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Capturing variations in inundation with satellite remote sensing in a morphologically complex, large lake

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SUMMARY

Poyang Lake is the largest freshwater lake in China, with high morphological complexity from south to north. In recent years, the lake has experienced expansion and shrinkage processes over both short- and long-term scales, resulting in significant hydrological, ecological and economic problems. Exactly how and how rapidly the processes of spatial change have occurred in the lake during the expansion and shrinkage periods is unknown. Such knowledge is of great importance for policymakers as it may help with flood/drought prevention, land use planning and lake ecological conservation. In this study, we investigated the spatial–temporal distribution and changing processes of inundation in Poyang Lake based on Moderate Resolution Imaging Spectroradiometer (MODIS) Level-1B data from 2000 to 2011. A defined water variation rate (WVR) and inundation frequency (IF) indicator revealed the water surface submersion and exposure processes of lake expansion and shrinkage in different zones which were divided according to the lake's hydrological and topographic features. Regional differences and significant seasonality variability were found in the annual and monthly mean IF. The monthly mean IF increased slowly from north to south during January–August but decreased quickly from south to north during September–December. During the lake expansion period, the lake-type water body zone (Zone II) had the fastest expansion rate, with a mean monthly WVR value of 34.47% in February–March, and was followed by the channel-type water body zone (Zone I) in March–May (22.47%). However, during the lake shrinkage period, rapid shrinkage first appeared around the alluvial delta zones in August–October. The sequence of lake surface shrinkage from August to December is exactly opposite to that of lake expansion from February to July. These complex inundation characteristics and changing process were driven by the high temporal variability of the river flows, the morphological diversity of the benthic landforms and the patterns of water movement. These results provide a foundation for basic hydrological and ecological studies and are valuable for the conservation and management of water resources in Poyang Lake.

1. Introduction and background

Poyang Lake is the largest freshwater lake in China. It is recognized internationally as an important wetland region in terms of the provision of habitat for migratory birds (Finlayson et al., 2010). Notably, Poyang Lake is particularly complex because of fluctuations in water inundation within and among years. The lake expands to a large water surface area in the summer high-water season but shrinks to a small area during the winter low-water season (Shankman and Liang, 2003; Feng et al., 2012). This high seasonal variation in water surface area is complicated in its spatial distribution and temporal processes. There is a significant difference in benthic topography among the different areas of the lake. The average topography elevation generally decreases from the south (>16 m) to the north (<12 m) (Cai and Ji, 2009). In addition, the varying discharges from upstream catchments into Poyang Lake and lake discharge into Yangtze River add further complexity to the variation in lake area (Guo et al., 2012). They also cause the spatial distribution and rate of change of the water surface area to vary considerably in different regions during the expansion and shrinkage periods. Indeed, the spatial distribution and the variation of the inundated area largely determine wetland/aquatic ecological conditions and the availability of water for irrigation and drinking (Qi et al., 2009; Williamson et al., 2009; Ariztegui et al., 2010; Du et al., 2011). The timing and duration of surface exposure and submersion also directly effects the wetland plant regeneration, species richness, and ecological conditions of the lake (Biggs, 1996; Nishihiro et al., 2004; Liu et al., 2006; Raulings et al., 2010). Therefore, the accurate assessment of the spatial processes of water inundation variation in Poyang Lake remains a challenge.

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Traditionally, the detection of spatial change in a lake relies on in situ gauge measurements and hydrological models. These methods, however, cannot provide an overall distribution pattern on a regional scale due to their low efficiency or sometimes absence in inaccessible regions (Alsdorf et al., 2007). Remote sensing techniques have advantages for large-scale studies, by offering images at different spatial and spectral resolutions with a short revisit time (Birkett, 2000; Cazenave et al., 2004; Plug et al., 2008; Huang et al., 2011). Recently, several researchers began investigating changes in the water surface area of Poyang Lake using remote sensing data. For example, Andreoli and Yesou (2007) and Hui et al. (2008) examined the variations in lake area during 2004–2006 and 1999–2000, respectively. Zhao et al. (2011) and Feng et al. (2012) also used remote sensing data to examine Poyang Lake's inundation change. These studies focused on changes in the entire lake, and none have addressed the spatial changes within this large region. It remains unclear where the inundation has changed and how rapidly the changes occurred, both of which have important practical implications for policymakers. More recently, Wu and Liu (2014) explored the lake's inundation changes in response to two extreme hydro-climatic drought events. It is more far away from a comprehensive understanding of the general variations of the complex lake, which is fundamental for policymakers to make decisions in eco-environmental management.

