Water resource monitoring over the Yangtze middle reaches exploiting dragon time series, enyisat, Beijing 1, altimetric data, and field measurements

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Nine years of water resources monitoring over the middle reaches of the Yangtze River, with ENVISAT, MODIS, Beijing-1 time series, Altimetric data and field measurements

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Abstract

Poyang and Dongting Lakes, major water resources and key elements for natural flood control and reduction within the Yangtze River middle basin, were monitored from 2000 to 2008, with a re-visiting period of 10 days, using ENVISAT ASAR, and completed by MODIS data, validated by Beijing 1 time series. GPCP and TRMM time series were utilized to derive regional meteorological indicators. At the lake scale as well as their subdivisions ones, results allowed the characterization of lake behaviors. Even if the Dongting and Poyang lakes mechanisms are substantially different, their water surface areas and water level variations exhibit a good similarity, including the same year of major flooding (2002) and the same year of lowest extent of inundation (2001). Both lakes present astonishingly low water levels and low surface areas in summer of 2006, being associated with a very early draw-off. Few reasons could explained it: (i) a rainfall deficit at the sub-watershed level; (ii) a hydrological event in the upper stream part, namely a possible closure of the Three Gorges Dam (TGD) gates; or (iii) a global climate change effect at the regional scale. The reasons for the dramatic water dropdown are neither a local rain deficit nor a change in the TGD management. The smallest water extent for wet season observed in 2006, appeared to be linked with a severe drought within the upper stream part of the Yangtze River basin. In addition, an impressive decreasing tendency of water surface and level is observed in the middle reaches of the Yangtze River, linked with relatively constant decreasing precipitations over the last decade. This synergistic utilization of data from earth observation systems and in situ data provide valuable information on water resource management at the scale of the middle Yangtze River watershed.

Key words

Altimetric, Dongting, Dragon project, ENVISAT, Poyang, TRMM

INTRODUCTION

The state of the water resources in the Yangtze River watershed is a major concern, influencing the life conditions of >400 millions of inhabitants, noting that the river basin also provides 70% of Chinese rice production, 40% of its cereal production and about 40% of its industrial production.

An important factor also dependent on these water resources is the biodiversity in the reaches of the Yangtze

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River. Factors such as climate fluctuations and human modifications (e.g. Three Gorges Dam) can also have significant impacts on this water system.

The Dongting and Poyang lake areas, considered key hydrological components in flood control in the middle Yangtze River basin, are two of the most regularly flooded areas in China. These lakes were selected as the test sites of the Flood DRAGON Project, part of the MOST-ESA DRAGON Program that is focused on science and applications development in China, mainly utilizing data from the ERS and ENVISAT missions (Desnos *et al.* 2004; Desnos & Li 2006). Based on experience gained in the former successful “flood dragon” project (Andreioli *et al.* (2007a), Li *et al.* 2008; Yesou *et al.* 2009), the focus of the Wetland – Flood DRAGON Project is water resources and environmental preservation. The common denominator of this focus is water level and water coverage, including (i) monitoring the low-lying inland waterbodies; (ii) monitoring water quality, erosion and water resources (i.e. water height and storage capacities); (iii) increased understanding of wetland ecosystems; and (iv) epidemiology. A second-level purpose of the Flood DRAGON Project is to extend and improve methods and tools for flood management, plus analyses of hydrological balances, with regard to preventing and forecasting, utilizing space technologies (Yésou *et al.* 2004, 2010; Li *et al.* 2006).

A considerable database was established for these two study lakes, including a large number of ENVISAT Products, Advanced-SAR (ASAR) ranging from global to high resolution and MERIS full-resolution optical data, acquired between January 2003 and December 2008 for Poyang Lake, completed by MODIS data for the period 2000–2003. For Dongting Lake, the database primarily comprised MODIS decade products exploited between January 2000 and December 2008. This database is completed by high-resolution Landsat, SPOT, CHRIS PROBA, ALOS AVNIR, PRISM & PALSAR, BEIJING 1 data and topographical SRTM data.

Water levels and coverage represent essential information on hydrological monitoring and characterization of hydrological dynamics. Two experimental and complementary methods were explored to determinate hydrological trends for Poyang and Dongting lakes: the combination of water levels recorded at a reference gauge station, with corresponding water coverage derived from earth observation data, and the combination of water coverage, with respect to water levels estimated by radar altimetry techniques. The observations and obtained results were integrated into a local and regional meteorological context, with a focus on water resource management, particularly induced by the Three Gorges Dam that became operational at the end of May 2003 and that since exhibits regular periods of infilling/water release.

STUDY AREAS

The study focused on the two major inland waterbodies in China, namely Dongting and Poyang lakes, both being located along the middle–lower reaches of the Yangtze River (Fig. 1).

Fig. 1. Location of Dongting and Poyang lakes inside the middle reaches of the Yangtze River watershed.

Poyang lake

Located in Jiangxi Province, Poyang Lake is the largest freshwater lake in China, constituting a major hydrological sub-system of the middle Yangtze River basin. It extends in a hollow depression in the north of the province at a very low elevation, only about 10 m a.s.l., surrounded by mountain chains.

The Poyang Lake watershed covers about 162 000 km^2 and includes Jiangxi Province's major rivers (Xiushui, Gan, Fuhe, Raohe, Xin), which flow from the south of Jiangxi Province to the north into Poyang Lake. Poyang Lake drainage has only a narrow outlet into the Yangtze River, which lies on the northern border of the province (Fig. 2). The lake undergoes very significant seasonal water level fluctuations, with the lake elevation varying between 9 and 18 m. Its size fluctuates between <1000 km^2 during the dry winter period and >3000 km^2 during the wet summer season (Fig. 3).

During a normal hydrological year, the discharge peak of the rivers of Jiangxi Province occurs between April and June during the rainy season, raising the water level of the lake. The river discharges decrease from July to September, although the water level of the Yangtze River increases during the same time. As a result, the drainage from the lake to the Yangtze River reverses, moving from the Yangtze River into Poyang Lake around mid-July (Shankman & Liang 2003). Thus, Poyang Lake and the lower section of the tributary rivers flood most years during the summer months. The major floods occur when high discharges from the Jiangxi rivers and the Yangtze River coincide. Seven major floods have occurred over the past 50 years (1954, 1973, 1977, 1983, 1992, 1995, 1998), with the most severe being recorded in 1998 (Shankman *et al.* 2006).

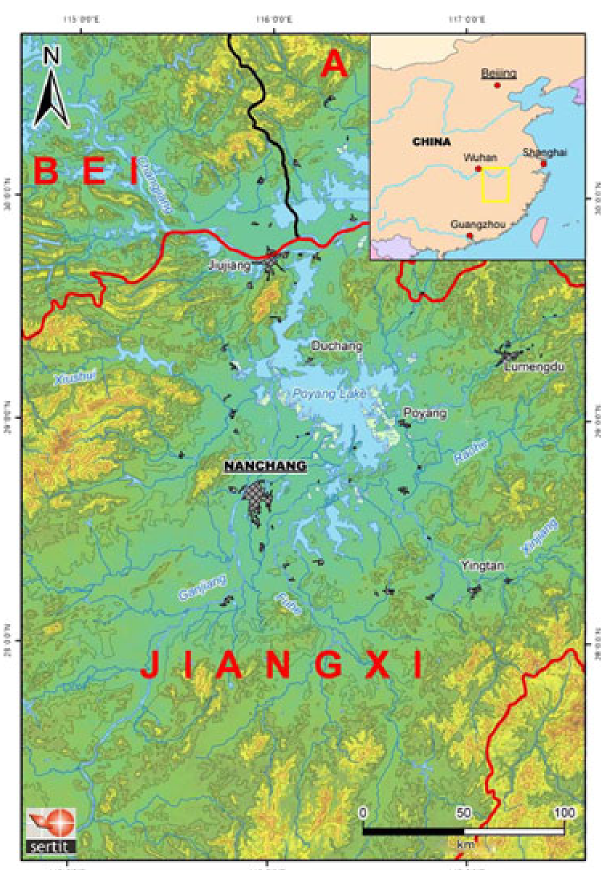

Fig. 2. Location of Poyang Lake.

The climate of the Poyang Lake region is subtropical humid, with a monsoon season. The monthly mean rainfall can reach 325 mm, with the precipitation period concentrated between April and August. The maximum precipitation occurs between May and June, with a lower step effect in July and August (Fig. 4).

