Glacier Remote Sensing

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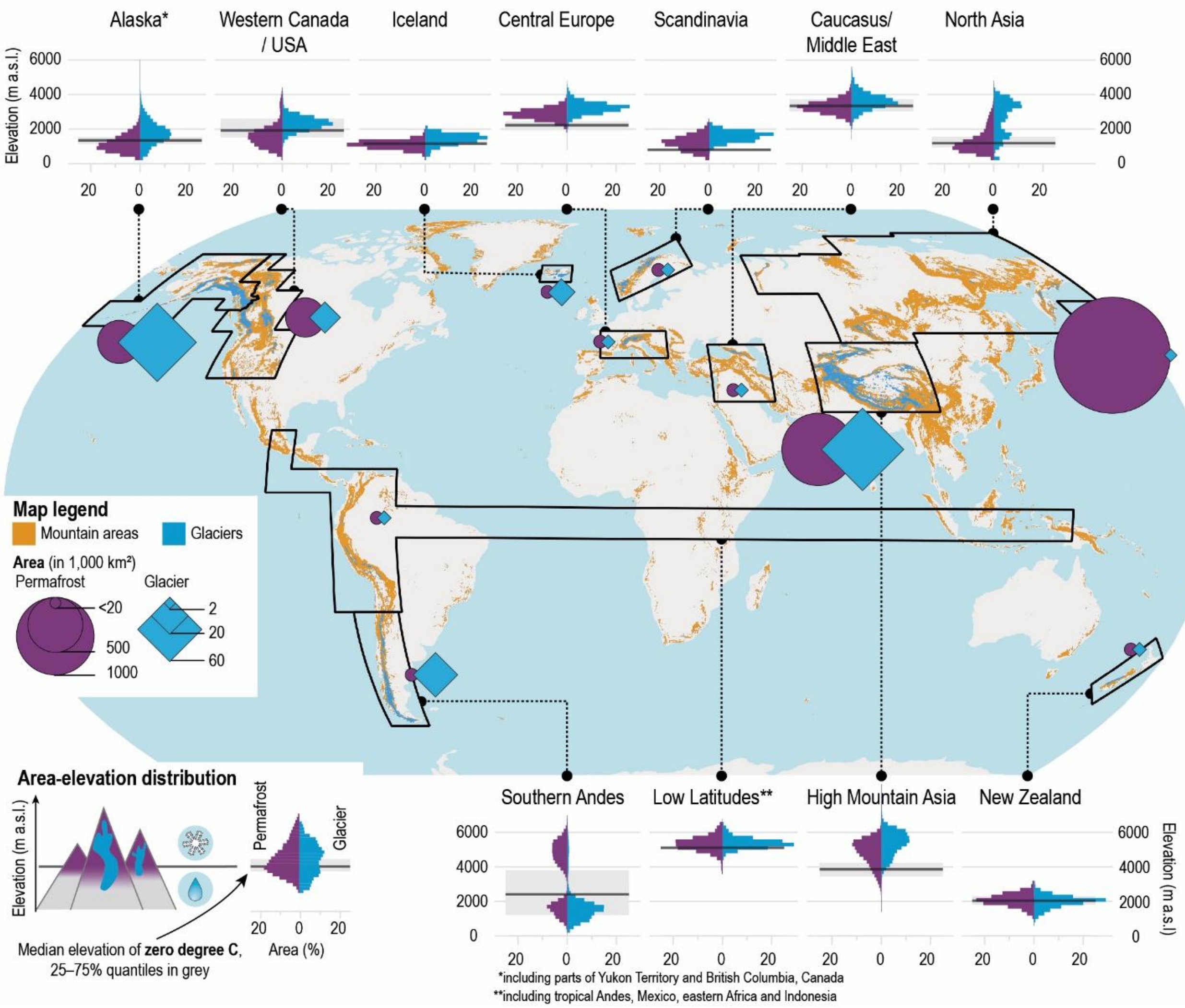
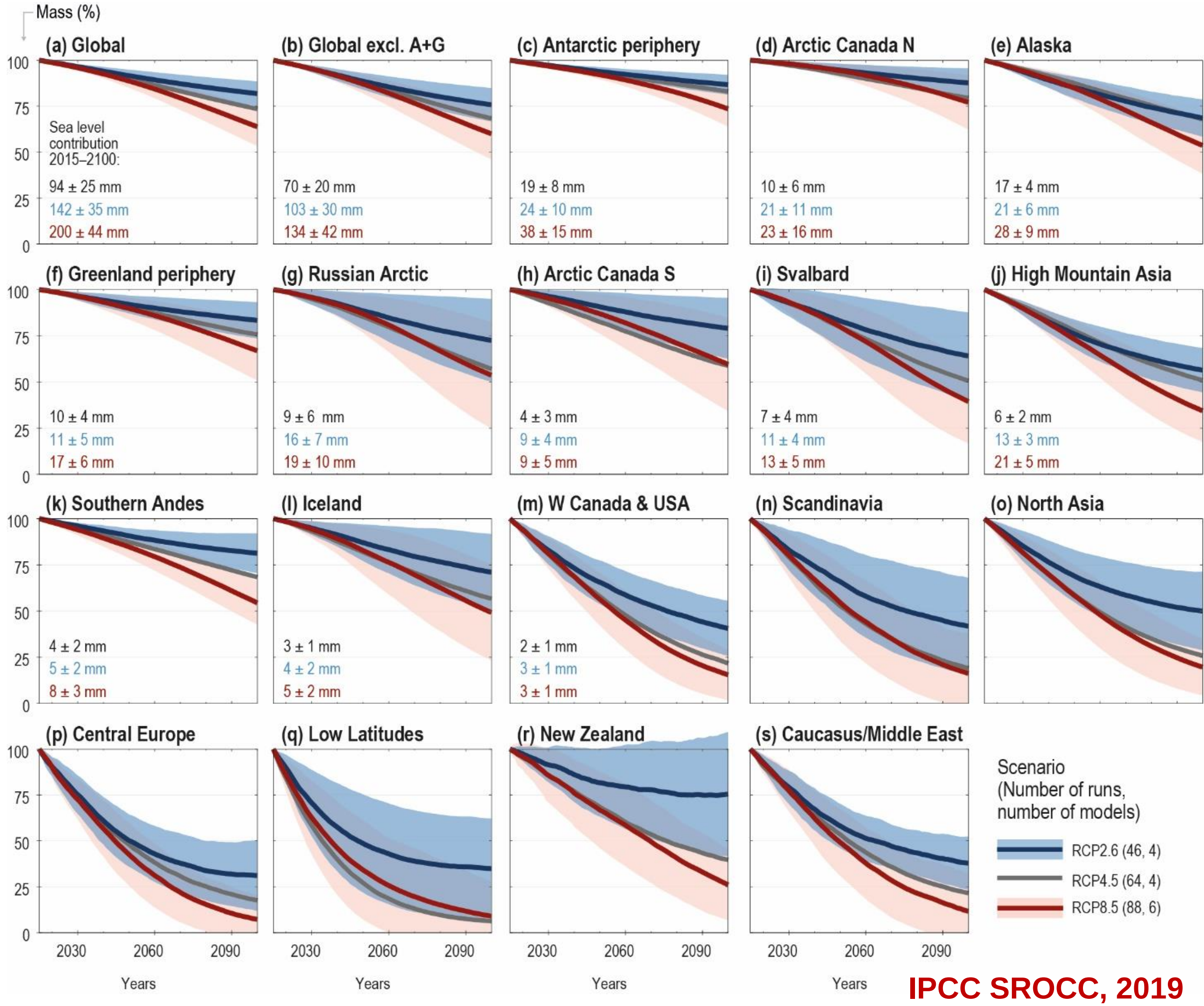
2024.08.15 Lanzhou

Contents

01. Background

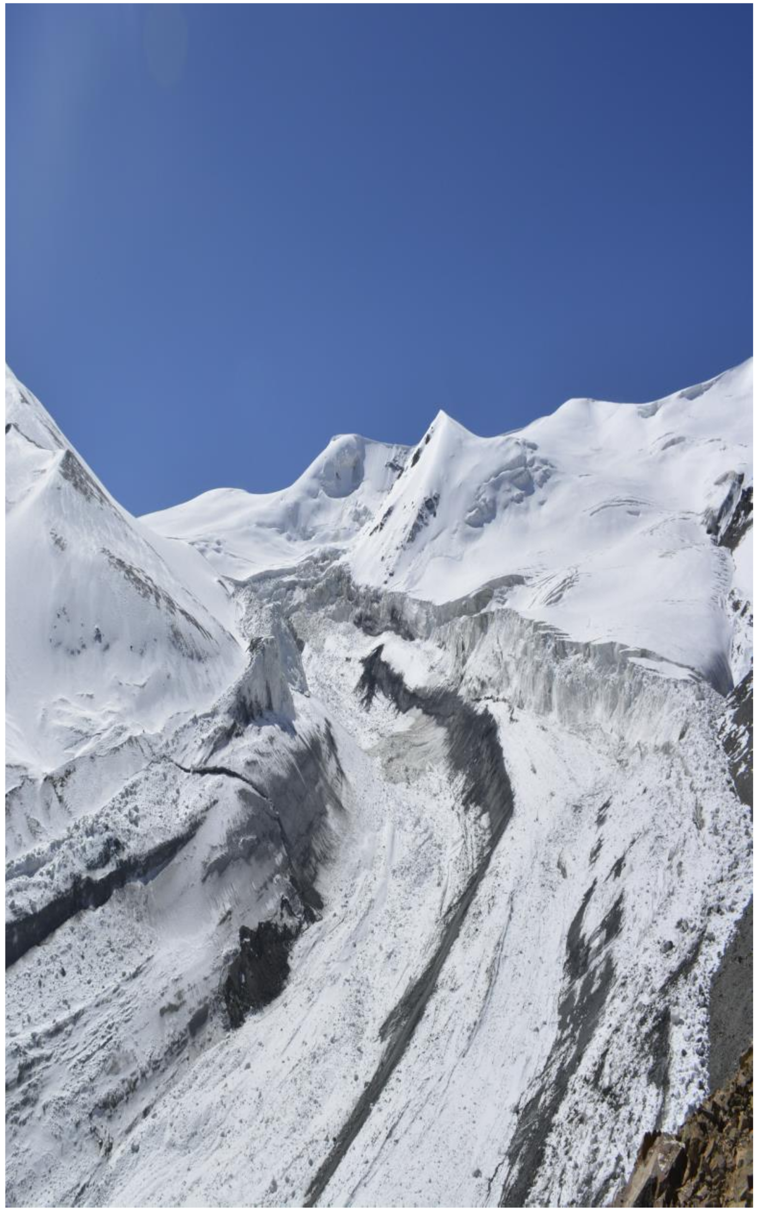




IPCC SROCC, 2019

- >274,000 glaciers globally with a totally area of 706,744 km^2 (RGI 7.0, 2023)
- Nearly all the glaciers are experiencing rapid changes (retreat and strong ablation) under global warming, with projected continuous wastage until the end of 21 century (IPCC SROCC, 2019)
- The fast melting of global glaciers (except polar icesheets peripherals) contributes >1/5 of sea level rise since 1970s (IPCC AR6, 2021)