Given this background, the goal of this study is to comprehensively explore the spatial–temporal distribution and the changing processes of inundation in Poyang Lake based on multi-temporal imagery and GIS analysis. This goal will be addressed through the following primary objectives: (1) to examine the spatial distribution characteristics of the water surface area at annual and seasonal scales using high-frequency, long-term MODIS images; (2) to analyze the regional differences of water inundation duration and water surface exposure/submersion variation rate in different geographic regions during expansion/shrinkage periods. Our findings should be valuable for hydrological safety and biodiversity conservation as well as information for preparation and precautions against extreme hydrological events.

2. Study area and data

2.1. Study area

Poyang Lake (28°22′–29°45′N, 115°47′–116°45′E) is located within the Yangtze River Basin in China. It is the primary component of the Poyang Lake wetland, which was included in the first batch of the Ramsar Convention List of Wetlands of International Importance. The main water supplies to the lake are from five rivers (Xiushui, Ganjiang, Fuhe, Xinjiang and Raohe) (see Fig. 1). The lake region is geographically divided into five zones according to its hydrological and topographic features (Wu and Liu, 2014; Zhou et al., 2011). Zones I and II are a channel-type water body zone and a lake-type water body zone, respectively, and are separated by the Songmen Mountain. Zone III (west branch of the Ganjiang and Xiushui alluvial delta zone), Zone IV (central and south branches of the Ganjiang and Fuhe alluvial delta zone) and Zone V (Raohe alluvial delta zone) are separated by five tributaries (Wu and Liu, 2014). Normally, the water level in the south is higher than in the north (Cai and Ji, 2009). However, from July to September, the elevated water level of the Yangtze River may impede the south–north water flow and the water level becomes similar across the lake's extent (Shankman et al., 2006).

Poyang Lake has a humid subtropical climate and a long-growing season. The seasonality of the precipitation in the five catchments induces significant variations in the water surface area of the lake throughout the year. In the high-water season, the five tributaries are flooded due to concentrated rainfall, resulting in a maximum lake surface area of greater than 3000 km^2 (Shankman and Liang, 2003). In the low-water season, the surface is remarkably variable because of its varied benthic topography. During this period, the water surface area of the lake shrinks to less than 1000 km^2 (Feng et al., 2012). The disconnected segments are separated by exposed floodplains, which provide essential habitats for thousands of winter migratory birds (de Leeuw et al., 2010).

2.2. Data acquisition and processing

A total of 466 cloud-free MODIS Level-1B (MOD02_QKM and MOD02_HKM) products covering the study area were acquired from the NASA Goddard Space Flight Center (GSFC) at http://ladsweb.nascom.nasa.gov for the period during 2000–2011 (Table 1). The MOD02 datasets contain calibrated and geo-located radiances for the visible and near infrared (NIR) bands. The green band and the NIR band were extracted from the datasets. The green band was resampled to 250-m resolution to match the resolution of the MODIS NIR band. All of the acquired MODIS images were registered with Universal Transverse Mercator (UTM) projection and the World Geodetic System datum (WGS-84).

In addition to these multi-temporal remote sensing images, daily precipitation and water discharge (2000–2011) were available at five hydrological stations (Wanjiabu, Waizhou, Lijiadu, Meigang, and Shizhenjie, Fig. 1). These data were used respectively to measure the discharge from the Xiushui River, Ganjiang River, Fuhe River, Xinjiang River and Raohe River. Likewise, monthly water discharge measured at the Hankou station (Fig. 1 inset) along the Yangtze River was acquired from the Hydrological Bureau of the Yangtze River Water Resources Commission of China. The data were used to measure the discharge and water flux from the Yangtze River. All of these discharge data will aid in understanding the spatial distribution and changing processes of lake inundation during the expansion/shrinkage periods.

3. Methods

In our previous study, we detailed the methods for extracting a water surface from satellite data and for estimating the inundation frequency with extracted water surfaces (Wu and Liu, 2014). For completeness, in this section, we describe these methods in brief.

To extract the water surface, the normalized difference water index (NDWI) (McFeeters, 1996) method was applied. This method has been demonstrated to be most efficient in the detection of water surfaces compared to other algorithms (Jain et al., 2005). The MODIS DN values were then transformed into NDWI. An optimal threshold value was determined between water surface and non-water features from a histogram generated from the pixel distribution of the image (Bryant, 1999; Liu et al., 2012). The lake's inundation extent can be delineated from the acquired images. The extracted water surfaces were evaluated with Landsat-derived results, and they proved to have a root mean square error of 137.3 km^2 and a relative error of 3.95% (Wu and Liu, 2014).

To depict the spatial patterns of water inundation and their regional variation, the inundation frequency (IF) and water variation rate (WVR) are defined as follows

$$P(m) = \frac{1}{N_m}\sum_{t=1}^{N_m} w_{m,t} \times 100\%, \quad (1)$$

$$P(y) = \frac{1}{12}\sum_{m=1}^{12} P(m) \times 100\%, \quad (2)$$

$$\mathrm{WVR} = \frac{UA_{n+i} - UA_i}{nTA_{n+i}} \times 100\%. \quad (3)$$