Poyang Lake is surrounded by large wetlands of floodplain and marshlands (lakeshore), of which a large part has been reclaimed as farmland over the past 100 years (Shankman & Liang 2003). After the dramatic floods of 1998, the Chinese government established a wetland restoration policy to increase the capacity of Poyang Lake, by abandonment or partial abandonment of 770 km^2 of reclaimed farmland in order to increase floodwater storage (Zhao 1999 in Shankman *et al.* 2009; Jiang *et al.* 2005, 2008). Poyang Lake was labelled as RAMSAR wetland site in 1996. These areas are natural reserves and rich ecosystems in which many fish and shellfish proliferate during the flood periods. This sector is also a major wintering area in Asia that blends >200 species of birds, including twenty endangered ones such as the Siberian cranes (Barzen *et al.* 2009; Cao *et al.* 2010; Higuchi 2010).

Dongting lake

Stretched across the Hunan and Hubei Provincial border, Dongting Lake is China's second largest waterbody. There are four main rivers (Xiangjiang, Zi, Yuan, Li) that flow into Dongting Lake from the south, and four outfalls that link it to the Yangtze River from the north (Fig. 5).

Like Poyang Lake, Dongting Lake acts as a huge retention basin for Yangtze River water during the flood season. The inflow from the Chang Jiang carries an enormous sediment load of 140 000 000 m^3 year^{-1} on average. The lake area, which normally is <500 km^2, might increase to 2500 km^2 during the flood season, when vast quantities of water from the Chang Jiang flow into the lake (Fig. 6).

The lake water flows back into the Yangtze River via a unique outlet at Yueyang (Fig. 5). During the dry season

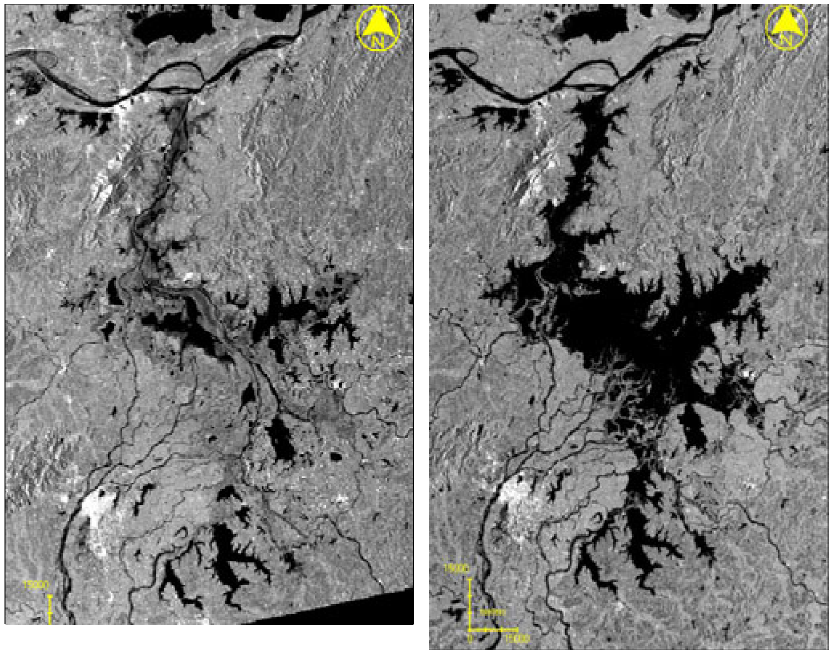

Fig. 3. Poyang Lake (observed by ENVISAT ASAR WSM sensor at low and high water level periods, respectively, in January and August 2004).

(October to April), more water is discharged from the lake than that enters it. As a result, the water level falls and a large part of the lake becomes dryland. Dongting Lake has also suffered over the past 80 years from several major floods (1931, 1935, 1954, 1973, 1977, 1983, 1991, 1995, 1998, 2007), with the most severe recorded in 1954 and 1998 (Shankman *et al.* 2006, 2009).

The serious shrinkage of Dongting Lake has led to the deterioration of its flood diversion and storage capacity, with flood disasters now becoming more frequent. A lake restoration strategy has been proposed to relieve flood-prone areas, as well as being a sustainable biodiversity environment, with the knowledge that Dongting Lake contains wetlands of international importance (RAMSAR label) that provide a habitat for many protected species, such as the wintering lesser white-fronted goose and the endemic merganser (Lei 2000; He *et al.* 2002; Barter *et al.* 2005; Cao *et al.* 2010).

WATER LEVEL RETRIEVAL, UTILIZING RADAR ALTIMETRY

Satellite radar altimetry has been widely used in different fields of continental hydrology, based on coupled satellite altimetry/*in situ* gauges measurements, or in more specific lake or river case studies (see Crétaux & Birkett 2006 and Calmant *et al.* 2008 for a full review of current literature on this research area). Fewer studies have been dedicated to studying floodplains from radar altimetry, mainly because of the difficulty in analysing altimetry waveforms over a complex varying surface (Birkett 2000; Crétaux & Birkett 2006).

Data and methods

The data used in this study were enhanced along track altimeter data distributed by CTOH/LEGOS. These data are derived from mission data distributed by the AVISO facility and also include up-to-date corrections not yet implemented in operational systems. Radar altimeter can give measurements vertically under the satellite. Using ENVISAT, the re-visit period is 30 days. If only one track is available over the targeted lake, water level sampling is 30 days. If two tracks are available for measurements, and if both give significant measurements, a better time resolution is possible.

For hydrology purposes, LEGOS has developed two software programs using altimetry measurements: one is dedicated to rivers and the other to lakes (Crétaux & Birkett 2006; Calmant *et al.* 2008). These software programs implement specific re-tracking of the radar wave reflected by inhomogeneous surfaces. For the river software, a “virtual station” has to be previously established. For the lake software, the data might be averaged over very long distances. Thus, it is necessary to correct for the slope of the geoid or, equivalently, the mean lake level. It is usually computed by averaging the altimetry data for the whole lifetime of the satellite, with the mean

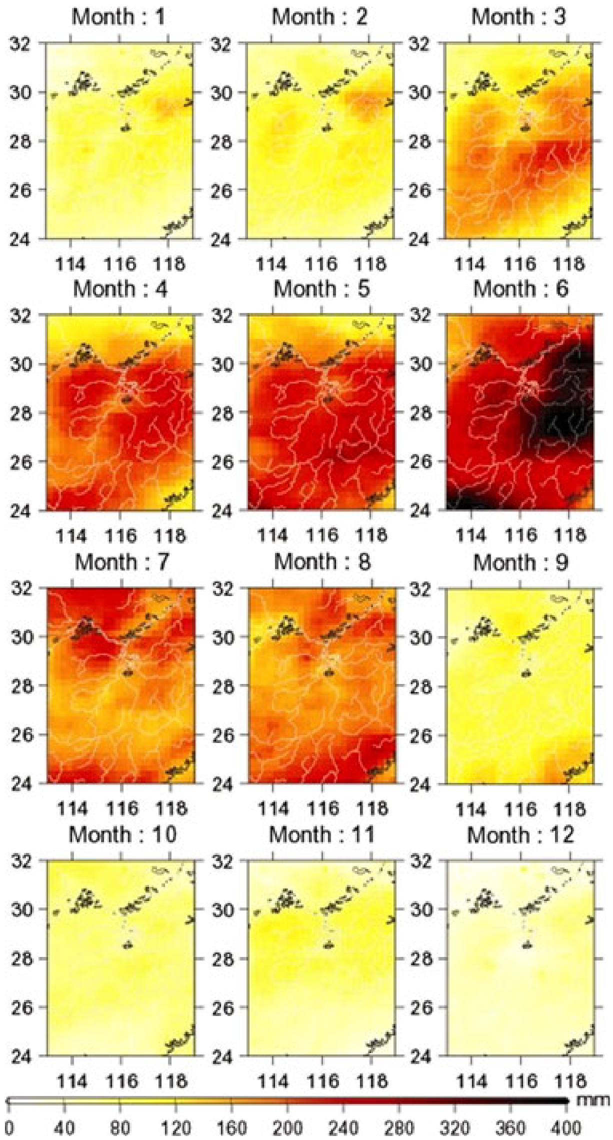

Fig. 4. TRMM monthly precipitation mean values over Poyang Lake, 1998–2009.

