Ground Subsidence caused by hydrologic loading derived by PS-InSAR: example to Bam Co Lake in Tibetan Plateau

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Abstract: Roving and permanent GPS survey in Tibetan Plateau provide adequate data for crustal deformation study, which demonstrate the collision of Eurasia Plate and India Plate, uplift of Tibetan Plateau. Most GPS sites within Tibetan Plateau show a significant positive vertical velocity, however, others show subsidence. We noticed that most sites show negative vertical velocity were distributed close to the lake, which implied that subsidence was caused by hydrological loading. By applying PS-InSAR technique to 27 SAR images observed by ENVISAT, we derived LOS velocity field around Bam Co Lake, where no significant active fault distributes and includes a GPS site showed subsidence, which suggested a funnel-shaped subsidence at a maxim LOS velocity about 2-3mm/yr around the lake. We also derived area change of this lake by using SAR amplitude images after geocoding and coherence maps of INSAR to assist, which suggest the lake do get large from 2003-2008. For Bam Co Lake is mainly supplied by surface runoff and glacier melting, lake area increasing and ground subsidence caused by hydrological loading may imply that climate change in Tibetan Plateau in last decade.

INTRODUCTION

As an extension of traditional D-InSAR, PS-InSAR overcomes the limitation of both temporal and perpendicular baseline, and shows an impressive ability of deriving time series and velocity field of urban subsidence (Perissin D, 2011; Ng A, 2011; Luo Q, 2012), GIA (Glacial Isostatic Adjustment) (Rignot E, 2002), volcanic deformation survey (Hooper A, 2007; Xu C, 2011) and tectonic deformation such as post-seismic and inter-seismic deformation (Burgmann B, 2006). However, for hydrological loading or underground mass absence leads to large deformation than tectonic, besides they are mainly vertical. Therefore when we targeted to study tectonic deformation, those nuisance items should be considered. For hydrological deformation is annual, roving GPS survey generally carried at the same season to avoid such influence. Permanent GPS sites also show annual fluctuate especially in vertical direction (Fu Y, 2011).

Due to climate change in the last few decades, the variation of precipitation, evaporation, permafrost ablation and glacial melting result in the fluctuation of lake's area of Tibetan Plateau. As the water tower of Asia and the third pole of the world, Tibetan Plateau's climate change is a proxy of global climate change. Recent study of satellite altimeter shows that most lakes in north Tibetan Plateau presented uplift while subsidence in the south (Zhang G, 2011). By applying CBERS images Bian obtained the area change of Bam Co Lake, which increased from 218Km^2 to 237Km^2 from 2003-2005, however Bian did not provide when the images were observed during the year while area of lakes fluctuates annually (Bian D, 2006). Just as Bam Co Lake, most lakes in Tibetan Plateau failed possessing any hydrological data. And for Bam Co does not spread large area, satellite altimeter provided only one epoch elevation information, thus no change could be found (Zhang G, 2011). We surveyed area of the lake by applying SAR images observed in summer in both amplitude and coherence methods.

Bam Co Lake is located in the east of Baingoin County north of Nyainqentanglha Mountains, Nagqu Prefecture, Tibetan Plateau. At a height of 4555 meter, it has an area of 190.0 Km^2. Precipitation of this area is about 300-400mm, and average temperature of 0~2° C. Its main supply is surface runoff, mainly by glacial melting(Wikipedia).

Data processing

1) SAR data processing & deformation field analyzing

We acquired 27 C-Band ASAR images observed by ENVISAT satellite from April 2003 to September 2008, Track 176, descending orbit. By considering temporal and spatial perpendicular baseline, we chose SAR image observed on April 30, 2006 as the master, while others as slaves. Temporal and spatial perpendicular baselines are shown in figure 1.

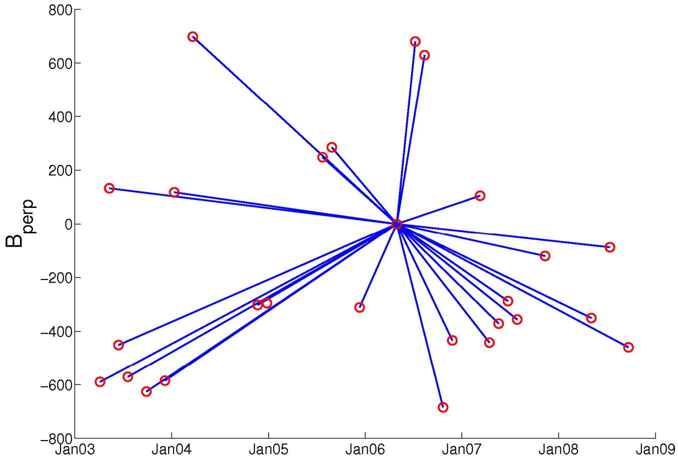

Figure 1: Baseline of 26 interferograms. Vertical axis is perpendicular baseline and horizontal axis is temporal baseline.

