Comparative study on climatic sensitivities and expansion of glacial lakes on the northern and southern slopes of the Himalayan summit region over the past three decades (1976 - 2008)

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1. Introduction
The Himalayan Mountain range is the highest and largest in the world. The range is approximately 2,900 km long, stretching from Afghanistan to Myanmar, and 250 - 400 km wide, from 27ºN to 36ºN in a curve shape. The Himalayan range is one of the most extensively glaciered regions in the world outside the Polar Regions. The climate of the Himalaya is controlled by the Indian monsoon system (Barry 2008; Tartari et al. 1998) because the Himalayas lie in the subtropical high-pressure belt. The precipitation decreases from the lower latitudes to the higher latitudes. In addition, the rainfall increases with altitude on the windward side and decreases in the leeward side. The precipitation plays an important role in accumulation of Himalayan glaciers, because the Himalayan glaciers feed 7 of Asia’s great rivers: Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze, and Yellow River. The significant flow contribution of Himalayan rivers during dry season is from snow and glaciers melt. It ensures a year-round water supply to billions of people in Asian region (Shrestha et al. 2005).

Since the second half of the 20th century, many glaciers in the Hindu Kush-Himalayan (HKH) region have retreated due to climate changes (Bajracharya et al. 2007; Dyrurgerov 2003; Immerzeel et al. 2009; Krishna 2005; Owen et al. 2009a; Shrestha et al. 2005). (Shrestha et al. 1999) stated that the temperature in the middle mountain and high Himalaya of Nepal is becoming warm, especially in the winter. The similar warming is also observed in the Tibetan Plateau. (Liu and Chen 2000) showed that warming is more pronounced in higher altitude than in lower ones in the Tibetan Plateau. This suggests that the Himalayas and the Tibetan Plateau are sensitive to and affected by climate changes. Thus, identifying glacial lakes, monitoring and analyzing glacial lakes’ changes are important for the regional environment and local ecosystem.

However, because some glacial lakes are located at the foot of high and steep mountains, the feature of glacial lakes which is covered by shadow is missed due to low solar elevation. Therefore, to identify these shadowed glacial lakes is very important in order to gain all information of glacial lakes.

From field survey and preliminary analysis, the applicant made a hypothesis that the glacial lakes located at the southern slope (Nepal) have retreated faster than the ones at the northern slope (China) due to different climatic conditions. That is, the changes of glacial lakes on the northern and southern slopes could be different, possibly due to climate changes. To analyze the different changes of glacial lakes between the northern and southern slopes, and study on driving forces that caused these changes are the key points for this study.
2. **Objectives**
There are three objectives of this study:
1. to identify the shadowed glacial lakes caused by high and steep mountains,
2. to reveal the tendency of glacial lakes changes on the northern and southern slopes over the past 32 years (1976 - 2008), and
3. to reveal what is the most driving force that influenced the changes of glacial lake on the northern and southern slopes in the Himalayan summit region.

3. **Study area**
The study area is located in the Everest region of the Himalayas, which covers the Northern slope in China and the Southern slope in Nepal (27°33’6.11” - 28°28’39.62” N, and 86°30’36.86” - 87°33’5.51” E, see Figure1). Because the northern and southern slopes can be distinguished by the crest of the mountain range which is also the international border that forms a definite line of demarcation between China and Nepal, this study estimates that the border represents the separations of the northern and southern slopes. Mt. Everest, the summit peak in the world, is located in the study area. It is known as Qomolangma Peak in China and Mount Sagarmatha in Nepal. The rocky summit of Mt. Everest is covered with deep snow all the year round. Its rock height is 8,844.43 m above sea level (a.s.l.) and its snow height is 8,848 m a.s.l. January is the coldest month. The summit temperature averages about -36°C and can drop as low as -60°C. July is Mt. Everest’s warmest month, the temperature on the summit never rises above freezing, the average temperature in July is -19°C (Heinrichs 2010). Wind can reaches more than 160 km an hour on the summit. Rainfall is dominated by topography. The total amount of rainfall from summer monsoon that penetrates into the Himalayan mountains remains nearly constant along strike (Bookhagen and Burbank 2010), however, the spatial rainfall distribution widely varies along with latitude and altitude gradient. The total studied area is 6,487 km$^2$, of which China and Nepal occupy 4,004 km$^2$ and 2,483 km$^2$, respectively. The altitude of this area ranges from 825 m to 8,848 m, the ground surface slope ranges from 0° to 87.93°.

