



## Original article

### Modern glacier dynamics in Mt. Tsambagarav in the Mongolian Altai Mountain Range

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#### ABSTRACT

This study presents the modern glacier dynamics in Mt. Tsambagarav in the Mongolian Altai Mountain Range over the last four decades. This is the first review of this type of glacier dynamics for this massif. Changes in glacier area in Mt. Tsambagarav are estimated using normalized indexes (Normalized Difference Snow Index and Normalized Difference Principal Component Snow Index). Spatial distribution of the modern glaciers delineated with Landsat Multispectral Scanner (MSS: resolution of 80 m), Landsat Thematic Mapper (TM: resolution of 30 m) and Landsat Operational Land Imager (OLI: resolution of 30 m) imageries. Result shows that Mt. Tsambagarav has lost 51.7% of the glacier area from 132.24 km<sup>2</sup> in 1977 to 63.92 km<sup>2</sup> in 2017. The loss in glacier area for Mt. Tsambagarav during the last 40 years reflect the rapid response of the modern glacier to climate change, i.e., it is highly sensitive to solar insolation and/or rapidly rising local and regional mean annual temperatures. The remote sensing data and field survey suggest that the modern glaciers would be disappeared on a scale of decades. Rapid melting of the glacier in this massif contributes to surface water resources in western Mongolia. This study demonstrates the importance of spatial analysis in the remote area for understanding the context of changes in the modern glaciers.

**Keywords:** *Glacier, Surface Water, Change, Landsat*

#### INTRODUCTION

As an important source of freshwater (e.g., Brown, 2000; Yang et al., 2003; Zhou and Li, 2003), estimating glacier dynamics on high mountains is crucial for understanding and hypothesizing local and regional hydrological cycles. Climate change can modulate water resources through altering glacier mass balances (Liu et al., 2015). Changes in modern glaciers in

the Mongolian Altai Mountain Range are an important component of the hydrological balance in the watersheds in western Mongolia (Orkhonselenge and Harbor, 2018).

Globally, glaciers have been abruptly melting due to climate change in recent years. According to Beniston and Rebetez (1996), environmental changes in high-latitude and high-altitude regions are prone to cryospheric changes such as

reductions of snow-covered areas due to global warming. This process is not being away from the high mountains in Mongolia lying on the high-latitudes. For instance, an area of the maximum glaciers in the Mongolian Altai Mountain Range during the Pleistocene decreased from 62900 km<sup>2</sup> to only 1100 km<sup>2</sup> (Orkhonselenge and Harbor, 2018).

High mountains in Mongolia were glaciated twice in the early and late Pleistocene (Tsegmid, 1969) due to uplifts during the new tectonic activities in the late Neogene and the early Quaternary periods (Jigj, 1976; Sanjmyatav, 2009). Glaciers in Mongolia were initially noted by Russian tourists and scientists since 1870s and they were scientifically studied since 1921 (Tsegmid, 1969). The dominant style of glaciation recorded in Mongolia is valley glaciers including hanging glaciers (Tsegmid, 1969) and alpine-style glaciations in the Mongolian Altai Mountain Range (e.g., Lehmkuhl et al., 2004; Blomdin et al., 2016). Paleoglacial landforms, including ice caps, valley glaciers, hanging glaciers, cirques, hummocky terrain, moraines and moraine-dammed lakes, are widespread in the Mongolian Altai, Khangai, Khentii and Khuvsgul Mountain Ranges.

Recent studies show that modern glaciers occupy small areas in these mountain ranges (Blomdin et al., 2016) and play a vital role in water resources in Central Asia (Orkhonselenge and Harbor, 2018). The glaciated areas have been decreasing rapidly in recent years (e.g., Davaa, 2010; Kamp et al., 2013; Orkhonselenge, 2016). The modern glaciers in Mongolia constitute over 70% of freshwater resources (Davaa, 2010) and/or water resources of 19.4 km<sup>3</sup> (Davaa, 2015), however the glacier areas rapidly decrease over the last half-century. Reviewing spatial and temporal patterns of modern glaciers is important not only to contribute to knowledge about how glaciers respond to climate change, but also to hypothesize the social, economic and ecological development in the region that depends heavily on glacial meltwater to sustain water supplies for agriculture and human consumption.

