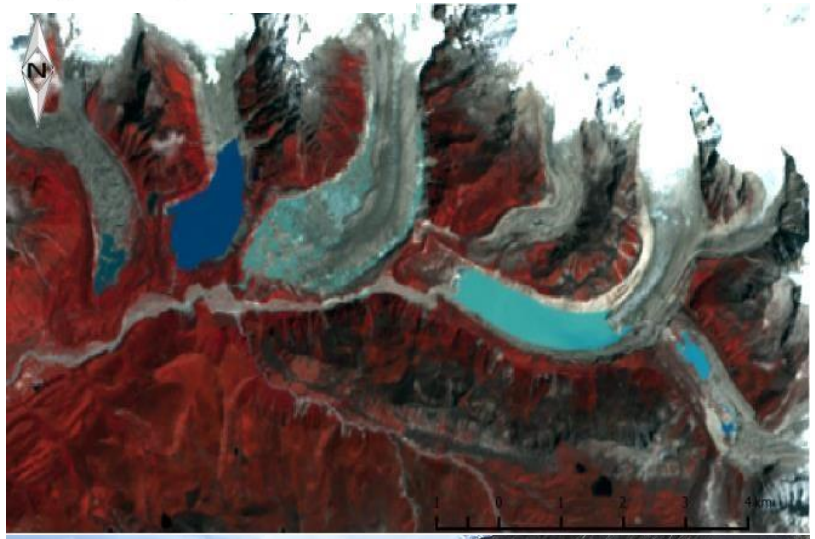
International Conference on Challenges of the Anthropocene (ICCA), 10-12 May 2017



Title: Satellite sensing of Luggye glacier mass balance since 2001 and variations of Luggye glacial lake over the past four decades in Bhutan Himalayas

Authors: Sonam Wangchuk & Jaroslaw Zawadzki
Warsaw University of Technology, Poland

Presenter: Sonam Wangchuk
Email: somwangchotc9091@gmail.com/sonam.wangchuk@bt.bt
Contact: +975 1777 29 22

OUTLINE

- ✓Introduction
- ✓Study area
- ✓Data and methods
- ✓Results and discussions
- ✓Conclusions

Introduction

- 885 glaciers, total area ~ 642±16.1 km^2 (Bajracharya, Maharjan, & Shrestha, 2014).
- Loss of glacier area is greater for clean-ice glaciers (Bajracharya et al., 2014; Veettil et al., 2015).
- Increase in the debris-covered area, formation and expansion of glacial lake is higher on the southern side of Bhutan Himalaya (Veettil et al., 2015).
- The formation of supraglacial lakes on debris-covered glaciers is restricted on the gradients of glacier less than 2^0 (Reynolds, 2000).
- Three types of glacial lakes in Bhutan Himalayas: I. supraglacial lakes. II. Moraine dammed glacial lakes/proglacial lakes/ice-proximal or ice-contact lakes. III. Unconnected lakes.

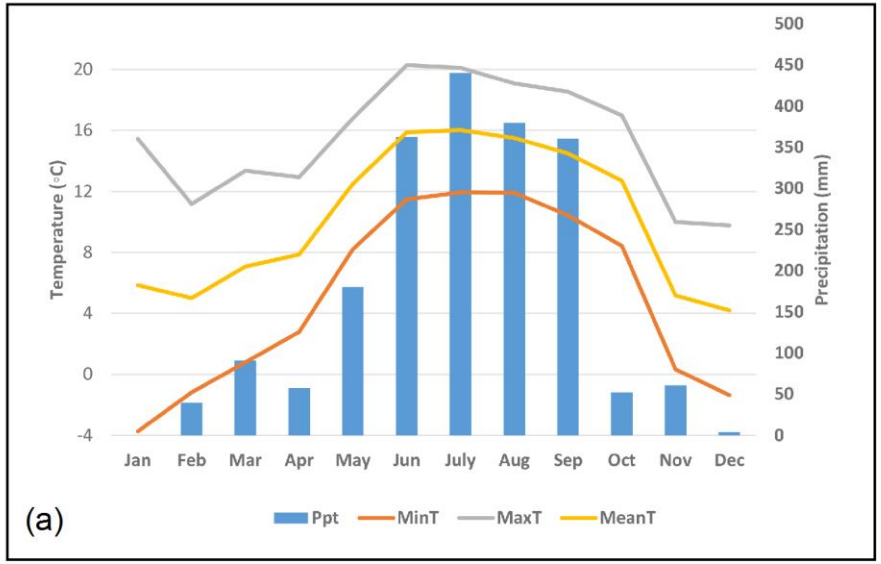
Introduction

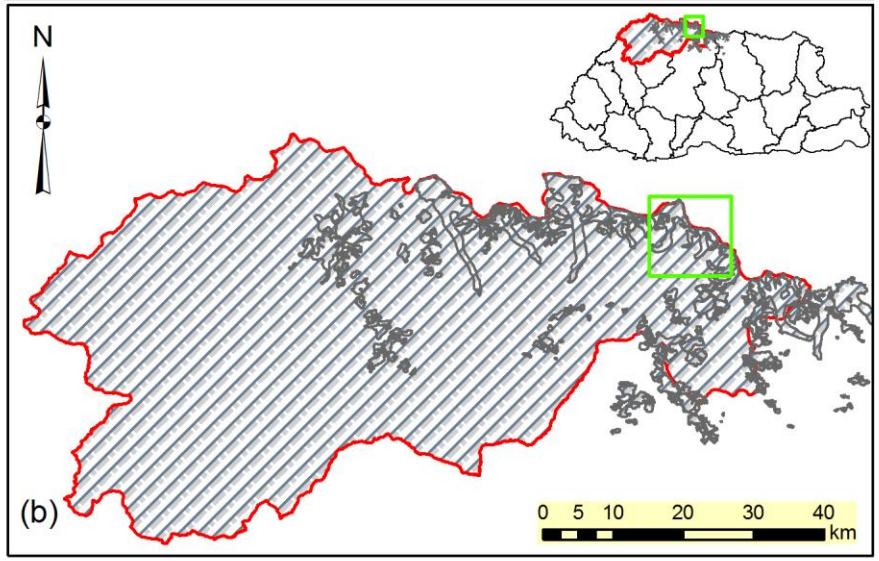
- Luggye glacial lake is a moraine-dammed glacial lake and is one of the PDGLs (Mool et al., 2001).
- Initially developed as supraglacial ponds on the surface of Luggye glacier in 1960s.
- Previous catastrophic record of outburst-October 7, 1994 (Ageta et al., 2000; Mool et al., 2001; Komori et al., 2012).
- GLOF volume-17.2±5.3 $x10^6$ m^3 (Fujita et al., 2008; Fujita et al., 2013).
- Steep lakefront area (SLA)-0.029 km^2, potential flood volume (PFV)-14.9 $x10^6$ m^3 (Fujita et al., 2013).

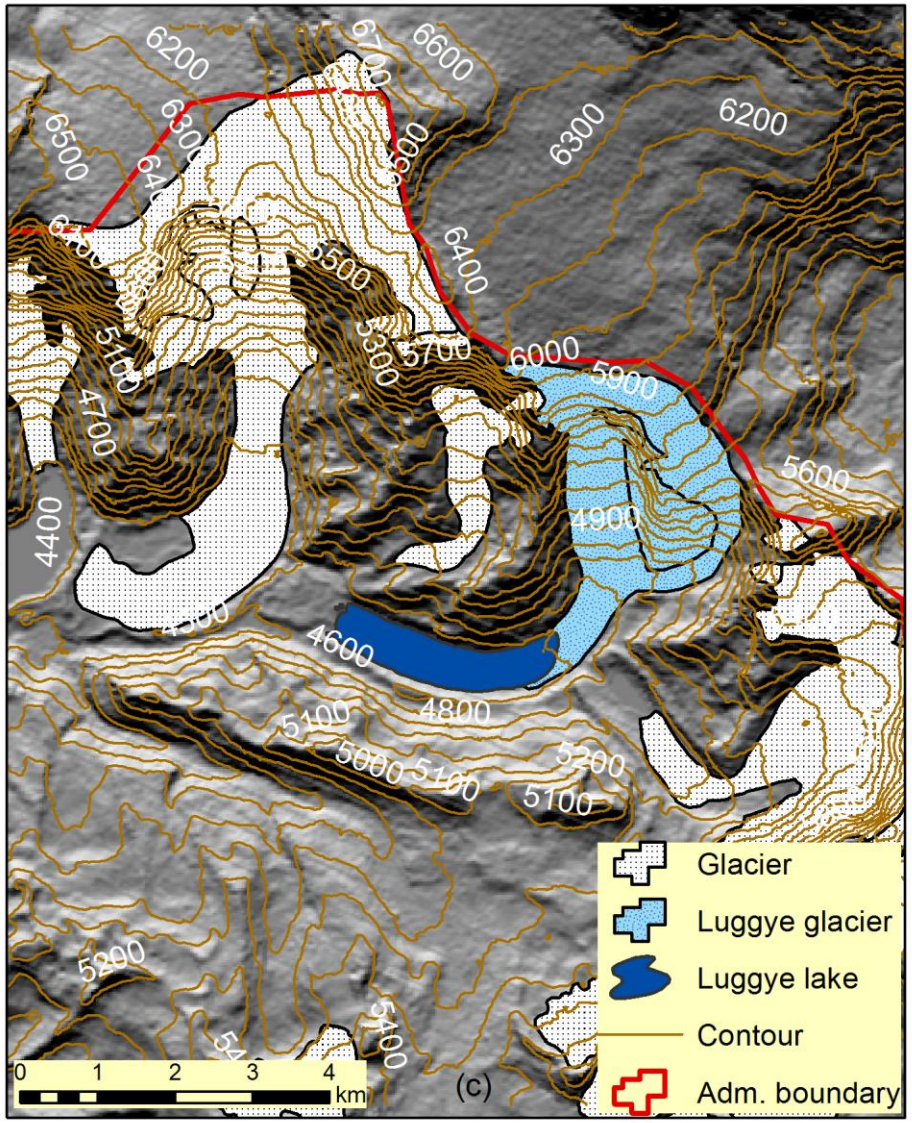
Introduction

- In this paper, we report in detail changes of Luggye glacier and glacial lake between 1972 and 2015 using Landsat satellite observations.
- Secondly, we present in-depth inter-annual variations of Luggye glacial lake and Luggye glacial terminus since meteorological data are available (i.e. 2006-2014).
- Thirdly, we determine elevation and mass changes of Luggye glacier since 2001 using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEMs.
- Fourthly, we discuss both the potential factors controlling the rapid expansion of Luggye glacial lake and likely future transformation of Luggye glacial lake.