Frequent occurrences of extreme glacier hazard in recent years



Collapses of 2 Aru glaciers, 2016

Collapse of Hailuogou Glacier, July 2022

Collapse of a glacier in Xinjiang, June 2023

Frequent occurrences of extreme glacier hazard in recent years

Glacier related debris flow, Sedongpu, Tibet, 2018

Glacier related debris flow, Northern India, 2021

02. Types of Glacier-Related Remote Sensing

Type of Remote Sensing

Optical Satellites

Widely Used Non-Commercial Optical Satellites to Study Glacier

Landsat series, USA

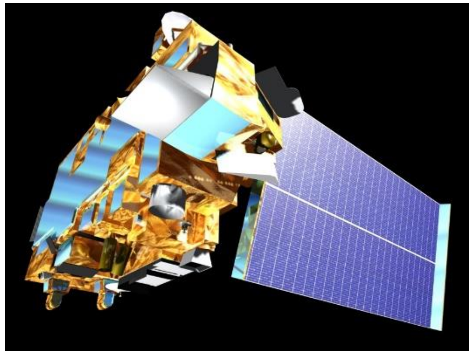
Landsat 1-5 MSS, 60 m, 1972-1992

Landsat 4-5 TM, 30 m, 1982-2012

Landsat 7 ETM+, 15/30 m, 1999-2024

Landsat 8-9 OLI, 15/30 m, 2013-present

MODIS Terra/ASTER, USA/JAPAN



Terra ASTER, 15 m, 1999-present

Sentinel-2, ESA

Sentinel 2A, 10/20/60 m, 2015-present

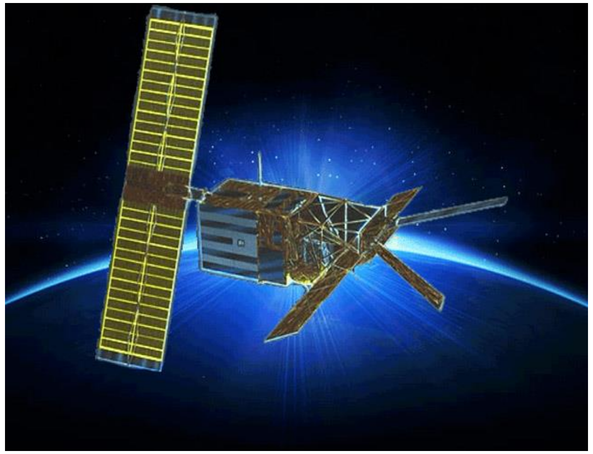
Sentinel 2B, 10/20/60 m, 2017-present

Type of Remote Sensing

Microwave Satellites

Widely Used SAR Satellites to Study Glacier

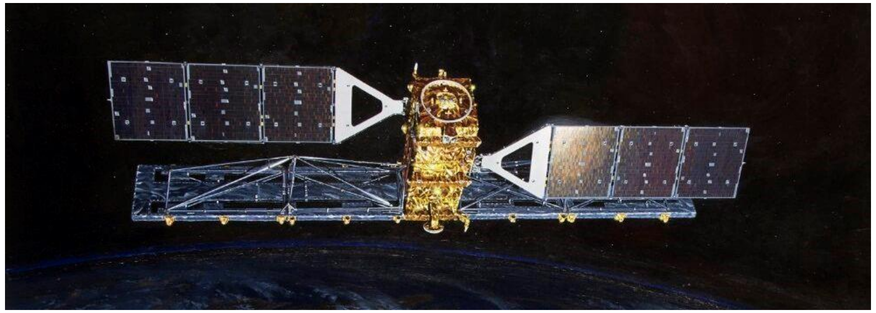
ERS-1/2, ESA



ERS 1, 6/30/26 m, 1991-2000

ERS 2, 6/30/26 m, 1995-2011

RADARSAT-1, Canada

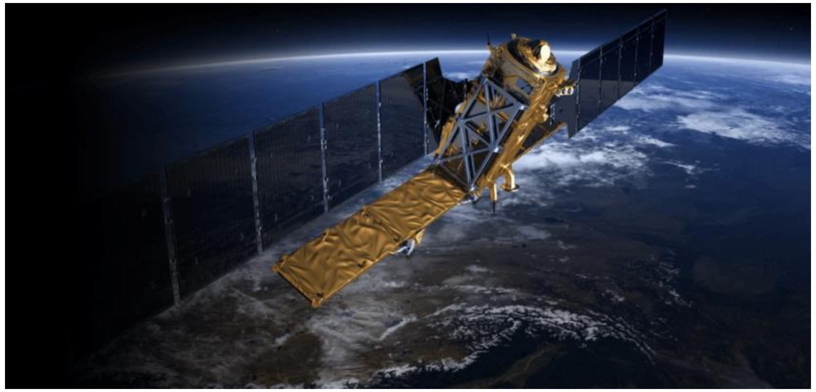


RADARSAT-1, 8/30/50-100 m, 1995-2008

ALOS PALSAR, Japan

RADARSAT-1, 10/20/30/100 m, 2006-2011

Sentinel-1, ESA



Sentinel 1A, 5/20/40 m, 2014-present

Sentinel 1B, 5/20/40 m, 2016-2022

Type of Remote Sensing

Spaceborne Remote Sensing

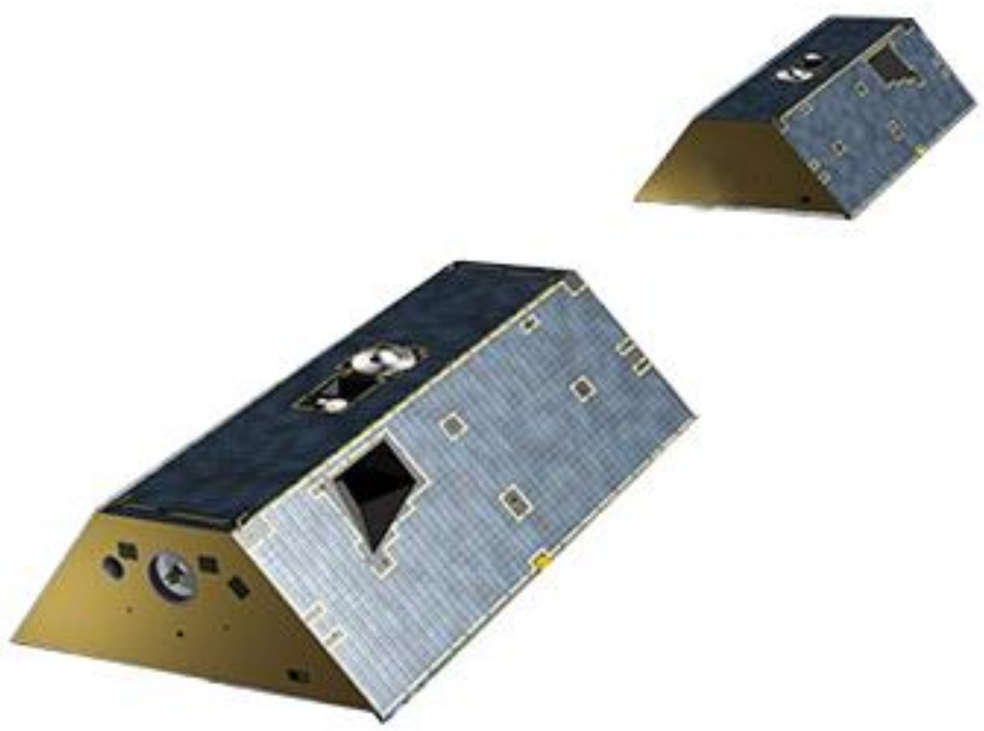
Altimetric Satellites

ICESat
2003-2009

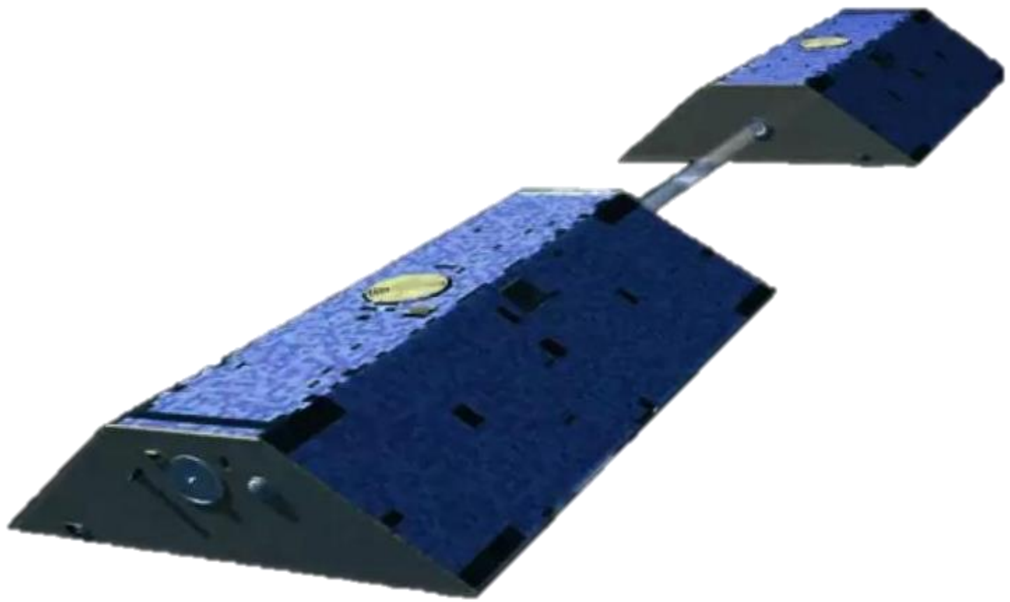
ICESat-2
2018-present

Type of Remote Sensing

Gravitational Satellites



GRACE
2002-2017

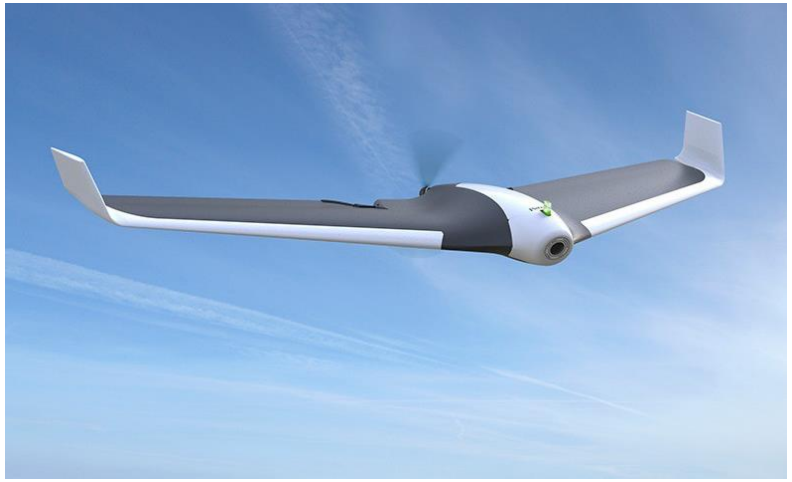


GRACE-FO
2018-present

Type of Remote Sensing

Airborne Remote Sensing

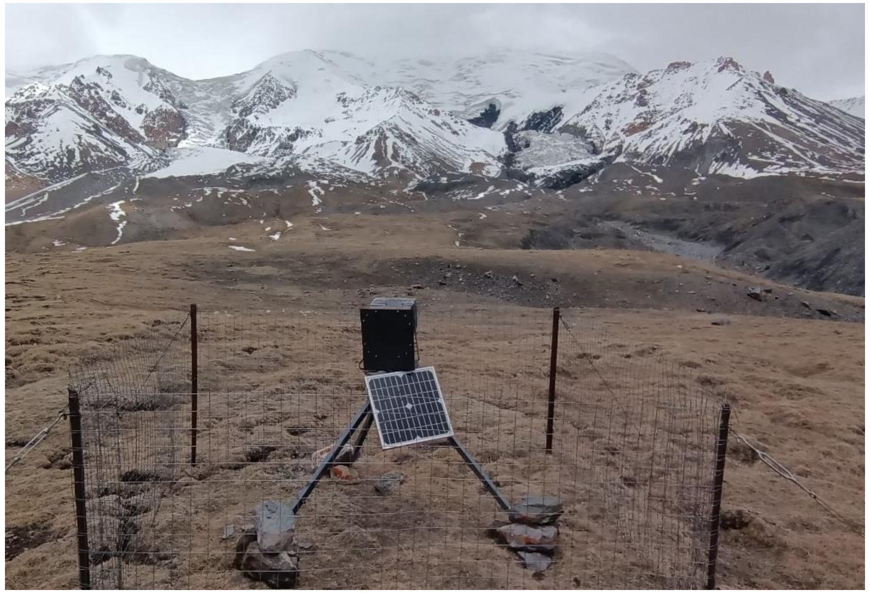
Manned Airborne Survey



Unmanned Aerial Vehicle (UAV) Survey

Type of Remote Sensing

Terrestrial LiDAR



Stereo time lapse camera

Ground Penetration RADAR

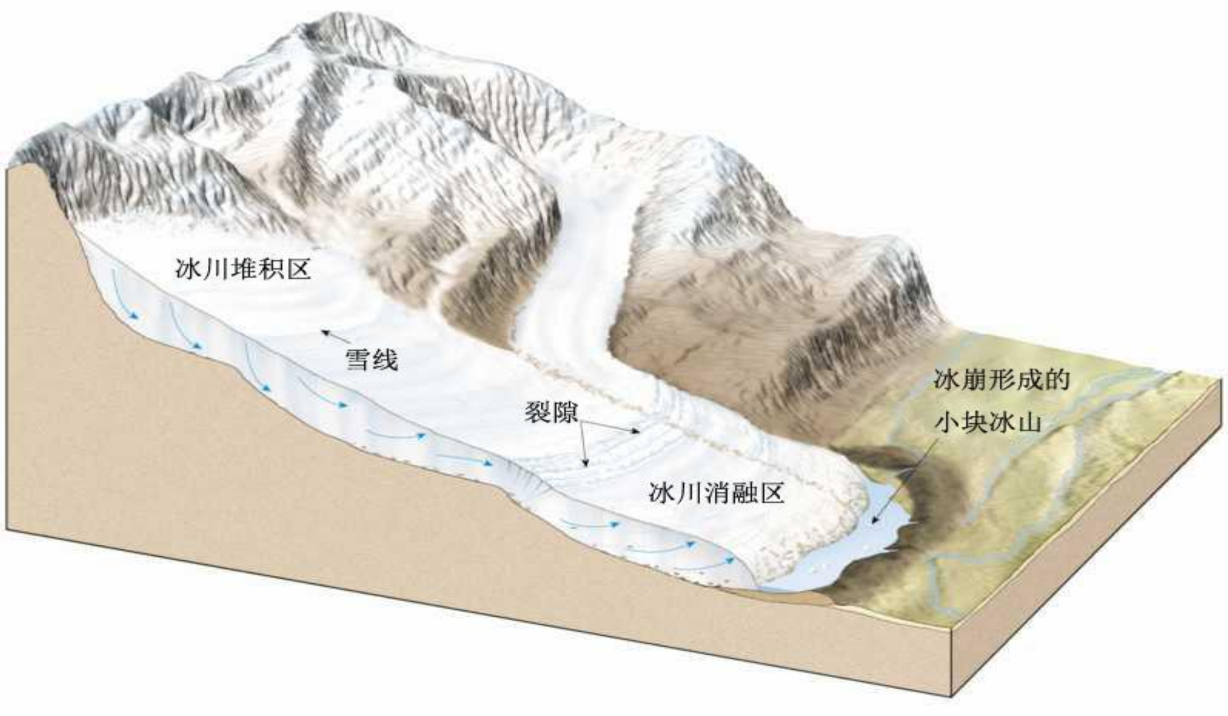
Portable field spectroradiometer

03. Changes of Glacier can be Remotely Sensed

Definition of Glacier

Flowing ice on earth surface transformed and evolved from accumulated snow and other solid precipitation.

Qin *et al.*, 2019. Dictionary of Cryospheric Science



Difference between glacier and snow

- Glacier: Survive for centuries to millions of years
- Snow: Survive only for hours, days, or months

Transformation from snow to glacier ice

- Compaction of thick snow in accumulation area
- Melt, infiltration into depth and re-freezing
- Rainfall infiltration and re-freezing

Glacier flow, ablation and related surface features

- Creeping, sliding toward low elevation under gravity
- Surface textures different from snow
  - Longitudinal: Flow lines
  - Transversal: Ice crack and Crevasses
- Trim line and apparent topographical features along glacier edge
- All the surface features are in changing along time

Glacier Changes

- **Most glacier parameters are in changing under climate warming**

Interior Changes:

Ice thickness	⇨ Determine the glacier volume
Ice temperature	⇨ Determine the glacier creeping capability
Internal drainage system Bed hydrologic properties	⇨ Affect the internal ablation and stability

Exterior Changes:

Glacier boundary/terminus	⇨ Determine the glacier area
Surface elevation	⇨ Reflect the glacier mass balance
Flow velocity	⇨ Reflect the glacier kinematic process
Surface albedo	⇨ Determine the surface ablation

04. Key Methods of Glacier Remote Sensing

Glacier Inventory

What is Glacier Inventory?

Registration of the glacier with necessary attributes via remote sensing and GIS.

Glacier Attributes to be Registered

- Area
- Perimeter
- Length
- Coordinates
- Name

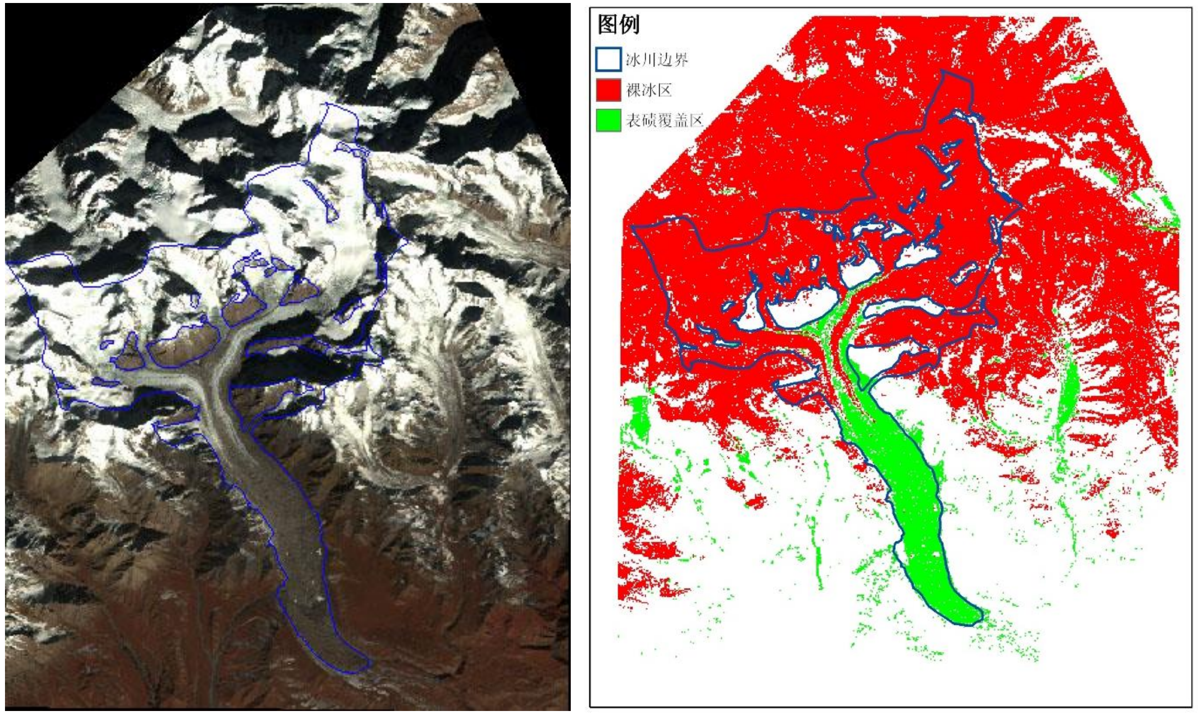
- Mean slope/aspect
- Mean elevation
- Maximum elevation
- Medium area elevation
- Tail elevation
- Area in different elevation band

- Equilibrium Line Elevation (ELA)
- Type
- Administrative region
- Hydrological region