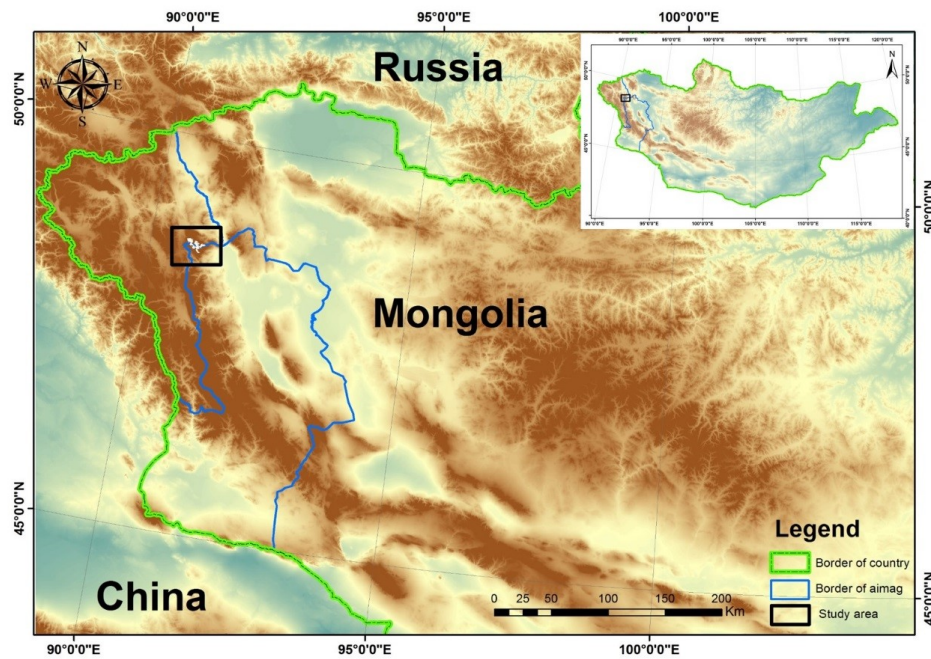
Here we infer glacier dynamics in Mt. Tsambagarav in the Mongolian Altai Mountain

Range during the last 40 years. For extensive investigations on glaciers in Mt. Tsambagarav there are still ongoing disagreements about the frequency, number and extension of paleoglaciers and modern glaciers. Previous studies on Mt. Tsambagarav have used a Normalized Difference Snow Index (NDSI) and Landsat 5 and 7 images. In this study we present precise data obtained from two different indexes and Landsat 5 and 8 images. To advance the knowledge on the modern glacier in this massif, we estimated and compiled the changes in area of the modern glacier in Mt. Tsambagarav in 1977, 1991, 2002 and 2017 based on NDSI, Normalized Difference Principal Component Snow Index (NDPCSI) and Landsat images. In this context, there are no previously published maps with these indexes and recent satellite data for this mountain massif.

#### **GEOGRAPHICAL SETTING**

The Mongolian Altai Mountain Range extends over 1000 km from Mt. Tavan Bogd (4374 m a.s.l.) in the northwest to Gichgene Mountain Range in the southeast (Murzaev, 1952) and it covers an area of over 248900 km<sup>2</sup>. There are numerous branch and isolated mountains elevated over 4000 m a.s.l. with paleoglaciers and modern glaciers in the Mongolian Altai such as Mt. Munkh Khairkhan (4231 m a.s.l.), Mt. Sutai (4226 m a.s.l.), Mt. Tsast Bogd (4208 m a.s.l.), Mt. Bugat (4041 m a.s.l.), Mt. Kharkhiraa (4040 m a.s.l.), Mt. Ikh Turgen (4030 m a.s.l.) and Mt. Turgen (4029 m a.s.l.). The dominant mountains in the Mongolian Altai consist of dislocated Precambrian stratigraphic sequences during the late Neogene and the early Quaternary (Tsegmid, 1969).