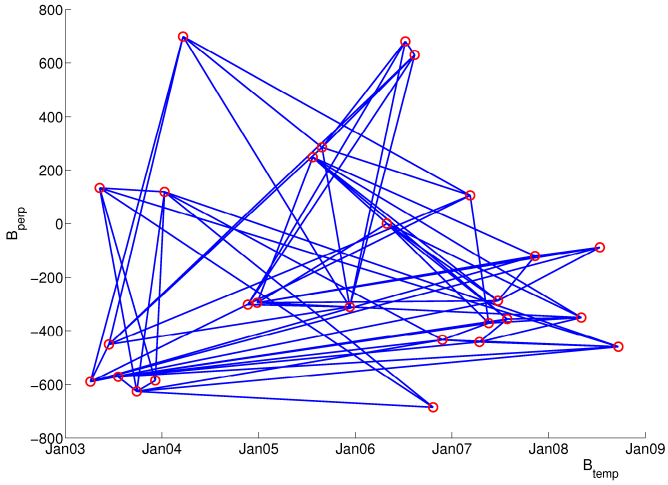

Figure 2: coregister pairs of 27 SAR images.

First we used ROI_PAC software (Rosen P, 2004) developed by JPL to focus raw SAR data to SLC (Single Look Complex) format, then we coregistered all 27 images into connectivity graph and formed 26 interferograms by using DORIS software (Kampes B, 1999) developed by Delft University of Technology. In coregister step, as the perpendicular baselines are mostly larger than conventional D-InSAR, coregistering the master with the slaves directly is high likely leading to failure, thus we coregistered those SAR image pairs with perpendicular baseline less than 100m, and then basically coregistered else images with three nearest neighbors by considering both temporal and special baseline, finally formed a connected graph, showing in figure 2. Phase caused by terrain was estimated and removed by using SRTM DEM model at a resolution of 3s(90 m). After that we chose the PS candidates by StaMPS program (Hooper A, 2004&2007), according to amplitude dispersion and phase SNR. Phase unwrapping was performed by SNAPHU program (Chen C, 2000) developed by Stanford University. For InSAR technique can only provide relative survey, we just simply presumed that the sum of deformation velocity was zero. When we wept the PS pixels, interferograms with baseline above 600m mostly performed bad coherence and thus would increase phase noise of PS points, by considering area in our study was non-urban and our seeking to provide enough PS pixels to describe the velocity field, we deleted interferograms with perpendicular baseline exceed 600m at phase SNR estimation and later steps.

In figure 3 we present the velocity field in LOS direction of Bam Co Lake area. Negative means away from satellite, similar to subsidence, for no active faults were found in this area, we simply presumed that velocity in LOS direction was contributed by vertical displacement. The velocity field demonstrates a funnel-shaped subsidence at a maximum relative velocity at 2-3mm/yr in LOS direction.