Glacier Inventory

Glacier classification from satellite images

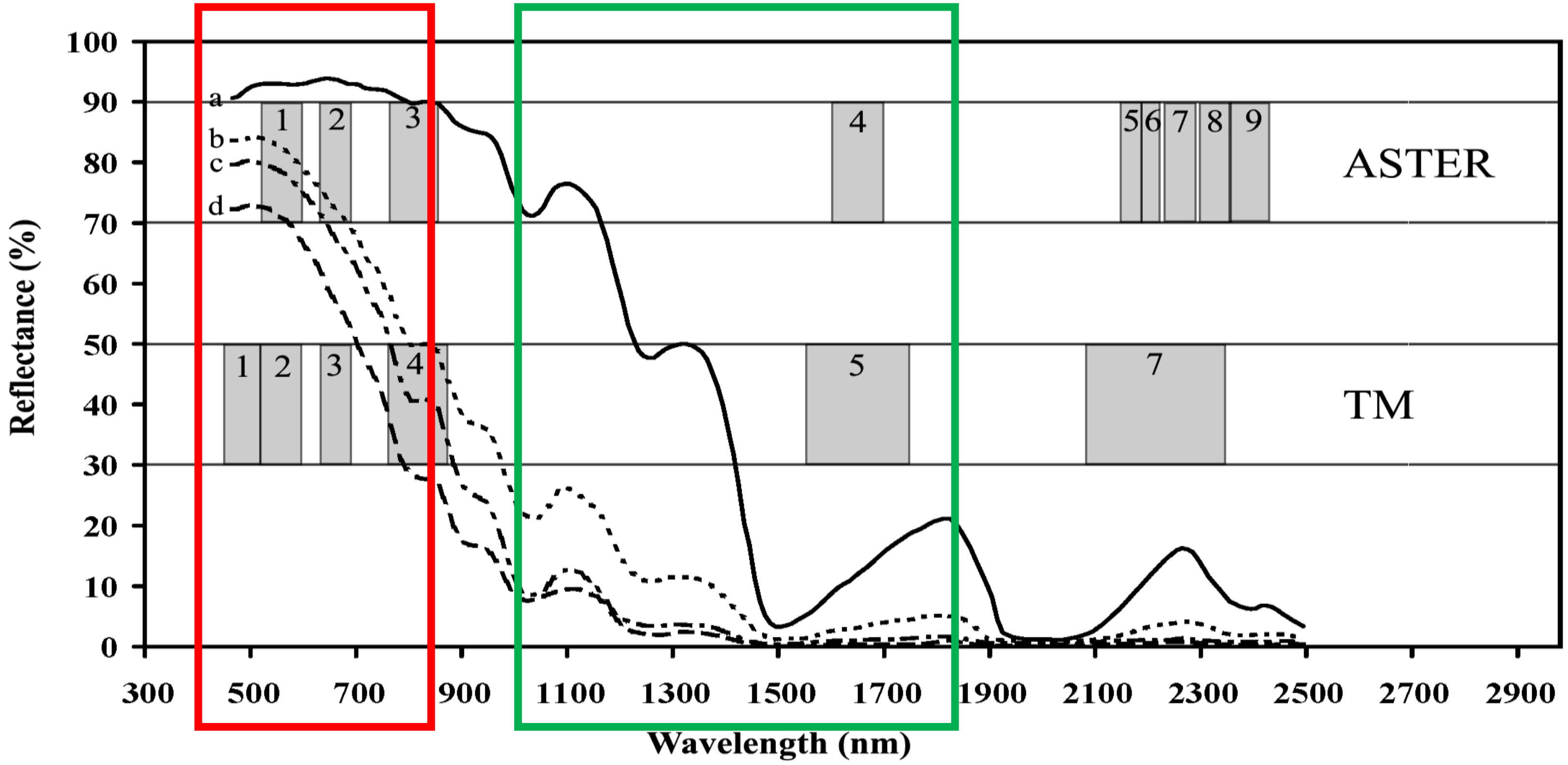
- Methods have been used
  - Brightness based classification
  - Supervised/Unsupervised classification
  - Decision tree based classification
  - Neural network based classification
- Widely accepted glacier classification method
  - Band Ratio Thresholding (BRT) method



Glacier classification via decision tree

Theoretical basis of the BRT method

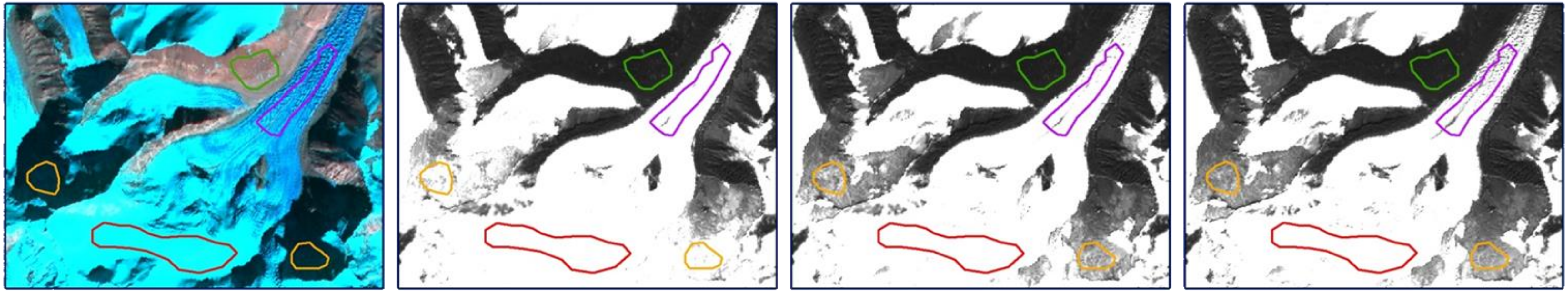
High reflectance of snow and ice in visible (380-750 nm) and near infra-red (1000-2500 nm) bands with extraordinary absorption in shortwave infra-red band.



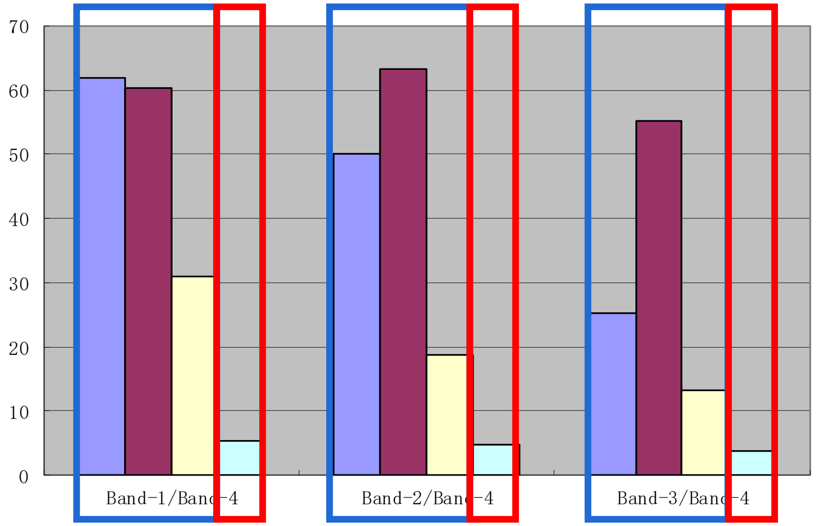
Reflectance curves of snow and ice

Glacier Inventory

Example for glacier outline extraction by band ration thresholding method



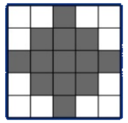
A B C D



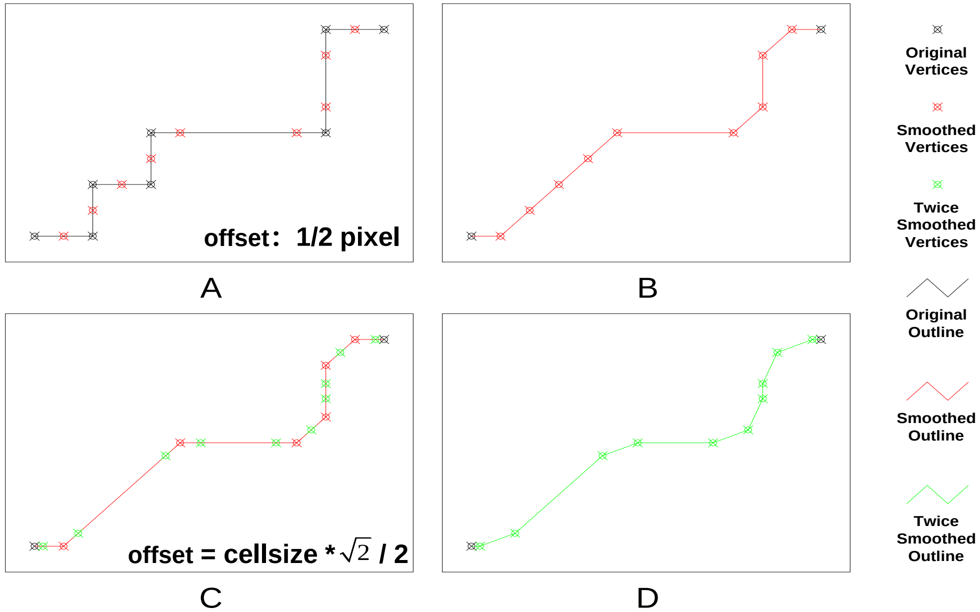
- ✓ **Strengthen the contrast between glacier and Non-glacier region in band ratio image**

A. ASTER image
B. Band 1/Band 4
C. Band 2/Band 4
D. Band 3/Band 4

Further steps to process the resulted band ratio image and extracted glacier outline



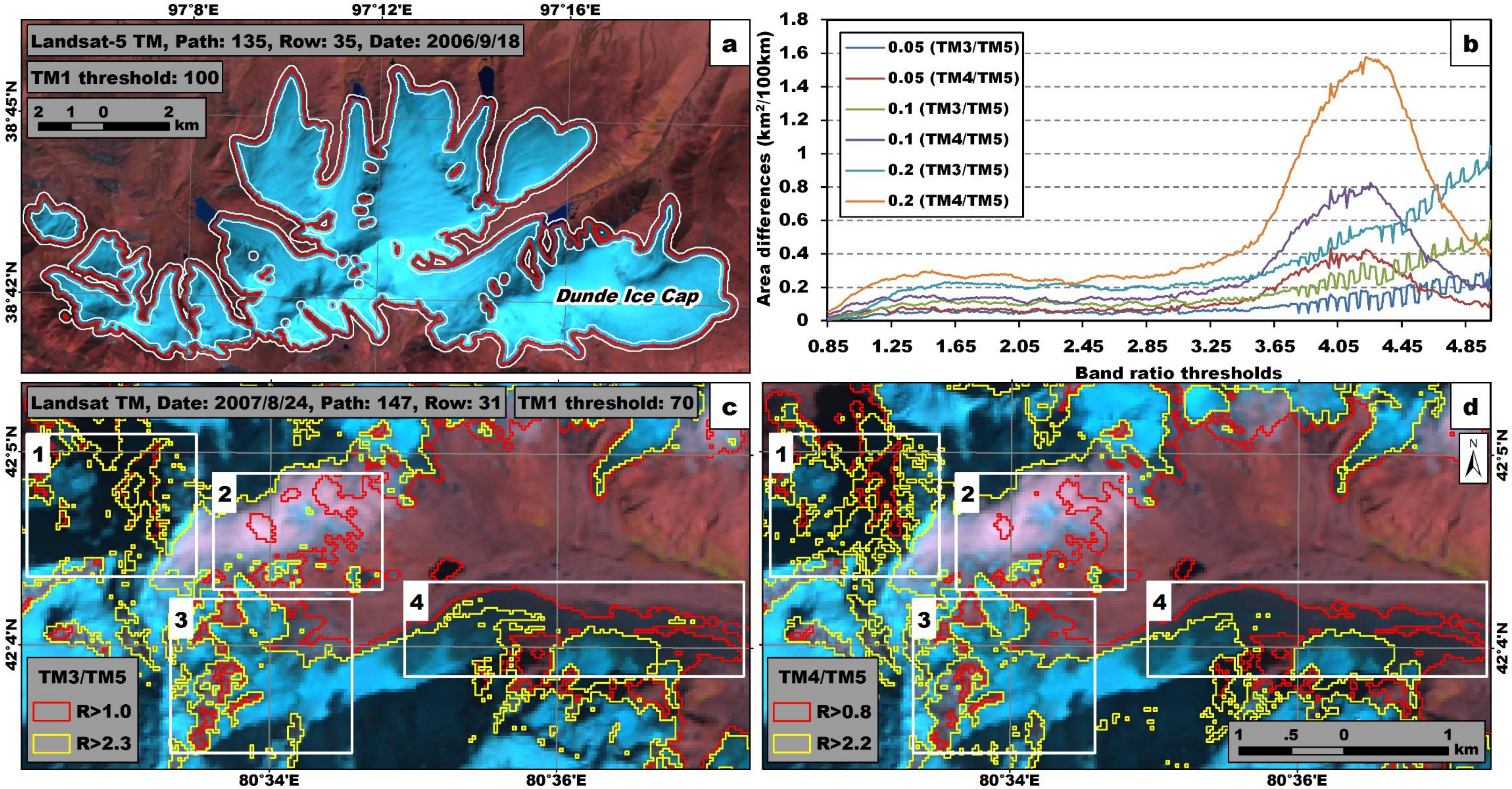
Structural element used in morphological "Open" and "Close" process



A. Original outline
B. Smoothed outline
C. Intermediate vertex removed outline
D. Twice smoothed outline

Glacier Inventory

Importance of manual revision on the extracted glacier outline



Importance of manual revision on the extracted glacier outline

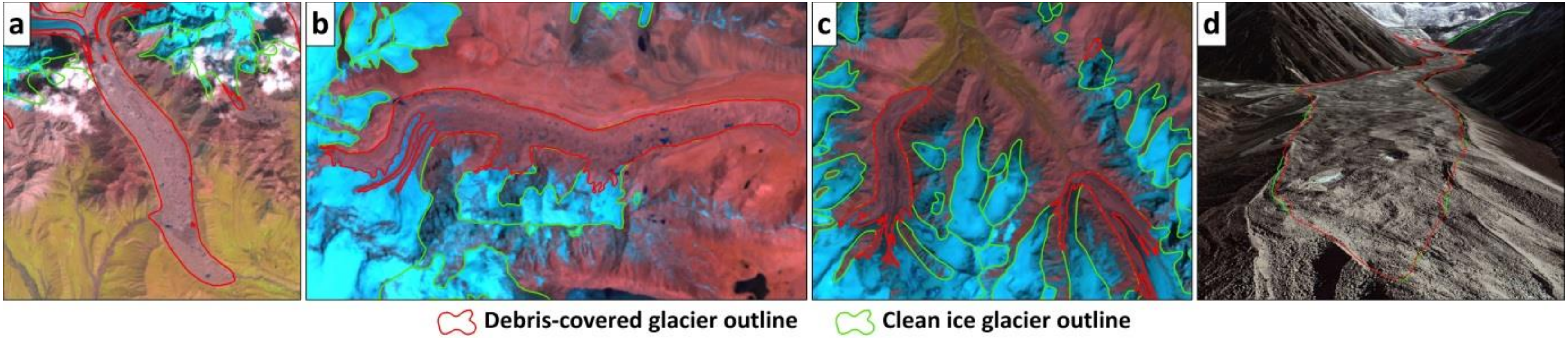
- Influences of seasonal snow:
  - Seasonal snow remnants exist somewhere on most satellite images in most time due to the high elevation / cold weather
- Influences of cast shadows:
  - Better satellite images only present in winter time in some regions due to special climate
- Influences of different ablation status on glacier tongue:
  - Melting glacier surfaces at lower elevation have different best band ratio thresholds with higher glacier regions

All the influences need to manually overcame by visual comparing satellite images acquired at different time/season

Glacier Inventory

Delineation of the outlines of debris-covered glacier

- Debris-covered glacier
  - Glaciers covered by different thickness debris on their tongues
  - Widely distributed among most large glacier centers all over the world
  - Currently no suitable automatic method can fulfill the requirements of glacier inventory
  - Suggest to delineate the outline manually by expertized person

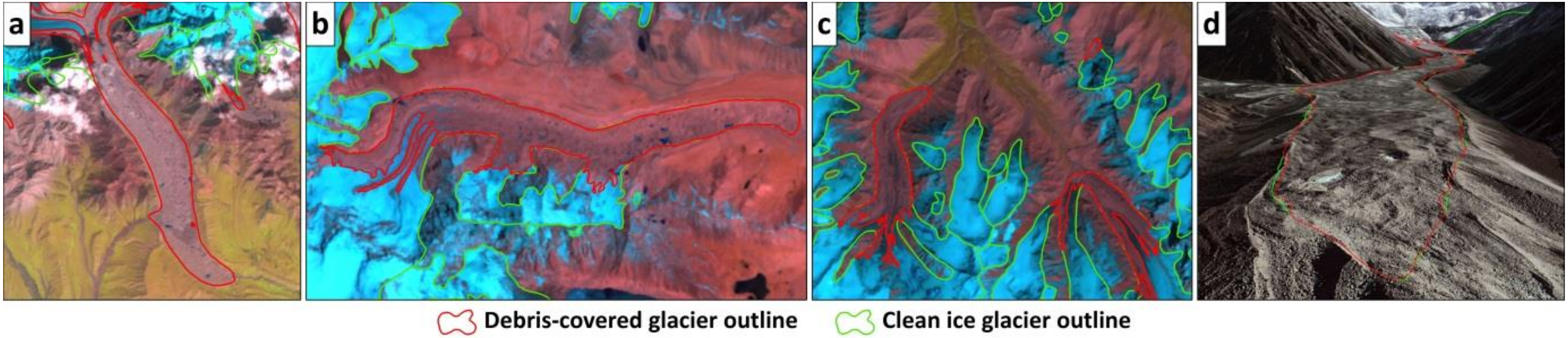


Glacier Inventory

Optical Remote Sensing

Delineation of the outlines of debris-covered glacier

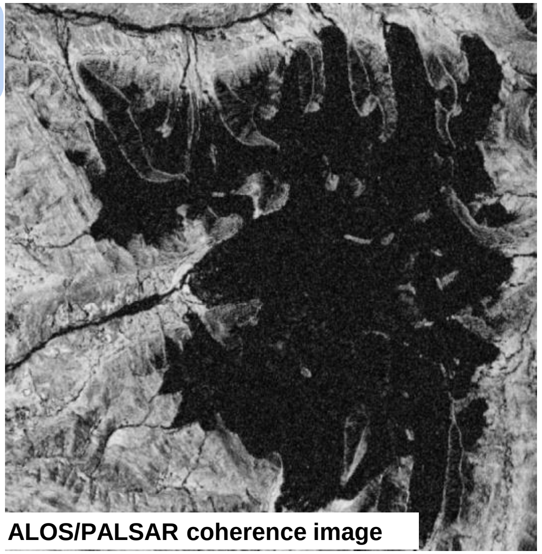
- Criteria to distinguish debris-covered glacier
  - Differences in image colors
  - Exist of supraglacial lakes
  - Exposure of sub-glacier river on terminus
  - Differences in topographical features

