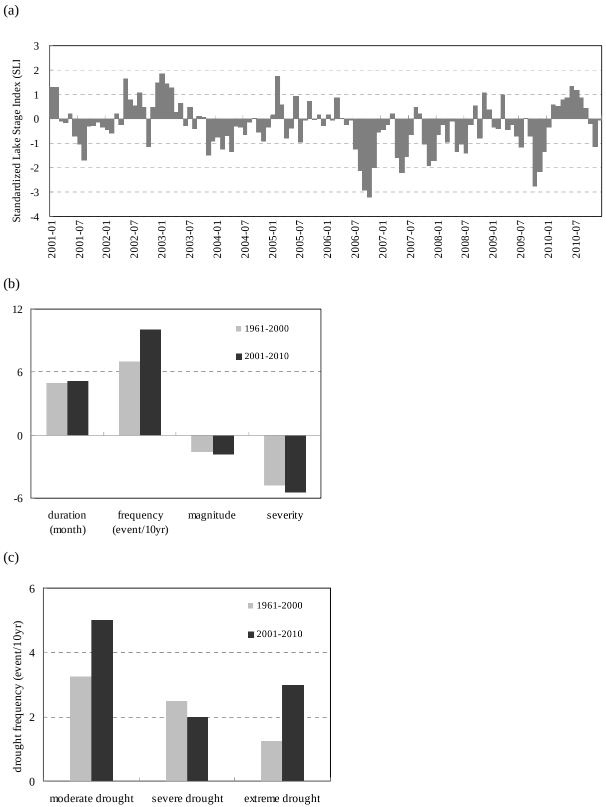

Figure 2. Poyang Lake droughts in 2001–2010. **(a)** Variation in the standardized lake stage index (SLI). **(b)** Drought duration, frequency, magnitude and severity, and **(c)** drought frequency for moderate, severe and extreme droughts, compared to 1961–2000.

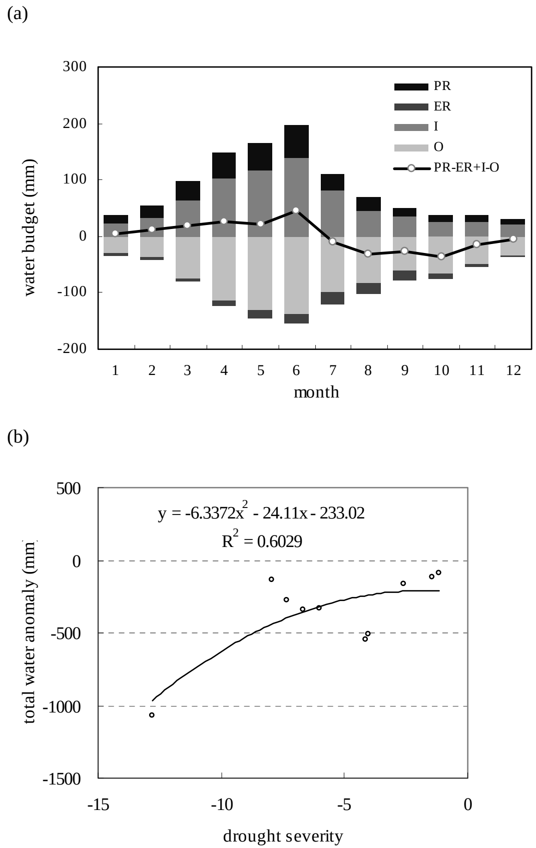

Figure 3. (a) Multi-year mean of monthly precipitation (P_R) and evapotranspiration (E_R) for the Poyang Lake region, lake inflow (I) from five major rivers of the Poyang Lake Basin, and outflow (O) into the Yangtze River. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin. **(b)** The relationship between drought severity and total water anomaly of ($P_R - E_R + I$) of each event for ten cases of Poyang Lake droughts.