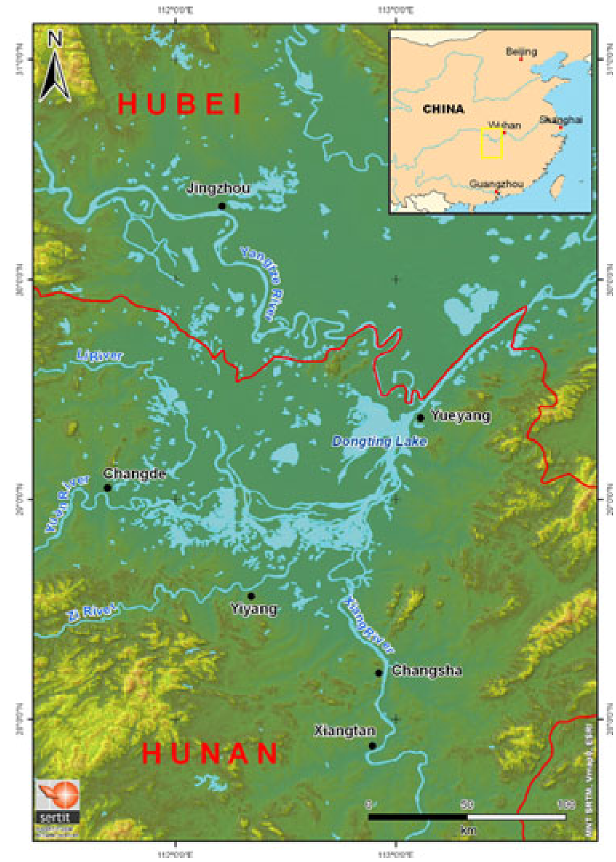

Fig. 5. Location of Dongting Lake.

lake surface then subtracted for each measurement to obtain the lake level at the time of the measurement. Two ENVISAT RA altimetric tracks cover both Poyang and Dongting lakes, being respectively 163 and 980, and 694 and 879 (Figs 7,8). In addition, a Jason 2 track is exploitable over Dongting Lake.

The applied method is an adaptation of LEGOS river software. Part of the tracks, for which the altimeter sees

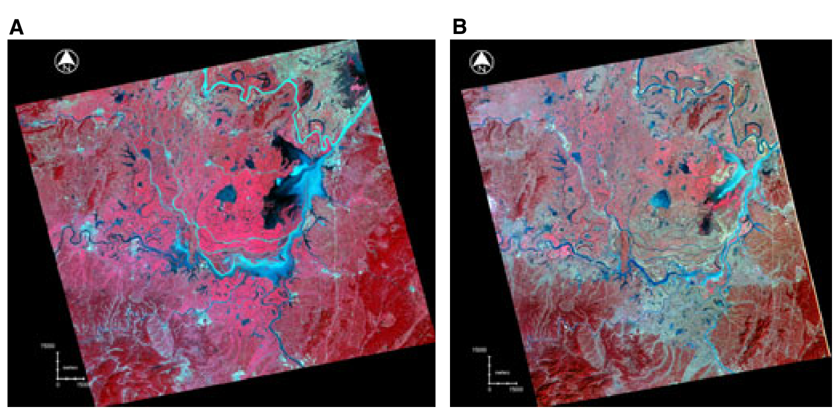

Fig. 6. Dongting Lake (observed by Beijing 1 sensor at low and high water level periods, respectively, in December 2008 and September 2007).

Fig. 7. ENVISAT altimeter tracks over Poyang Lake.

Fig. 8. ENVISAT tracks over Dongting Lake (yellow) and Jason 2.

water during all seasons, has to be selected. A segment >3 km is recommended for a correct algorithm result.

As already mentioned, a major difficulty in using radar altimetry is the variability of surface occupation in floodplains from the dry to the wet season. This situation induces complexity in selecting individual measurements for computing the water level. Basins like Poyang Lake that are constituted by several sub-waterbodies at different heights during the low water stage also complicate data selection. To avoid these problems, backscatter coefficient of the radar echo might be applied to select the analysed part of the track (Crétaux & Birkett 2006), or one can use additional information coming from optical remote sensing imagery.

Poyang lake water height monitoring, utilizing radar altimeter

Two approaches for exploiting remote sensing imagery during processing of the ENVISAT altimeter data have been carried out over Poyang Lake. The first one is based on the exploitation of medium-resolution MODIS data to identify the targeted waterbody at each date of ENVISAT acquisitions. The second is based on the definition of the adequate segment from optical high-resolution data, Beijing 1.

Initially, processed MODIS data were used in this study to select altimetry data along the tracks of Topex-Poséidon and ENVISAT satellites to estimate water level variations in different parts of the inundation area (Fig. 9). The 8-day mosaic images were acquired over the period February 2000–March 2008, and interpolation of the classification along the line's segment corresponding to the radar altimetry tracks was produced. Altimetry data were selected for pixel considered as open water by MODIS classification, and water level time series over different waterbodies in the Lake Poyang basin were then calculated.

The water level time series obtained for the central part of the lake, using ENVISAT data with and without data selection deduced from MODIS classification, are presented in Figure 10. The MODIS–ENVISAT synergy benefit is well highlighted, mostly for the low-level water period, allowing a more realistic retrieval of water levels during the dry season. The time series allow characterization of the monsoon behaviour of the water level, with

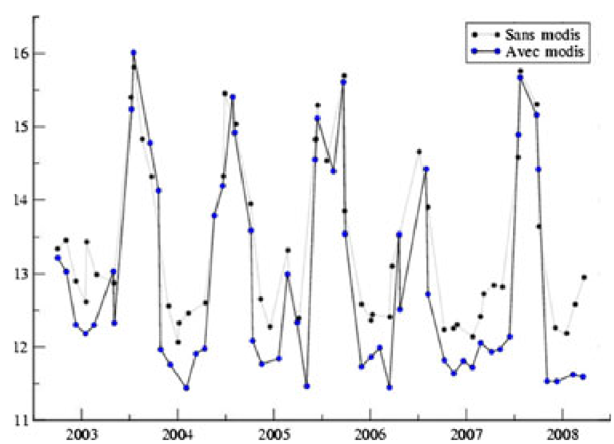

Fig. 9. Poyang Lake water level retrieval based on the conjoint exploitation of ENVISAT altimeter and optical MODIS data (blue curve).

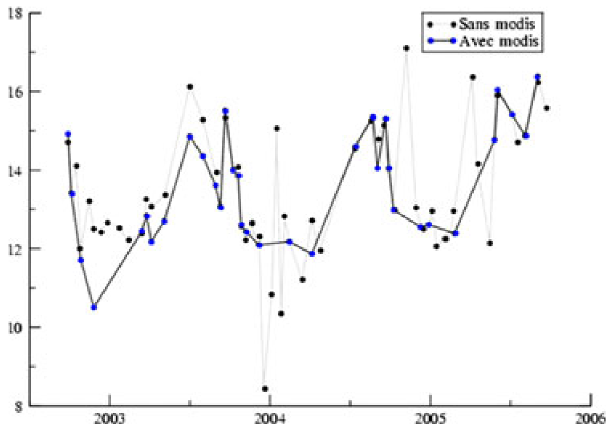

Fig. 10. Bang Hu water level retrieval (based on conjoint exploitation of Topex altimeter and MODIS data).

a succession of high and low water levels, respectively, during the wet and dry seasons. It also allowed the highlighting of an unusual February flood in 2005 (Fig. 9).

Exploiting Topex data from 2002 to 2006, a similar approach has been carried over the Bang Hu, a non-gauged lake in the Poyang Lake Natural Reserve (PLNR). The results highlight the value of the approach of selecting a target waterbody, based on optical data. When water retrieval derived information from optical data, a step effect, around 12.5 m, is obvious (Fig. 10). This effect is because of the fact that lakes of the Poyang Natural Reserve (PNR), during the dry season of the year, are disconnected from the main lake, thereby perhaps protected by their own levels.

This step effect is also well documented for the surrounding lakes (Da HuChi, Sha Hu, Mei Xi Hu) by water recordings from gauge stations (Fig. 11). During winter, PNR lakes are disconnected from the main lake, presenting a relatively high water level in regard to the river and lake levels.

In the second approach, the analysed segment was selected from a Beijing 1 time series. A good selection of the analysis zone is provided by Beijing 1 image in low water, being acquired on 30/11/2007 (Fig. 12). Unfortunately, the algorithm is not able to operate properly with these data. Thus, the analysis zone was extended on tracks 163 and 980 over Poyang Lake (Fig. 13). Six and a half years of altimetric water level allows the identification of seasonal water variations of this monsoon lake. The water level began to increase in early May, reaching a maximum level in July–August. The draw-off of the lake began in mid- to late September, except for 2006, when the draw-off started in mid-August. The time series again highlight an unusual February flood in 2005.