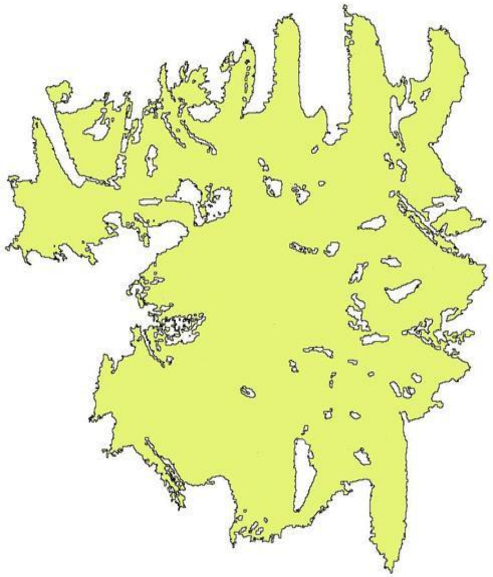


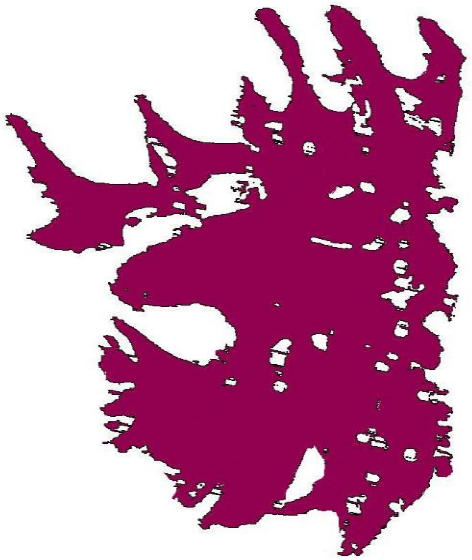
SAR Remote Sensing

Theoretical basis: low InSAR coherence

- Glacier flow and surface ablation causing the lost of coherence of between SAR images acquired with longer time interval when processing with interferometrical methods
- The lower coherence of glacier covered region can be used to classify and extract the glacier outlines
- Can be used on regions with serious snow/cloud covers at all seasons







Limitation:

- Some regions of glacier with low activity cannot be correctly classified

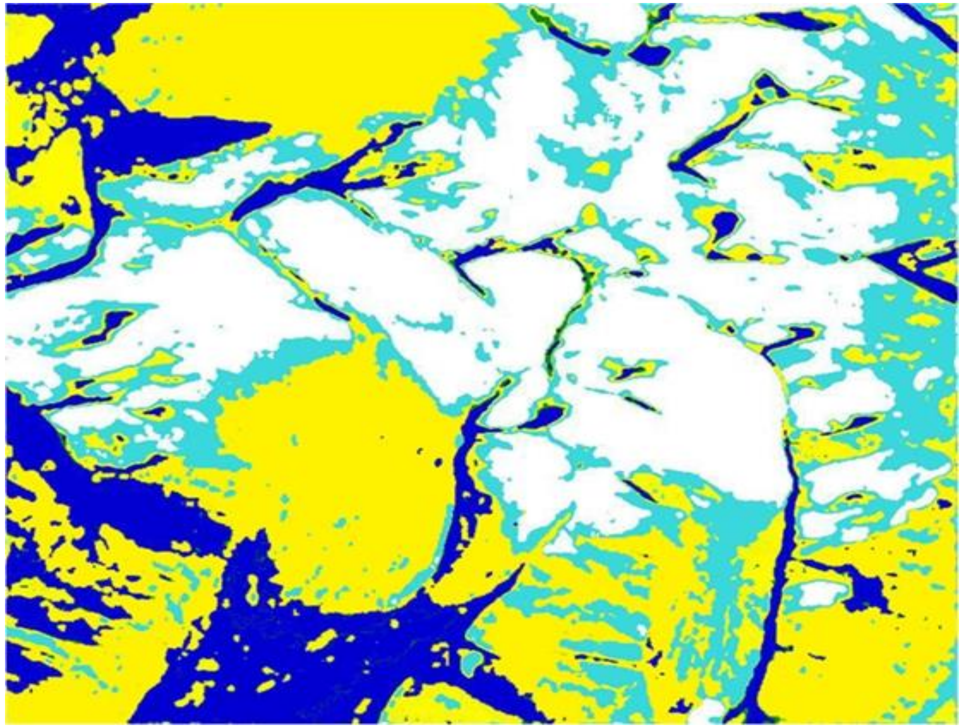
SAR Remote Sensing

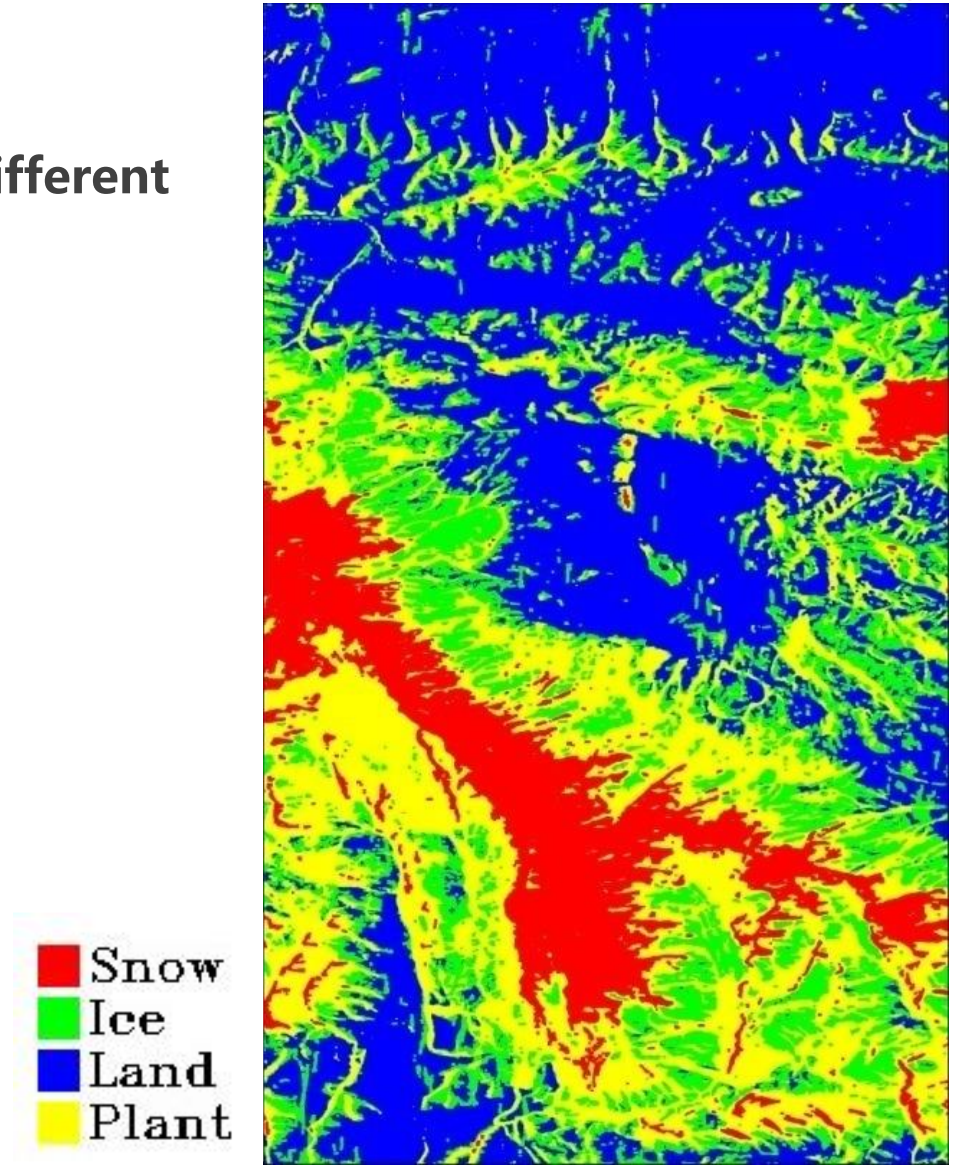
Theoretical basis: full polarization SAR

- The fully polarized SAR image show some patterns for different land cover types similar to optical satellite images

Limitations:

- Low accuracy comparing to optical satellite image





Glacier Inventory

Definition of Ice Divide

- Geographical boundaries differentiate the glaciers with melting water flow to different basins, normally represented by topographical ridgeline

Theoretic basis

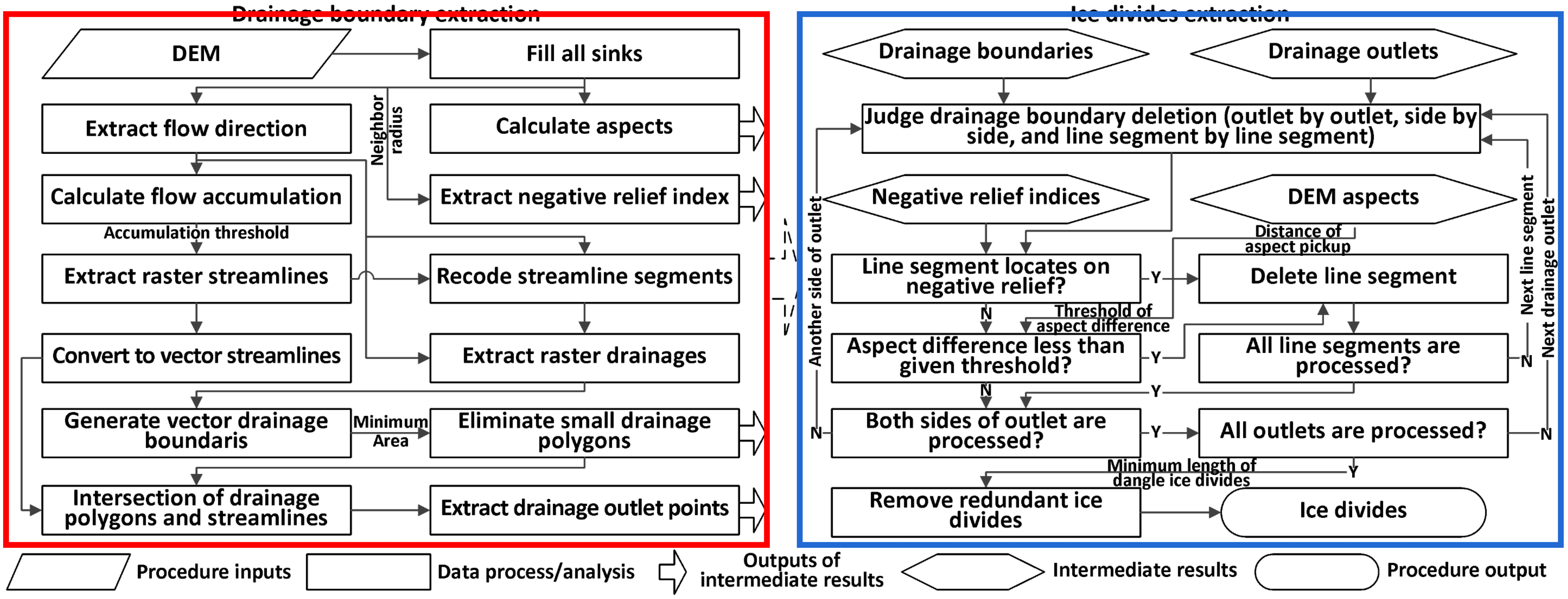
- Terrain aspects along the ice divides have large difference

Software and tools needed

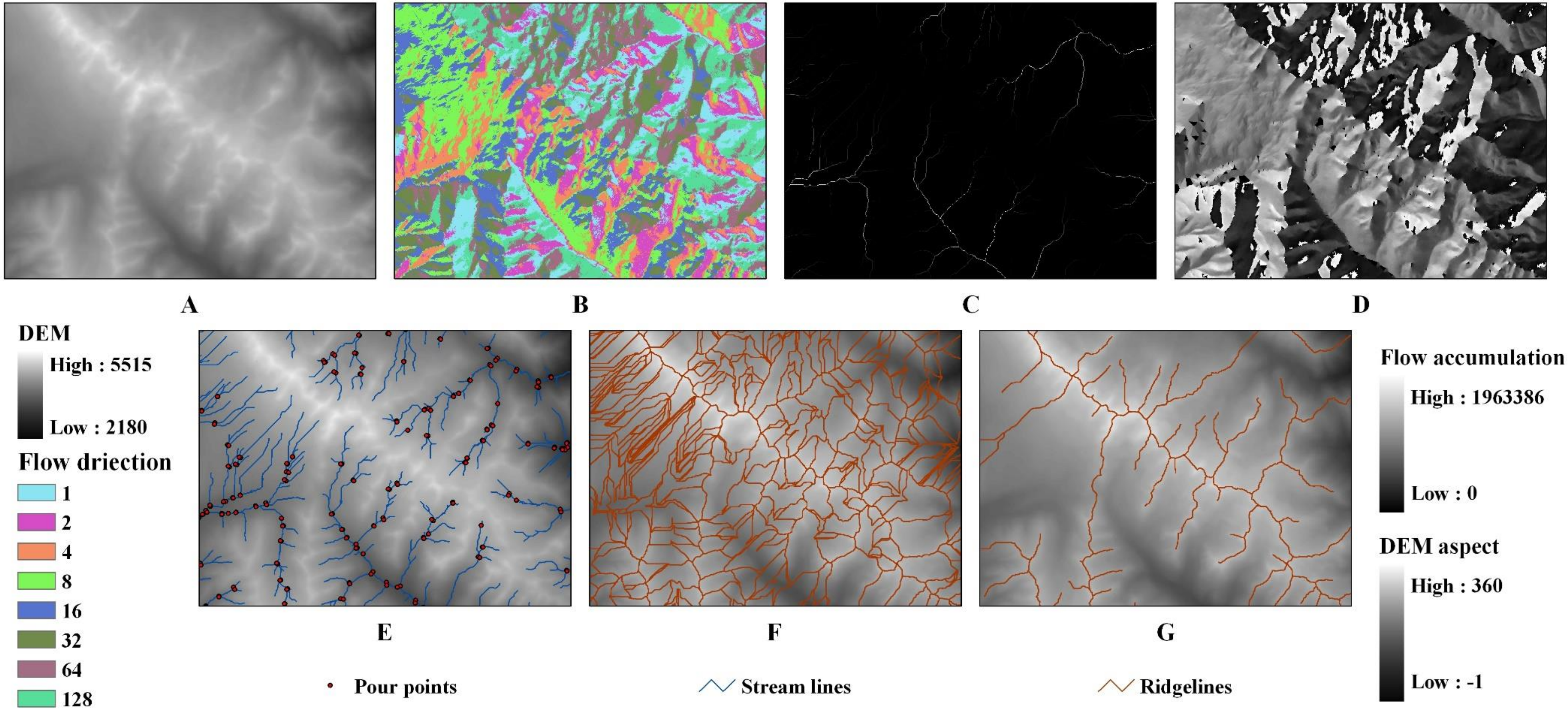
- ArcGIS Workstation (ArcINFO)
- Self-developed IDL program

NOTE: Manual revision are always needed to correct errors caused by poor DEM quality and improve the accuracy of the extracted ice divides

