Recent increased frequency of drought events in Poyang Lake Basin, China: climate change or anthropogenic effects?

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Abstract The Poyang Lake wetland of China is in the first batch of the Ramsar Convention List of Wetlands of International Importance. Poyang Lake's surface area has decreased drastically in the past three decades, and hydrological droughts have occurred more frequently in the region in recent years. It is unclear which factors are responsible for the change and to what extent. This study utilized satellite remote sensing to investigate the recent increase of drought events in the region. The Moderate Resolution Imaging Spectroradiometer (MODIS) data were used to retrieve the lake variations in the last decade. The Global Precipitation Climatology Centre (GPCC) data sets were incorporated to analyse the water cycle in the basin. Our results revealed no significant increasing or decreasing long-term trend in precipitation. The lake surface reached minimum levels in the winters of 2003, 2006 and 2009, corresponding to three severe hydrological droughts in the basin. Case examinations showed less precipitation in 2003 and greater evapotranspiration in 2006, but this was not the case for 2009. The explanation is likely related to operation of the Three Gorges Dam, the largest dam in the world. Overall, the increased frequency of droughts was very likely related to the dam construction and operation and climate change, in addition to land-use and land-cover change.

Key words Poyang Lake, China; multi-temporal satellite remote sensing; climate change; hydroclimatology

INTRODUCTION

Poyang Lake is the largest freshwater lake in China, and is the primary component of the Poyang Lake wetland. The wetland was included in the first batch of the Ramsar Convention List of Wetlands of International Importance. In the recent decade, Poyang Lake experienced drastic hydrological change. Severe drought events occurred more frequently and the changes resulted in hydrological, biological, ecological and economic consequences in the region. Yet it is unclear which factors were responsible for the changes.

Poyang Lake has an average depth of 8 m; but its surface area varies seasonally from over 3500 km^2 in summer to less than 1000 km^2 in winter. The lake becomes separated during the low-water period. There are only a few hydrological stations distributed around the lake. Due to different ecological, hydrological and meteorological situations, water levels are often different in the separated areas. Therefore, the conventional water-level record may not represent the actual hydrological conditions in the area.

This study utilized satellite remote sensing to investigate the recently increased drought events in the region. We reconstructed historical lake changes in terms of water surface area from multi-temporal satellite data. We then analysed the lake variation and hydro-meteorological variables at seasonal and inter-annual scales. Here we discuss the possible mechanisms of the recent severe drought events.

METHODS

In remote sensing, a water body is the most discernible target. It can be easily extracted from a satellite image using a single-band or a multi-band index (Richard & Mary, 1988; Goward *et al*., 1991; McFeeters, 1996). Because water strongly absorbs radiation in the near-infrared (NIR) wavelength and reflects most radiation in the visible wavelength, it can be easily differentiated from vegetation, soil and other land covers. The visible band is often combined with the NIR band to form an index for water delineation. In this study, we used the normalized difference water index (NDWI) defined as follows (McFeeters, 1996):

$$NDWI = \frac{\rho_G - \rho_{NIR}}{\rho_G + \rho_{NIR}} \quad (1)$$

where ρ_{NIR} is surface reflectance in the NIR band, and ρ_G is a value in the green band. In practice, both surface reflectance and satellite digital number (DN) have been used for the calculation (e.g. Teillet *et al*., 1997; Carlson & Ripley, 1997). In this case, NDWI becomes:

$$NDWI_{DN} = \frac{DN_G - DN_{NIR}}{DN_G + DN_{NIR}} \quad (2)$$

where DN_{NIR} and DN_G indicates DN in the NIR and green bands, respectively. It is well-known that atmospheric- and/or sensor-induced variation in DN may result in variations of *NDWI*, and subsequent delineation. Our study showed that the use of either $NDWI_{DN}$ or *NDWI* could achieve equivalent results in water delineation (Liu *et al*., 2011). Therefore, we utilize $NDWI_{DN}$ rather than *NDWI*. In the histogram of $NDWI_{DN}$, an optimal threshold value needs to be determined for separating water from background.