Thanks to the availability of a discontinuous gauge records series from Duchang Hydrological Station; it was possible to compare water levels retrieved from space with *in situ* data (Fig. 13). There is a good coherence of water levels during high water period, with a relatively good global correlation (R^2 = 0.8498). During low water periods, therefore, there is a sensitive difference between the field-measured water levels and those obtained via altimetry. Taking into account the May–October period over 6 years, i.e. twice longer than previously published studies (Liu 2006; Lui 2009), water level relationships were also investigated. The correlation at the high water period is very high, with an R^2 = 0.9379 (Fig. 13).

Dongting lake water height monitoring, utilizing radar altimetry

With regard to Dongting Lake, ENVISAT RA tracks 694 and 879 can be processed. Avoiding islands and levees in

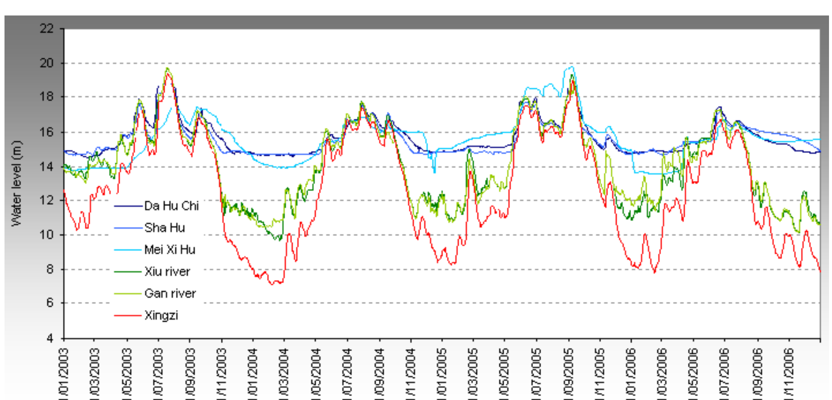

Fig. 11. Relationship of water levels between the disconnected lakes (Da HuChi, Sha Hu, Mei Xi Hu) of the Poyang Natural Reserve and the main lake, as measured at Xingzi and Gang rivers.

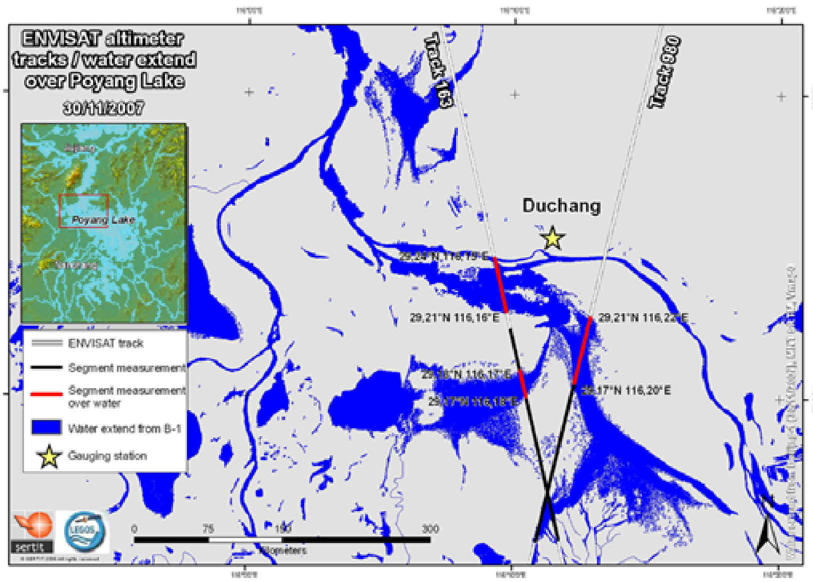

Fig. 12. Track segments analysed for Poyang Lake (red, selected segments for altimetry analysis).

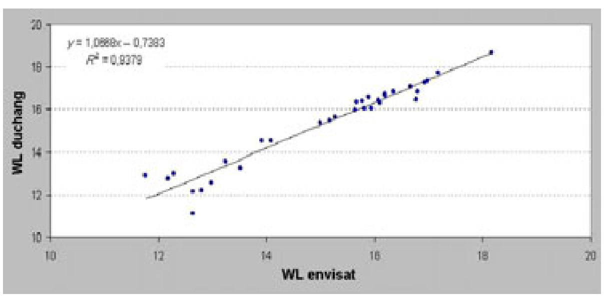

Fig. 13. Comparison of water levels from altimeter and water height measurements at Duchang water station.

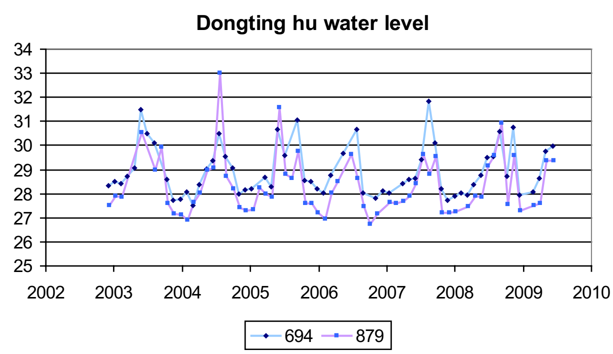

Fig. 14. ENVISAT RA water level of Dongting Lake.

the southern part, a good altimetry water level determination was achieved (Fig. 14).

Over the 7 years of monitoring, the seasonal effects are evident, with a classical shape characterized by an increased water level beginning in April, reaching a maximum in July, and sharply decreasing at the end of August/beginning of September. The year 2006 also presents the lowest maximum level of all the summer records.

The Jason 2 track is also available since May 2008. Its 10-day re-visiting period allows a more regular characterization of water level variations (Fig. 15). Comparison with *in situ* water level records validates these determinations. Even if altimetric water levels appear to be a little underestimated, in terms of trends, there is an impressive correspondence between altimetric water levels and those derived from *in situ* determinations (Fig. 15).

WATER SURFACE MONITORING, BASED ON SATELLITE IMAGERY

Imaging satellites time series have been utilized for Poyang and Dongting lakes to monitor their water surfaces over the period 2000–2008.

Database and methods

A very rich and dense earth observation database has been established for Poyang Lake through the DRAGON projects (Andreoli *et al.* 2007a,b; Yesou *et al.* 2009, 2010). The database also contains a unique optical HR validation set. The dataset also contains a unique optical HR validation set. Composed by Landsat and Beijing-1 time series, with respectively 7 and 16 images. These were acquired during different hydrological periods and was utilized to assess the water extraction approaches of MR data (Huber *et al.* 2010). Monitoring the Poyang Lake water

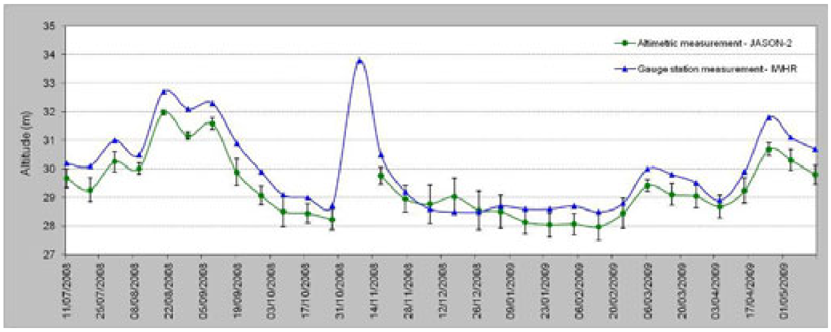

Fig. 15. Dongting Lake water level (derived from Jason 2 tack 2; green, altimetric water level; blue, water level from gauge station).

surface area was based on a set of 233 ENVISAT medium-resolution images acquired from 2003 to 2008, with an averaged re-visiting delay of 8 days. This analysis was completed with the use of 120 MODIS images, mostly covering the period 2000–2003. Finally, monitoring of water coverage dynamics was carried out over a period of 9 years, with an averaged re-visit time >10 days (Fig. 16).

A similar effort was carried out for Dongting Lake by the IWHR (China Institute of Water Resources and Hydropower Research). Owing to the effects of weather conditions on the satellite abilities to collect data, the MVC (maximum value composite) method was utilized to produce a water surface area monitoring result for every month in a year.

Poyang lake surface variation monitoring between January 2000 and December 2008

Based mostly on MODIS and ENVISAT time series, the Poyang Lake water area was estimated (Fig. 9). Water surface computation was performed without taking Junshan Lake (south of Poyang Lake, with an estimated surface area of 174.8 km^2) into account, the latter considered to be disconnected from Poyang Lake. Rivers and small depressions around the lake were also not taken into account.