Extraction of Ice Divides

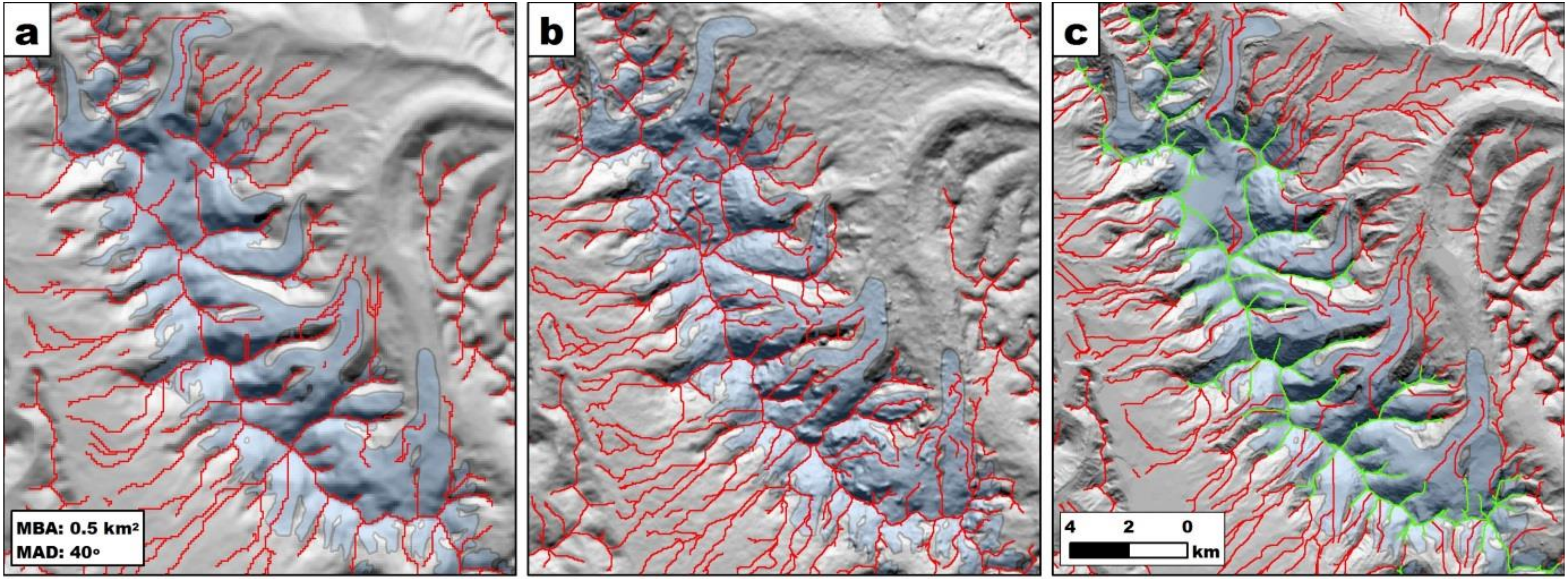


Description of Ice Divides Extraction



Glacier Inventory

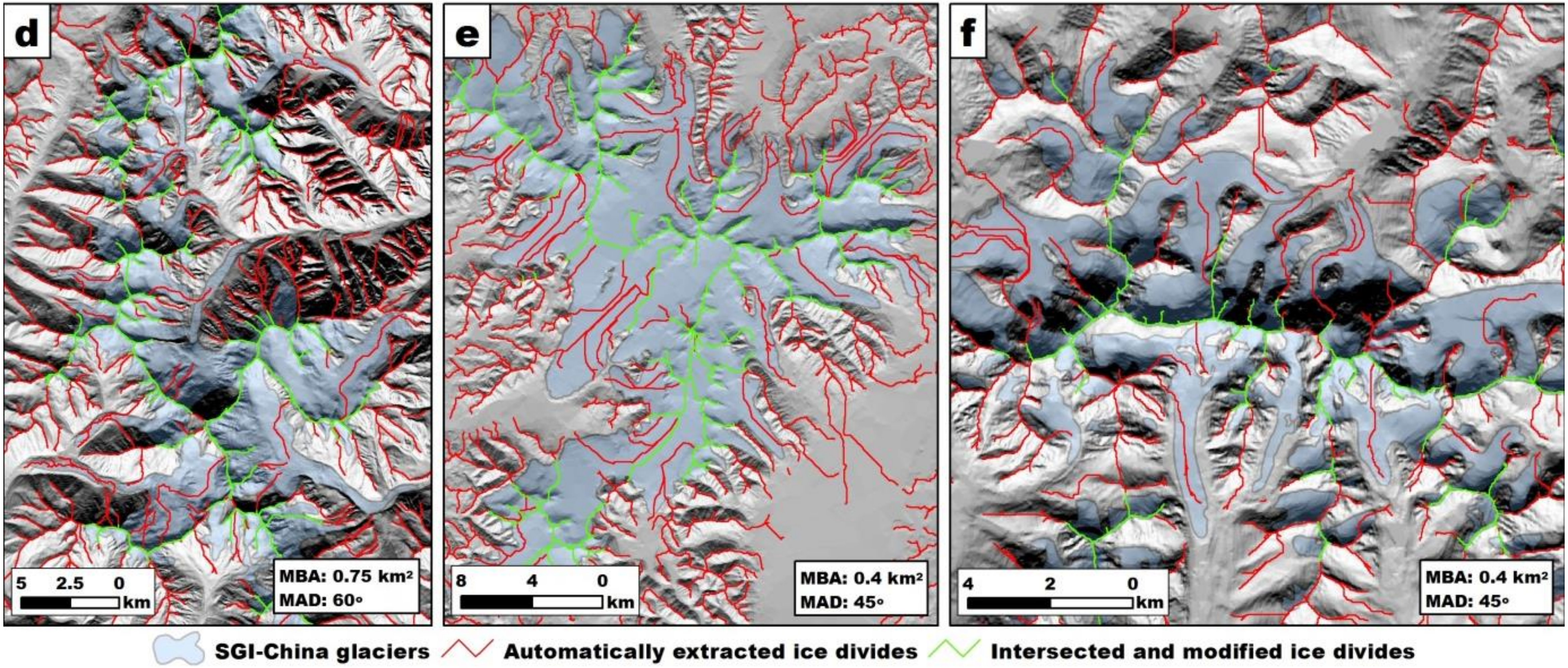
Comparison between different DEMs



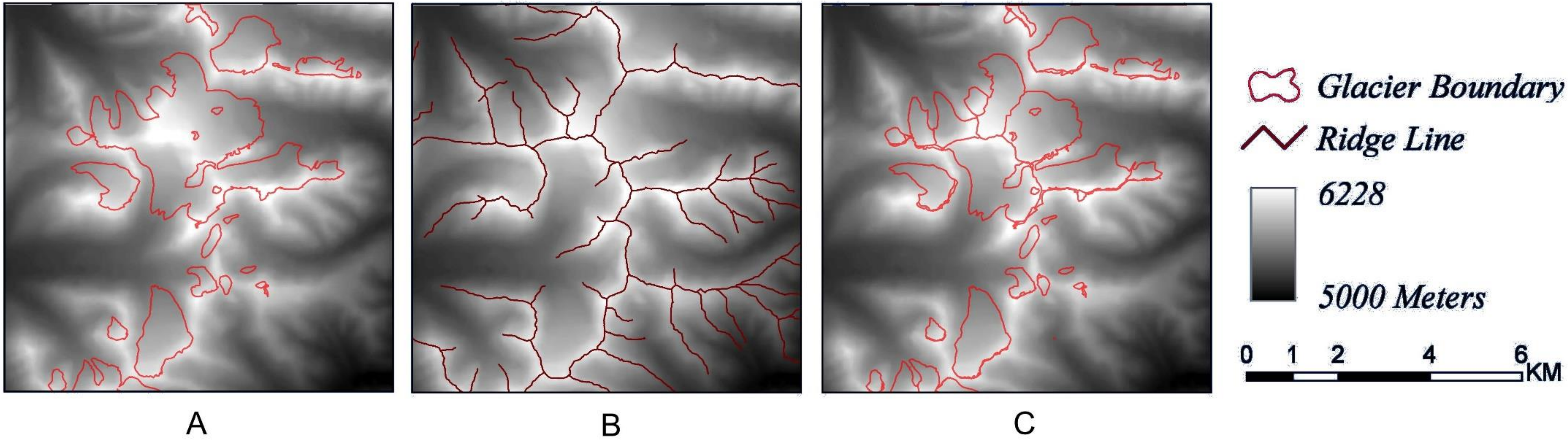
SRTM (90m) | ASTER GDEM (90m) | 1:50,000 TOPO DEM (30m)

Glacier Inventory

Comparison among different landforms

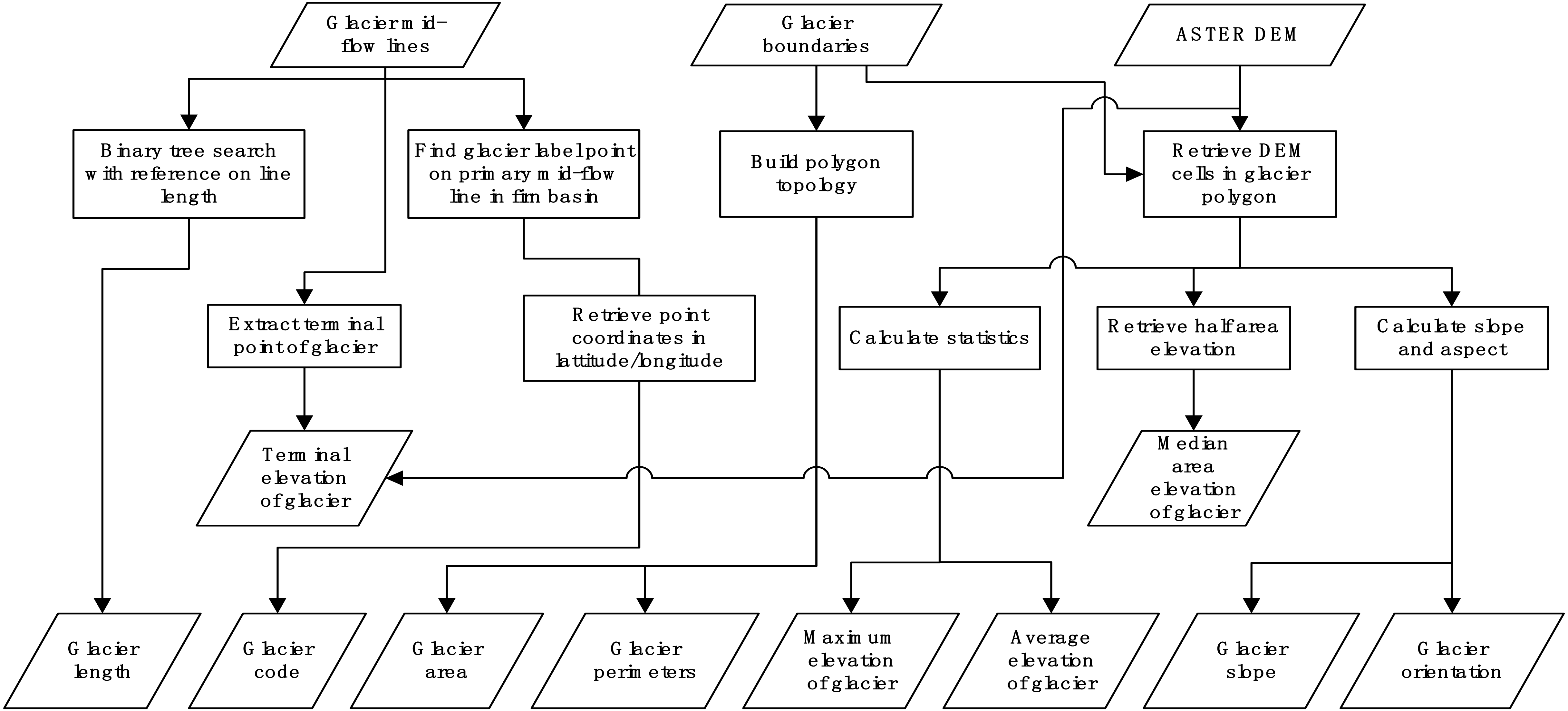


Example of separation glacier complex with ice divides



Glacier Inventory

Other Glacier Attributes



Flowchart of automatic calculation of glacier attributes

Glacier Inventory

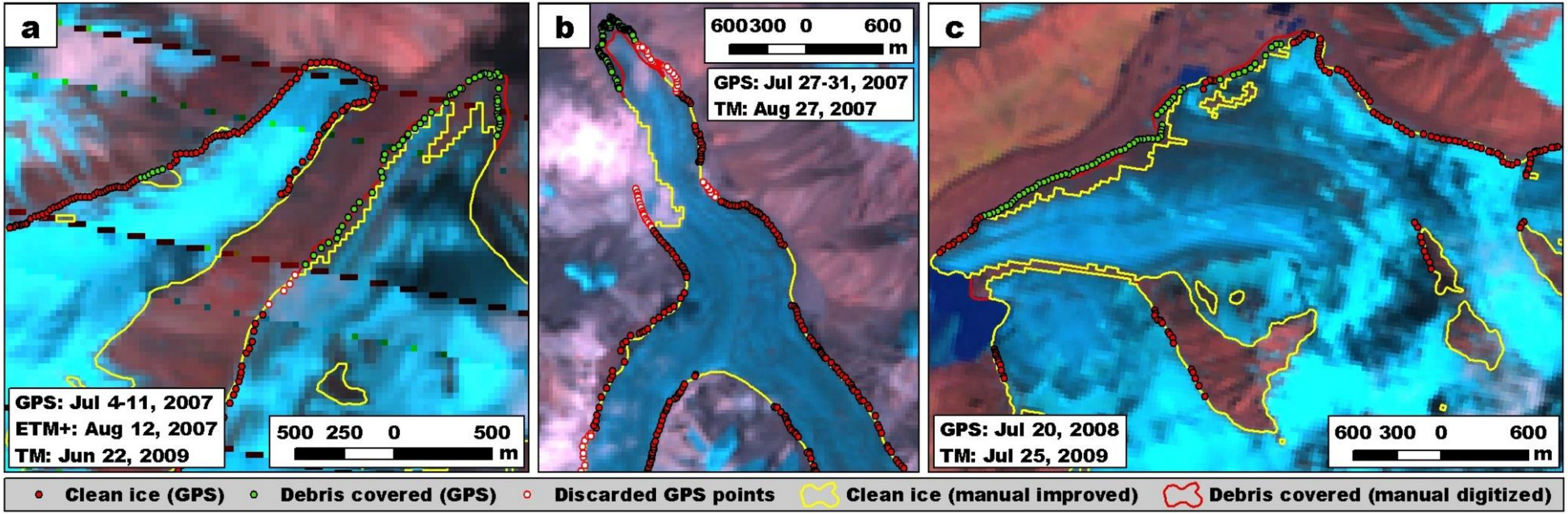
Basic Equations

$$E_A = L_c E_{p_c} + L_d E_{p_d} + L_i E_{p_i}$$

- E_A: Glacier area error
- E_{pc}: Clean-ice outline positioning error (±10 m)
- E_{pd}: Debris-covered outline positioning error (±30 m)
- E_{pi}: Ice divides positioning error (±30 m)
- L_c, L_d, L_i: Length of clean-ice and debris-covered glacier outline, and ice divides