STUDY MATERIALS AND DATA PROCESSING

Poyang Lake is located within the Poyang Lake Basin, which is a sub-basin of the Yangtze River Basin of China (Fig. 1). The lake water flows into the Yangtze River via the Hukou, located at the north end of Poyang Lake Basin. Our study area covers the lake by 28°22′–29°45′N, 115°47′–116°45′E. It is in the humid subtropical climate zone. The dominant land covers include water body, wetland vegetation, agricultural fields, grassland, and bare land surfaces.

We acquired nearly 400 scenes of multi-temporal MODIS (Moderate Resolution Imaging Spectroradiometer) data. These images were used to extract water surfaces over the area for the period from 2000 to 2009. MOD02_QKM and MOD02_HKM data were acquired from the Warehouse Inventory Search Tool (https://wist.echo.nasa.gov/). The MOD02_QKM and MOD02_HKM data sets contain Level-1B calibrated and geolocated at-aperture radiances for visible and NIR bands (Masuoka *et al*., 1998). The MOD02_HKM data sets were used to extract

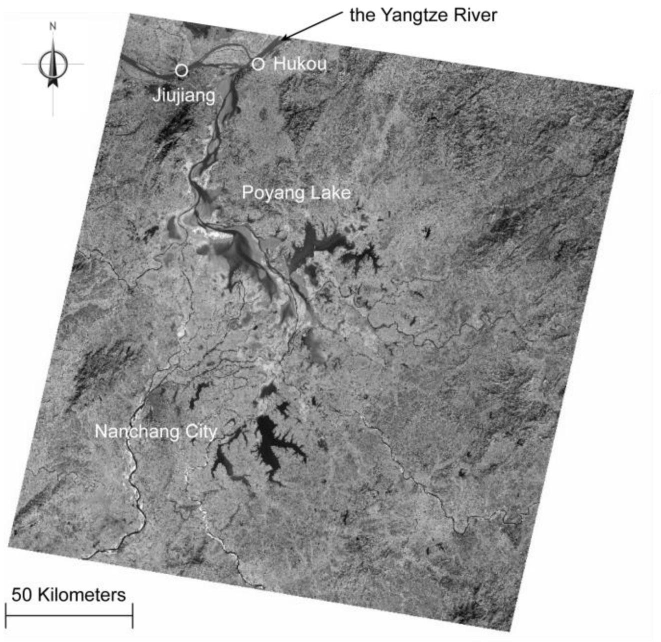

Fig. 1 A false colour image of Poyang Lake region in 1999, in which indicates the Yangtze River, and Hukou and Jiujiang hydrological stations.

DN-values in the green band (0.545–0.565 μm) at 500-m resolution, and the MOD02_QKM to extract DN-values for the near-infrared band (0.841–0.876 μm) at 250-m resolution. To match the spatial resolution of NIR bands, the 500-m green-band data were resampled into 250-m using a nearest neighbour algorithm. All the acquired Landsat and MODIS data were re-projected onto the Universal Transverse Mercator (UTM) with a World Geodetic System datum (WGS-84).

Equation (2) was then applied to produce NDWI images. The NDWI histogram was generated for delineation of water surface. An optimal threshold value was determined from each histogram through comparison with typical objects (e.g. lake banks). The segmented water surfaces were also confirmed through visual inspection with ground-truth data. In this way, water surfaces were obtained for all the images used.

Water discharge data of the Chanjiang River Basin was acquired from the Changjiang Water Resource Commission. Meteorological data including wind speed, surface air temperature and humidity were obtained from the China Meteorological Administration. Precipitation data were obtained from the Global Precipitation Climatology Centre (GPCC) at http://gpcc.dwd.de/. The Global Satellite Mapping of Precipitation (GSMaP) data were acquired from sharaku.eorc.jaxa.jp/GSMaP_crest/index.html. These data sets were used to investigate the possible mechanisms of recent droughts.

RESULTS AND DISCUSSIONS

Changes in Poyang Lake surface area during the recent decade

Poyang Lake has a remarkable seasonal feature. At an inter-annual scale, Fig. 2(a) illustrates the change in lake area during the high-water period (September) from 2000 to 2009. Water surface area decreased from 3617 km^2 in 2000 to 1266 km^2 in 2006, marking a historical minimum record. It then started to increase and reached an area of 2640 km^2 in 2009.