The smallest surface recorded by MERIS data (*ca.* 750 km^2) was in February 2004, with the record tending to illustrate a lower-than-normal Poyang Lake water level. The largest surface area was estimated to be about 3400 km^2, based on MODIS data acquired in June 2002. The average Poyang Lake surface area is estimated to be 1850.88 km^2. The size of Poyang Lake, including perennial waterbodies and areas of water level variations, was estimated to be 3337 km^2.

An assessment of the relationship between water surfaces, as observed by satellite imagery and water level measured by gauge stations, has been made utilizing daily recordings from the Duchang Station. The obtained linear regression model indicates a strong positive relationship between water area and water level, with 83% of the variance of Poyang Lake water level being explained, a good result similar to that obtained in the literature (Huber *et al.* 2010). It must be noted that the water surfaces were derived from multisensor data from low- to high resolution. Even better results could be obtained with the use of mostly medium- and high-resolution data (Huber *et al.* 2010).

According to this water area monitoring exercise, the typical monsoon behaviour of the lake is well observed,

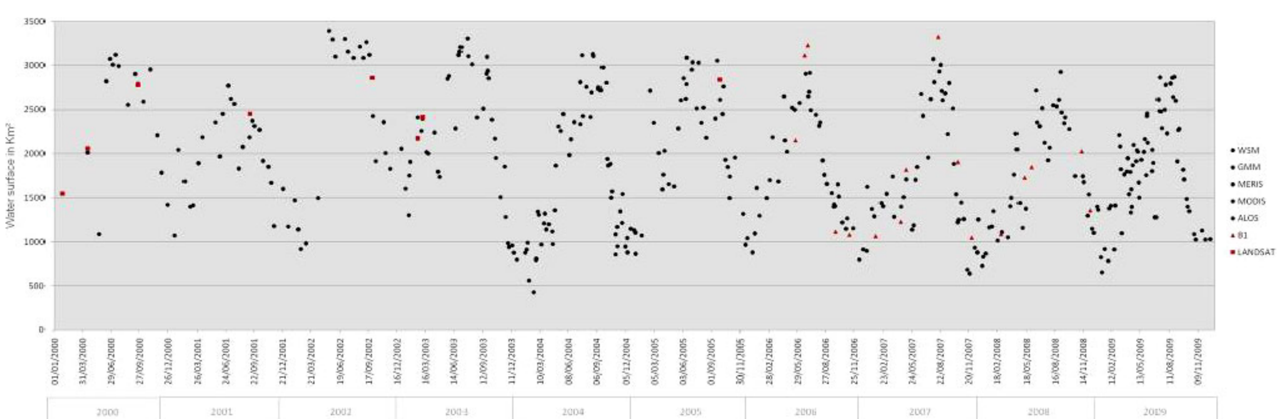

Fig. 16. Water surfaces monitoring based on ENVISAT/MODIS missions analysis (red dots, validation HR data).

with a minimum surface area occurring in the winter time. It increased in spring (May), with a maximum of water coverage observed in July and August (Fig. 17). The observed draw-off of the lake begins in September, being relatively fast (1 month). A finer analysis indicates that four groups of behaviours can be distinguished.

A first group, one that is similar to the classical monsoon behaviour, regroups the years 2000, 2002, 2004, 2007 and 2008, even if some minor variations can be observed from 1 year to another. The second one is characterized with a large water area during winter time, being observed in 2003. The third type corresponds to the year 2005, with an astonishing flood occurring at the end of the dry season in February. This unusual event was also recorded at gauge stations located all around the lake, and by field observations (Burnham J., Oral communication). The last one, observed in 2006, was marked by a very low summer water area, combined with very early and fast water re-draws, beginning in mid-August.

One other major result of the processing of 9 years of satellite imagery is highlighting of the decreasing amplitude tendency of minimum and maximum water surfaces since 2002 (Fig. 17).

Based on the water surface areas, it was possible to generate submersion time estimate maps on an annual basis, as well as for the overall period of analysis (Andreoli *et al.* 2007a,b). From the submersion time estimate map (Fig. 18), flooding events induce not only a simple dilution of waterbodies but also a translation of flooded areas inside the depression. Around 3 months per year (25% of a year), the Poyang Lake area exceeds 2500.0 km^2. And about 80 days per year, the lake size is below 1000 km^2.

The median lake area is about 1823 km^2, meaning these areas are under water for half a year (183 days). Nearly 90% of the maximal size of the lake corresponds to the lakeshore (area of water level variations), ~3140 km^2.

The estimated yearly submersion time is only representative of hydrological conditions of the analysed years, considering that 2002 exhibited an important flood event, 2004, 2007 and 2008 were characterized by normal Poyang Lake water levels without pronounced floods and, as previously mentioned, 2001 and 2006 were very dry years, with very low water levels during the summer months. Such an approach, which also utilizes residue analysis, can be useful to localize temporary and spatial water deficits, such as the one that occurred in 2006, or at the opposite water extreme, as in 2002 (Fig. 19).

Monitoring Dongting lake surface variations from 2000 to 2008, based on MODIS time series

The water area of Dongting Lake was estimated on the basis of MODIS decade synthesis data (Fig. 20).

The maximal water area and submersion time were estimated for each year between 2000 and 2008; and an averaged Dongting Lake submersion time estimation was also produced (Fig. 21).

The waterbody area exhibits an important fluctuation of 1500 km^2 from the dry season to the wet (monsoon)

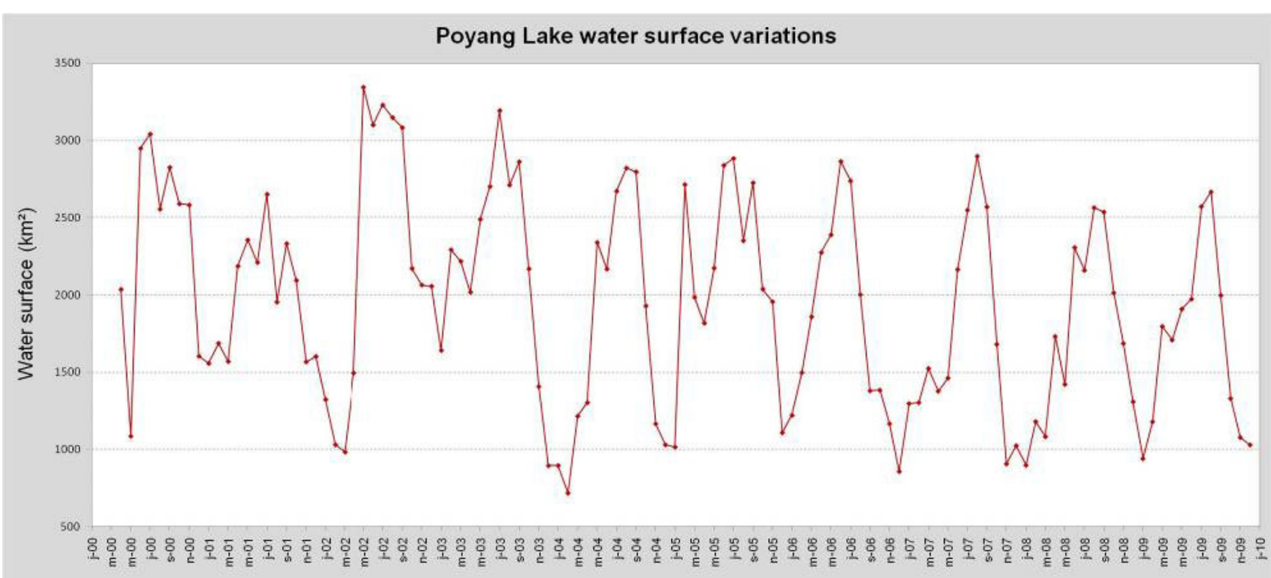

Fig. 17. Decreased amplitude tendency of minimum and maximum water surfaces over 9 years of monitoring over Poyang Lake.