Mt. Tsambagarav, elevated at 4008 m a.s.l., is an isolated mountain in the east of the Mongolian Altai Mountain Range in western Mongolia (Fig. 1). This massif is surrounded by the high mountains in the west and the Depression of Great Lakes in the east, i.e., it lies at the easternmost edge of the Mongolian Altai (Fig. 1). Glacier in Mt. Tsambagarav constitutes a part of remnants of a large former paleoglacier that covered the great part of the Mongolian Altai during the Pleistocene, i.e., it is one of mountains covered with paleoglaciers and



**Fig. 1.** Geographical location of Mt. Tsambagarav in the Mongolian Altai Mountain Range in western Mongolia.

modern glaciers.

The modern glacier and moraines in Mt. Tsambagarav are shown in Fig. 2. The modern glacier in Mt. Tsambagarav is considered as an erosional surface glacier among the three types of modern glaciers in Mongolia of (1) mountain-slope glaciers of 75.2% (cirques, hanging

cirques and hanging), (2) valley glaciers of 21% (depression, cirque valley and hanging valley) and (3) erosional surface glaciers of 3.8% (degraded flat peaks) (Davaa and Oyunbaatar, 2012).

Mt. Tsambagarav receives a maximum annual precipitation of 300–350 mm and it constitutes



**Fig. 2.** A view of the modern glacier on southwestern slope of Mt. Tsambagarav. Photo by A. Orkhonselenge on 08.10.2013.

one of the glaciated mountains recharging surface water in western Mongolia. The modern glacier in Mt. Tsambagarav feeds rivers draining into Khovd River (Myagmarsuren and Namkhai, 2015). According to the Khovd meteorological station, lying at 88 km southeast of the mountain, annual average air temperature is 1.8°C with monthly average temperatures of 19°C in summer and -25.5°C in winter, and annual average precipitation is 210 mm.

**METHODS**

This study focuses on precise estimation and delineation of the modern glacier dynamics in Mt. Tsambagarav. In calculation of glacier area, Landsat imagery data, NDSI, Snow Grain Size Index (SGSI), Normalized Difference Snow Thermal Index (NDSTI) and NDPCSI are broadly used today. In the estimation of the glacier dynamics in Mt. Tsambagarav, two indexes of NDSI and NDPCSI are used.

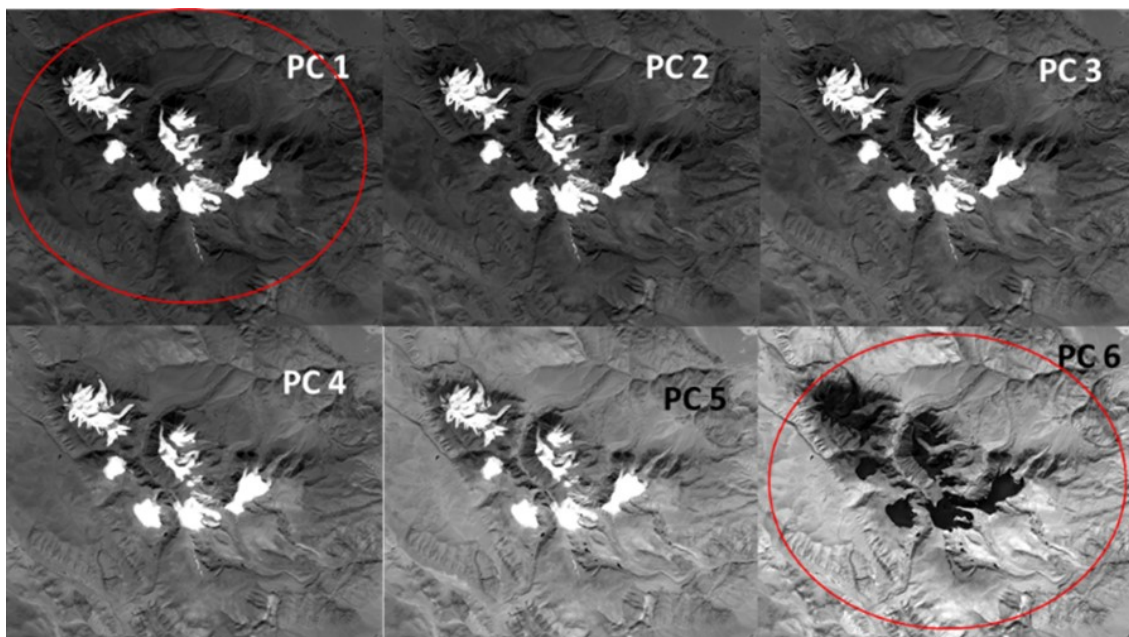
Firstly, NDSI is a useful tool to differentiate periods with and without snow and to clarify clouds, snow and glacier (Negi et al., 2009). An advantage of NDSI is that it is based on landform changes and it is able to detect snow on mountain shadow (Kulkarni et al., 2002). NDSI value ranges from -1 to 1, and values more than 0.4 are taken into account as glaciated