In the past decades, three severe drought events occurred in the region. At the end of September 2003, the water surface area remained at nearly 3000 km^2, a relatively large size. The surface area decreased quickly to nearly 2000 km^2 at the end of October (Fig. 2(b)). In 2006, the largest water surface area was 1703 km^2 in July and it remained relatively low for the whole year (Fig. 2(c)). In 2009, the maximum area was 2640 km^2 in July, August and September, with a sudden decrease to 738 km^2 at the end of October (Fig. 2(d)).

Recent droughts and their possible mechanisms

According to the GPCC data, the mean of annual precipitation in Poyang Lake Basin was 1570 mm/year. There was no significant increasing or decreasing trend in precipitation in the region at the decadal scale. The mean of annual discharge was 645 mm/year at Hukou. The annual discharge had a slight increasing trend from the 1950s to 1990s, but it declined in the 2000s. The water level fell to the minimum values in the winters of 2003, 2006 and 2009, corresponding to three severe hydrological droughts which occurred in the basin.

Table 1 shows the mean values of annual precipitation, surface air temperature and air humidity for the whole basin in2003, 2006 and 2009. Precipitation was low in 2003, normal in 2006, and relatively low in 2009. Discharge at Hukou was high in 2003, normal in 2006 and relatively high in 2009. High surface temperatures and low humidity in these three years imply high evapotranspiration. From a perspective of the annual water balance, each drought event was related to different hydrological and meteorological combinations. In 2003, the low precipitation and high discharge resulted in low water storage and the subsequent hydrological drought. In 2006, both precipitation and discharge were at normal levels and the drought was attributed to high evapotranspiration. The annual temperature was as high as 19.7°C, 0.9°C higher than the multi-year mean. In 2009, both low precipitation and high discharge contributed to the drought. Surface temperature was 0.6°C higher and humidity was 5.3% lower than the multi-year mean. These conditions would result in high annual evapotranspiration.