Study area



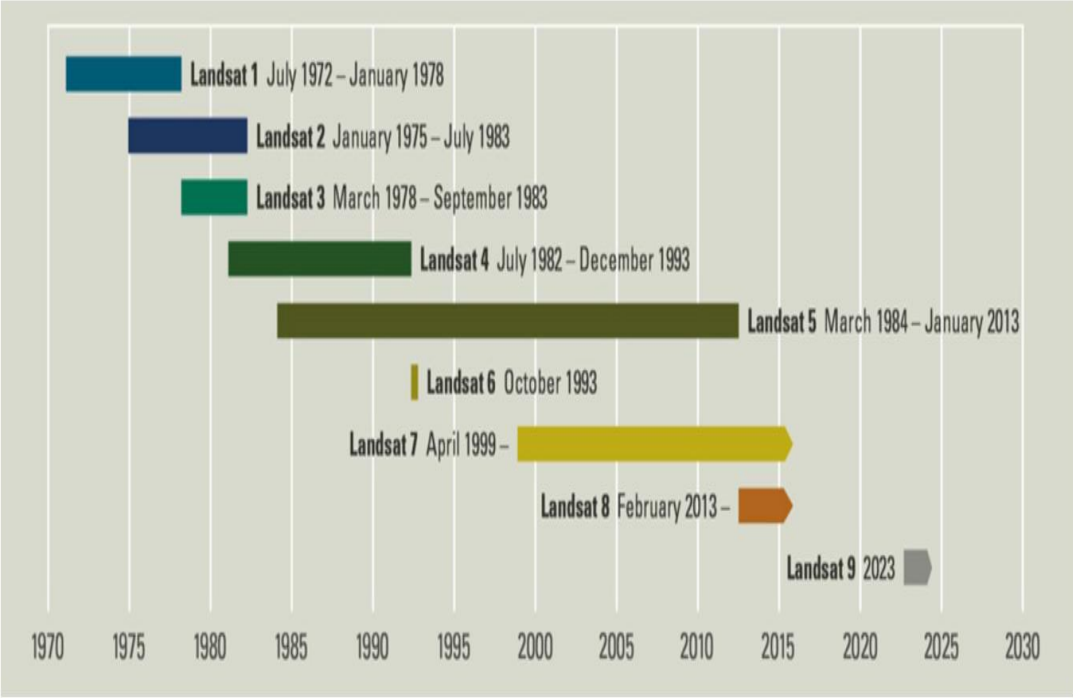




- The study area is Lunana, located in northern part of Bhutan Himalayas.
- Numerous sizes and types of glaciers and glacial lakes are present there.
- In particular, Luggye glacial lake is located at 28^0 05' 33.5" N, 90^0 17' 53.5" E in Pho Chu sub-basin.
- It is one of the main glacial lakes directly feeding Punatshang Chhu river.
- Luggye glacier is associated with both clean and debris-covered glacier, it has a direct contact with Luggye glacial lake.

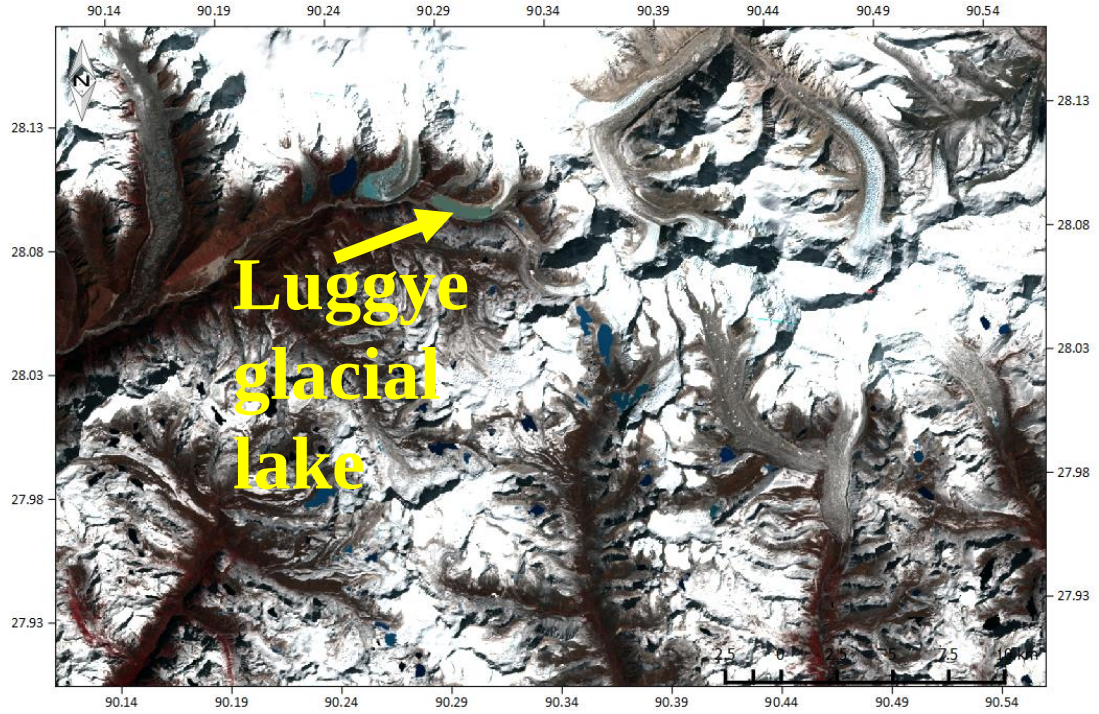
Data

- Landsat data were imported from USGS archive (http://earthexplorer.usgs.gov/).



Timeline series of Landsat missions

- ASTER data were accessed from https://reverb.echo.nasa.gov/reverb/



Landsat-5 TM (RGB: 4, 3, 2 bands) taken on 2011-11-08.

Blue features in the image are glacial lakes

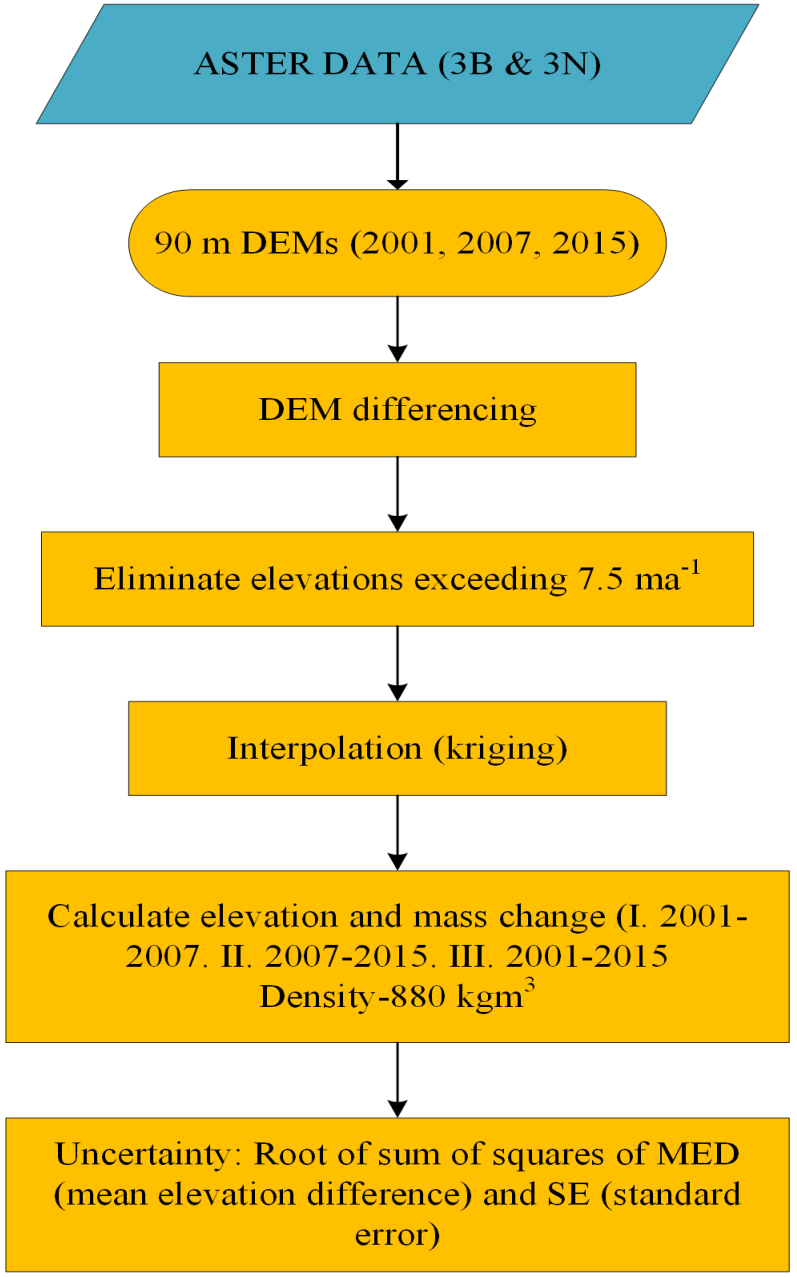
Data

- Landsat Level-1T data products are radiometrically and geometrically terrain corrected data.
- It acquires images of the Earth surface at **30 m** spatial resolution.
- ASTER has four visible/near-infrared bands (VNIR) each having **15 m** resolution.
- Additionally, it has a nadir band (3N) and backward-looking band (3B) with a stereoscopic capabilities for generating DEM.
- Climate data (2006-2014) around the study region was provided by the Department of Hydro-Met Services, Ministry of Economic Affairs, Thimphu, Bhutan.