Two types of validation on glacier outline positioning accuracy

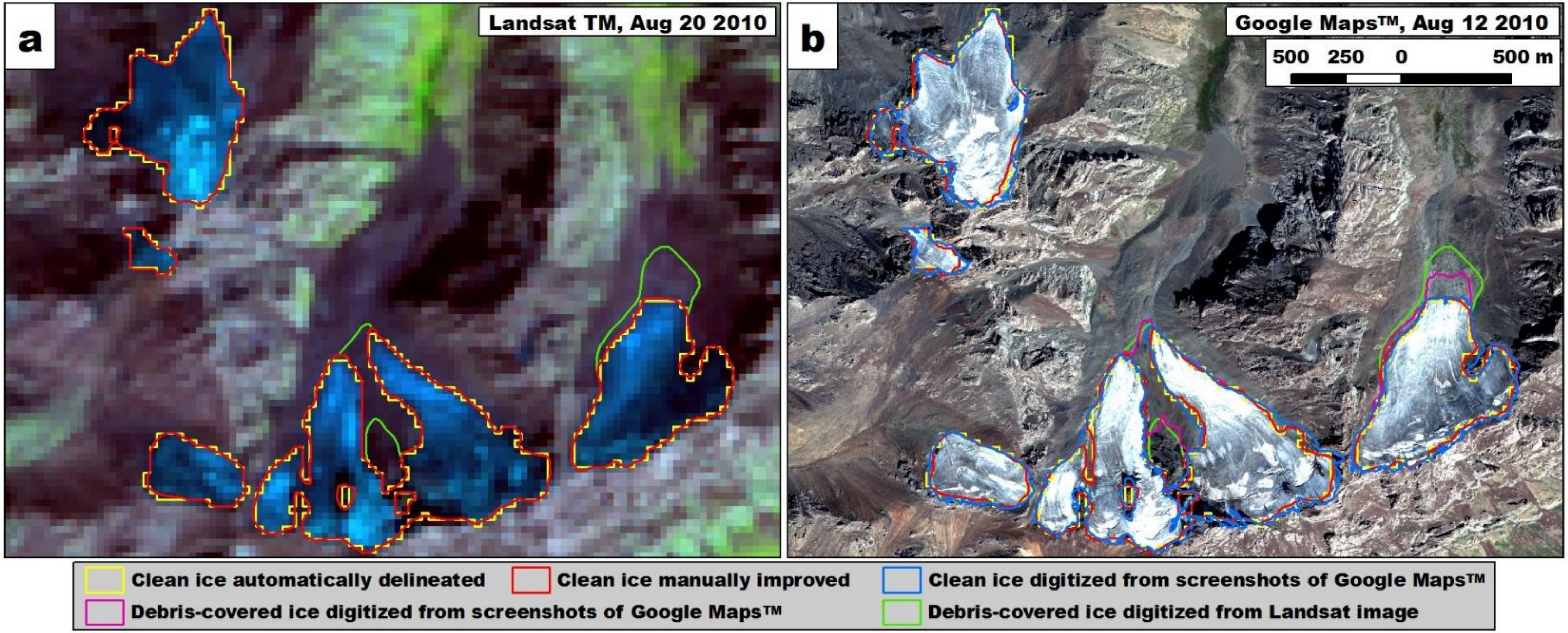
- Validated by in-situ RTK-GPS trace points along the glacier outline



Glacier Inventory

Two types of validation on glacier outline positioning accuracy

- Validated by comparison with the outline delineated from high resolution satellite images



Glacier Area Change

Using multi-temporary glacier inventories / glacier outlines

- Other attributes beside glacier area and/or length are not necessary, if simply study the glacier areal change

Glacier change error assessments

$$E_{AC} = \sqrt{E_{A_1}^2 + E_{A_2}^2}$$

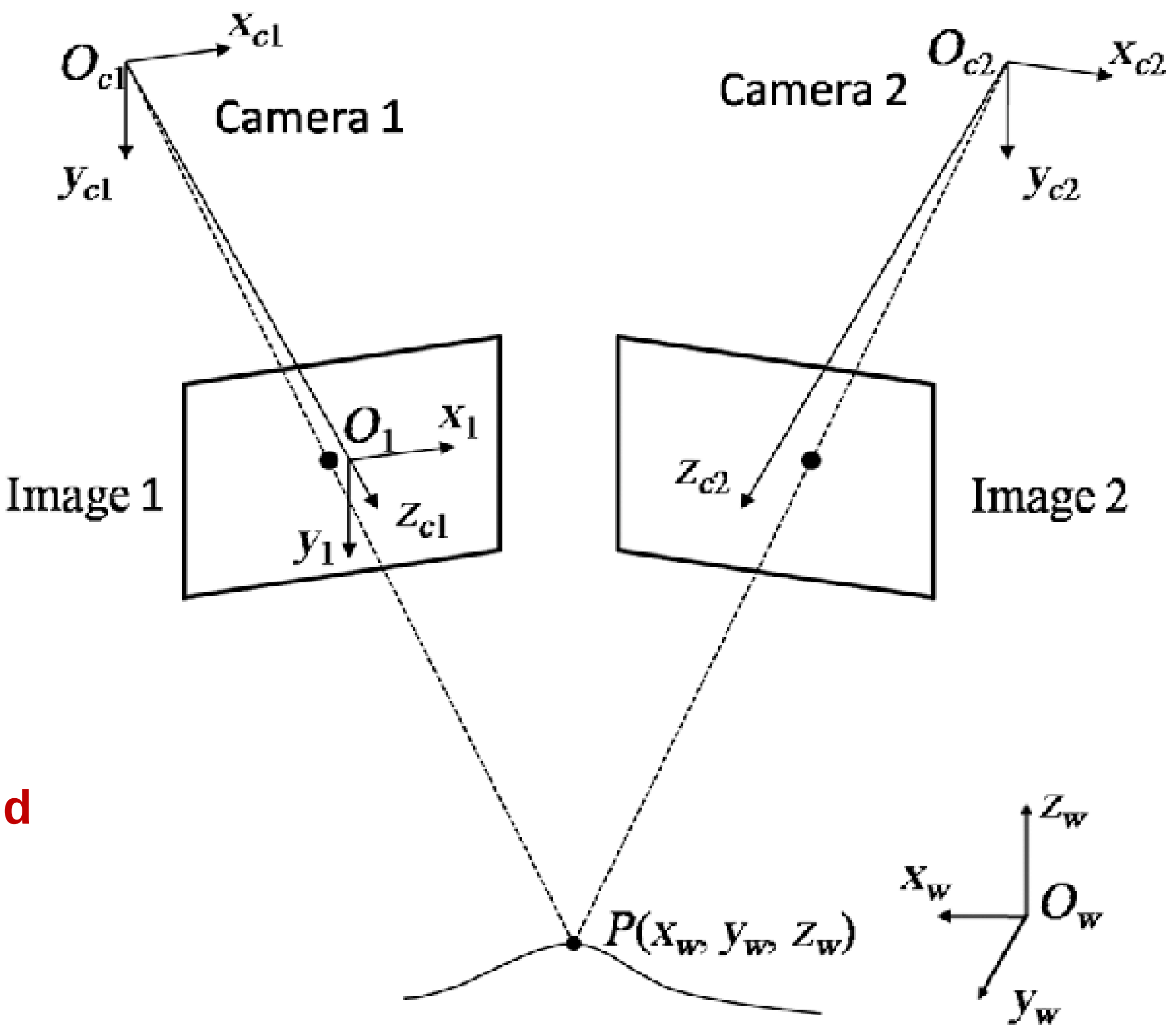
– E_{AC}: Glacier area change error

– E_{A1}, E_{A2}: Uncertainties of glacier areas at two time points

Glacier Volumetric Change

Theoretical Basis

- Based on geometric relationship between different cameras / sensors
- Need precise location, angle (interior and exterior) of cameras / sensors
- Retrieve the surface elevation by the parallax on images captured by different cameras / sensors

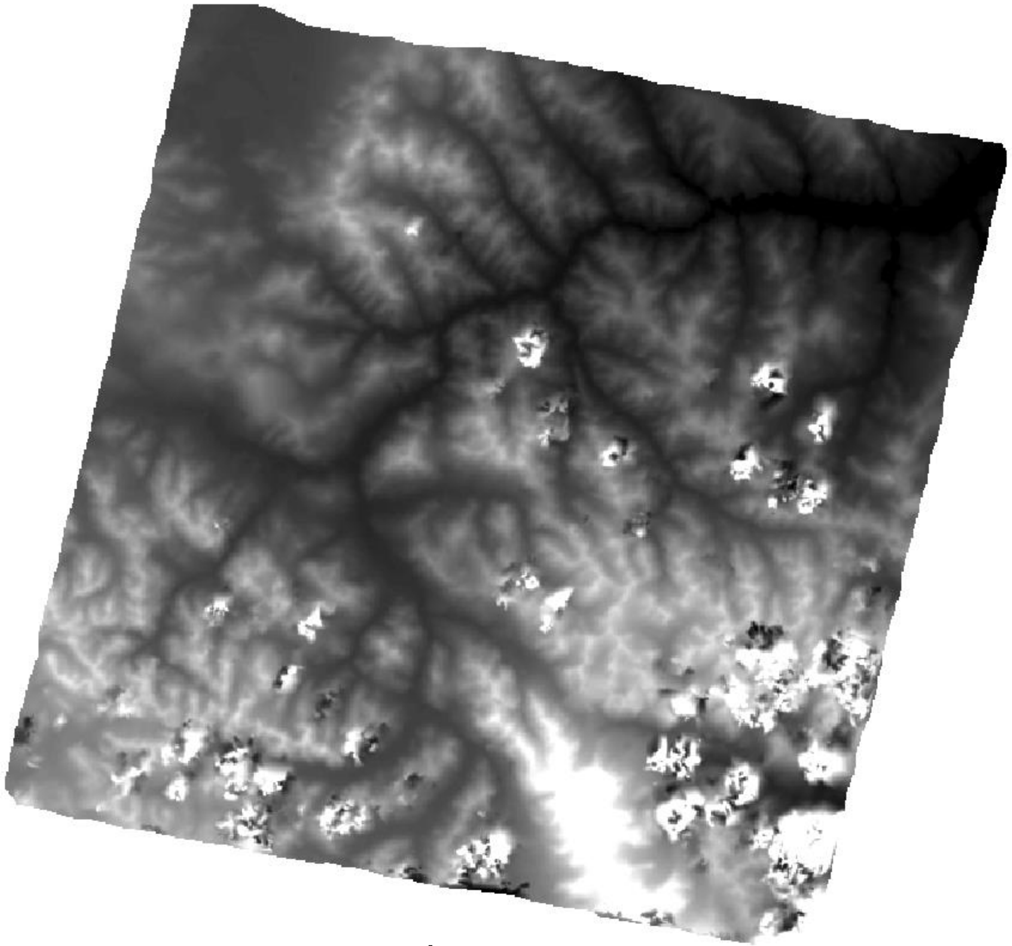


Shortcomings:

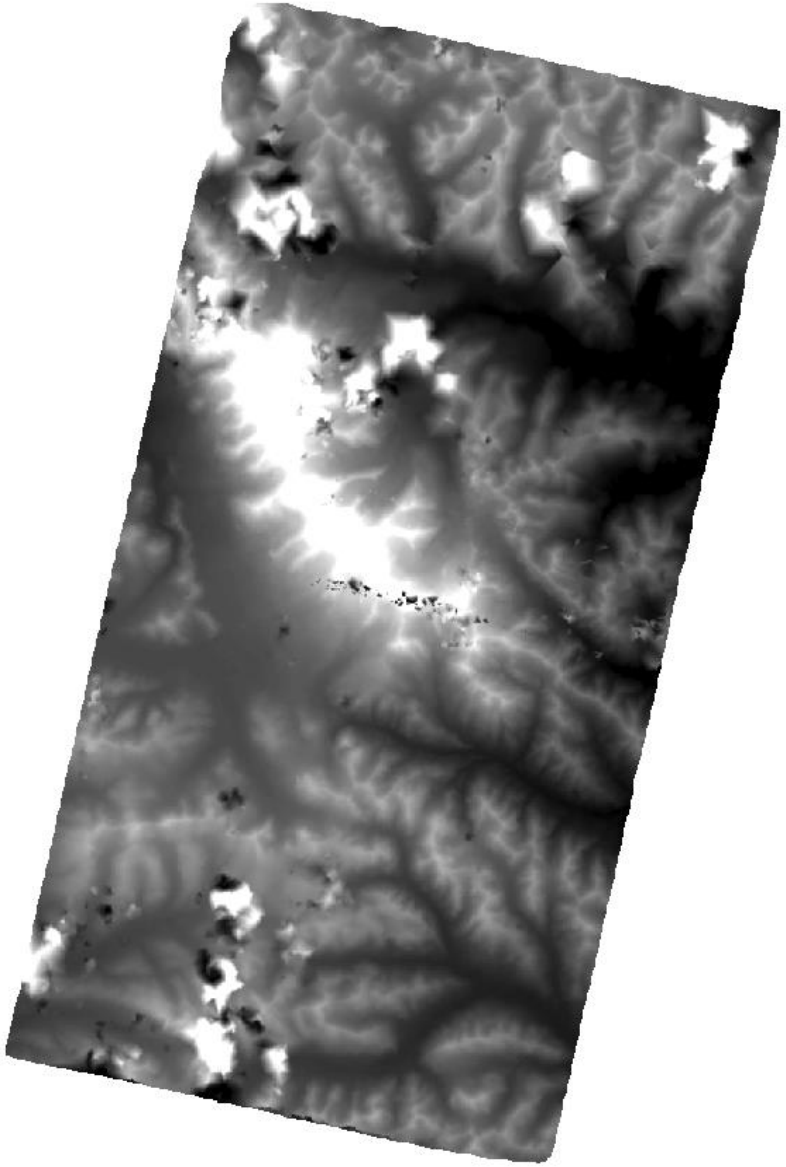
- **Can be easily affected by clouds, cast shadow, and terrain overly**
- **Have higher requirements on the radiometric resolution of cameras / sensors (to avoid spectral oversaturation)**

Glacier Volumetric Change

Examples of spaceborne photogrammetry



Terra/ASTER DEM

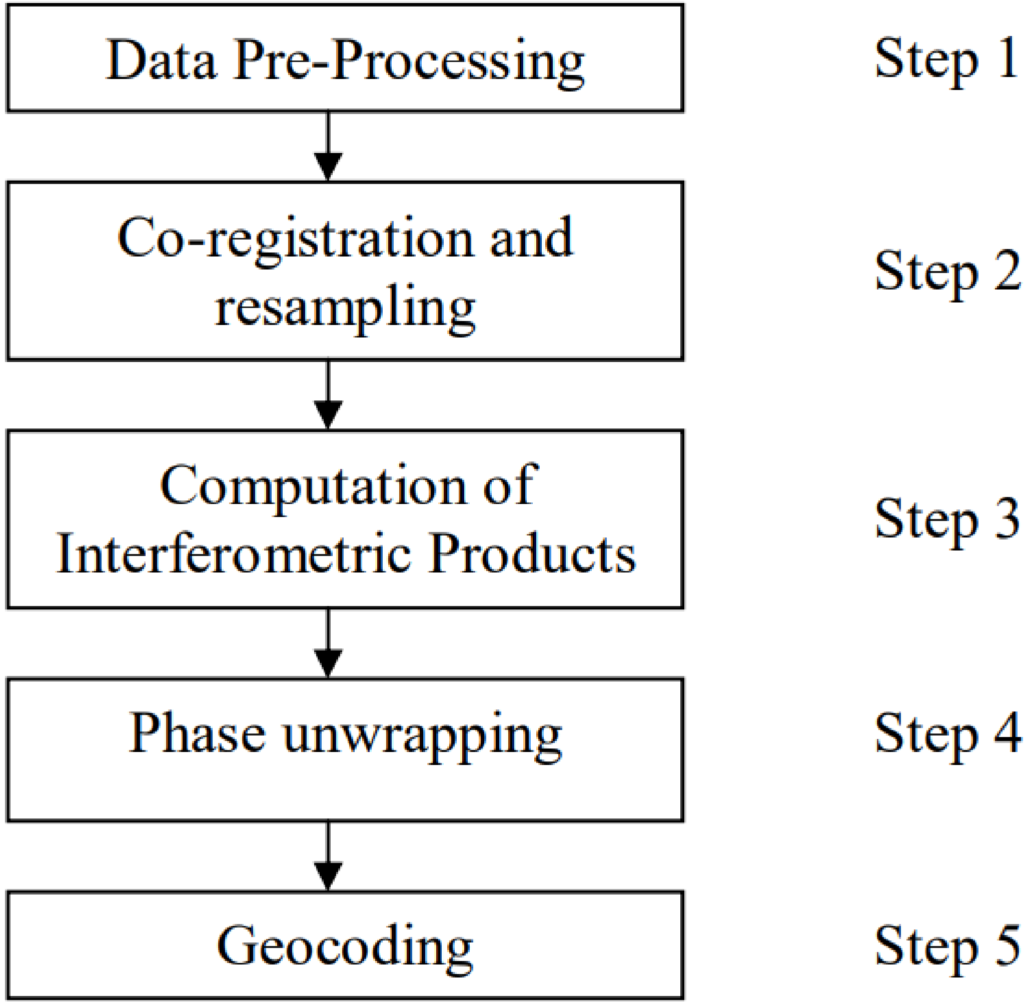


IRS/P5 DEM

Glacier Volumetric Change

Theoretical Basis

- SAR images consist magnitude (brightness) and phase value, described as being complex
- The phase value in complex SAR image contains information about the distance to the ground, and the texture of the terrain
- Unwrapping the phase value from the interferogram image will provides the information about ground surface elevation