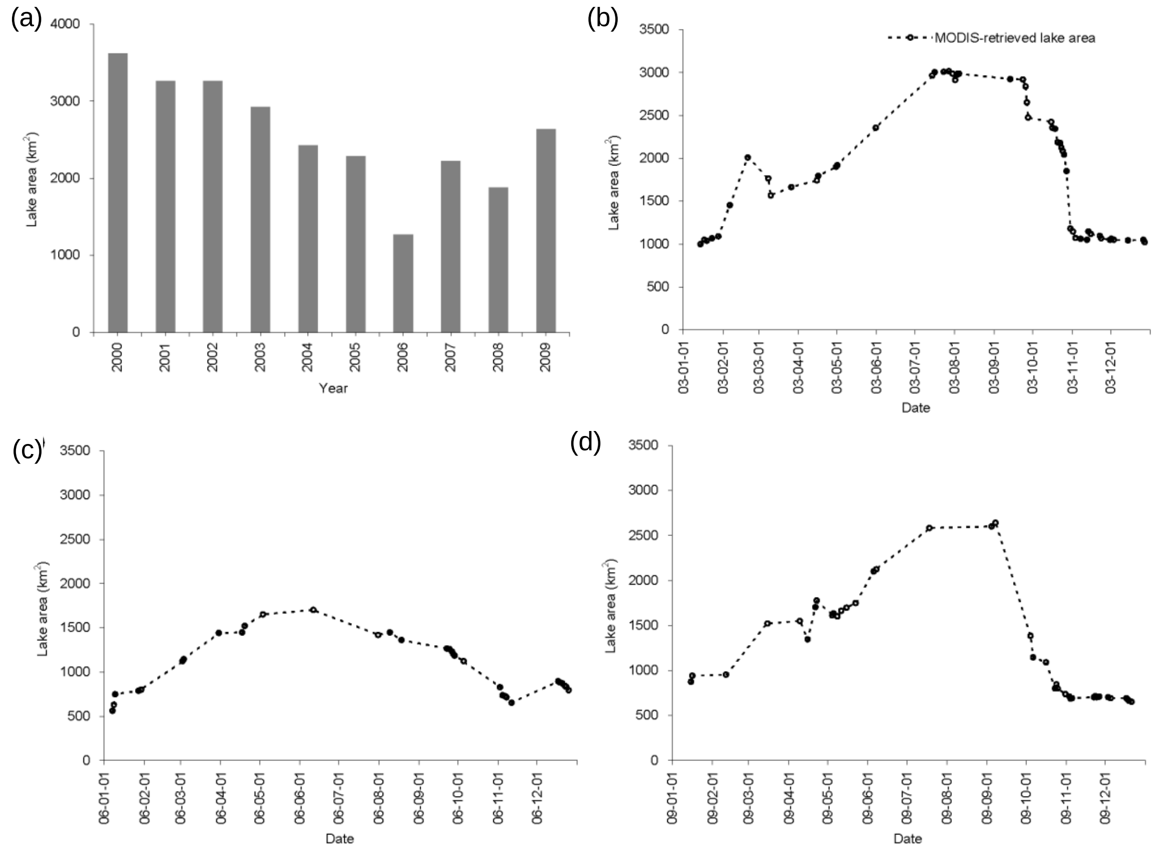

Fig. 2 Change in Poyang Lake surface area: (a) from 2000 to 2009, and in (b) 2003, (c) 2006 and (d) 2009.

Table 1 Mean precipitation, discharge, surface air temperature and air humidity for Poyang Lake Basin in 2003, 2006 and 2009.

	2003	2006	2009	Multi-year mean (1957–2009)
Precipitation (mm/year)	1463.8	1665.5	1524.2	1570.0
Discharge at Hukou (mm/year)	780.0	654.0	689.5	645.0
Surface air temperature (°C)	19.5	19.7	19.4	18.8
Air humidity (%)	75.6	76.5	72.8	78.1

Analysis at the seasonal scale would be helpful for understanding of the mechanisms of recent frequently occurred droughts. Figure 3 shows seasonal variations of water level, air temperature and humidity in 2003, 2006 and 2009. In 2003, water levels decreased sharply August (Fig. 3(a)). It was unclear if the decrease was related to the decrease in upper stream precipitation or an artificial construction. On the other hand, the large annual discharge at Hukou was very likely related to the low water level at Jiujiang, where a gauge station was established to measure water discharge of the Yangtze River. A low water level would generate a large hydraulic gradient from the south to the north of Poyang Lake. This facilitates lake water to flow into the Yangtze River. In addition, Poyang Lake basin experienced a very hot summer (Fig. 3(b)). Surface temperatures were very high and humidity was as low as 60%. In general, precipitation, evapotranspiration and water discharge all significantly contributed to the 2003 drought and lake shrinkage.

In the spring and summer of 2006, both lake area and water level increased gradually (Fig. 3(c)). However, they decreased in July, much earlier than usual (i.e. late September) at Hukou. Water levels were much lower than the multi-year mean values in both summer and autumn, and accompanied by a severe drought event in 2006. Given the precipitation and discharge were normal, the major contribution was from evapotranspiration. As described earlier,