![Figure 1 Study area in the Himalayan summit region](image)
4. Methodology

4.1. Data preparation

Imagery data of Landsat and Terra satellites were utilized in this study. The datasets include MSS with a spatial resolution of 60 m in December 1976, TM with a spatial resolution of 30 m in November 1992, ETM+ with a spatial resolution of 30 m in October 2000, and ASTER with a spatial resolution of 15 m in January 2008 and November 2009. Because the data of MSS in 1976 and ASTER in 2008 did not cover the study area fully, MSS in 1975 and 1977, and ASTER in 2009 were utilized as a supplement and reference. Thus, the results of glacial lake extraction from MSS in 1975 and 1977, and ASTER in 2009 were assigned to the classification in 1976 and 2008 respectively. In total, sixteen scenes of image data were used in order to mosaic covering the whole study areas. The ASTER Global Digital Elevation Model (ASTER GDEM) data (ERSDAC 2011) were used for terrain analysis and elevation extraction for each glacial lake.

4.2. Method

The method is summarized in Figure 2.

Based on the selected satellite imageries, a DSGL (Detection of Shadowed Glacial Lakes) model, an original method developed by the applicant, which was published in Chinese Geographical Science, was applied for identifying glacial lakes for open water as well as for shadowed water. The DSGL model is an advanced method, which combines Normalized Difference Water Index (NDWI) (McFeeters 1996), slope analysis, and histogram equalization (HE) method, and is powerful to detect glacial lakes in the shadowed environment at high mountains.

Image analysis was conducted by ENVI® 4.7. The identified glacial lakes were converted from raster data to feature data (polygons of shape files), and their attributes were edited by ArcMap® 10. Because the
lowest resolution among the sensors used in this study was 60 m, the minimum identifiable pixel size should be 0.0036 km$^2$. However, since the output polygons from raster cells were smoothed into simpler shapes compared to the input raster's cell edges, the size and shape of each lake was slightly changed. The size of 0.0036 km$^2$ in raster data was changed to 0.0020 km$^2$ in polygons. Hence, the threshold of glacial lake identification was decided to be equal or greater than 0.0020 km$^2$ in this study. The area (km$^2$) and quantity were calculated in four periods of 1976, 1992, 2000, and 2008 in order to evaluate the changes of the glacial lakes. To calculate the area of each polygon feature (glacial lake) was accomplished using the calculate geometry function in ArcMap$^\text{®}$ 10.

Terrain analysis includes altitude, angle of inclination, aspect, and radiation. It was applied to ASTER GDEM. The polygon feature and ASTER GDEM were used to calculate the altitude of each glacial lake. It was defined the sum of altitude value in a polygon feature divided by the number of pixels in a polygon features. The calculation of other three terrain factors is based on the watershed in which the glacial lakes located. Watersheds can be delineated from a DEM by computing the flow direction to determine the contributing area. Aspect identifies the slope direction. The downslope direction of the maximum rate of change in value from each cell to its neighbours was calculated. Angle of inclination represents the rate of change of elevation for each digital elevation model (DEM) cell. It uses an accelerated atan() function which is six times faster, and the approximation error is always less than 0.3 degrees. The solar radiation was calculate across a landscape or for specific locations, based on methods from the hemispherical viewshed algorithm (Dubayah and Rich 1995; Rich et al. 1994) and the model further developed by Rich and Fu (2000) and Fu and Rich (2002).

