IDENTIFYING THE ERRORS IN MONITORING GLACIER CHANGES BY MULTI-SOURCES DATA USING REMOTE SENSING AND GIS TECHNIQUES IN MT. NAIMONA'NYI REGION IN THE WESTERN HIMALAYAS ON THE TIBETAN PLATEAU IN CHINA

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KEY WORDS: Glacier variation; Geographic Information System (GIS); Remote Sensing; the hybrid grid unit; Mt. Naimona'Nyi; Himalayas; Mt. Geladandong; Tibetan Plateau

ABSTRACT:

The paper compares the results of two alternative methods for studying glacier variations in Mt. Naimona'Nyi in the western Himalayas on Tibet. This paper describes a grid method for studying multi-temporal glacier variations from space. By combining glacier spatial data from various satellite images or maps at sequential times, the grid method allows us to detect both dynamic variation and random noise in glacier distribution among the sequential data sets due to different data sources. Our results show that random noise, equal to 5.5% of the total glacier area in the Mt. Naimona'Nyi region, as taken from individual classification results by bands algorithms, was much larger than that of the measurement uncertainty calculated by sensor resolution and co-registration error. Glaciers in the region both retreated and advanced during the last several decades. Retreat dominates, however, and accelerates. Most of the glacier retreat area occurs at the termini of glaciers in the southeastern slopes of the two regions, whereas most of the glacier advance area occurs at the termini of glaciers in the northwestern slopes. The glacier recessions in the Mt. Naimona'Nyi of the Himalayan regions are dramatic compared with Mt. Geladandong region in the central Tibetan Plateau.

1. INTRODUCTION

Remote sensing satellite techniques, including microwave data and optical imagery have been frequently used in global-scale glacier surveys, because of the large number of most alpine glaciers and their remoteness. Common methods of research on variation in glacier distribution by remote sensing focus on how to extract glacier information from individual multispectral satellite images by various methodologies.

In general, these methods use individual images from different epochs for glacier classification, compare the length of glacier termini or quantity of glacier areas and finally visualize the combined results by overlaying vector-vector data in a map or vector-raster format (Williams et al., 1997; Kääb et al., 2005; Khromova et al., 2006).

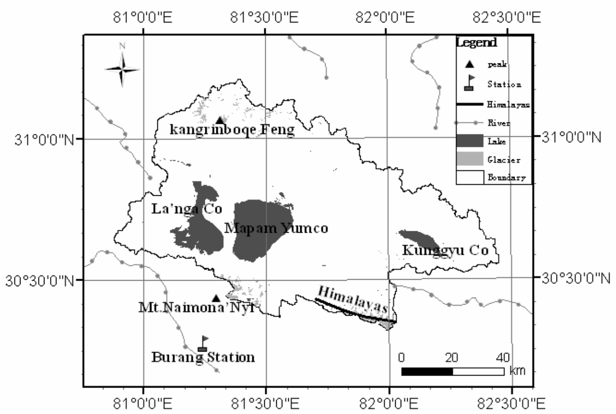

Fig. 1 Geographic position of the Mapam Basin

The weakness of the common method, however, is that it overlooks discrepancies such as random noise from multiple factors. This includes different data sources, different resolution, common geolocation errors along the mapped multi-temporal glacier boundary of the co-registered satellite images, misclassification from individual images, caused by uncertainties from the manual mapping of debris-covered ice, regions in cast shadow or perennial snow fields that are attached to a glacier, etc. Such discrepancies commonly exist

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among images and maps from different data sources like satellite images, aerial photographs, topographic maps or historical maps when optimizing the temporal research scope (Khromova et al., 2006). In addition, commonly used visualization methods using digital overlays of individual maps, are not able to clearly show glacier retreat or advance in space for more than 3 periods. Therefore, in this study we used a hybrid grid method to account for map variation in regional glacier distribution.