Methods: Mapping of clean-ice glacier, debris-covered glacier, and lake area

I. Band Ratio: Band 4/Band 5 for TM, Band 5/Band 6 (OLI)-mapping of clean-ice glacier.
II. Band Ratio: Band 6/ (band 4/band 5) for TM; Thermal band 1or 2/ (band 5/band 6) for OLI-mapping of debris-covered glacier.
III. Normalized Difference Water Index (NDWI): (Band 4 - Band 2) / (Band 4 + Band 2)-mapping of lake water.
IV. Manual digitization for area and perimeter in GIS software.
V. Uncertainty estimations.

Methods: Glacier elevation change and mass balance



Methods: Glacier elevation change and mass balance

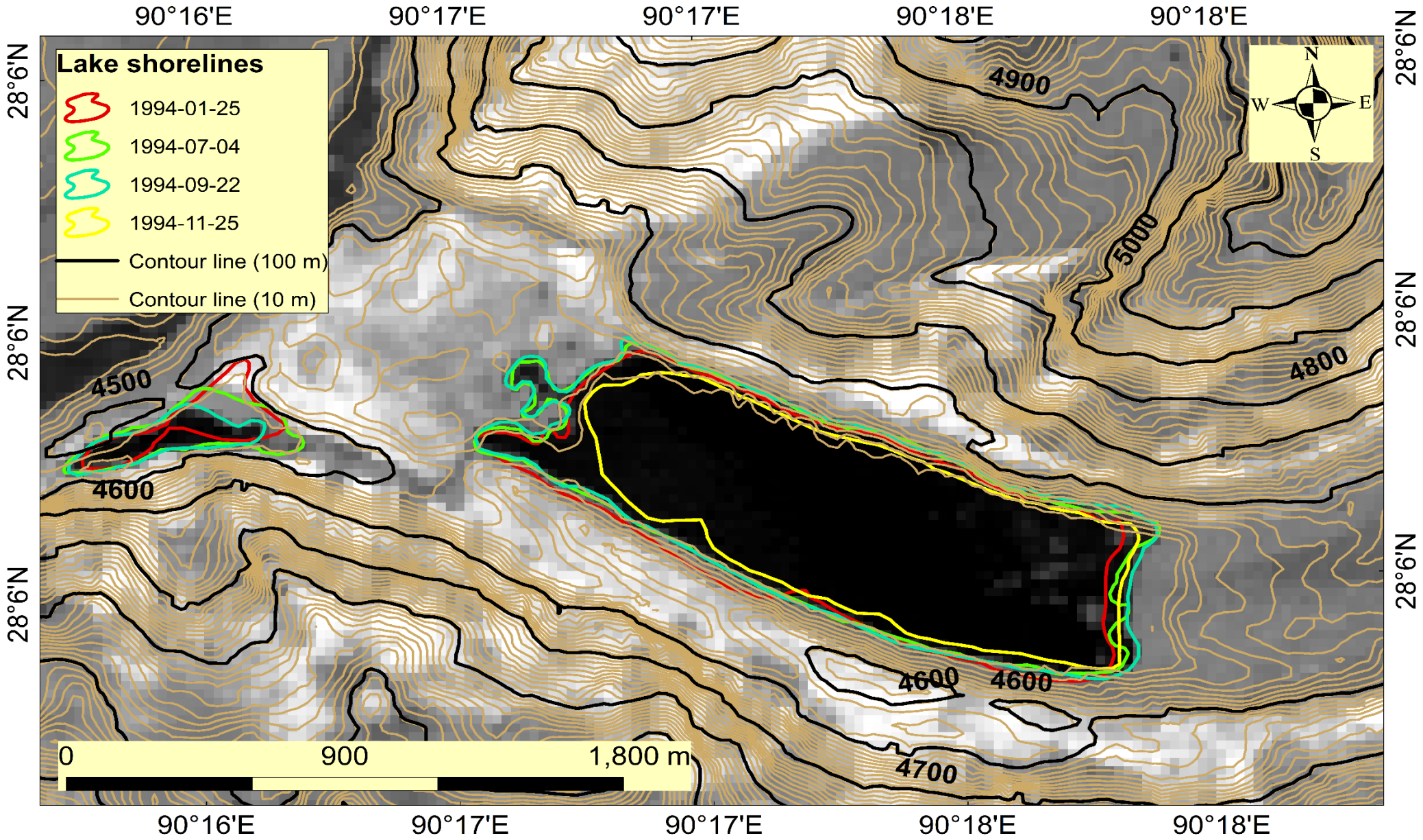
- Prepared 90m resolution ASTER DEMs for the year 2001, 2007 and 2015 respectively using ENVI DEM extraction module.
- DEM differencing method (Bolch et al., 2011; Thakuri et al., 2016) was used to compute the glacier elevation change.
- Elevation difference greater than 7.5ma^{-1} was considered as possible outliers (Nuth & Kääb, 2011; Nuimura et al., 2012) and hence eliminated from the data.
- The remaining data gaps were interpolated by kriging.
- Calculated elevation and mass change for three temporal periods: I. 2001-2007. II. 2007-2015. III. 2001-2015.
- For the mass balance estimation, a density of 880 kgm^{3} was assumed.
- Uncertainty-root of sum of squares of MED (mean elevation difference) and SE (standard error) (Bolch et al., 2011).

Results and Discussions

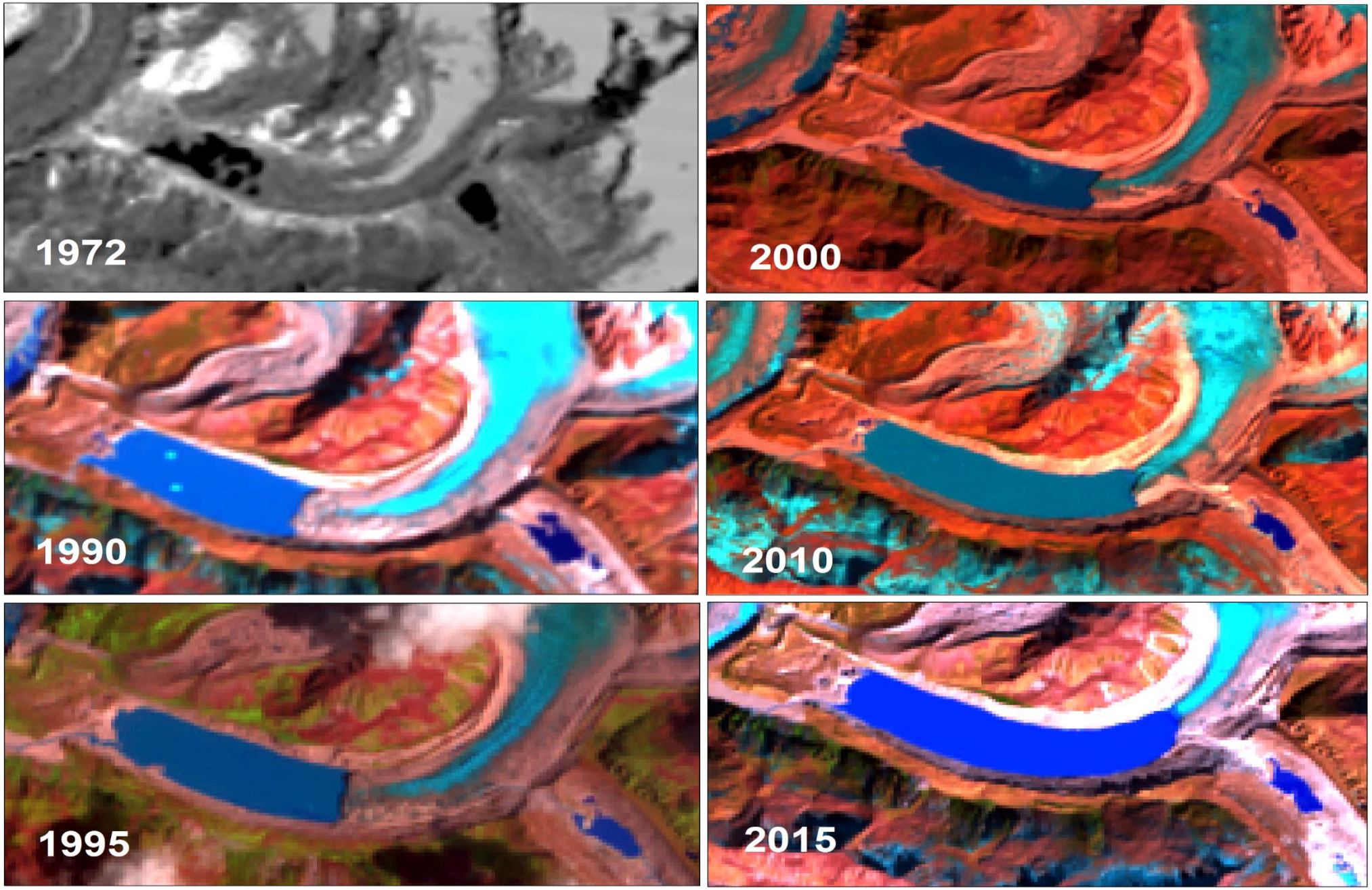
I. Lake surface area

- ✓The lake has continuously grown and reached maximum area of **1.31 ± 0.12 km^2** in September 22, 1994.
- ✓The lake area shark by **17.5 %** (0.974 ± 0.07 km^2) after the catastrophic outburst in October 7, 1994.
- ✓Analysis of satellite data indicated that the lake has attended the area of **1.58±0.11 km^2**. It is a **62.21 %** increase in area since outburst in 1994.
- ✓Between 1972 and 2015, the surface area of lake has increased by 1.18±0.19 km^2 **(229.07%)** and expanded at the mean rate of **0.03±0.005 km^{2}a^{-1}**.
- ✓ Recent period (2010-2015) showed **highest expansion rate (0.05 km^{2}a^{-1})** compared to other periods. Furthermore, a major expansion has occurred between 2007 and 2008 with the expansion rate of **0.11 km^{2}a^{-1}**.