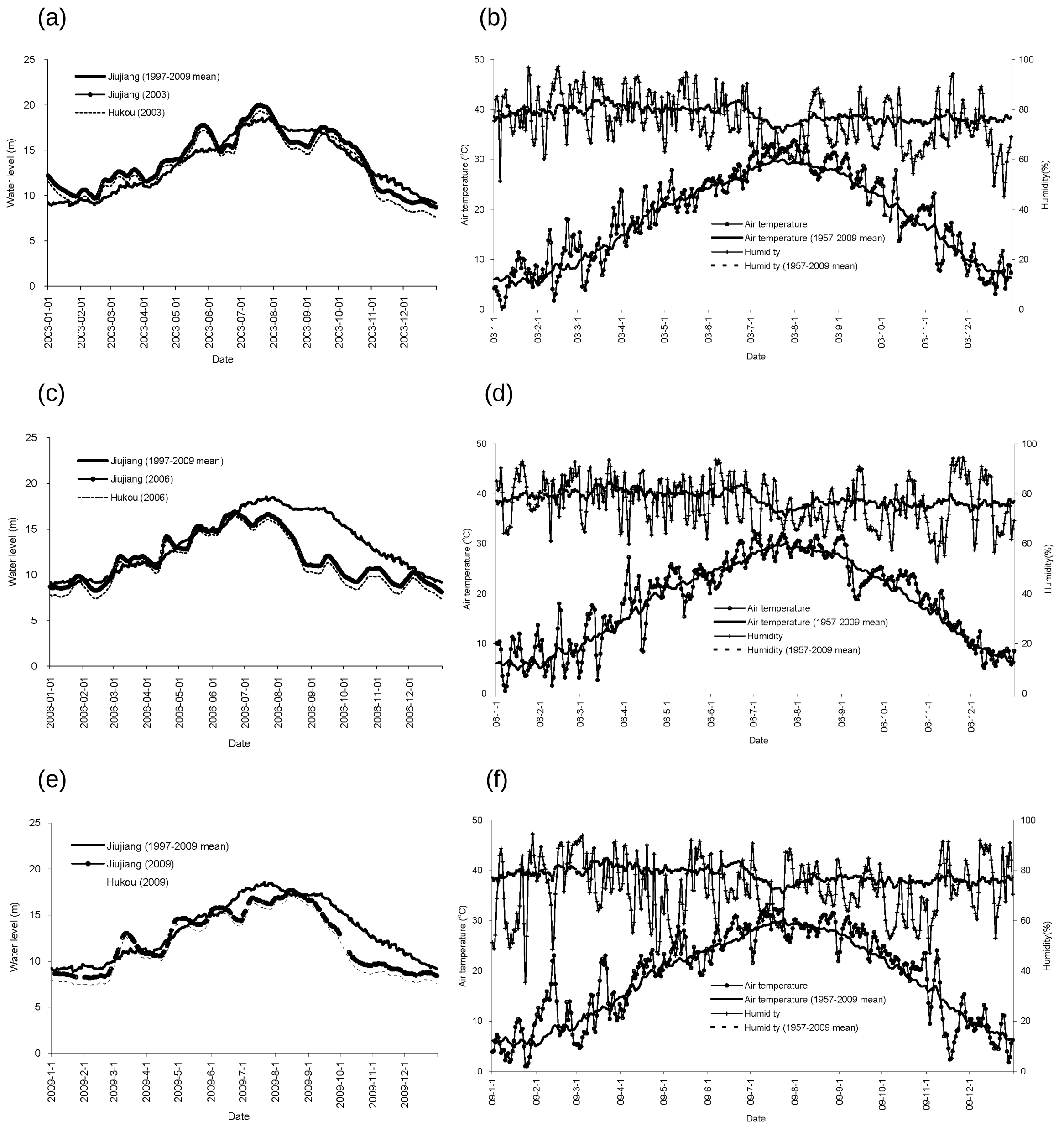

Fig. 3 Seasonal variations in water level, air temperature and humidity in: (a)–(b) 2003, (c)–(d) 2006 and (e)–(f) 2009.

the annual mean of surface air temperature was 0.9°C higher than the multi-year mean and the annual mean humidity was 1.6% lower than the multi-year mean; both values indicate that more evapotranspiration occurred in this year. In the autumn especially, air temperature was generally higher than the multi-year mean. The increased evapotranspiration depleted water within the basin.

Precipitation was slightly low in 2009, but water discharge was still relatively high. This required a relatively large hydraulic gradient from the south to the north of Poyang Lake. Notably, surface air temperature was quite high in September and October, corresponding to a low-water period. Overall, both the high hydraulic gradient and high evapotranspiration contributed to the 2009 drought.

Additionally, thousands of reservoirs have been constructed within Poyang Basin in the recent decades. Land cover has also experienced changes with the increased development of regional economies. Both may increase or decrease basin-scale evapotranspiration. By chance, the Three

Gorges Dam was in operation after 2003. The water level of the Three Gorges Reservoir reached 135 m in 2003, 156 m in 2006, and 172 m in 2009. It was hard to isolate water storage effects of the reservoir from the drought events. Detailed investigation is necessary before a conclusive conclusion can be made.

CONCLUDING REMARKS

This study used satellite remote sensing to retrieve water surfaces of Poyang Lake for investigation of the recent increased drought events. The results showed no significant increasing or decreasing long-term trend in precipitation. The lake water surface reached the minimum level in the autumn and winters of 2003, 2006 and 2009, corresponding to three severe hydrological droughts in the basin. Detailed examination found less precipitation in 2003 and high evapotranspiration in 2006. The major reason was different for each drought, but all droughts were accompanied by hot weather or high evapotranspiration. Less precipitation but high discharge implied a high hydraulic gradient from the south to the north of Poyang Lake. Possible explanations are related to operation of the Three Gorges Dam, and climate change, in addition to local land-use and land-cover change. Further study is under way.

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