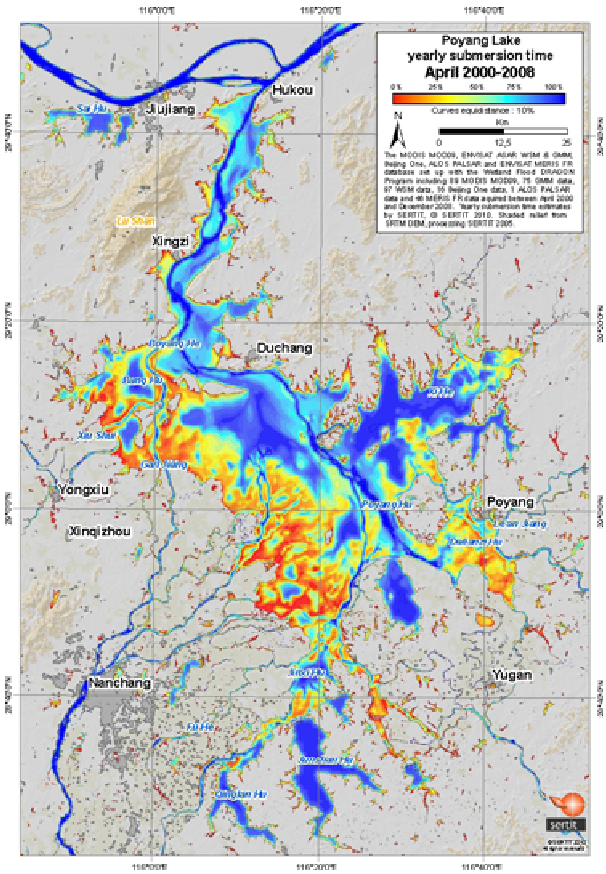

Fig. 18. Poyang Lake submersion time estimation derived from ENVISAT low- and medium-resolution data time series acquired between 2003 and 2008.

season. The maximal flood surface area, about 2400 km^2, was detected between July and September for each year. Infilling and draw-off periods occur, respectively, between March and June, and September and November. The low water level period began in November and lasted until April (Fig. 20).

As previously mentioned in regard to the average behaviour of Poyang Lake, the Dongting Lake average behaviour can vary during the observation period. In addition to the 2006 low water surface area observed for a wet period, the most important tendency comprises the dramatically decreasing amplitude observed during the monitoring period (Fig. 20).

DISCUSSION

This innovative synergetic exploitation of altimeter, medium-resolution SAR and optical data, combined with *in situ* recording, allowed a characterization of the hydrological behaviour of two of the major water resources in China, Poyang and Dongting lakes, over a period of 9 years (Fig. 22). The annual submersion time estimates provide a spatial and regional overview of land submersion mechanism inside the depression of the lakes with the recognition sub-systems.

Even if the mechanisms of Dongting and Poyang lakes are substantially different, their water surface areas and water level variations exhibit a good concordance. Both lakes exhibit a global decrease in amplitude tendency of

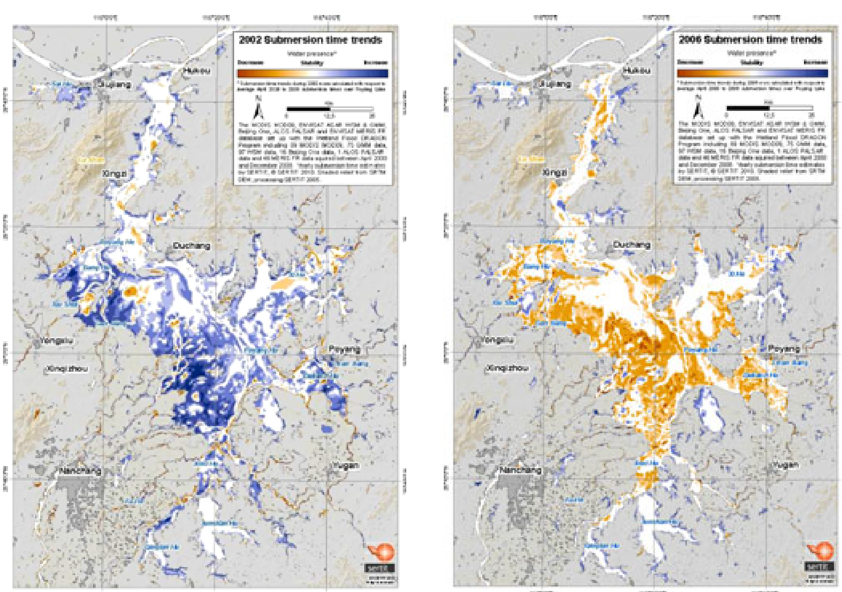

Fig. 19. Residues analysis of years 2002 and 2006 (characterized respectively by the largest water surface area observed during the analysis period and an important water area deficit, located mostly in the central part of Poyang Lake).

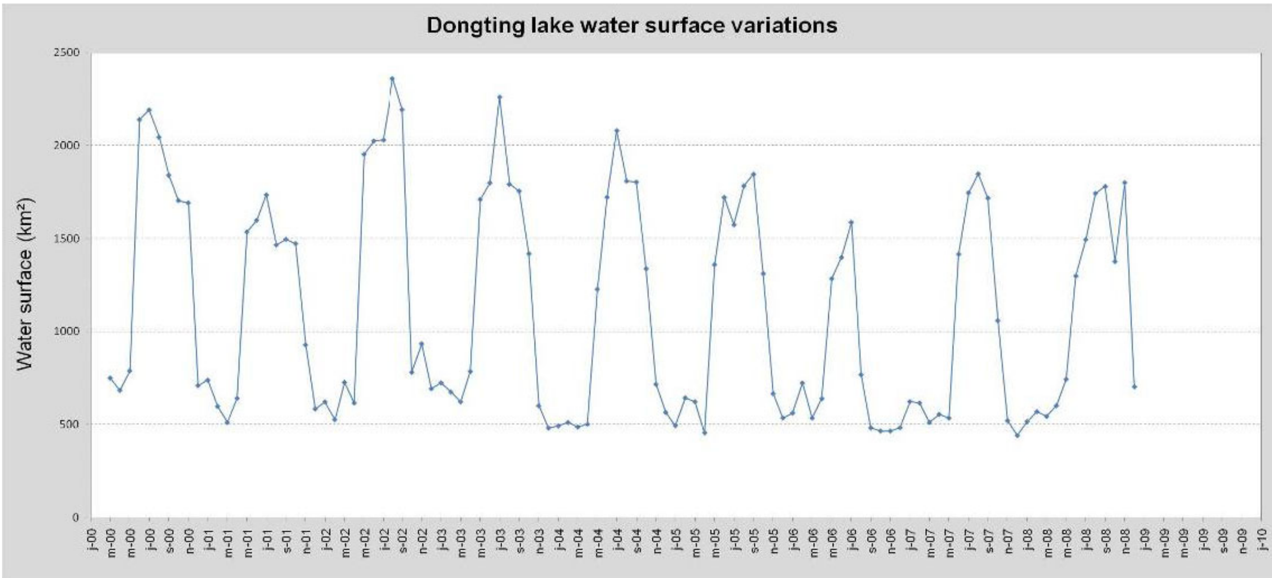

Fig. 20. Dongting Lake surface variations derived from MODIS products, 2000 and 2008.

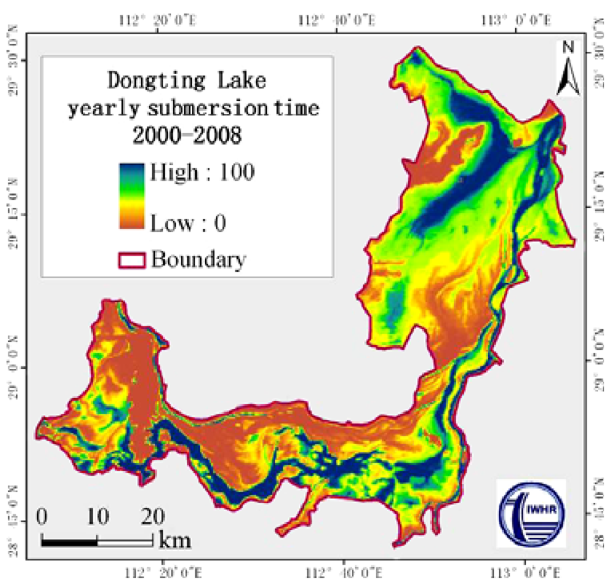

Fig. 21. Dongting Lake submersion time estimation derived from MODIS data time series acquired between 2000 and 2008.

minimum and maximum water surfaces and levels. Based on rainfall estimations derived from GPCP and TRMM, a relatively constant decreasing quantity of precipitation over the last decade (2000–2008) over the Poyang Lake watershed is observed, a phenomenon that might affect the general water resources in the region (Fig. 23).

The two lakes exhibited the lowest flooding surface area in 2001 and the largest flooding surface area in 2002. In summer 2006, astonishingly low water levels and low water surface areas were observed for the two lakes in the summer of 2006, along with an even more surprising, very early and rapid draw-off of the water from the lakes. If the 2001 lowest water surface areas can be explained by severe drought that affected SW Asia (Wang *et al.* 2010), and the highest water surface areas of 2002 are linked to very heavy rains, the similar behaviour of the two lakes in 2006 must be investigated.