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(a)

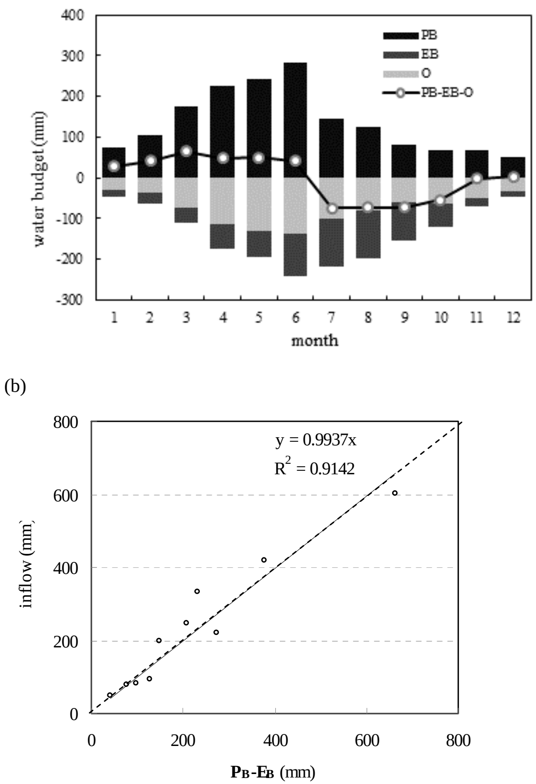

Figure 4. (a) Multi-year mean of monthly precipitation (P_B) and evapotranspiration (E_B) for the Poyang Lake Basin, and outflow (O) into the Yangtze River. **(b)** The relationship between $P_B - E_B$ and inflow for ten cases of Poyang Lake droughts. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.

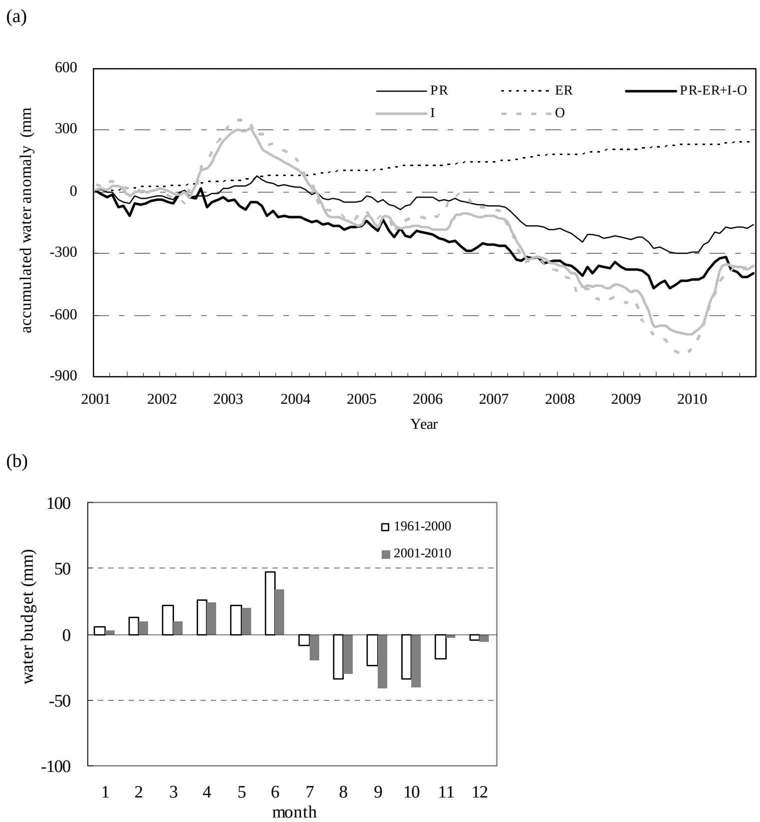

Figure 5. (a) Accumulated anomaly of water components and **(b)** water budget at the Poyang Lake region for 2001–2010 compared to 1961–2000. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.