area. NDSI is indicated with an equation (Eq. 1) formulated by Hall et al. (1995), Xiao et al. (2002) and Kulkarni et al. (2006).

$$NDSI = \frac{band_{green} - band_{swir}}{band_{green} + band_{swir}} \quad (Eq. 1)$$

Secondly, NDPCSI is more advanced than NDSI because of its direct detection of glaciated areas. In the estimation of NDPCSI, removing areas of lakes and rivers is not required. Then the glaciated areas are compiled after reclassifying raster data and picking pixels up with values more than 0.4. With NDPCSI, Principal Component Analysis (PCA) allows us to understand multiple scale data of abrasion and accumulation zones. Determining which wavelength is important to consider the glaciated areas is required (Pope and Rees, 2014). The PCA was used to determine changes in area of the modern glacier in Mt. Tsambagarav depending on climatic factors. In calculation of NDPCSI based on an equation (Eq. 2), channels 1 (PC 1: brightest) and 6 (PC 6: darkest) of Landsat image were taken into account (Fig. 3). PC 1 reflects snow albedo, while PC 6 shows snow absorption (Sibandze et al., 2014).

$$NDPCSI = \frac{PC_{brightest} - PC_{darkest}}{PC_{brightest} + PC_{darkest}} \quad (Eq. 2)$$



**Fig. 3.** Maps from channel PC 1 to channel PC 6 of Landsat data showing the areas of modern glacier in Mt. Tsambagarav based on NDPCSI: Source data on 09.17.2017.

In delineation showing spatial distribution of the modern glaciers (Fig. 4) medium-resolution satellite imagery data with a low percentage of clouds on Landsat Multispectral Scanner with resolution of 80 m (MSS: 08.13.1977), Landsat Thematic Mapper with resolution of 30 m (TM: 08.09.1991; 09.17.2002) and Landsat Operational Land Imager with resolution of 30 m (OLI: 09.17.2017) are applied.