Variations of Luggye lake in 1994

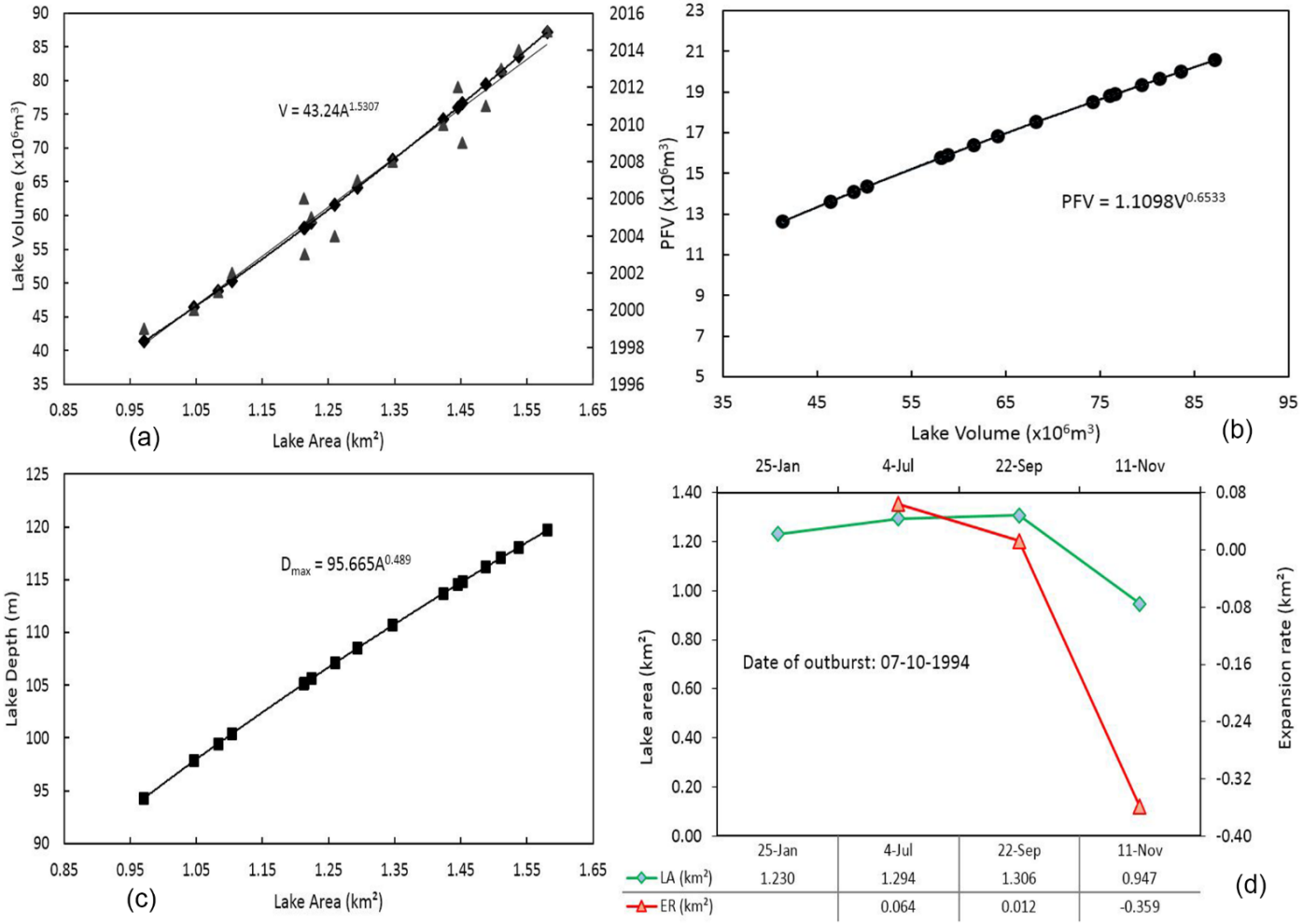


Areal evolution of Luggye lake



II. Lake volume

✓ The volume of the lake has increased from 39.78x10^6 m^3 to 87.17x10^6 m^3 between 1994 and 2015.



✓It is a **twofold increase in volume** of the lake since 1994 outburst.

✓The latest PFV expected is **20.55x10^6 m^3** in case of outburst

✓The PFV can be calculated by the relation ***PFV=1.1098V$^{0.6533}$***, if volume of a lake is known.

✓The relationship indicated that areal increase of lake corresponds to increase in the volume of the lake, lake depth, and PFV respectively.

III. Variations of glacier terminus

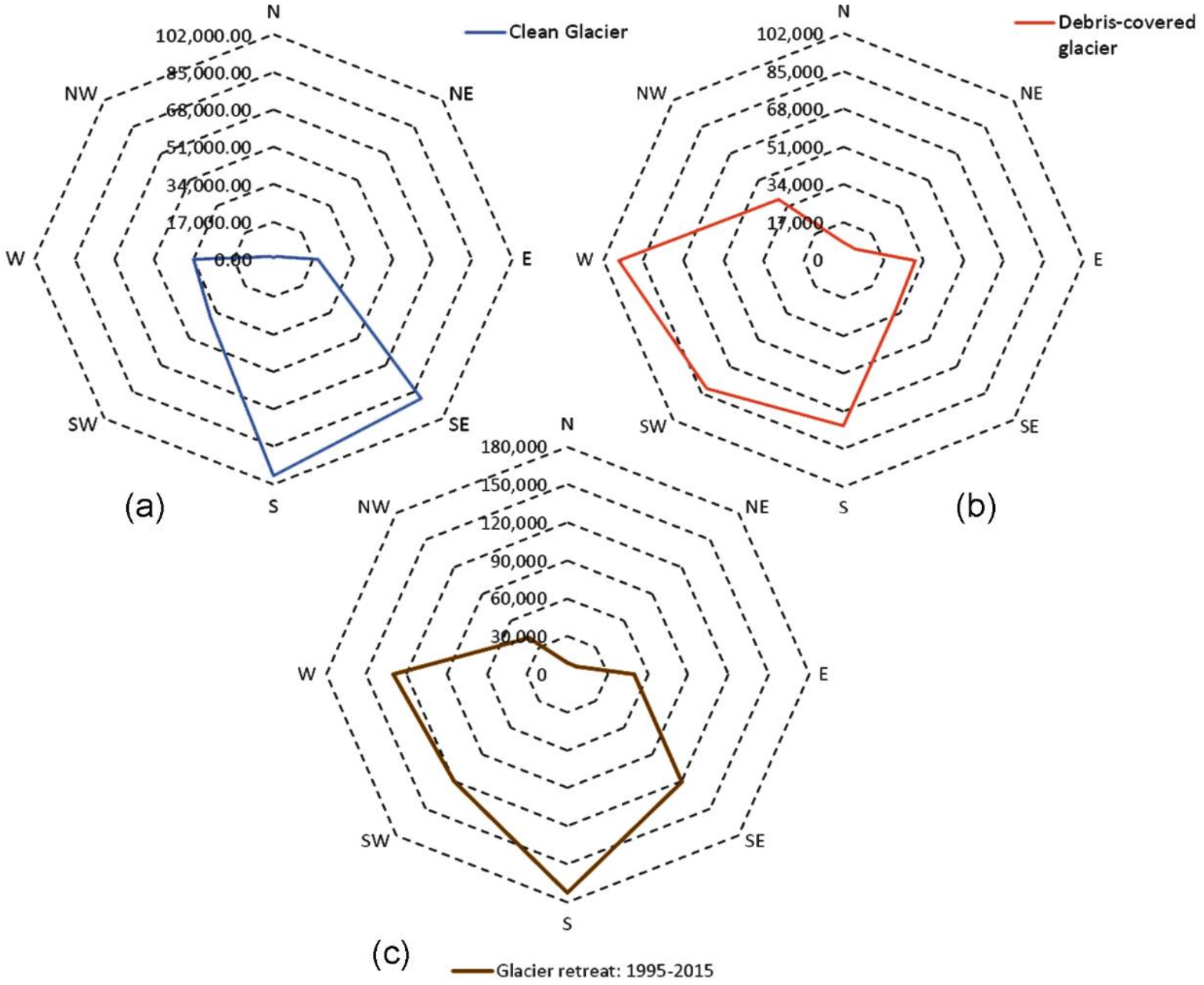
Period	Terminus retreat (m)	Retreat rate (ma^{-1})
1972-1976	-91.493±84.852	-22.873
1976-1987	-446.766±67.082	-40.615
1987-1990	-189.471±42.426	-63.157
1990-1995	-259.500±42.426	-51.900
1995-2000	-156.913±42.426	-31.383
2000-2005	-232.987±42.426	-46.597
2005-2010	-295.727±42.426	-59.145
2010-2015	-215.959±42.426	-43.192

- ✓ Total terminus retreated length:**1888.8 m**.
- ✓ Average rate per year: **43.93 ma^{-1}**.

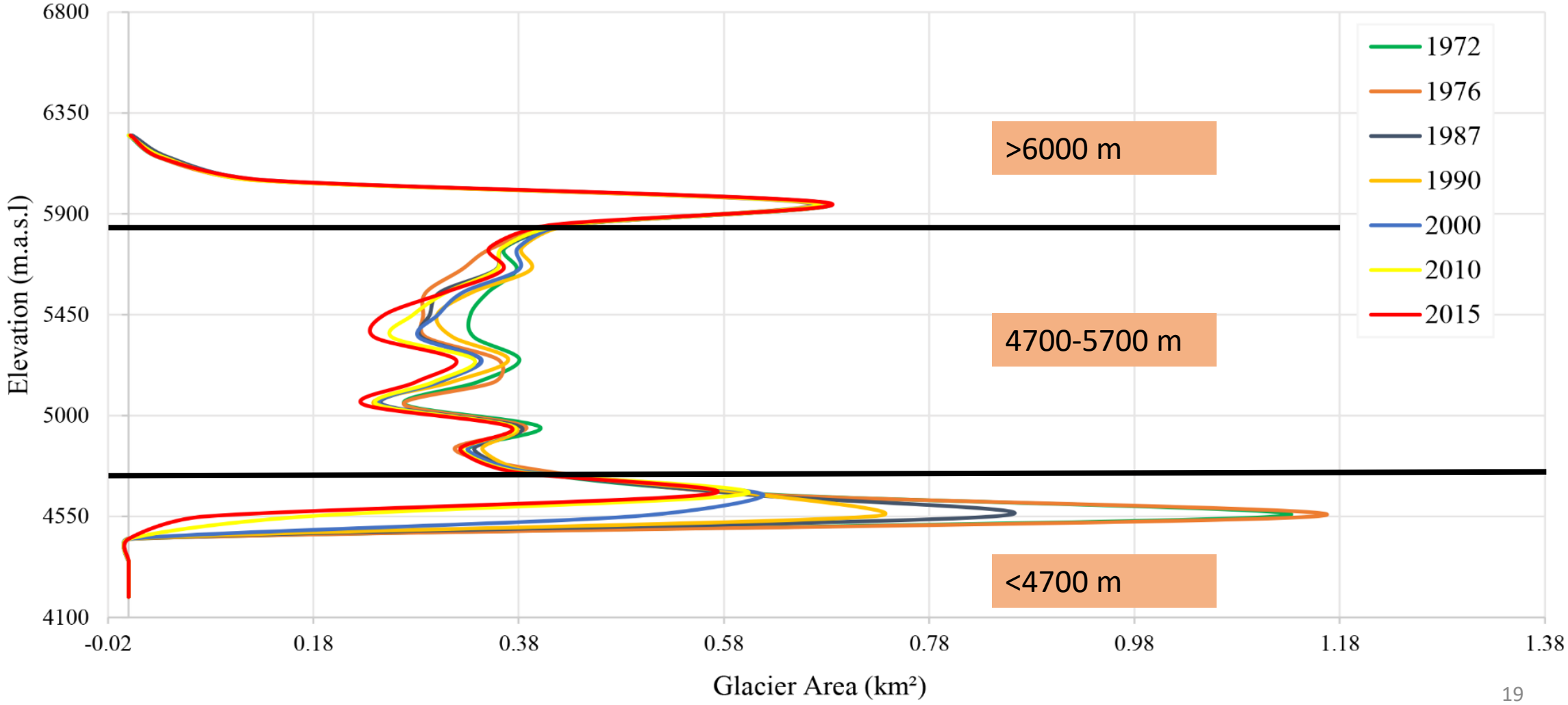
IV. Variations of glacier area (1972-2015)