The study focuses on the glacier variations by multi-temporal data from space in Mt. Naimona'Nyi region, which is the highest peak of the south-western Himalayan Mountains, 81^{o}E–81^{o}47'E; 30^{o}04'N–31^{o}16'N (Fig. 1). We use a series of satellite images and topographic maps that are combined using a Geographical Information System (GIS) (Ye et al., 2006a, 2006b). Classification results are combined from individual images by algebraic operations in the Arc/Info Grid module, enabling us to track glacier variation during the corresponding period both on maps and in tables. The hybrid digital value from each grid cell identifies areas of glacier advance or retreat in each period by visualization and quantification. Instances when grid cells indicate changes that occur more rapidly than is considered feasible are rejected as "noise" or "mismatches", being discrepancies commonly existing in sequential data sets. The hybrid grid method can distinguish between noise (e.g. 5775, geolocation noise or misclassifications) and real glacier changes occurring during decades. These can be handled by the manual assignment of remap values. The results in the regions obtained using both the "common method" and the "hybrid grid method" and the eliminated "noises" were presented, compared and discussed in this paper.

2. MAIN BODY

2.1 Data used

Glacier variation in the Mt. Naimona'Nyi region has been surveyed using a series of digital images, i.e., Landsat MSS (the Landsat Multispectral Scanner) in 1976, Landsat TM (the Landsat Thematic Mapper) in 1990 and 1999, and ASTER in 2003. We also use 1:50,000 topographic maps produced from aerial photographs acquired in 1974 and the 1:50,000 Digital Elevation Model (DEM), which is surveyed and mapped by State Bureau of Surveying and Mapping in China (Ye et al., 2006a). Upland of moraines exists that was left from the retreat of ancient glaciers in the Mt. Naimona'Nyi region. The termini of modern glaciers are at approximately 5300 m elevation, with a piece of very likely debris-covered glacier in the south (Fig.2, a-d). According to meteorological data from the Burang Station (3,900 m a.s.l., Fig. 1) during the period from 1973 to 2004 (Ye et al., 2008), the average summer air temperature in the months from April to October when monthly mean temperature are above 0°C equals 9.3 °C, annual precipitation equals 168.6 mm during in the period from 1973 to 1975 (Guan et al., 1984) with an annual evaporation of 2197.4mm. The annual precipitation decreased to 117.1 mm during the period from 2000 to 2004 at the Burang Station.

2.2 Methods

Multi-temporal and multi-source digital satellite images for the Mt. Naimona'Nyi regions were orthorectified using DEM. The accuracy of all ortho-rectification was within one pixel. All image data were converted from different sources to a common format defined in Arc/Info with Transverse Mercator projection and Krasovsky1940 spheroid. Precise co-registration for all ortho-images was based on the 1:50,000 topographic maps, which were used as the common base. All co-registration errors were within one image pixel also.

Glaciers from all the individual images/maps were mapped by unsupervised ISODATA clustering by 20 clusters of snow/glacier or non-glacierized area in Mt. Naimona'Nyi. All results were reclassified by supervised classification, and some snow-covered non-glacierized areas were removed by filter methods and manual editing. Glacier classifications from all individual images/maps in Mt. Naimona'Nyi region were showed in Fig.2.

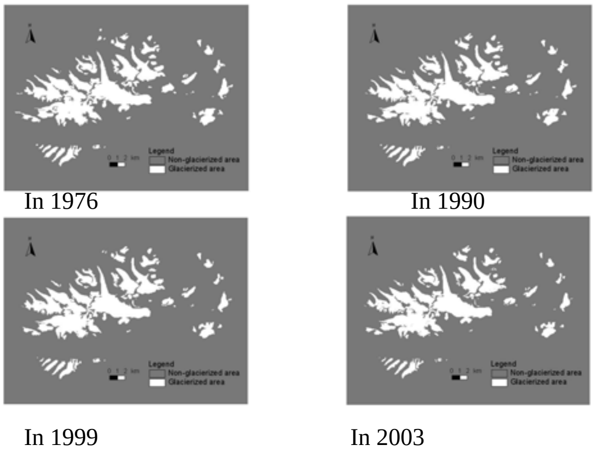

Fig.2 Classification results from individual digital satellite imagery in Mt. Naimona'Nyi region

Glacier classifications from all individual images were recoded by assigning the value 5 or the value 7 according to the classification scheme given above. Till now, common methods of research on glacier variations by remote sensing would finish the data interpretation process and compare the calculation results from individual data sets (e.g. Williams et al., 1997; Paul, 2001; Kääb et al., 2002; Khromova et al., 2006).