### RESULTS

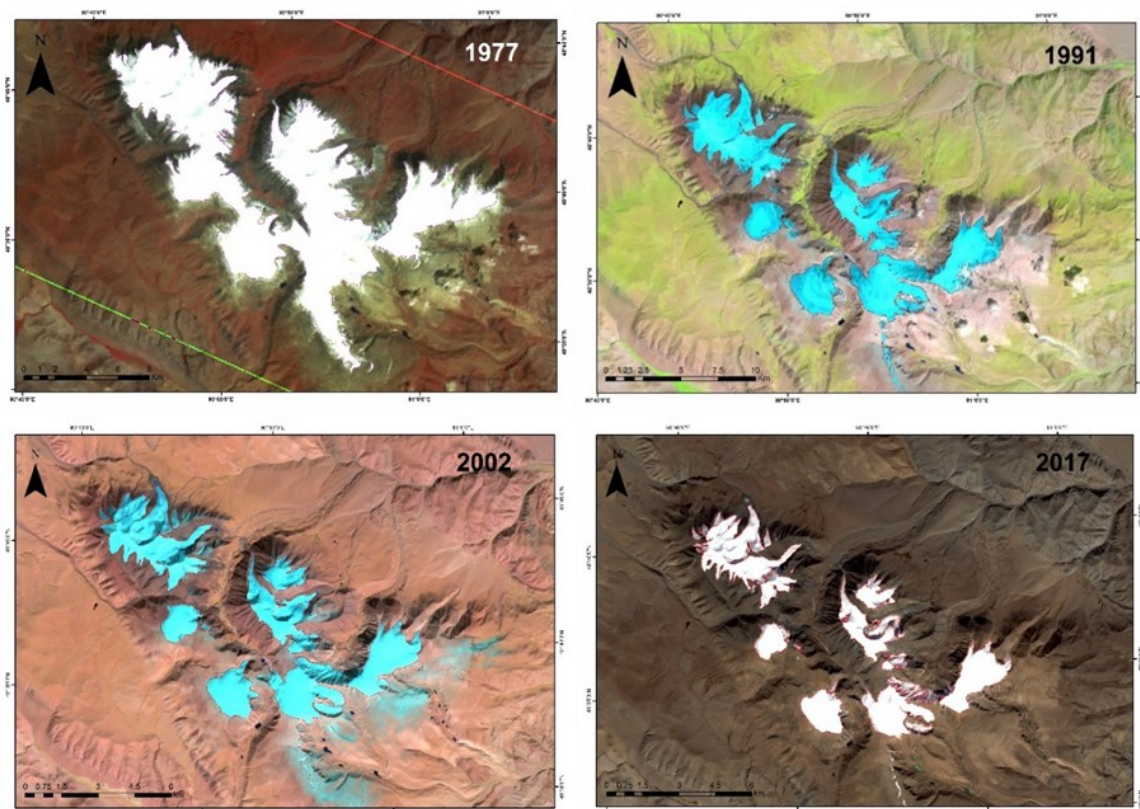
The modern glacier extents in Mt. Tsambagarav are spatially estimated in 1977, 1991, 2002 and 2017 using Landsat, NDSI and NDPCSI. The result shows instructive difference between the two indexes. NDSI indicates the glaciated areas more in detail than other landforms. However, for specters, the NDSI is not good at recognizing high resolution of shallow water body and differentiating the glaciers from other objects. Whereas NDPCSI shows the glaciated areas directly without any requirement of additional steps to remove areas of lakes and rivers (Fig. 3), i.e., it is much efficient to

compile the glaciated areas based on Landsat imagery data.

Area of the modern glacier in Mt. Tsambagarav decreased from 132.24 km<sup>2</sup> in 1977 to 8.473 km<sup>2</sup> in 1991, 72.04 km<sup>2</sup> in 2002 and 63.92 km<sup>2</sup> in 2017 (Tables 1, 2; Figs. 4, 5). The area of the modern glacier in Mt. Tsambagarav was lost by 35.9% (47.51 km<sup>2</sup>) between 1977 and 1991, 9.7% (12.69 km<sup>2</sup>) between 1991 and 2002, and 6.1% (8.12 km<sup>2</sup>) between 2002 and 2017 (Table 1). In total, the modern glacier area has been lost by 51.7% (68.32 km<sup>2</sup>) during the last 40 years from 1977 to 2017 (Table 1; Fig. 5).