Few reasons can be advanced to explain the behaviour of the lakes in 2006. Possibilities include a rainfall deficit at the sub-watershed level, or an event in the upper stream part of the basins. This could include a possible closing of gates at the Three Gorges Dam (3GD) to infill the reservoir, or it might be a more global climate change effect at the regional scale.

From an analysis of the water levels and water flows recorded at the Three Gorges Dam and the Gezhouba Dam (located ~40 km downstream of the Three Gorges Dam) on a weekly basis, some trends in the management of Three Gorges Dam can be observed.

The water level and water flows at the Three Gorges Dam complex are accessible. Analysis of the compiled data indicates that the beginning of the infilling of the dam at the end of May 2003 is well marked by an elevation in water level of about 50 m within 2 weeks (Fig. 24).

The water level of the reservoir do not increase much from June 2003 to October 2006, which was a period characterized by small water discharge during the wet season. In mid-October 2006, a new trend is observed, corresponding to a yearly cycle beginning in the fall (first days of October), characterized by a relatively important

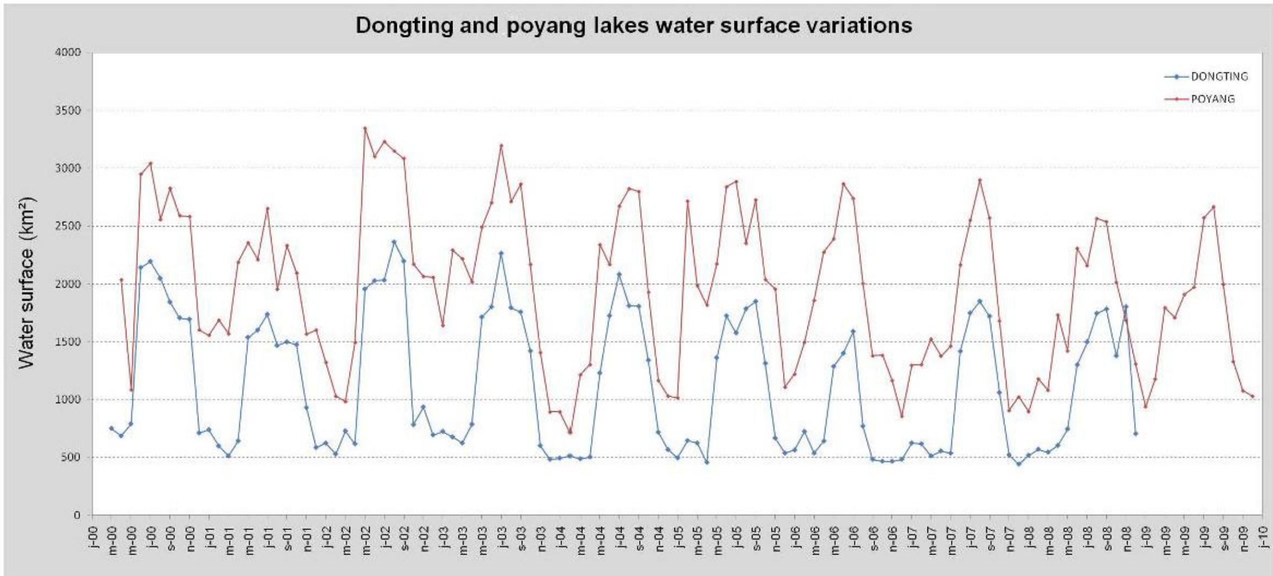

Fig. 22. Dongting Lake and Poyang Lake surface variations, 2000 and 2008.

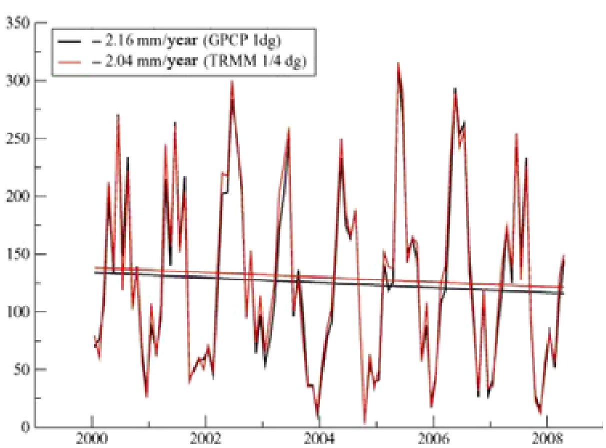

Fig. 23. Decreasing TRMM and GPCP precipitation trends.

increased reservoir water level (19.25 m), followed during the winter by a small water release. An interesting element can be observed in the water flow behaviour. Measured at the Three Gorges Dam outlet and the Gezhouba Dam, the water flow trends of the Yangtze River are typical of those from a monsoon region, with low values in the dry season and highest values during the wet season (Fig. 24). The important element is the relatively low Yangtze River flow during the wet 2006 season, with a flow peak of <30 000 $m^3 s^{-1}$, a quantity equivalent to about one-third less than that of a normal wet season. This signifies an enormous water resource drop during the 2006 wet season.

The utilization of meteorological information at the regional scale is less obvious. In regard to the Poyang Lake watershed (24–32°N, 113–119°E), the analysis of the TRMM series, more precisely the residual analysis for the year 2006, indicates that the year 2006 appears to be wetter. The Poyang Lake area in 2006 exhibited a relatively higher quantity of precipitation than usual for the months of March to July. Only August 2006 exhibited a marked water deficit (Fig. 25). Meteorological analysis of the summer 2006 event for the Poyang Lake scale is somewhat contradictory to the observed smallest water surface areas for a wet season. As indicated in recent publications, it would be expected that intense rain over the Poyang Lake watershed would induce an increased water level and water surface area.

The reasons for the relatively low water level and water surface area of Dongting and Poyang lakes have to be investigated more upstream from the lakes, and on a larger scale (i.e. the upstream part of the Yangtze River). In fact, an analysis of the TRMM time series must be performed over 10 × 10 square degrees (25–35°N, 100–110°E).

Based on the year 2006 residual analysis, the observed tendency over this width area depends on the month, ranging from a quasi-normal year (January– March) to an increasingly drier tendency, with few very localized water excesses (June–August). The averaged water deficit along the Yangtze River course in August is about 100 mm. For the year 2006, the drought effect is characterized by an important rainfall deficit over the upper Yangtze River watershed. This important drought has already been clearly identified at the provincial scale, namely in the Sichuan Province (Jia & Menenti 2009). Utilization of TRMM data throughout the entire Yangtze River

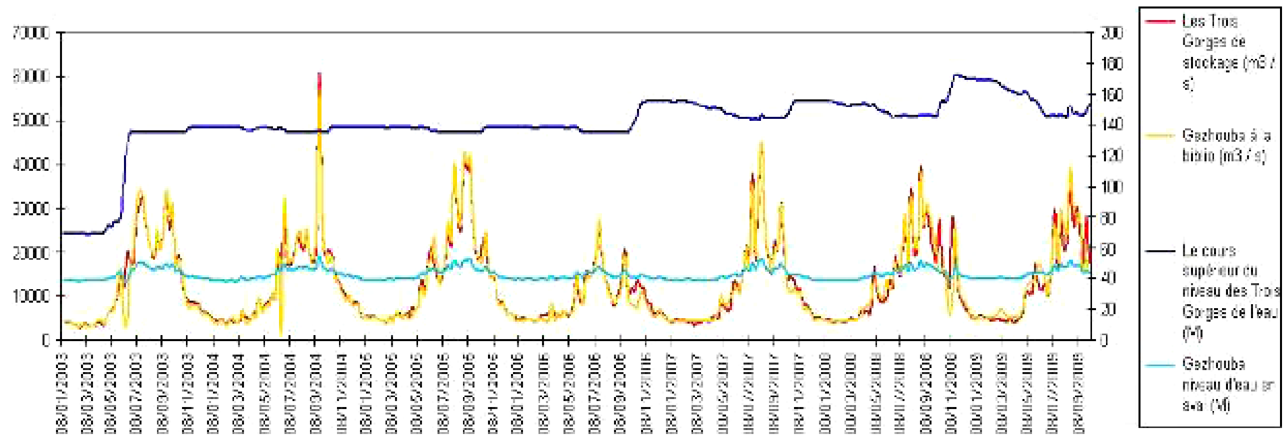

Fig. 24. Water level and water flows recorded at Three Gorges Dam, and water flow at Gezhouba Dam (water levels: dark blue, Three Gorges reservoir; light blue, Gezhouba Dam; water flows: red, Three Gorges reservoir; orange, Gezhouba Dam).