Based on the usual method, we had tried a hybrid grid method for studying glacier variations by means of GIS and Remote Sensing techniques (Ye et al., 2006a; 2006b). We used 30 m grid-cell as the basic unit, i.e., all glacier classification results from individual images were re-sampled to the same pixel size by 30 m grid cell resolution. The one digit values 5 and 7 from each grid cell were combined over time using the classification results from the four images: the 1976, 1990, 1999, and 2003 images in the Mt. Naimona'Nyi area by map algebra. This generated a hybrid-grid map with a four digit value in each grid cell, i.e. the hybrid grid data. Interpretation of this map served to simulate glacier change during the corresponding period (Eq (1)). This step enabled us to track glacier variations during the corresponding period both on maps (Fig. 3) and in tables (e.g. Table 1).

$$Glacier\_Nyi = Nyi1976 \times 1000 + Nyi1990 \times 100 + Nyi1999 \times 10 + Nyi2003, \quad (1)$$

where Glacier_Nyi is the desired hybrid grid data on glacier variation during 1976-2003 in the Mt. Naimona'Nyi area; Nyi1976, Nyi1990, Nyi1999, and Nyi2003 are the classification results from the images of 1976, 1990, 1999, and 2003 respectively.

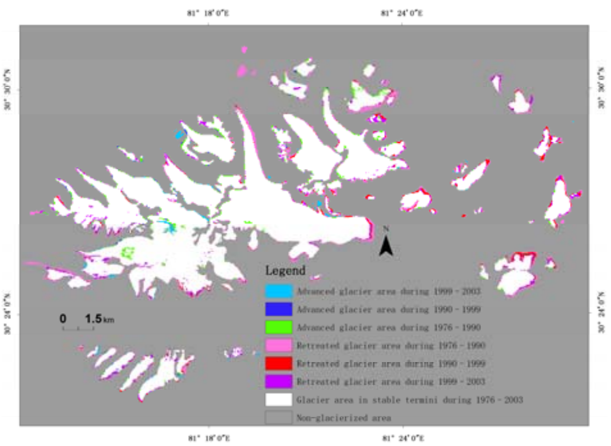

Fig. 3 Glacier area variations in the Mt. Naimona'Nyi region during 1976–2003

Various types of glacier variation occur in the original synthesized data (Table 1). We therefore developed a methodology to understand the principal changes. We analyzed the different types and reclassifications of the grid cells according to the four-digit value (Ye et al., 2004) in order to identify glacier retreat and advance areas. What's more, the four digit value from each hybrid grid cell is also used to differentiate between random noise, caused by geolocation error or misclassifications, and real glacier changes during the observation period. The primary principles for distinguish real glacier changes were based on characteristics of glacier dynamics, e.g., for a glacier near steady state it is not unusual to retreat over the small distance of one or several pixels, then advance, then show no change and then retreat again in decades. Instances in which the hybrid grid cells indicate changes that occur more rapidly than is considered possible (e.g., 5757, 7575, etc.) are considered random noise due to geolocation errors or misclassifications, caused by different data sources, co-registration errors, misclassifications from regions in cast shadow or differences in perennial snow cover that are attached to a glacier. For example, a value of 5757 stands for grid cell variation by "non-glacierized area, glacier area, non-glacierized area, glacier area" in classification results from the series of sequential images.