### DISCUSSIONS

The changes in the spatial distribution of the modern glacier in Mt. Tsambagarav during the last four decades indicate the alpine glaciers advanced in the past and rapid retreats of the modern glaciers in the last half-century (Fig. 5). The area of the modern glacier in Mt. Tsambagarav has significantly decreased over the last seven decades (Table 2). Our result is comparable to other works in Mt. Tsambagarav



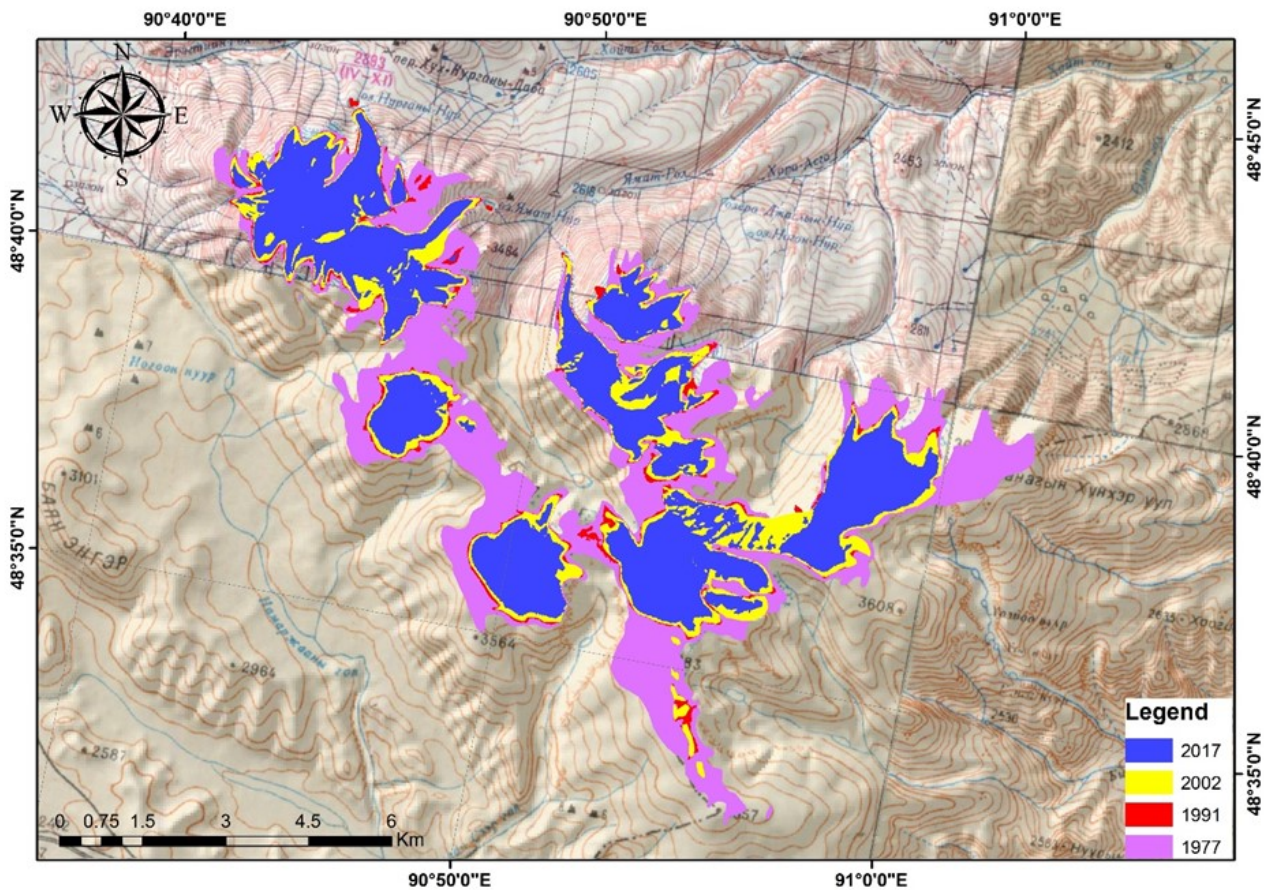
**Fig. 4.** Spatial distribution of modern glaciers in Mt. Tsambagarav in 1977, 1991, 2002 and 2017.