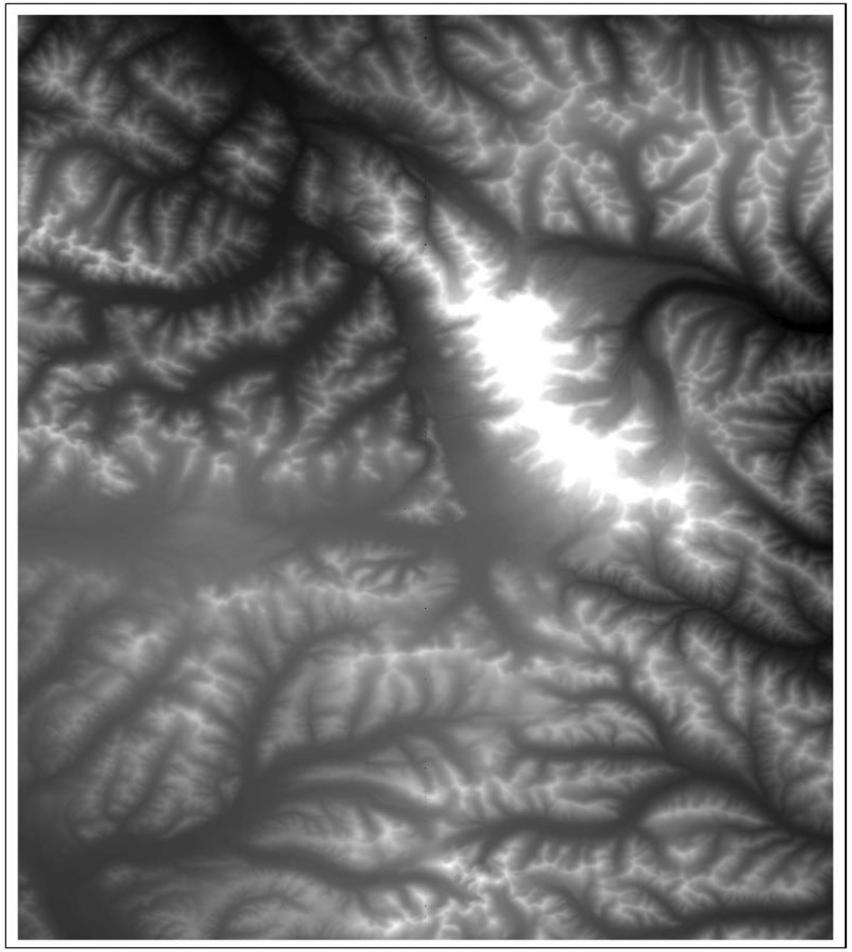


Shortcomings:

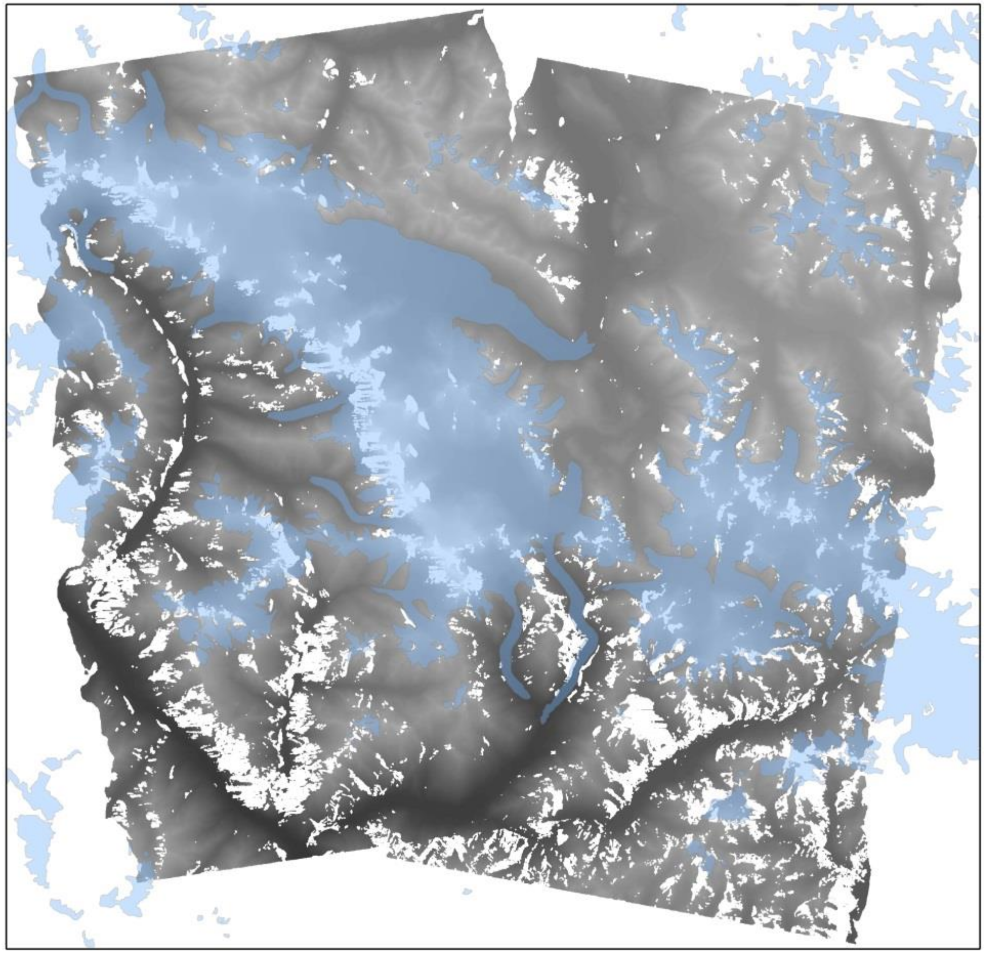
- Processing is relatively computational laborious
- Penetration of microwave into snow/ice
- Can be strongly affected by topographical overlay

Glacier Volumetric Change

Examples of spaceborne InSAR DEM



TerraSAR/TanDEM, Anyemaqen, 2013



TerraSAR/TanDEM, Gangrigabu, 2014

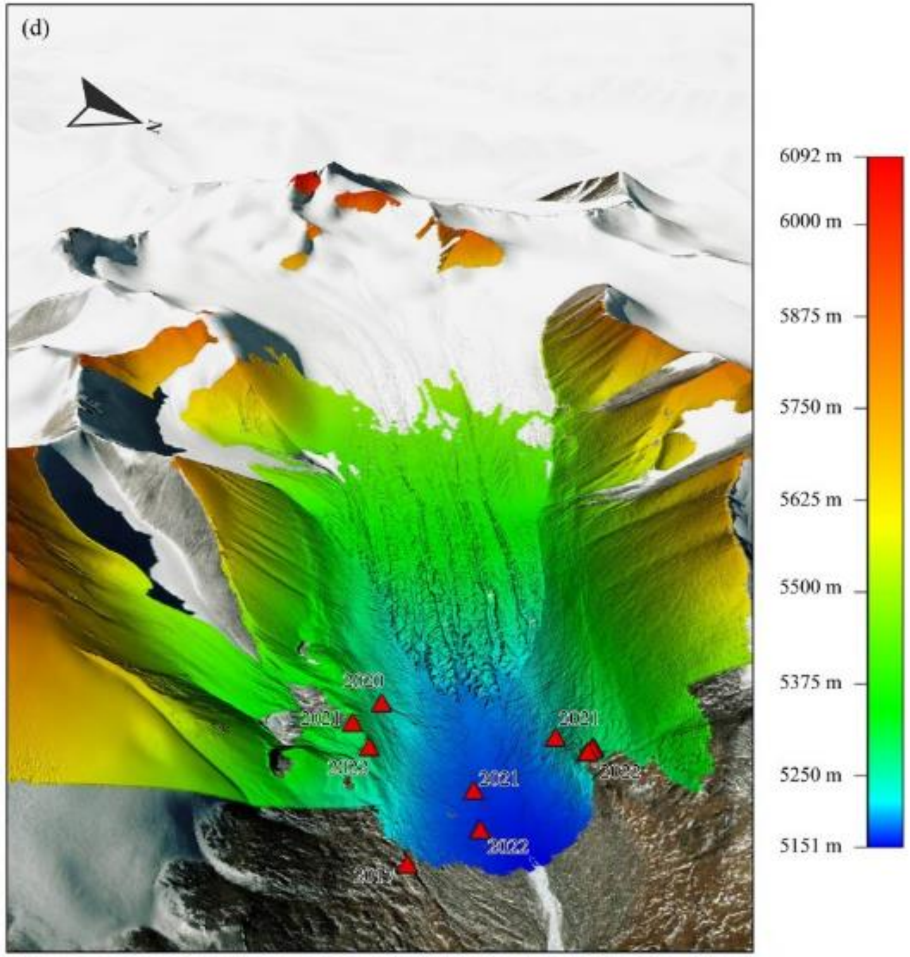
Glacier Volumetric Change

Theoretical Basis

- Calculating the surface elevation by transmission time of laser beam between the sensor and surface based on their geometric relationships

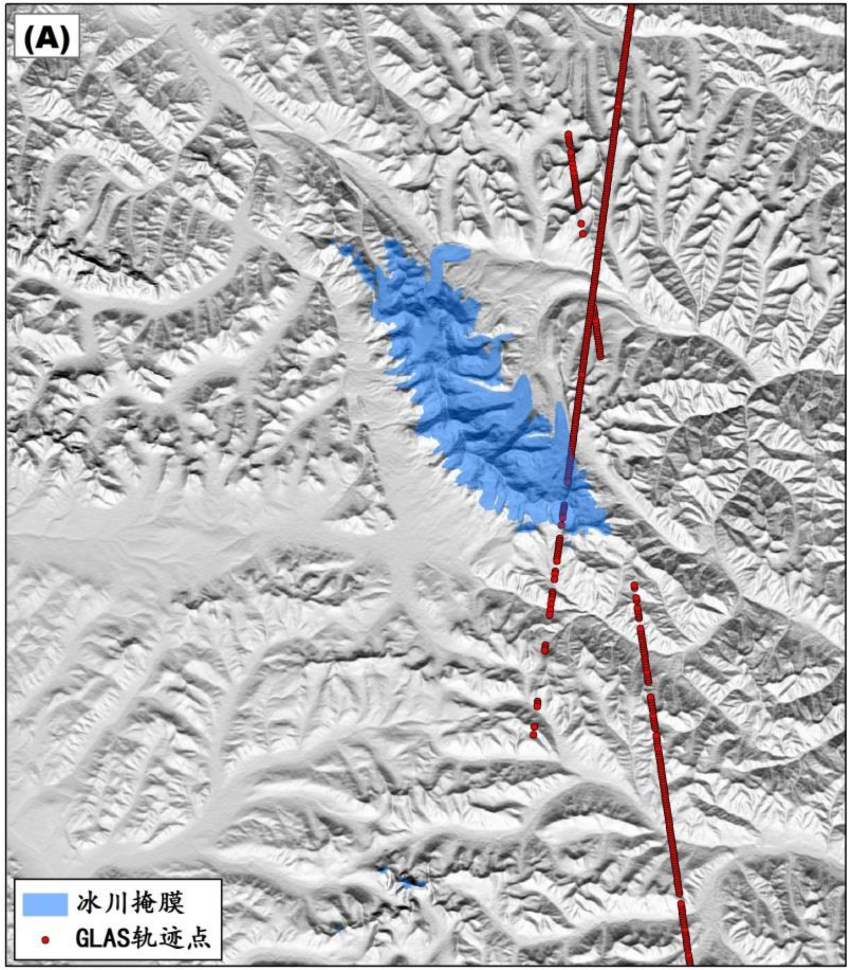
Shortcomings:

- The location of sensor need to be very precise
- Ease to be affected by fogs, clouds, and topographical overlay
- Spaceborne laser altimeter has limited coverage on glacier

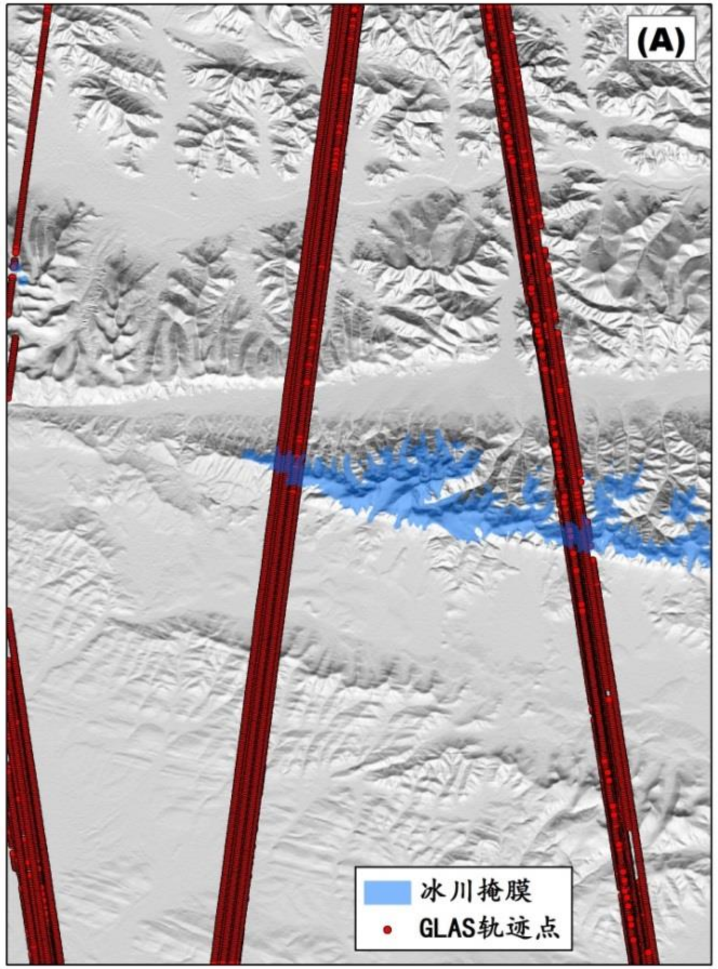


Glacier Volumetric Change

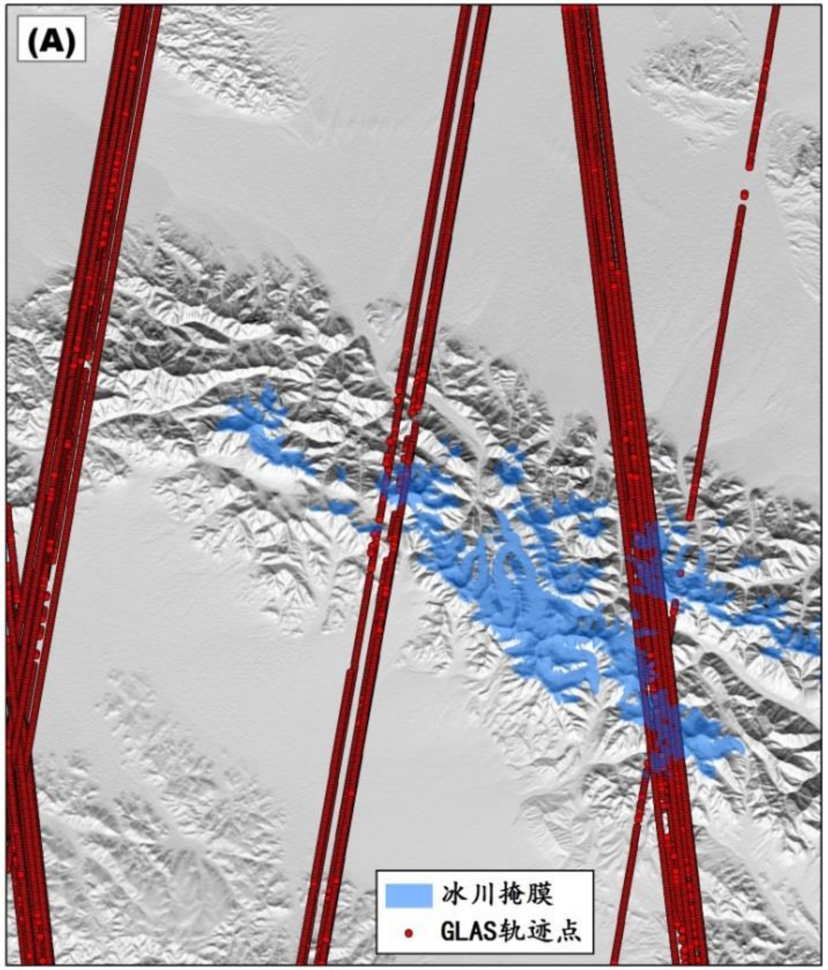
Examples of ICESat/GLAS footprints distribution