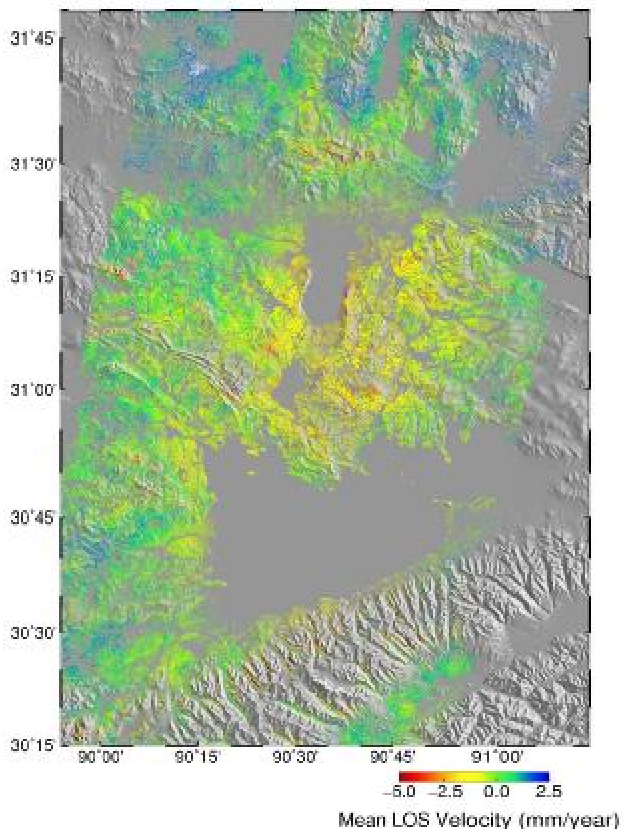

Figure 3: deformation field in LOS direction in Bam Co and adjacent area, minus means away from satellite, similar to subsidence.

We compiled PS pixels between 31.22N to 31.25° N（approximately 31° 13′ ~ 31° 15′ ）, and in figure 4 presenting a profile of velocity field in LOS. Black line is mean velocity and red lines stand for RMS. The blank is due to SAR images decorrelation at water area. Bank of the Bam Co Lake presents the maximum subsidence around 2-3mm/yr.

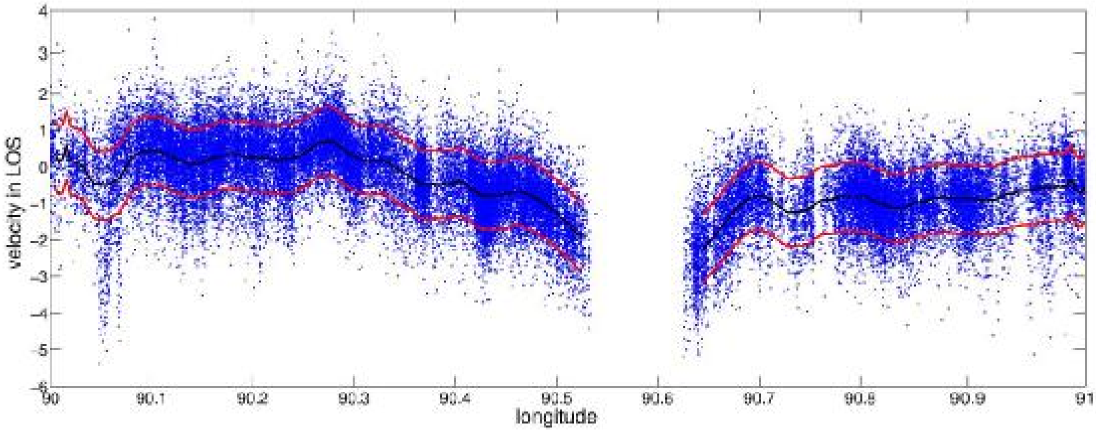

Figure 4: Profile of LOS deformation field between 31.22~31.25° N. Black line is mean velocity and red line stand for RMS.

Figure 5 shows the time series of phase difference with respect to the master image observed on April 30, 2006. 2π radius stands for 2.828cm displacement in LOS, negative means closer to the satellite similar to uplift (different from velocity field), while positive means subsidence. In the velocity map, we up side down the direction for an intuitive view. In both velocity field and phase difference time series, subsidence of around area of Bam Co Lake presented a funnel shape. However, center of the funnel was not located in the middle of the lake but a bit south, this might cause by the area increasing of the small unnamed lake in the south and/or orbital ramp.