- ✓The area of clean glacier has decreased by **19.69%** (-0.95 km^2) at the average rate of 0.02 km^2a^{-1} (0.46 $\%a^{-1}$).
- ✓The maximum retreating rate (2.12 $\%a^{-1}$) was observed between 1972 and 1976.
- ✓The recent (2010-2015) retreating rate is 0.44 $\%a^{-1}$.
- ✓Debris-covered glacier area has decreased by **14.12%** at the rate of -0.33 $\%a^{-1}$.

Area loss versus aspect



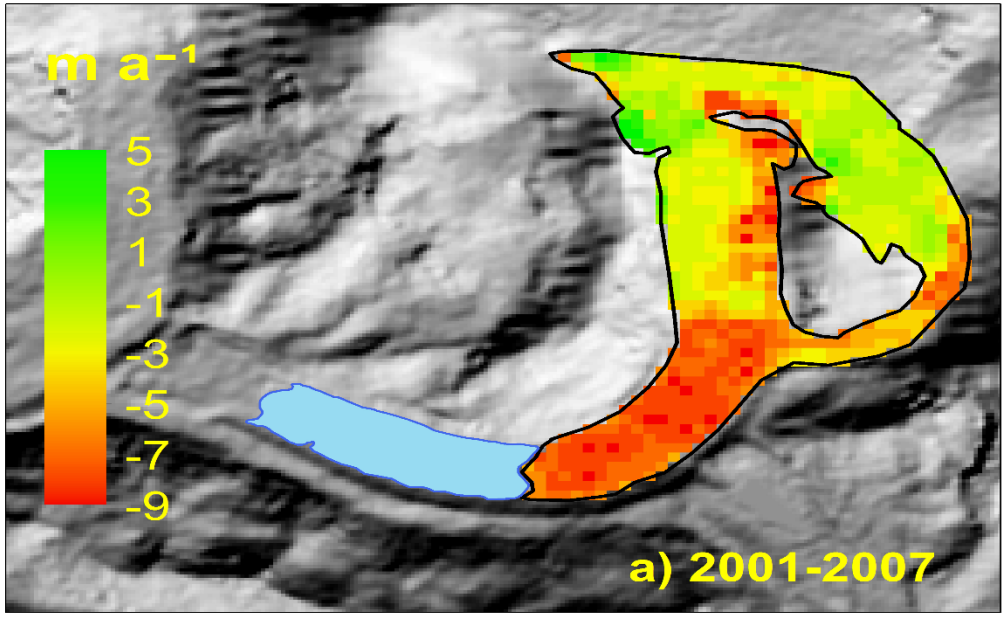
Hypsographic curve of variations of Luggye glacier area (1972-2015)

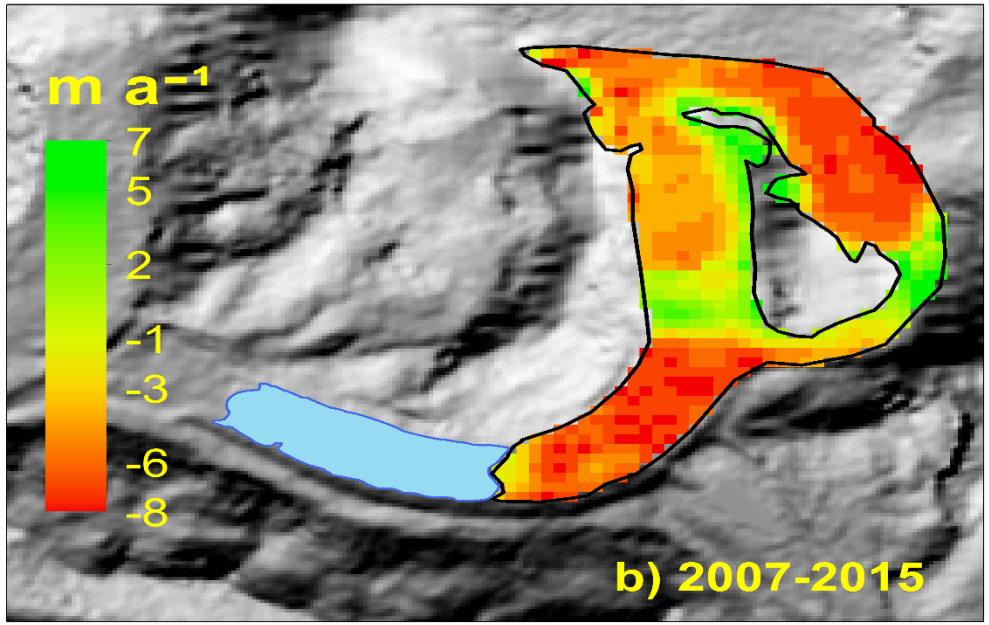


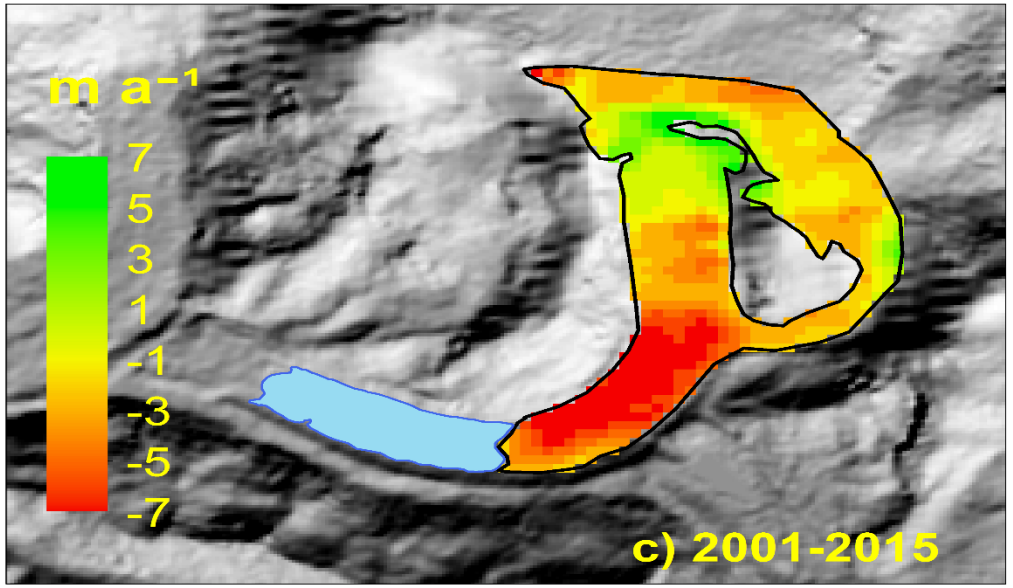
V. Glacier elevation and mass balance change (2001-2015)

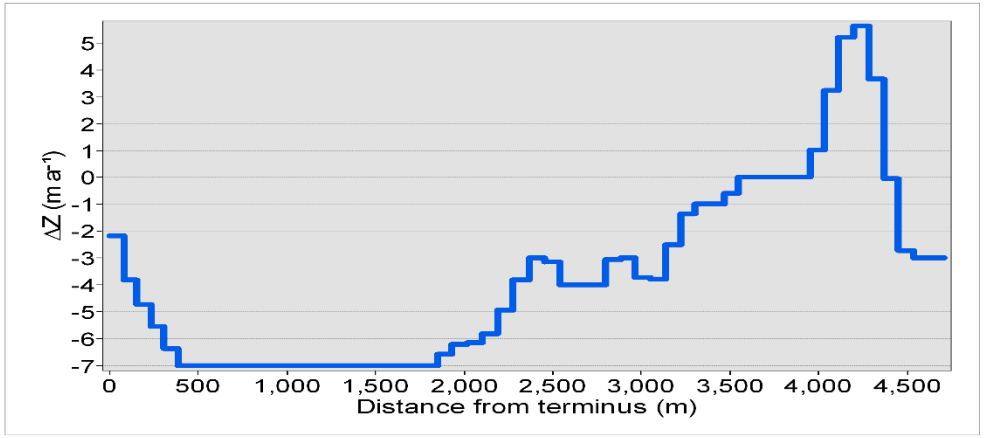
Period	Downwasting rate (ma^{-1})	Specific mass balance ($mw.e.a^{-1}$)
2001-2007	3.54±2.63	2.54±2.59
2007-2015	3.37±2.28	2.80±2.25
2001-2015	2.81±1.97	2.17±1.96