Based on regression analysis from DEM-derived data, the equations were constructed in order to predict time-series temperature and precipitation in the Himalayan Summit Region. Terrestrial Air Temperature: 1900-2010 Gridded Monthly Time Series (V 3.01) from Willmott and Matsuura, Terrestrial Precipitation: 1900-2010 Gridded Monthly Time Series (V 3.02), and ISLSCP II HYDRO1k Elevation-derived Products were used to develop this climate modelling. The area of the Plateau of Tibet whose zoning are ET and Dwd based on Köppen’s climate classification was the target regional area for the climate modelling. These equations will be used to produce high spatial resolution time-series climate data as a downscaling method.

5. Results
By using the DSGL model, the shadowed glacial lake completely emerged so that the boundary of glacial lakes was able to be identified visually (see Figure 3, published in the Chinese Geographical Science).
Based on the analysis of Imja Lake and Karda Lake, and its terrain analysis, the growth speed of both lakes declined over time and difference between two lakes were significant ($p<0.05$) (see Figure 4). Figure 5 presents the values of these terrain (aspect, angle of inclination, altitude) variables in histogram form. For all terrain variables, there were significant differences between northern slope and southern slope ($p<0.05$). These results were published in Natural Resources.
Figure 5 Aspect, angle of inclination, and altitude on northern and southern slopes.

Figure 6 shows the pairwise scatterplots between temperature data. The temperature data was highly correlated each other. In this figure, temp1976, temp1992, temp2000, and temp2008 denotes annual temperature in 1976, annual temperature in 1992, annual temperature in 2000, and annual temperature in 2008, respectively.

Pairwise Scatterplots of Temperature Variables

Figure 6 Pairwise plots of temperature data
Coefficients estimated by linear regression model to fit equation: \( T_i = f(T_{1976}) = \beta_0 + \beta_1 \times T_{1976} \) was shown in Table 1. For all models, the Multiple \( R^2 \) showed high value (\( \geq 0.95 \)). These models were considered to be sufficient for practical use.

Table 1 Coefficients estimated by linear regression model to fit equation:

<table>
<thead>
<tr>
<th>( T_i )</th>
<th>( \beta_0 ) ( p&lt;0.001 )</th>
<th>( \beta_1 ) ( p&lt;0.001 )</th>
<th>Multiple ( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{1992} )</td>
<td>-0.38 ( p&lt;0.001 )</td>
<td>0.96 ( p&lt;0.001 )</td>
<td>0.99</td>
</tr>
<tr>
<td>( T_{2000} )</td>
<td>0.16 ( p&lt;0.001 )</td>
<td>0.94 ( p&lt;0.001 )</td>
<td>0.99</td>
</tr>
<tr>
<td>( T_{2008} )</td>
<td>0.64 ( p&lt;0.001 )</td>
<td>0.96 ( p&lt;0.001 )</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Figure 7 shows the pairwise scatterplots between precipitation data, respectively. The precipitation data was highly correlated each other. In this figure, prec1976, prec1992, prec2000, and prec2008 denotes annual precipitation in 1976, annual precipitation in 1992, annual precipitation in 2000, and annual precipitation in 2008, respectively.

Coefficients estimated by linear regression model to fit equation: \( P_i = f(P_{1976}) = \alpha_0 + \alpha_1 \times P_{1976} \) was shown in Table 2. For all models, the Multiple \( R^2 \) showed high value (\( \geq 0.94 \)). These models were considered to be sufficient for practical use.