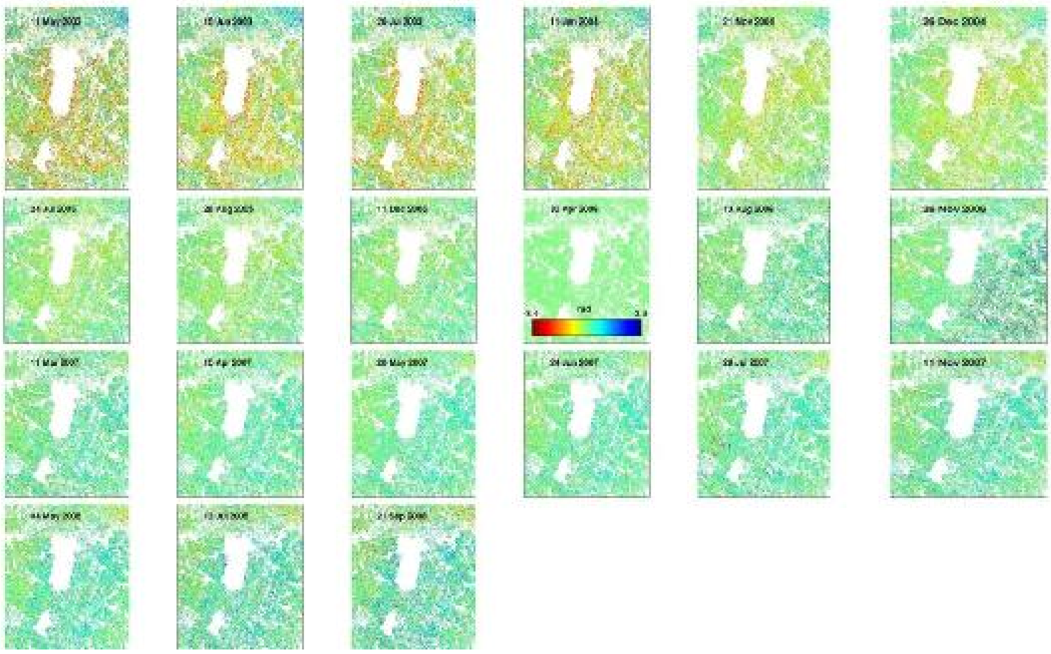

Figure 5: Time series of deformation from the processed PS, with respect to the master image taken on April

30th, 2004, which was drawn on by color bar. Negative (warm color) color stands for closer to the satellite than the master image, vice versa.

2) Compare to GPS result

Only one roving GPS site exists in our study area, which showed subsidence. We have conducted 2-epoch GPS survey in 1997 and 2006. We analyzed with GIPSY-OASIS software developed by JPL. Data analysis is divided into two steps: 1) site coordinates are deduced from GPS raw data with a network solution strategy; 2) site velocities are estimated from the time series of GPS site positions by a network velocity solution.

Assuming a linear displacement behavior for each site, the weighted least-square was performed with input of all daily solutions to estimate their coordinates and velocities (Yang S, 2008). We obtain the subsidence velocity of this site is -6.38mm/yr with a RMS of 1.19mm/yr. According to the coordinate of the GPS site, we averaged time series of adjacent PS points and present in figure 6.

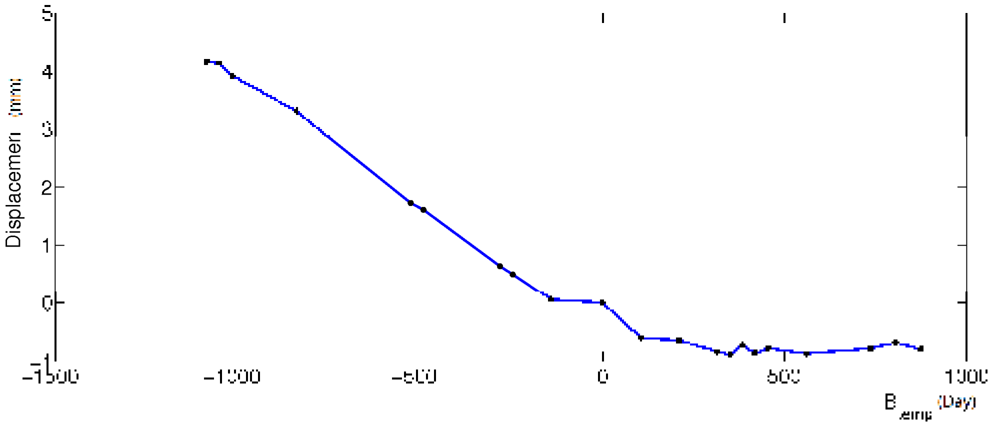

Figure 6: average time series of PSs adjacent to GPS site. Black dots mean SAR observations.

Temporal baseline is respect to the mater image taken on April 30th, 2006. We could see that before the mater image taken is significant and almost linear, however after that, subsidence seems stopped. Time series shown in figure 5 also present that the significant change from red to green before the master, but no obvious color change after that.