Glacier elevation change of Luggye glacier

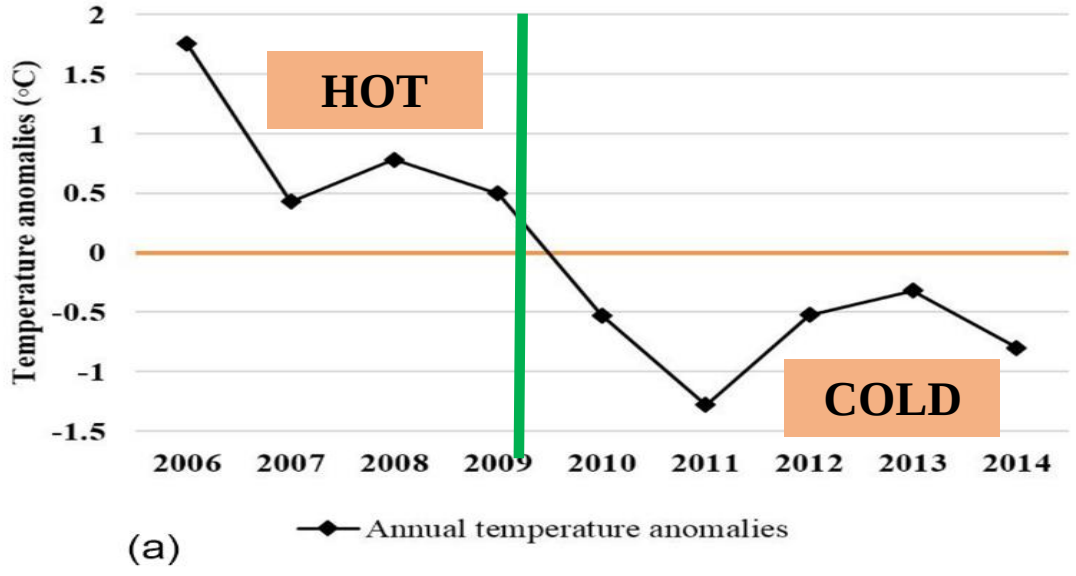


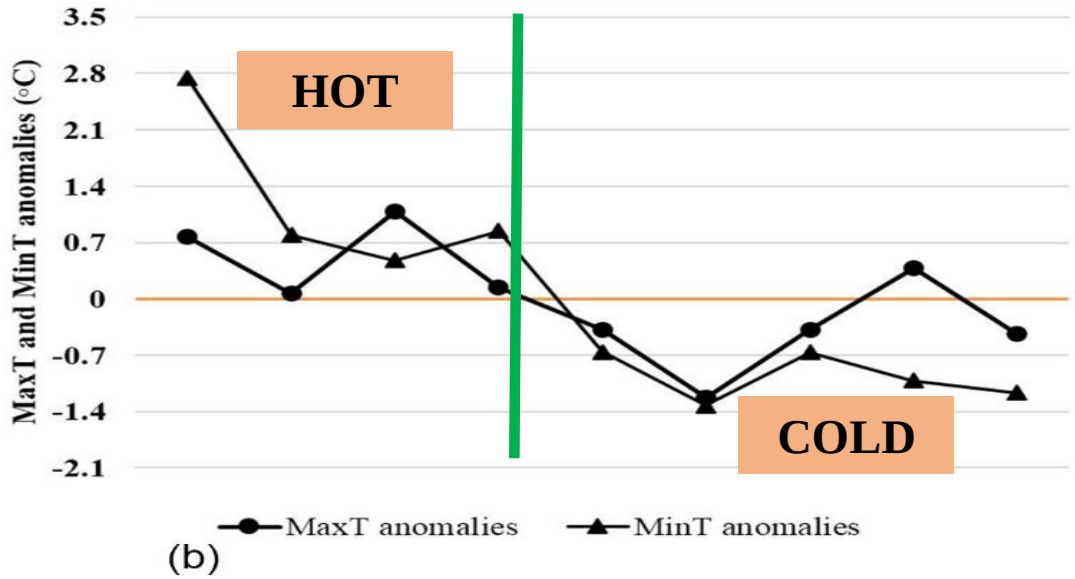


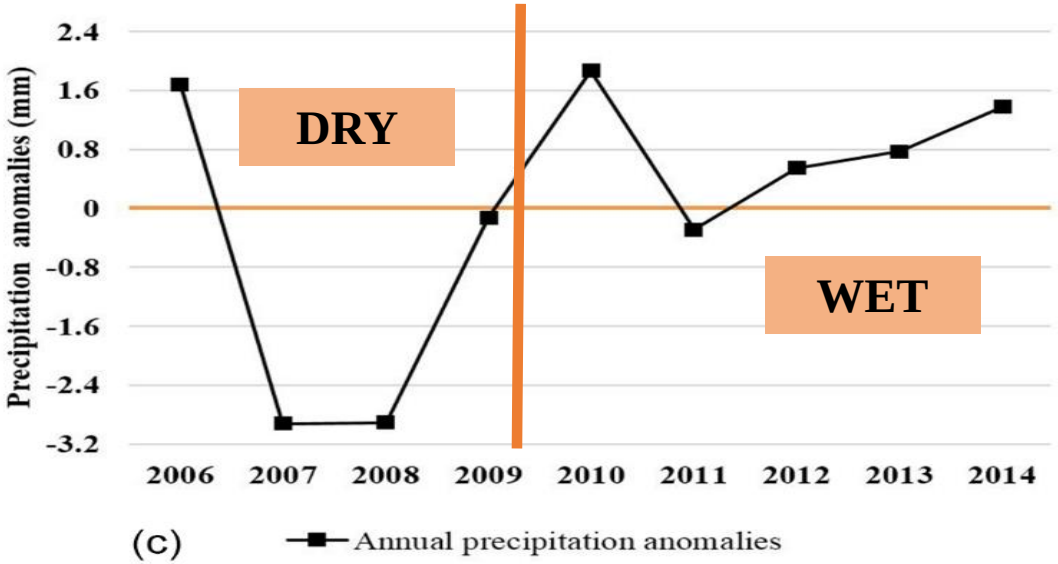


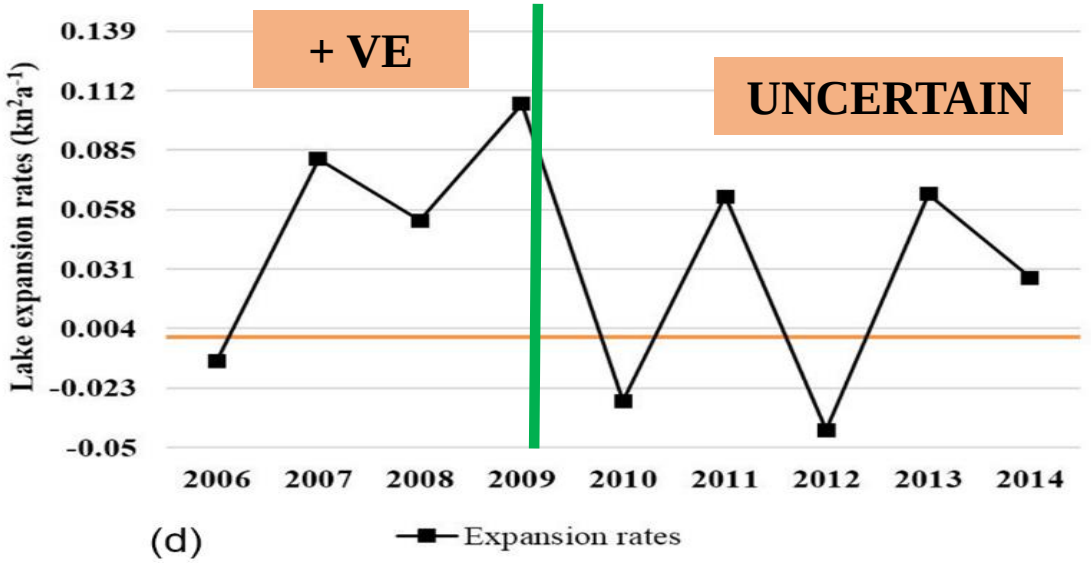


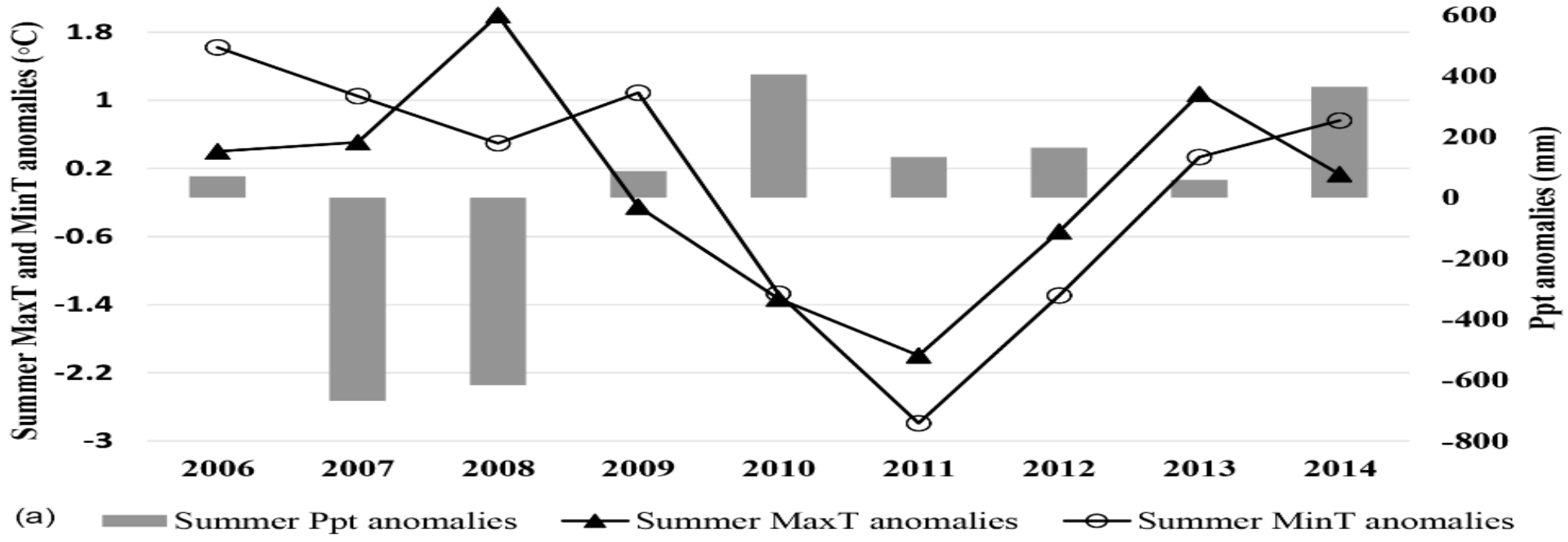
VI. Changes in annual precipitation and temperature trends as potential driving factor for rapid lake growth