Gridcell Value	Count of gridcells	Area (km^2)	Re-code	Category of variation
5555	714479	643.03	9	Non-glacierized area in 1976–2003
5557	120	0.11	3	Advanced glacier area in 1999–2003
5575	1188	1.07	8	Random noises in glacier area
5577	230	0.21	2	Advanced glacier area in 1990–1999
5755	1494	1.34	8	Random noises in glacier area
5757	266	0.24	8	Random noises in glacier area
5775	824	0.74	8	Random noises in glacier area
5777	2035	1.83	1	Advanced glacier area in 1976–1990
7555	4659	4.19	4	Retreated glacier area in 1976–1990
7557	205	0.18	8	Random noises in glacier area
7575	1371	1.23	8	Random noises in glacier area
7577	706	0.64	7	Glacier area in stable termini in 1976–2003
7755	2091	1.88	5	Retreated glacier area in 1990–1999
7757	648	0.58	7	Glacier area in stable termini in 1976–2003
7775	3540	3.19	6	Retreated glacier area in 1999–2003
7777	82141	73.93	7	Glacier area in stable termini in 1976–2003

Table 1 Information table of the integrated grid on glacier change process in the Mt. Naimona'Nyi region (Gridcell area, $900m^2$)

2.3 Results

In the Mt. Naimona'Nyi region, the traditional method for quantifying classifications from individual images and maps in glacier monitoring shows that the area of glaciers was 87.04 km^2 in 1976 and decreased to 79.39 km^2 in 2003. The rate of change varies during different periods. Recession was 2.59 km^2 during 1976–1990 (or 0.19 km^2 a^{-1} on average), 0.80 km^2 during 1990–1999 (or 0.09 km^2 a^{-1}), and 4.27 km^2 during 1999–2003 (or 1.07 km^2 a^{-1}). The total decrease in glacier area between 1976 and 2003 was equal to 7.66 km^2 or 8.8% (Table 4). Implementing the hybrid grid method we found discrepant gridcells of ever glacierized area by 4.81 km^2 (or 5.5% of the glacier area by 87.04 km^2 in 1976, including 2.41 km^2 or 2.77% grid units (by values of 5575 and 5755) were reclassified as non-glacierized area and 2.4 km^2 or 2.76% gridcells (by value of 5757, 5775, 7557 and 7575) were identified as random noises from glacier variations) were picked out and eliminated from glacier changes during 1976–2003. Further, 1.22 km^2, or 1.62% of the stable glacier area (75.15 km^2, Table 2) have been corrected into stable glacier area (Table 2), where gridcell values equal to 7577, 7757.

Value of the hybrid grid unit	Recode	Area (km^2)	Category of variation
5777	1	1.83	Advanced glacier area during 1976–1990
5577	2	0.21	Advanced glacier area during 1990–1999
5557	3	0.11	Advanced glacier area during 1999–2003
7555	4	4.19	Retreated glacier area during 1976–1990
7755	5	1.88	Retreated glacier area during 1990–1999
7775	6	3.19	Retreated glacier area during 1999–2003
7777, 7757, 7577	7	75.15	Glacier area in stable termini during 1976–2003
5757,5775, 7557, 7575	8	2.4	Random noises in glacier area
5555,5575, 5755	9	645.44	Non-glacierized area during 1976–2003

Table 2 Remap table of glacier variations by the hybrid grid in the Mt. Naimona'Nyi region (km^2)

Year	Area by common method	Area by hybrid grid method	Area difference	Percentage of random noises (%)	Value of the hybrid grid unit(remap table)
1976	87.04	84.41	2.63	3.02	7777,7757,7577,7555, 7755,7775
1990	84.46	82.04	2.42	2.87	7777,7757, 7577,7755,7775,5777
1999	83.66	80.37	3.29	3.93	7777,7757, 7577,7775,5577,5777
2003	79.39	77.29	2.1	2.65	7777,7757, 7577,5557,5577,5777

Table 3 Glacier area change in the Mt. Naimona'Nyi region during 1976–2003 (km^2)

Periods	Variation in area (km^2)	Variation rate (%)	Annual variation rate (% a^{-1})	Annual variation (km^2 a^{-1})
1976-1990	-2.37 (-2.59)	-2.81 (-2.97)	-0.20 (-0.21)	-0.17(-0.19)
1990-1999	-1.67 (-0.80)	-2.04 (-0.95)	-0.23 (-0.11)	-0.19(-0.09)
1999-2003	-3.08 (-4.27)	-3.83 (-5.10)	-0.96 (-1.28)	-0.77(-1.07)
Total	-7.12 (-7.66)	-8.44 (-8.80)	-0.31 (-0.38)	-0.26(-0.28)