3) Area increasing of Bam Co Lake

When a SAR image was formed, for its low backscattering coefficient, water generally demonstrates small and homogenous amplitude unless there is significant wave; besides, for water surface always fluctuate, it never present a good coherence in interferograms, therefore, we can apply both amplitude map of SAR images and coherence map of interferograms to identify water surface. However, sometimes water presents high amplitude due to waves and ground present bad coherence due to large temporal baseline and/or spatial perpendicular baseline, therefore we combined two methods to identify water surface. We used ROI_PAC to process interferograms of Jul 20th~Jun 15th, 2003, Jul 9th~Aug 13th and Jul 13th~Sep 21st, 2008 in two pass method. The perpendicular baseline, 118.52~146.98m, -51.22~-88.28m and -388.52~-374.95m, respectively, are much less than the critical perpendicular baseline of ERS/ENVISAT, that is 1100m (Hooper A, 2004). Hence, all interferograms present a good coherence on ground. Due to glacier melting and abundant rain, lake is larger in summer than in other seasons. Therefore, three coherence maps present the area of the lake in summer, which were Jul 20th, Jul 9th and Jul 13th, respectively.

In Figure 7, we present the amplitude maps in summer, the dark and homogeneous area can be considered as lake. In Figure 8, we demonstrate the coherence map in three interferograms in 2003, 2006 and 2008, decorated area stand for lake. It is obvious that area of Bam Co increased from 2003 to 2008, especially in the north area, where terrain is smoother. South part the lake also grew wide from 2003 to 2008, which proved Bian D's work. We identified the lake by applying both amplitude maps and coherence maps applying Global Mapper software. Area of Bam Co and the unnamed lake in the south of Bam Co increased from 207.98Km^2 and 45.66Km^2 in 2003 to 235.43Km^2 and 48.69Km^2 in 2006 and 242.17Km^2 and 49.70Km^2, respectively. Area of these two lakes, Bam Co and the unnamed lake increased by 16.4%与 8.8% in five years, respectively. If this phenomenon was result by increased glacial melting and/or permafrost ablation, it could be a proxy of global warming. We could see that increasing from 2003 to 2006 is more significant than 2006 to 2008, which consistent with the subsidence time series if the deformation is completely elastic.

Table 1: Lake area of Bam Co and unnamed lake in the south.

Year	Area of lake（Km^2）	Percentage of Increasing (With respect to 2003)
2003	207.98、45.66	100%、100%
2006	235.43、48.69	113.2%、106.6%
2008	242.17、49.70	116.4%、108.8%

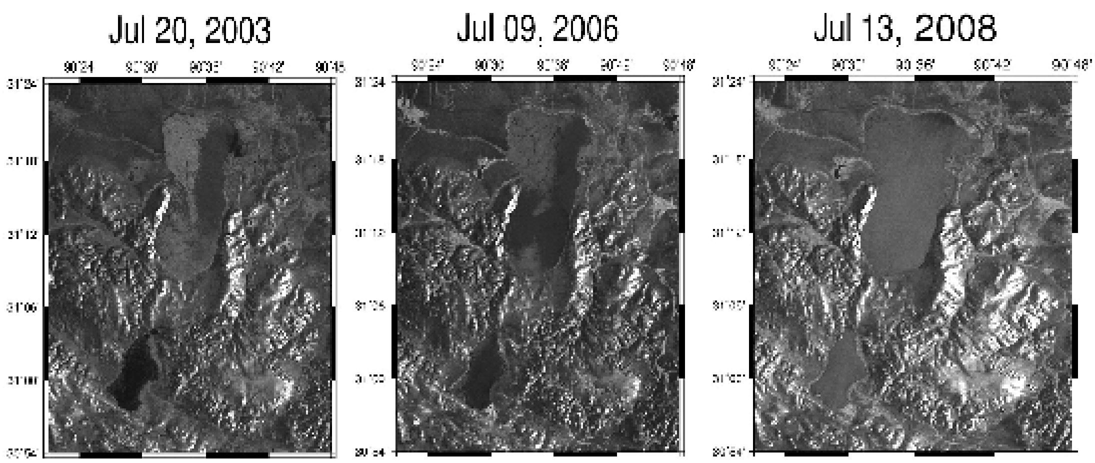

Figure 7: SAR amplitude image of 2003, 2006, 2008 in summer.