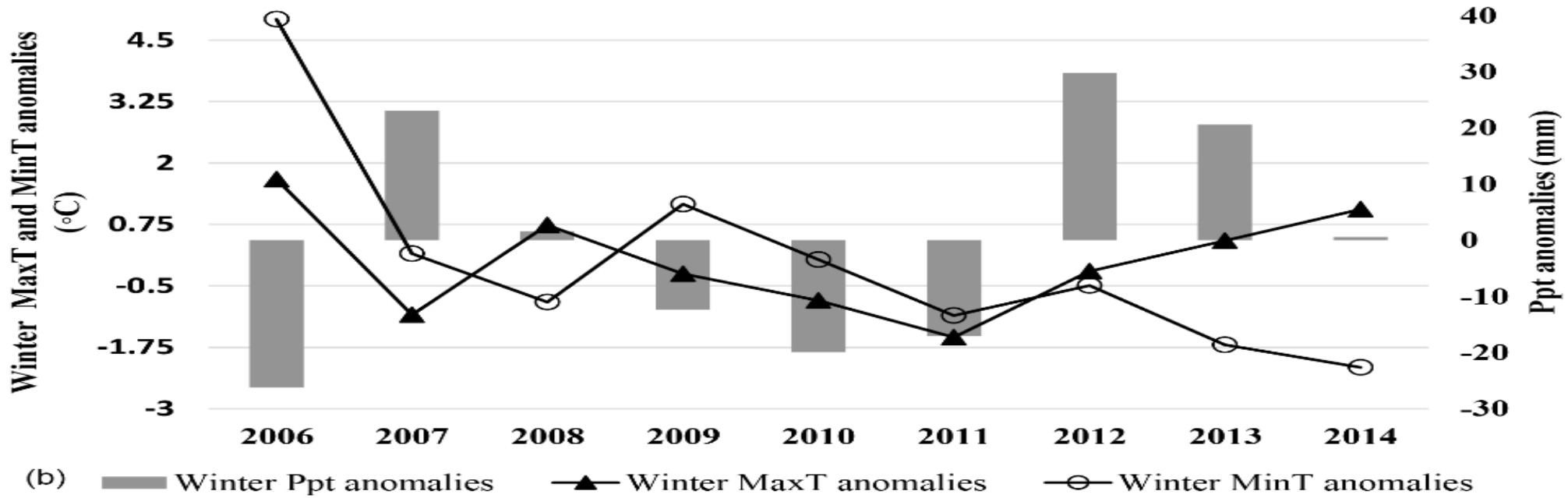




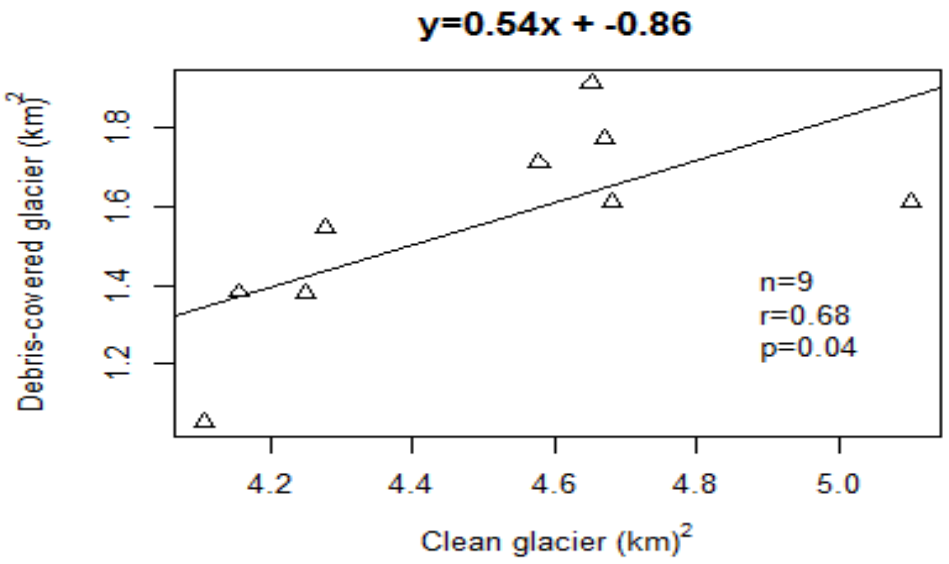


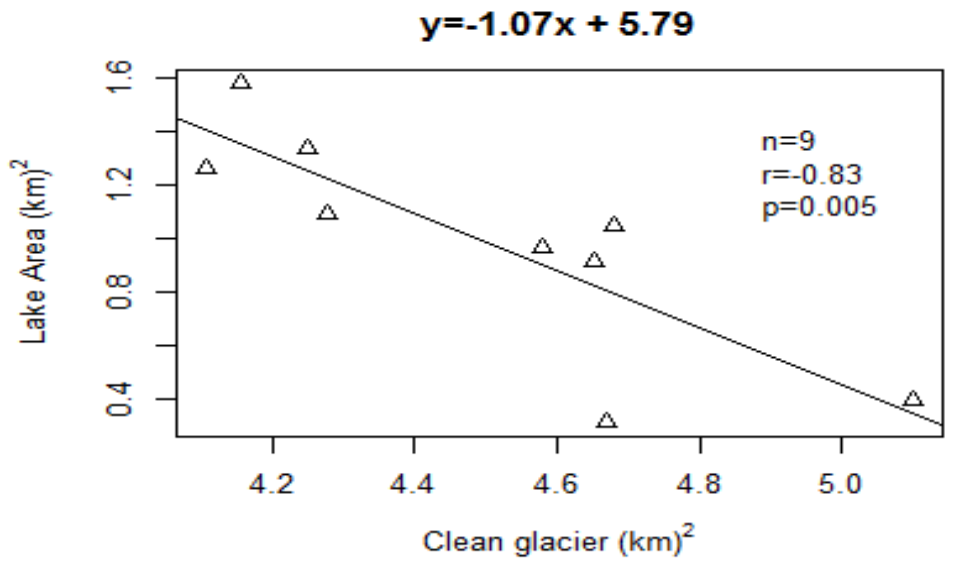


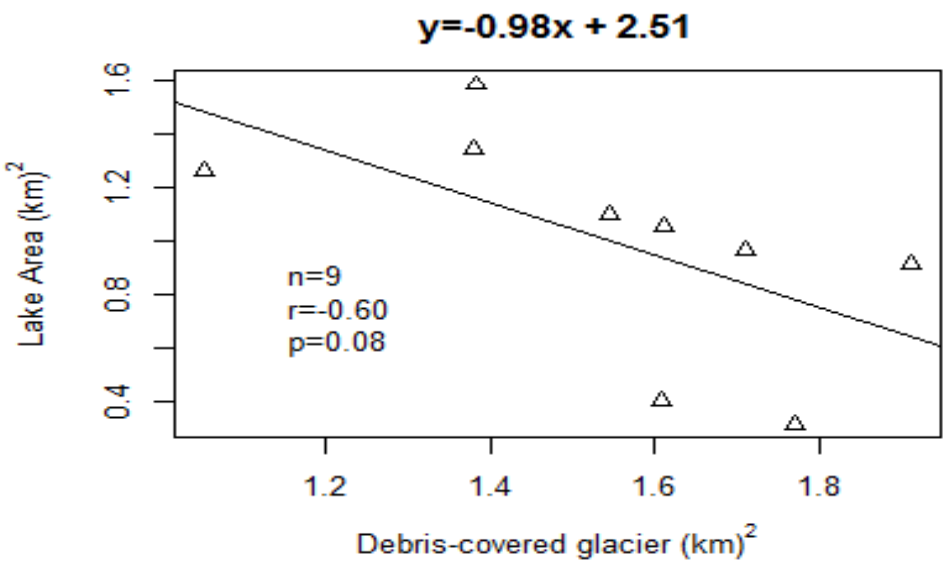

Summer MaxT and MinT anomalies (°C)
1.8
1
0.2
-0.6
-1.4
-2.2
-3
600
400
200
0
-200
-400
-600
-800
Ppt anomalies (mm)
2006
2007
2008
2009
2010
2011
2012
2013
2014
(a)
Summer Ppt anomalies
Summer MaxT anomalies
Summer MinT anomalies

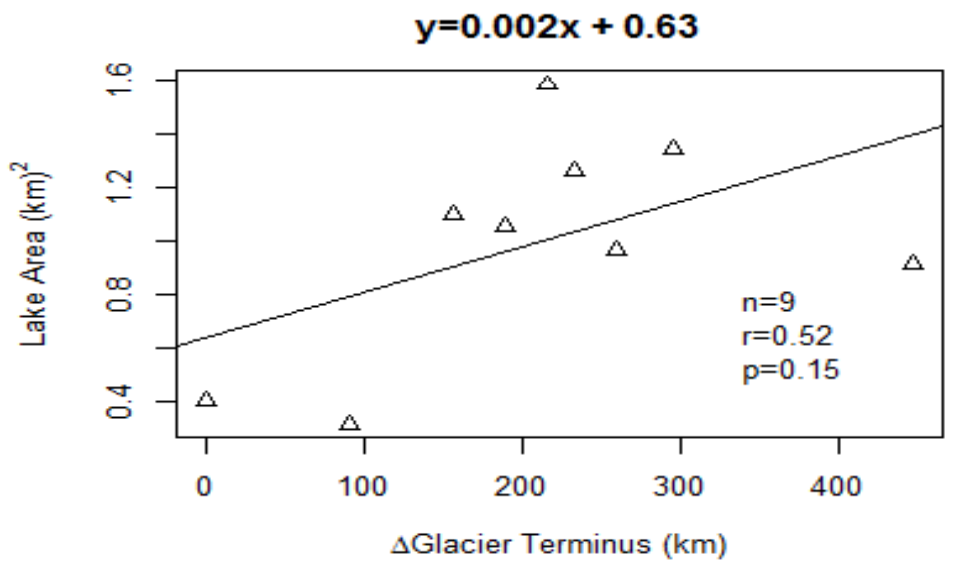

Winter MaxT and MinT anomalies (°C)
4.5
3.25
2
0.75
-0.5
-1.75
-3
40
30
20
10
0
-10
-20
-30
Ppt anomalies (mm)
2006
2007
2008
2009
2010
2011
2012
2013
2014
(b)
Winter Ppt anomalies
Winter MaxT anomalies
Winter MinT anomalies