Table 2 Coefficients estimated by linear regression model to fit equation:

<table>
<thead>
<tr>
<th>( P_i )</th>
<th>( \alpha_0 ) ( p&lt;0.001 )</th>
<th>( \alpha_1 ) ( p&lt;0.001 )</th>
<th>Multiple ( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{1992} )</td>
<td>3.48 ( p&lt;0.001 )</td>
<td>0.94 ( p&lt;0.001 )</td>
<td>0.95</td>
</tr>
<tr>
<td>( P_{2000} )</td>
<td>3.56 ( p&lt;0.001 )</td>
<td>1.03 ( p&lt;0.001 )</td>
<td>0.96</td>
</tr>
<tr>
<td>( P_{2008} )</td>
<td>7.18 ( p&lt;0.001 )</td>
<td>0.95 ( p&lt;0.001 )</td>
<td>0.94</td>
</tr>
</tbody>
</table>
The best model to predict $T_{1976} = f(x_i)$ where $T_{1976}$ is the temperature data in 1976, $x_i$ is the DEM-derived variables and/or geographic coordinates (latitude or longitude) ($i = 1, 2, ..., n$) was a multiple linear regression model with interaction between independent variables of latitude, longitude, 5 aspect related variables, 6 CTI related variables, 8 Elevation related variables, and 5 slope related variables ($R^2=0.85$, AIC=1451, number of parameters=180). The best model to predict $P_{1976} = f(x_i)$ where $P_{1976}$ is the precipitation data in 1976 was a multiple linear regression model with interaction between above-mentioned variables ($R^2=0.77$, AIC=5225, number of parameters=171).

The changes from 1976 to 2008 between the northern and southern slopes were summarized in Figure 8, which included the quantity, area, and surface elevation of glacial lakes. Both of the quantity and area of glacial lakes on the northern and southern slope increased over 32 years.

![Figure 8 Distribution of glacial lakes in 1976, 1992, 2000, and 2008, respectively.](image)

<table>
<thead>
<tr>
<th>Year</th>
<th>Elevation (m)</th>
<th>Quantity</th>
<th>Area ($\text{km}^2$)</th>
</tr>
</thead>
</table>

Table 3 Time-series changes of glacial lakes between the northern and southern slope
<table>
<thead>
<tr>
<th>Year</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>SD</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>3747</td>
<td>4918</td>
<td>5746</td>
<td>468</td>
<td>103</td>
<td>0.002</td>
<td>0.064</td>
<td>0.853</td>
</tr>
<tr>
<td>1992</td>
<td>3746</td>
<td>4918</td>
<td>5842</td>
<td>498</td>
<td>142</td>
<td>0.002</td>
<td>0.060</td>
<td>0.844</td>
</tr>
<tr>
<td>2000</td>
<td>3743</td>
<td>4904</td>
<td>6170</td>
<td>484</td>
<td>204</td>
<td>0.002</td>
<td>0.048</td>
<td>0.944</td>
</tr>
<tr>
<td>2008</td>
<td>3744</td>
<td>4866</td>
<td>6172</td>
<td>516</td>
<td>241</td>
<td>0.002</td>
<td>0.049</td>
<td>1.025</td>
</tr>
</tbody>
</table>

The changes of glacial lakes from 1976 to 2008 between the northern and the southern slopes were summarized in Table 3. At the northern slope, the total area of glacial lakes expanded by 5.128 km², the quantity of glacial lakes increased by 138 from 1976 to 2008. The dimension of 95% glacial lakes was 0.004-0.206 km² in 1976, 0.003-0.218 km² in 1992, 0.002-0.208 km² in 2000, and 0.002-0.205 km² in 2008. 95% of glacial lakes on the northern slope were located between 4,254-5,663 m in 1976, 4,204-5,663 m in 1992, 4,179-5,625 m in 2000, and 4,105-5,692 m in 2008. On the Southern slope, the total area of glacial lakes expanded by 5.021 km², the quantity of glacial lakes increased by 108 from 1976 to 2008. The dimension of most glacial lakes was 0.003-0.245 km² in 1976, 0.003-0.320 km² in 1992, 0.003-0.300 km² in 2000, and 0.002-0.202 km² in 2008. 95% of glacial lakes on the southern slope were located between 4,497-5,357 m in 1976, 4,151-5,329 m in 1992, 4,145-5,355 m in 2000, and 4,168-5,378 m in 2008.