(Table 2) and it is relatively consistent with those estimated by Erdenetuya et al. (2006) and Kadota and Davaa (2007). For instance, the glacier area of 71.52 km<sup>2</sup> in 2002 estimated by Erdenetuya et al. (2006) was quite close to our result in the year, although the authors used different Landsat imagery data (Table 2). These studies in 1991 and 1992 used Landsat 5

imagery data, however there was a gap between the estimations (Table 2). The continuous trend in decrease of the modern glacier area in Mt. Tsambagarav may have been impacted by climate change with rising temperature and falling precipitation. In Mongolia, average air temperature has risen by 2.24°C, while average precipitation has dropped by 7.3% over the last 70 years since 1940s (Batima et al., 2005). The climate change in Mongolia has been reflected in increase of mean annual air and soil temperatures, decline in duration of rainfall, rapid melting of glaciers and permafrost, and strengthening evaporation and desertification. The spatial analysis of the modern glacier in Mt. Tsambagarav coincides with that resulted from other high mountains in the Mongolian Altai Mountain Range. Recent studies (e.g., Kamp et al., 2013) show that current climate change takes a pronounced effect on present-day glaciers in Mongolia. For example, in the northeastern part

**Table 1.** Decreased area of the modern glacier in Mt. Tsambagarav.

No	Year	Duration (yr)	Loss of glacier area (km <sup>2</sup> )	Per-cent
1	1977-1991	14	47.51	35.9
2	1991-2002	11	12.69	9.7
3	2002-2017	15	8.12	6.1
	1977-2017	40	68.32	51.7



**Fig. 5.** Changes in extended area of the modern glacier in Mt. Tsambagarav in 1977-2017.

**Table 2.** Changes in area of the modern glacier in Mt. Tsambagarav over the last seven decades

Data source	Year	Area (km <sup>2</sup> )	References
Topo map	1940	105.09	Erdenetuya et al., 2006
Landsat 1	1977	132.24	This study
Landsat 5	1991	84.73	This study
Landsat 5	1992	90.98	Erdenetuya et al., 2006
Landsat 7	2000	74.08	Erdenetuya et al., 2006
Landsat 7	2000	74.08	Kadota and Davaa, 2007
Landsat 7	2002	71.52	Erdenetuya et al., 2006
Landsat 5	2002	72.04	This study
Landsat 8	2017	63.92	This study

of the Mongolian Altai, Lehmkuhl (2012) identified glacier retreat by 75-79 m for toe-to-summit of snowline altitudes between the Little Ice Age (LIA) limits and positions in 1948 and 1991. Moreover, the modern glaciers in the Mongolian Altai as a whole have shrunk in size by 22% during the past 50-60 years (Davaa, 2010).

Furthermore, Lehmkuhl et al. (2004) reconstructed the Equilibrium Line Altitudes (ELAs) located at around 3000 m a.s.l. in the northeastern and 3700 m a.s.l. in the southeastern mountains in the Mongolian Altai. Orkhonselenge and Harbor (2018) noted that Mt. Ikh Turgen in the Mongolian Altai lost 45.6% of its total glacier area between 1970 (41.4 km<sup>2</sup>) and 2011 (18.9 km<sup>2</sup>) and the ELA of the glaciers retreated in elevation by 98 m on north and 144 m on south aspects. This study in Mt. Tsambagarav demonstrates the trend in decrease in area of the modern glaciers in the Mongolian Altai Mountain Range.

### CONCLUSIONS

The area of the modern glacier in Mt. Tsambagarav in the Mongolian Altai Mountain Range in western Mongolia is reviewed in 1977, 1991, 2002 and 2017 using NDSI, NDPCSI and Landsat data. During the last 40 years the Mt. Tsambagarav has lost about ~52% of its modern glacier. The continuous trend in decrease of the modern glacier in Mt. Tsambagarav over the last seven decades coincided with those resulted from high mountains in the Mongolian Altai, which may have been related to impact of global

warming. For further estimation of the impact of climate change on the modern glaciers, detailed field survey and geochronological analysis are required to check the spatial analysis presented in this study. Such work allows us to gain the complete understanding of response of the modern glacier in the high mountains of Mongolia to the climate and other controlling drivers.

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