VII. Correlation between glacier variables

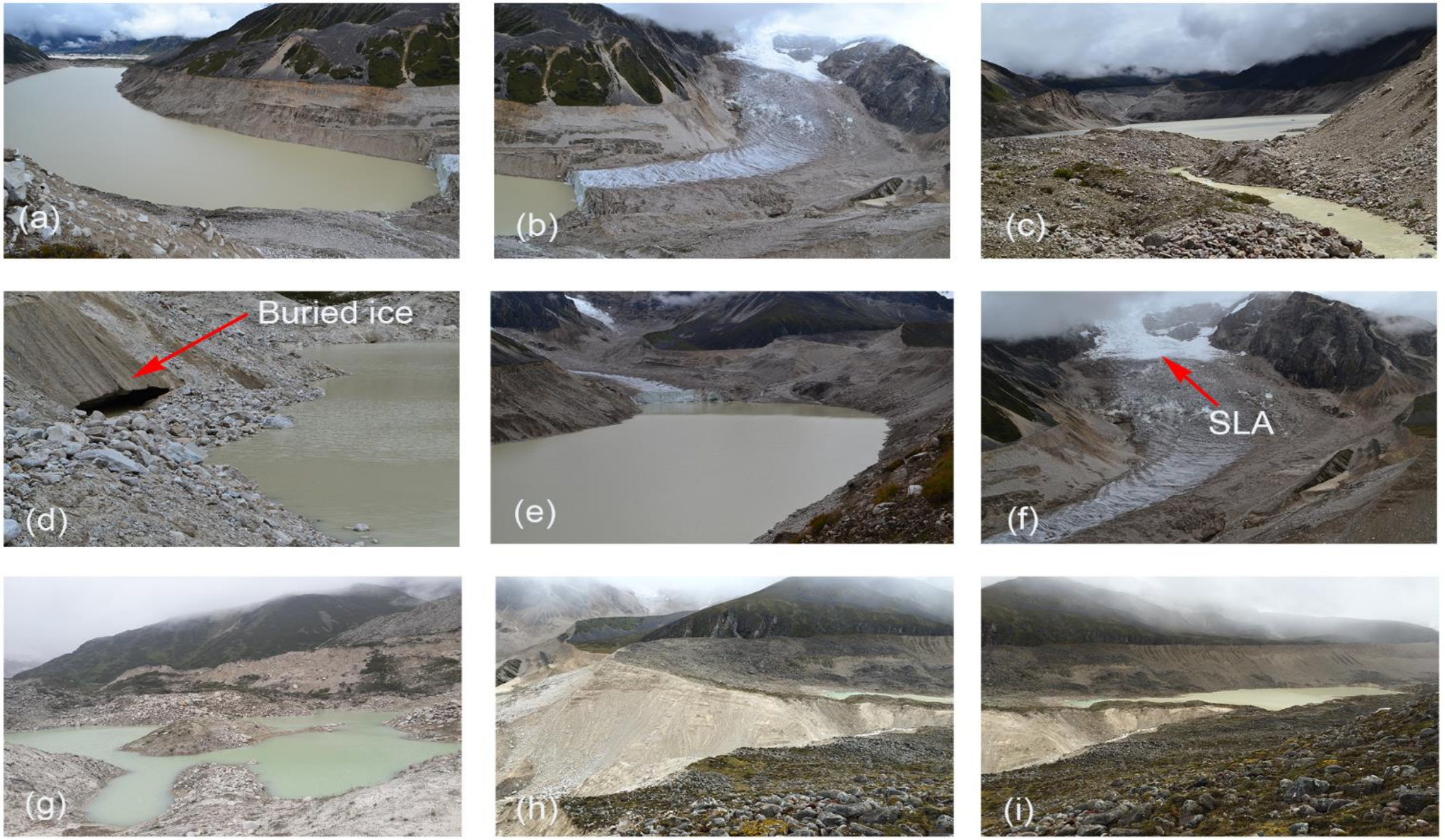








VIII. Report through the field visit



(a) Luggye lake, (b) Luggye glacier, (c) Lake outlet, (d) buried ice, (e) Luggye lake and glacier, (f) Snow line altitude, (g) Supraglacial ponds, (h) Eroded moraine, (i) Upstream lake

VIII. Report through the field visit

Through field observation, we confirmed that Luggye glacial lake is potentially dangerous due to the following reasons:

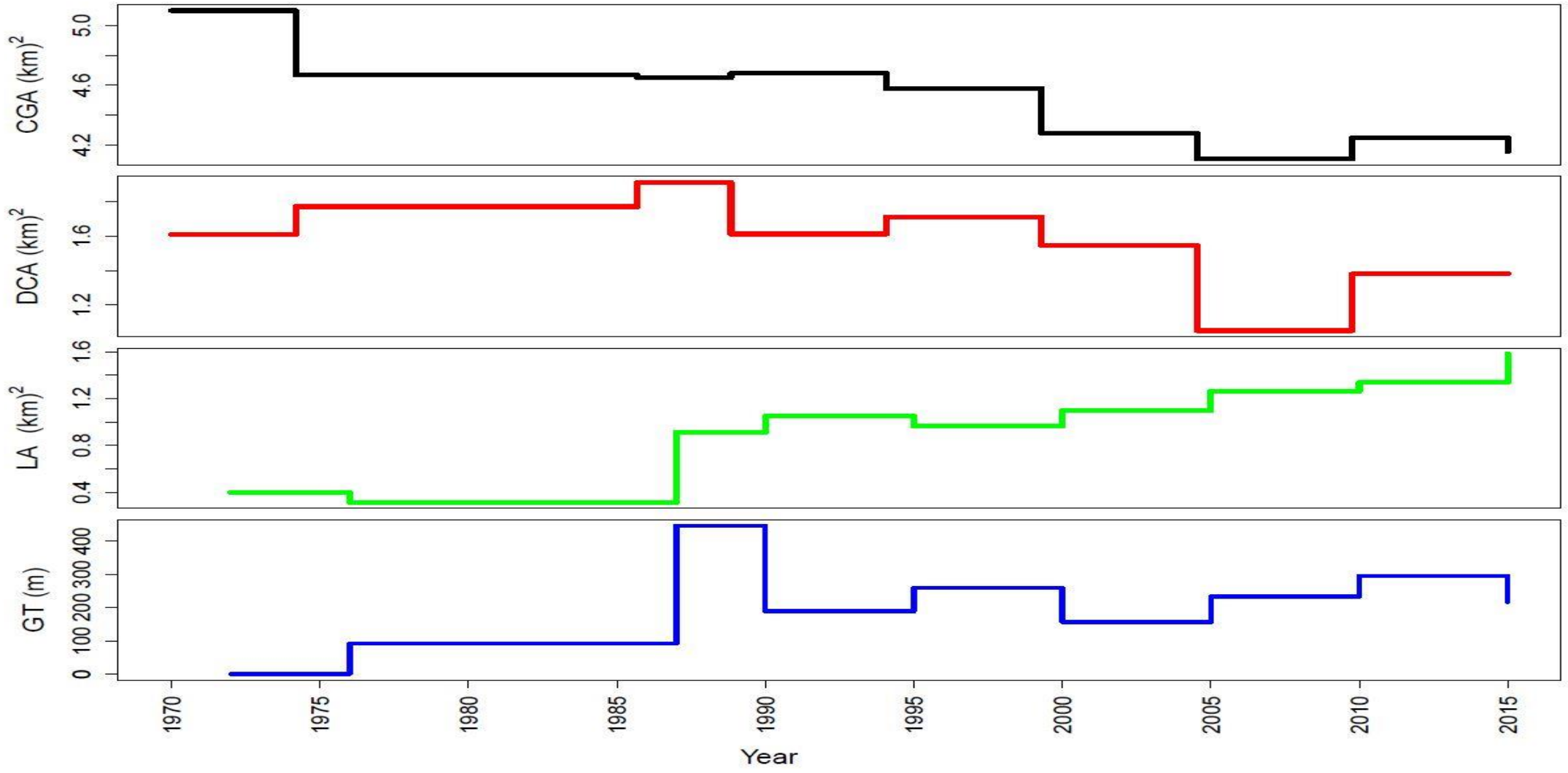
I. Large lake size and enormous volume of water

II. Active expansion fronts of the lake

III. Vulnerability of dam due to erosion of moraines

IV. High probability of mass movement into the lake

Conclusions



Overall trends of glacier variables. **CGA:** Clean Glacier Area; **DCA:** Debris-covered Glacier Area; **LA:** Lake area; **GT:** Glacier Terminus

Conclusion

- ✓The volume of the lake has increased approximately twofold since 1994.
- ✓Luggye glacier has also displayed mass loss and surface lowering at significant rate.
- ✓The rapid growth of Luggye glacial lake is due to areal shrinkage and negative mass balance of Luggye glacier induced by fluctuations in climate parameters over time.
- ✓Since expansion rate and volume of Luggye glacial lake water are essential trigger for possible outburst, we strongly recommend to monitor them through situ work, supplementing by systematic remote sensing observation.

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Contact: +975 1777 29 22

THANK YOU FOR YOUR ATTENTION!

INTERACTIVE SESSION

Is Luggye glacial lake really dangerous???

Acknowledgment

This work was supported by the Rufford Small Grants for Nature Conservation under the grant "Hazard assessment of Luggye glacial lake using GIS and remote sensing: an alternative long term approach for conserving aquatic habitat, Punatshang Chhu, Bhutan".

Presenter: Sonam Wangchuk
Email:
somwangchotc9091@gmail.com/
sonam.wangchuk@bt.bt
Contact: +975 1777 29 22

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Certificate of Appreciation

Awarded to

Mr. Sonam Wangchuk

for chairing the session and
presenting a paper during the Conference

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