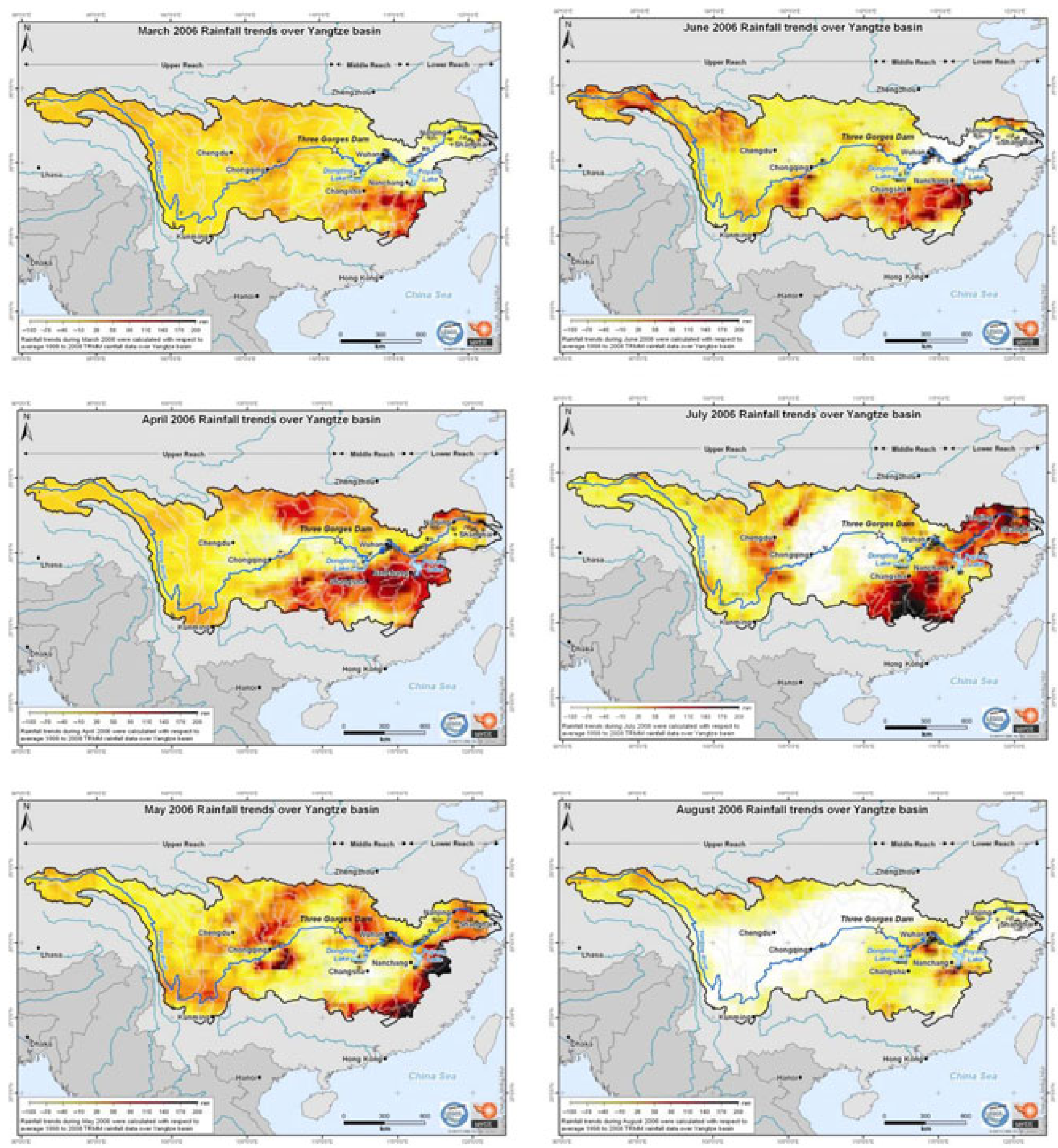

Fig. 25. TRMM rainfall residual analysis performed over Yangtze River watershed for March–August 2006.

watershed will likely highlight this drought phenomenon at the watershed scale. The consequences of this relatively severe drought event located 1500–2000 km from Poyang and Dongting lakes in the upper stream portion of the Yangtze River basin are very important. In the downstream part of its watershed, the Yangtze River does not play its hydraulic fate role, thereby not trapping water within the Dongting and Poyang depressions. And even if rainfall at the sub-basin scale allowed the lake tributaries to fill the lakes, the water flows away. And in addition to the small inundation surfaces, the final consequence is the very early draw-off of the lakes (i.e. nearly one and a half times sooner than usual).

Considering this relationship between rainfall at the Yangtze River watershed scale and the Poyang Lake water surface exhibited in the summer of 2006, it would also be very interesting to analyse this relationship over a longer time period (i.e. >9 years; see Fig. 26). At the Yangtze River basin scale, there is a strong correlation ($R^2 = 0.73$) between rainfall and the Poyang Lake water surface. The correlation for the Poyang Lake watershed itself was much weaker ($R^2 = 0.17$). Furthermore, the relationship between rainfall and water surface area over time exhibits a quasi-systematic delay between rainfall peaks and increased water surface area. This is a classic delay, well described over the study areas (Shankman *et al.* 2009).

Based on synergistically altimetry data series and earth observation images, monitoring of the two major freshwater lakes in China over a relatively long period of 9 years was realized. This work also represents the first utilization of nearly all altimetry resources (Topex, Envisat, Jason 2) over these lakes, and over a period twice as long as previous studies (Chu *et al.* 2008).

At the lake scale, the obtained results allowed characterization of the behaviours of the lake and their subdivisions. At a regional scale, these two major Chinese water resources exhibited very similar behaviour, being driest during the summer of 2001, exhibiting the largest floods in 2002 and a suspicious summer of 2006. With regard to the significant drop-down observed in the year 2006 for Dongting and Poyang lakes, investigations revealed that it was not because of either a local rain deficit or a change in the management of the Three Gorges Dam. The observed smallest water surface area and water level during the wet season appeared to be linked to a relatively severe drought within the upper stream part of the Yangtze River basin. In addition, an impressive decreasing tendency of water surfaces and water level at the regional scale over the nearly 10 years of larger-scale monitoring is observed in the middle reaches of the Yangtze River. This can also be seen extending to the dry 2001 and the flooded 2002 years, as indicated by the impressive correlation between rainfall at the Yangtze River watershed level and Poyang Lake water characteristics.

Further works should also be conducted on IceSat's LIDAR data to detect along a track topography slope. Combining this information with water extent data derived from remote sensing imagery, and also with water levels derived from altimeter, will allow for the evaluation of water volume changes in Poyang Lake.

Another step in this ongoing research will be the integration of water surface areas from 1998 to 2000, based on Passager Vegetation data, and from 2009 to 2010, based on DRAGON time series (i.e. ENVISAT; Beijing 1 data). Preliminary results from recent ongoing work on the 2010 flood event in Poyang and Dongting lakes indicate that the water extent for 2010 is very similar to that for 2002. Future work would allow the characterization of a non-regular cycle of floods (1998, 2002, 2010) and driest tendencies. The origin of the flood–drought cycle might now be analysed in a more global meteorological context, in terms of El Nino and La Nina. This approach would contribute to a better understanding of water resource availability within the context of water management. It also will provide valuable information for understanding flood mechanisms within a context of disaster management in the middle and lower reaches of the Yangtze River basin.

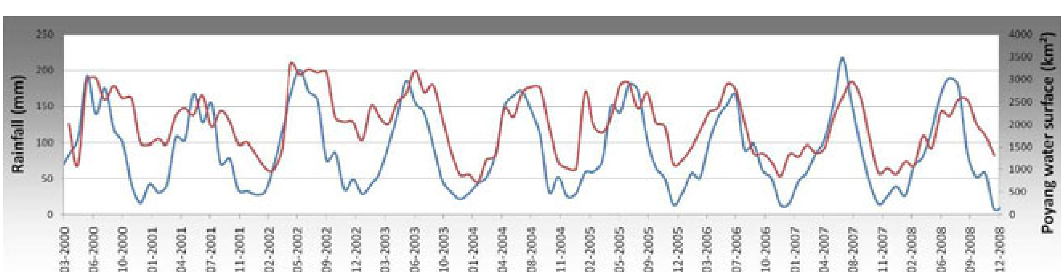

Fig. 26. Relationship between water surfaces of Poyang Lake (red) and TRMM precipitations at Yangtze River watershed scale (blue).

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