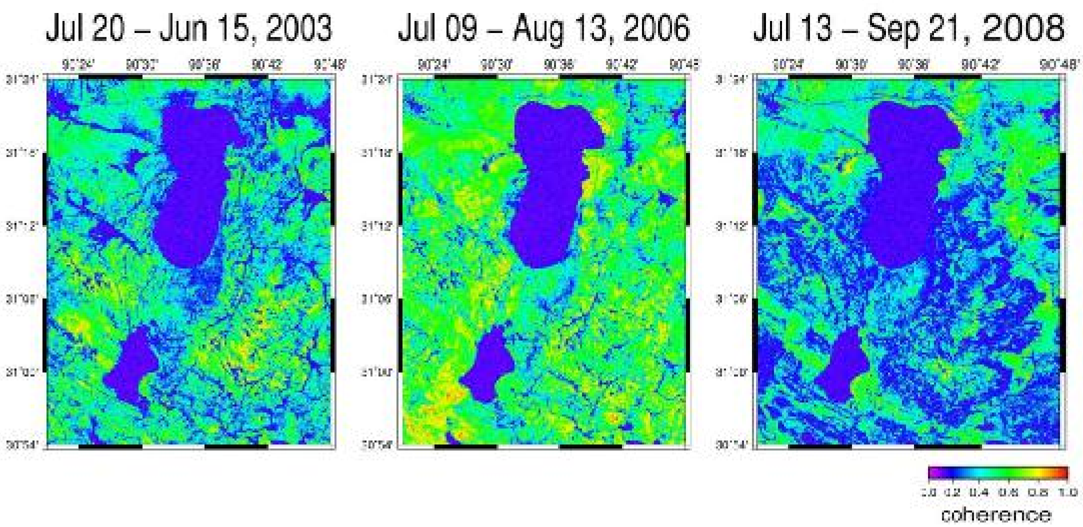

Figure 8: Interferograms coherence image of 2003, 2006 and 2008.

Error analysis and Discussion

For atmosphere delay, DEM error, looking angle error and slant angle error were all estimated and eliminated by PS-InSAR method, we do not discuss them anymore. In StaMPS process strategy, temporal low pass filtering was applied for reducing atmosphere delay effect, this could be the reason for no annual fluctuate show, which acts almost the same as atmosphere (Hooper A, 2007).

Orbital ramp, caused by the discrepancy between real orbit and precise orbit obtained by GPS or DORIS receiver on satellite, presents a bilinear error in interferograms, similar to flat-earth effect. Generally we subtract orbital ramp used a FFT based method under the assumption that no linear deformation exist in SAR image's coverage. This assumption do exist when co-seismic deformation field do not compromise the edge of the interferograms and/or subsidence in urban area (Ng A, 2012; Wang Q, 2011). However in our study, deformation caused by hydrological loading, and permafrost melting in summer and freezing in winter, it is not rigid to make the assumption of no bilinear deformation. This could also be a reason for the funnel-shaped subsidence located not in the center of Bam Co Lake.

Deformation velocity surveyed by GPS is larger than PS-InSAR, the possible reasons could be but not limit to:

1) Time series was surveyed in different year, 1997 and 2006 for GPS while 2003~2008 for SAR images. However according to in situ information (Wikipedia), the area of Bam Co Lake is 190.9 Km2, but according to CBERS and/or SAR images, even if in 2003, area of the lake is larger than the former information.

2) Vertical time series could fluctuate annually, and we only obtained roving two-epoch GPS survey, this could be result in error.

3) PS-InSAR provides only relative deformation, while GPS survey is absolute.

Studying on temperature and precipitation in the last few decades in Tibetan Plateau shows that climate getting warm and precipitation moving to north may due to monsoon (Du J, 2001&2004). Warming could result in melting of permafrost. All these could be the reason for increasing of Bam Co Lake, as well as all other lakes in north Tibetan Plateau, where distribute vast permafrost, such as Siling Co Lake and Nam Co Lake.

Conclusion

We obtained 27 C-band SAR images observed by ENVISAT/ASAR, and derived velocity field in LOS direction around Bam Co Lake in Tibetan Plateau. Besides, we surveyed the area increasing of Bam Co Lake in 2003, 2006 and 2008 by applying amplitude maps of SAR images and coherence maps of interferograms. The result indicates that during 2003~2008, district around Bam Co Lake present a funnel like subsidence which may be caused by hydrologic loading of Bam Co Lake. The subsidence velocity field derived from PS-InSAR also conforms to the GPS survey. We suggest that global warming may lead to the increasing hydrologic loading of Bam Co Lake. Our job implies that vertical deformation is sensitive to hydrologic loading or glaciers loading change, therefore vertical velocity by GPS survey cannot stand for a large area like horizontal velocity do.

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