Anyemaqen, Kunlun Mountain



Yuzhufeng, Kunlun Mountain

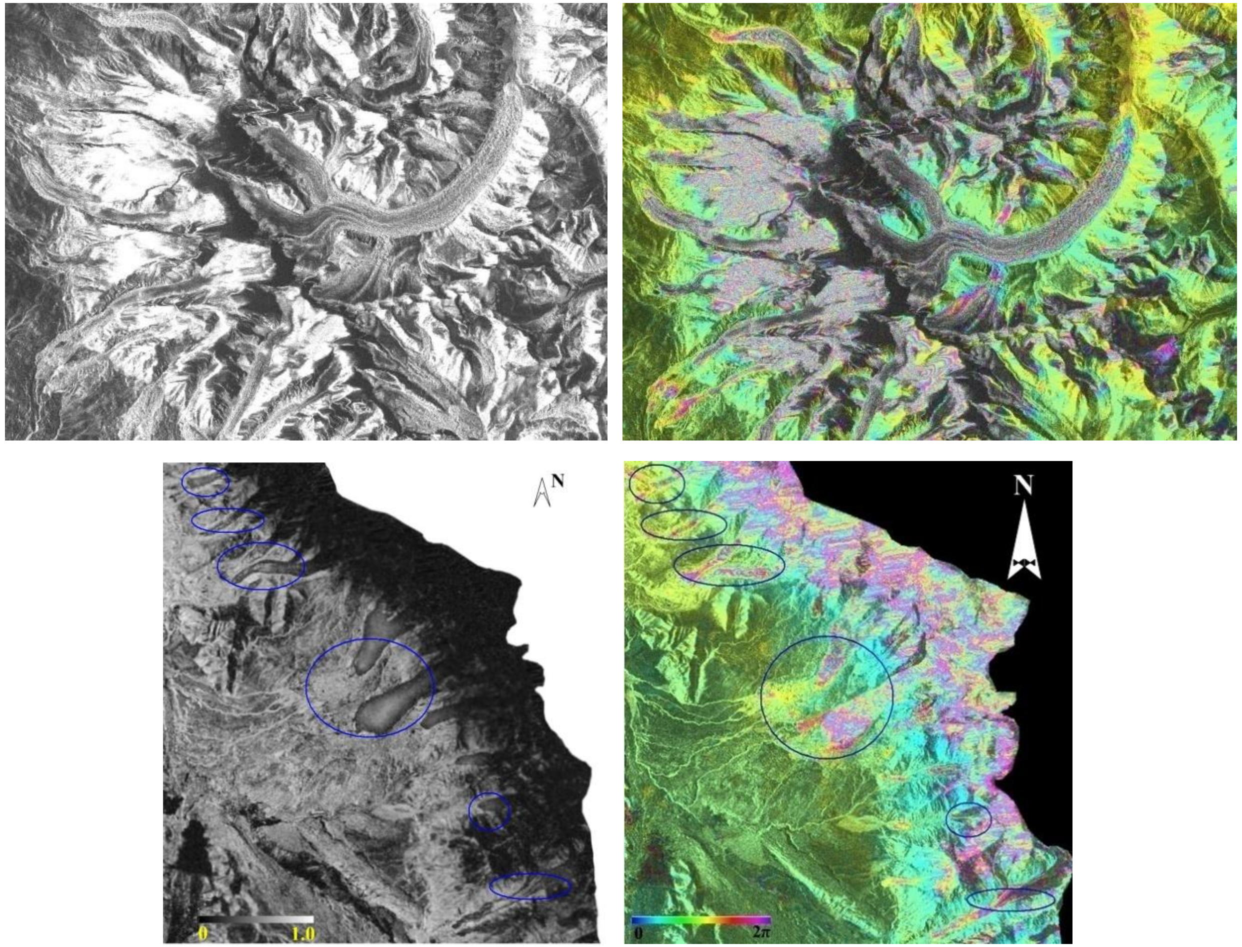


Daxueshan, Qilian Mountain

Glacier Flow Velocity

Theoretical Basis

- The InSAR interferogram image can also be used to decoding the 3-D surface changes, in case of two SAR images were capture at different time points



Shortcomings:

- Cannot generate the interferogram image due to larger glacier surface change caused low coherence between two SAR images acquired with long time interval

Interferogram and interferometric fringe, Kongur Muntain

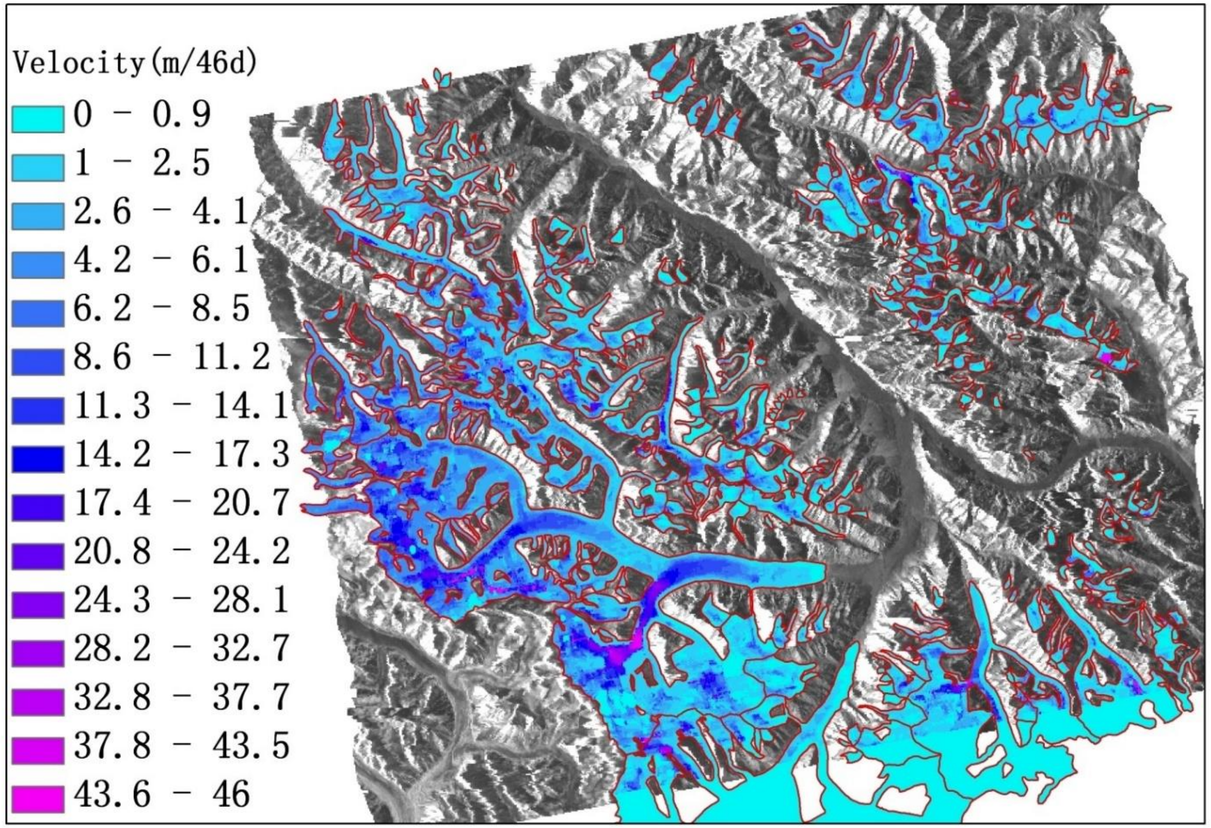
Glacier Flow Velocity

Theoretical Basis

- The InSAR interferogram image can also be used to decoding the 3-D surface changes, in case of two SAR images were capture at different time points

Shortcomings:

- **Cannot generate the interferogram image due to larger glacier surface change caused low coherence between two SAR images acquired with long time interval**

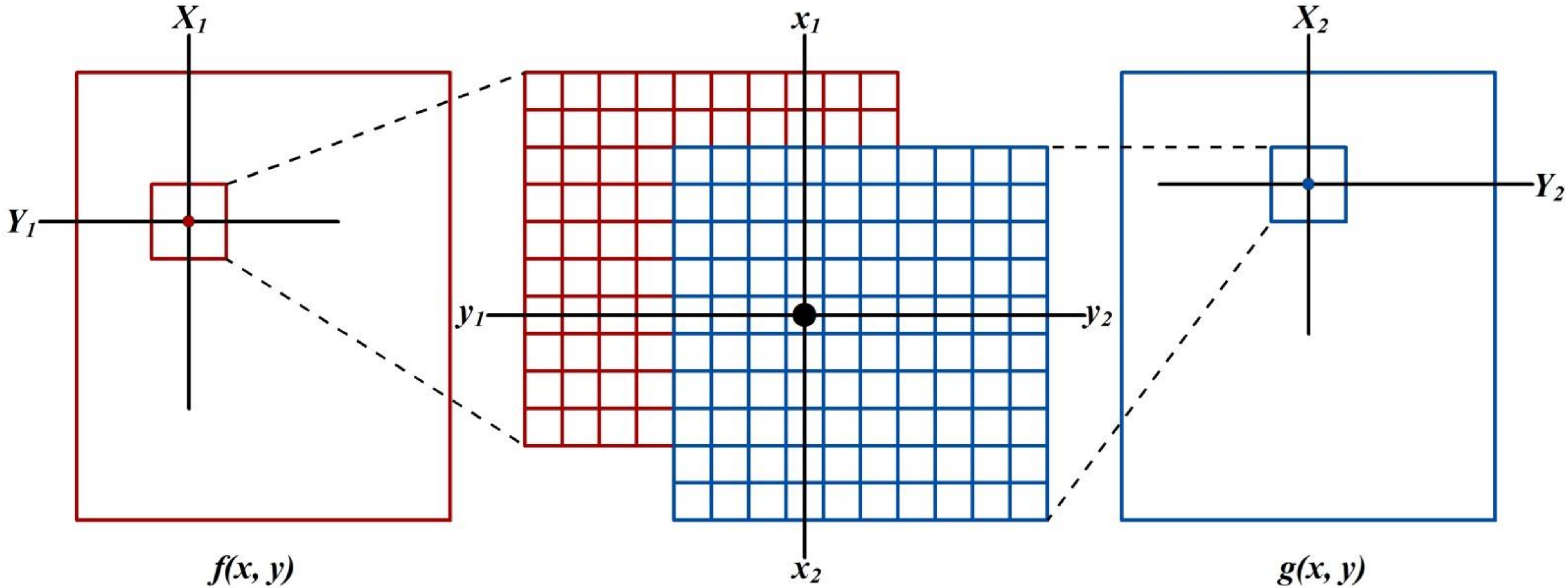


InSAR velocity, Kongur Muntain

Glacier Flow Velocity

Theoretical Basis

- The glacier surface textures are moving together with glacier flow
- The change in surface texture can be ignored by algorithm in relatively shorter time period
- Both SAR and optical images can using this method to extract glacier surface speed



Glacier Flow Velocity

Theoretical Basis

- The glacier surface textures are moving together with glacier flow
- The change in surface texture can be ignored by algorithm in relatively shorter time period
- Both SAR and optical images can using this method to extract glacier surface speed

$$R(x_1, y_1, x_2, y_2) = \frac{\sum_{i=-\frac{m}{2}}^{\frac{m}{2}} \sum_{j=-\frac{n}{2}}^{\frac{n}{2}} \{[f(x_1+i, y_1+j)-\bar{f}] \cdot [g(x_2+i, y_2+j)-\bar{g}]\}}{\sqrt{\sum_{i=-\frac{m}{2}}^{\frac{m}{2}} \sum_{j=-\frac{n}{2}}^{\frac{n}{2}} \{[f(x_1+i, y_1+j)-\bar{f}]^2 \cdot [g(x_2+i, y_2+j)-\bar{g}]^2\}}}$$

- $f(x_1, y_1)$, $g(x_2, y_2)$: pixel values at (x_1, y_1) location on master and (x_2, y_2) on slave images
- $\bar{f}$, $\bar{g}$: mean pixel value in the searching window on the master and slave images
- m, n: width and height of the searching window

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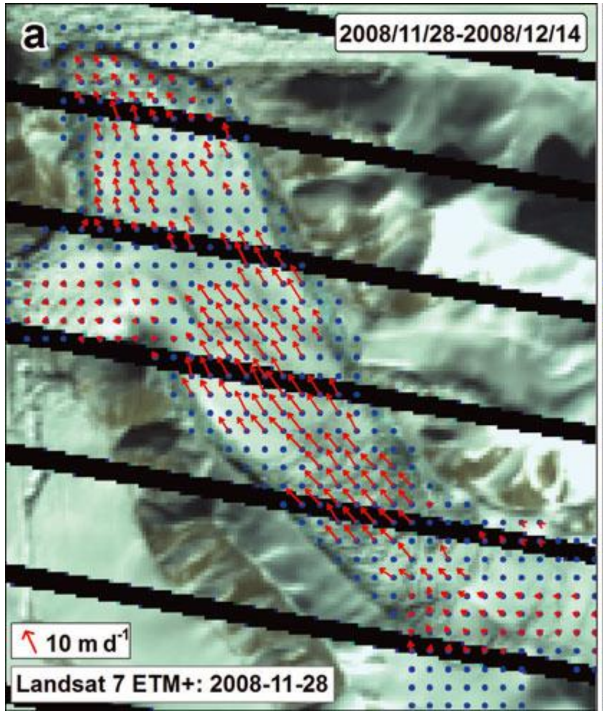
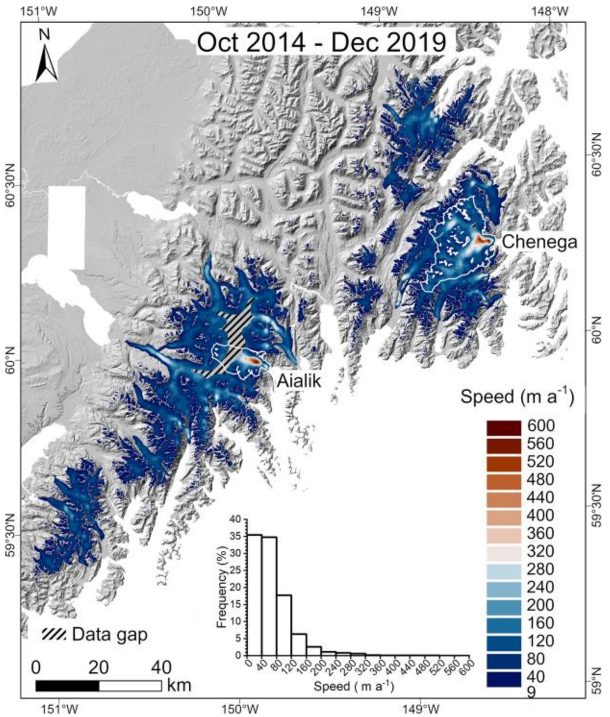
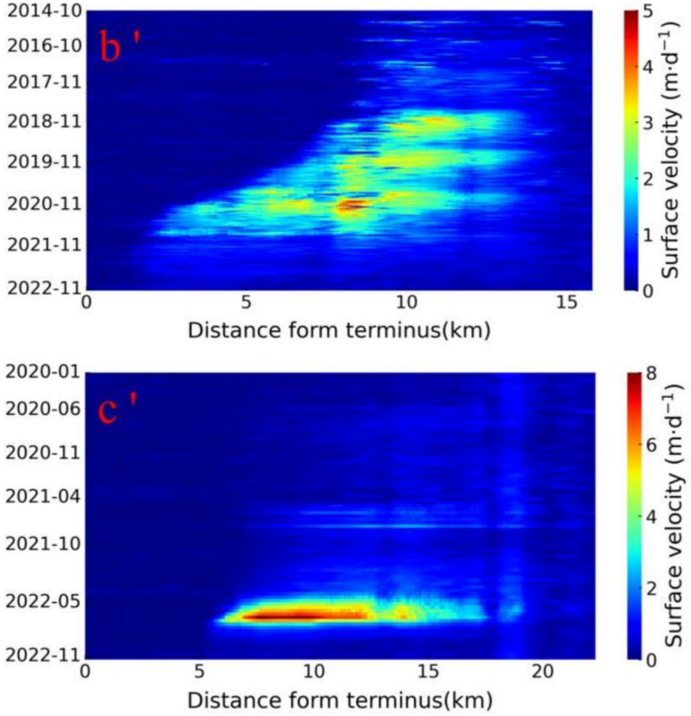


Point-wise velocity, Muztag



Surficial velocity, Kenai, Alaska



Profile velocity change, west Kunlun

Thanks for your attention!

Any suggestion and question are welcomed!