There were two peaks of aspect on the northern slope which face to SSE and SSW. On the other hand, there were three peaks which face to SE, SSE, and SSW on the southern slope. For the angle of inclination, the southern slope is steeper than the one on the northern slope. The radiation that it received on the northern slope is more than the southern slope. The driving forces analysis will be conducted.

**Achievements**

**Requirements:**
- Original Syllabus: GAO II, Approved Date 2010-12-22
- Skill Building Subject: Digital Earth, Approved Date 2010-03-03
- Teaching Experience: Advanced Research (EG2)/2010S, Approved Date 2010-08-25
- Foreign Language Proficiency: formal presentation in English, IELTS (5.5), and international conference presentations, Approved Date 2011-11-09

**International journal (peer-review)**
- Wenbo Chen, Tomoko Doko, Hiromichi Fukui, Wanglin Yan, Changes in Imja Lake and Karda Lake in the Everest Region of Himalaya, Natural Resources, 2013 Vol.4 No.7, P.449-455 (English)
International conferences and Symposium (Paper & Oral Presentation)

- Chen W., Monitoring Glacial Lakes Changes in Himalaya Area During the Last Thirty Five Years, APN - CODATA Joint Workshop on Open Access to Global Change Data and Information in Asia-Pacific Region, Xining/Qinghai – Lhasa/Tibet, China, 23-31 May, 2012. (English)
- Wenbo CHEN, Wanglin YAN, Tomoko DOKO, Hiromichi FUKUI, Space-based information and risk assessment of glacial lake in Everest Region, Himalaya, The 11th Science Council of Asia (SCA) Conference, Ulaanbaatar, Mongolia, 4-6 July, 2011. (English)
- Wenbo CHEN, Hiromichi FUKUI, Tomoko DOKO, Comparison study on expansion of glacial lakes in Northern and Southern slope of Himalaya, The 34th International Symposium on Remote Sensing of Environment, Sydney, Australia, 10-15 April, 2011. (English)
- Wenbo CHEN, Hiromichi FUKUI, Tomoko DOKO, Detection Glacial Lakes under the Shadow Environment Using ASTER Data in Himalaya, Nepal, The 3rd International Symposium on Sentinel Earth - Advance in Satellite Imagery Data and GIS and Their Application, Hokkaido University, Sapporo, Japan, 3-5 November, 2010. (English)

International conferences and Symposium (Poster)

- Wenbo Chen, and Tomoko Doko, Journey to Himalaya, the 9th GIS Community Forum, Tokyo, Japan, 30-31, May 2013. (English)
- Wenbo Chen, Tomoko Doko, Tomohiro Ichinose, and Hiroyoshi Higuchi, Spatial analysis of migration patterns of satellite-tracked tundra swan in East Asia, the 9th GIS Community Forum, Tokyo, Japan, 30-31, May 2013. (English)
- Chen W., The Sketchbook of Tibetan Eco-Environment – The Himalayan Fieldwork in 2012, the 3rd Environmental Innovators Symposium, Yokohama, Japan, 21-22, Dec. 2012. (English)
- Wenbo CHEN, Hiromichi FUKUI, Ponthip LIMLAHAPUN, Tomoko DOKO, Space-based information for monitoring glacial lakes in Himalaya, International Symposium on “Benefiting from Earth Observation: Bridging the Data Gap for Adaptation to Climate Change in the Hindu Kush-Himalayan Region”, Kathmandu, Nepal, 4-6 October, 2010. (English)

**Advisory group**

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Co-research advisor: Hiromichi Fukui, Professor, Chubu Institute for Advanced Studies, Chubu University

Co-research advisor: Hikaru Kobayashi, Professor, Faculty of Environment and Information Studies, and Graduate School of Media and Governance, Keio University

**Process for acquiring the Ph.D. degree**

<table>
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<tr>
<th>Date</th>
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<tbody>
<tr>
<td>Jan. 18 2014</td>
<td>Dissertation hearing</td>
</tr>
<tr>
<td>Jan. 31 2014</td>
<td>Final examination if the applicant passes the Dissertation hearing</td>
</tr>
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