Table 4 Glacier area change in the Mt. Naimona'Nyi region during 1976–2003 with results by common method in the parenthesis (km^2)

Differences in size in this region between the traditional method and the hybrid grid method are summarized in Table 3. After the random noise removal from each individual classification, we notice that glacier recession clearly accelerates (Table 4). Recession was equal to 2.37 km^2 during 1976–1990 (or 0.17 km^2 a^{-1} on average), 1.67 km^2 during 1990–1999 (or 0.19 km^2 a^{-1} on average), and 3.08 km^2 during 1999–2003 (or 0.77 km^2 a^{-1} on average) (Fig. 3 and Table 4). The glacier area in this region was 84.41 km^2 in 1976 and 77.29 km^2 in 2003 (Table 3), showing a total decrease of 7.12 km^2, i.e. 8.44% or 0.31 % a^{-1}, 0.26 km^2 a^{-1} (Table 4).

2.4 Discussion

The measurement accuracy of the position of the glacier front by remote sensing satellite images is limited by both the sensor resolution (Williams et al., 1997) and the coregistration error (Hall et al., 2003; Silverio and Jaquet, 2005). Calculated by the sensor resolution and coregistration error (Ye et al., 2006a), the maximum measurement uncertainty in area extent of glaciers was approximately 0.015 km^2 in the Mt. Naimona'Nyi region, and 0.042 km^2 in Mt. Geladandong area. Using the hybrid grid method, however, we eliminated more than 2.5 km^2 of random noise or 3.0% of the total glacier area in 1976 from classification results in the Mt. Naimona'Nyi region (Table 2). Similarly, corrections of approximately 11 km^2 of random noise or 1.2% of the total glacier area in 1969 was made for the Mt. Geladandong area. Such random noise among sequential data sets was much higher than that of the measurement uncertainty by sensor resolution and coregistration error. Therefore, uncertainty in glacier monitoring by satellite images mainly originates from such random noise in sequential data sets, caused by geolocation error or misclassifications.

Comparing the results of the hybrid grid method with those obtained by a traditional method, we found that the hybrid grid method could quantify a clear acceleration in glacier retreat in the Mt. Naimona'Nyi region.

It is still not clear however, how our method can distingTable 4 Glacier area change in the Mt. Naimona'Nyi region during 1976–2003 with results by common method in the parenthesis (km^2)

uish between geolocation error or misclassification noise for values like 5775 or 7557 at a larger temporal scale. Not all identified discrepancies or random noise in the maps could be corrected by the hybrid grid method without further study or verification, like for example, some advanced glacier area in the Mt. Naimona'Nyi region (Fig.3).

3. CONCLUSIONS

The hybrid grid method can distinguish between random noise due to geolocation noise or misclassifications from real glacier changes occurring over periods of decades. Based on algebraic operations within grid cells, discrepancies are detected and eliminated. The comparison of this method with traditional method demonstrates an improvement in quantifying glacier variation. The identified discrepancies or random noise is much larger than that of the measurement uncertainty limited by sensor resolution and co-registration error. This may affect the way in calculation of measurement uncertainty in glacier change monitoring by satellite imagery. Not all detected random noise, however, could be corrected by this method without further study or verification by field survey.

Results obtained in this study show that areas of both glacier retreat and advance exist in the western Himalaya Mountains. Retreat dominates, dramatic and accelerates through time in the Himalayas. The 0.31% a^{-1} retreat in the Mt. Naimona'Nyi region during 1976–2003, were larger than the average 0.175% a^{-1} retreat of glaciers in high Asia in the last 40 years since the 1960s (Yao et al., 2004) and the 0.18% a^{-1} area loss in the Mt. Geladandong region (Ye et al.,2006a) in Central Tibet during 1969–2002.

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