Ph.D Defence

Monitoring of Glacier Dynamics using Synthetic Aperture Radar techniques

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Importance of Glacier studies

- Glaciers are natural indicators of climate change
- Glacier fluctuations (changes in glacier area, position, terminus, and mass balance) are frequently used to illustrate the consequences of climatic fluctuations
- Glaciers act as a double-edged sword

  - Hydropower generation, irrigation, drinking water
  - Natural disasters like GLOF and avalanches, but their biggest impact is yet to come: through SLR

- **Glacier velocity** is one of the most fundamental parameters in the study of ice dynamics (Jiskoot, 2011)

Glacier movement

- The ice flow velocity is a basic feature of glaciers and it is one of the most fundamental parameters in the study of ice dynamics
- The surface velocity of the glacier refers to the combination of both Internal deformation and basal sliding
- **Internal deformation**: Deformation/distortion of ice within the glacier; **basal sliding**: Sliding over its bed
- The flow at each point is a **function of the thickness and surface slope** (Nye, 1960)

$$\boxed{U_s = U_b + \frac{2A}{n+1} \tau_b{}^n H}$$

$$\boxed{\tau_b = f \rho g \mathrm{H} \sin \alpha}$$

U_s and U_b: Surface and basal velocity respectively A:creep parameter, *f*:shape factor *n*:Glenn constant g:acceleration due to gravity, *H*:ice thickness, α :surface slope (Paterson, 1981)

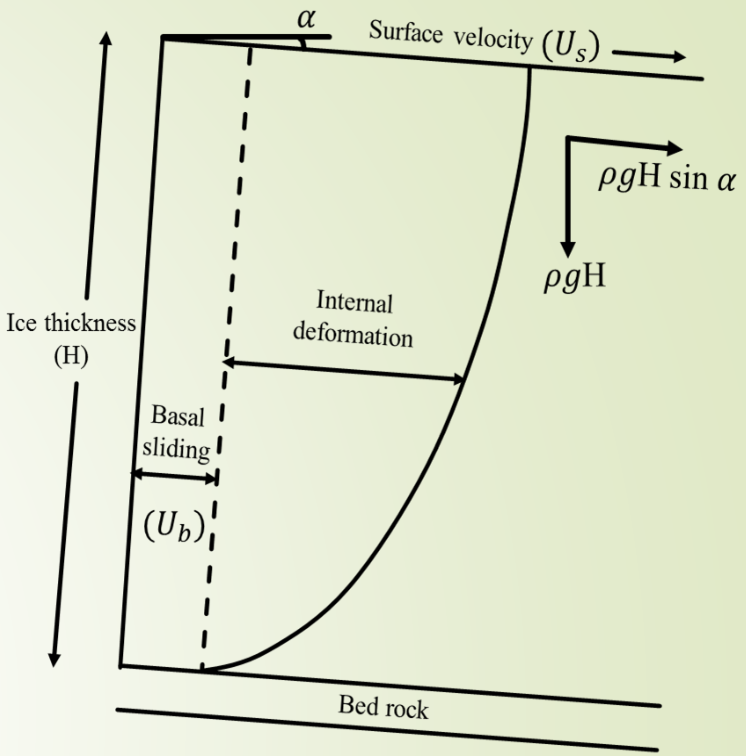
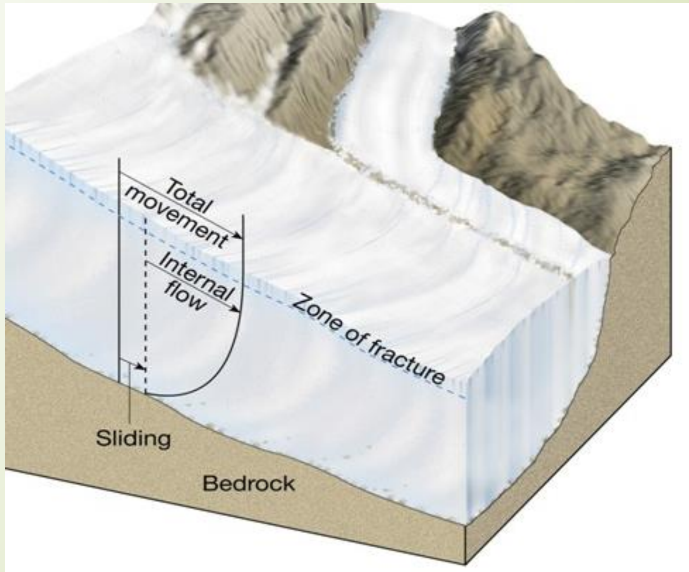


Figure: Schematic diagram of glacier surface velocity distribution



Methods for monitoring glacier velocity

- Field based techniques

  Theodolite and triangulation, GPS

- Remote sensing techniques

  DInSAR (uses phase information of SAR images) → **2-pass** (uses external DEM) / **3-pass** (external DEM not required)

  The 3-pass DInSAR technique for glacier velocity estimation was no longer used after the termination of ERS tandem mission

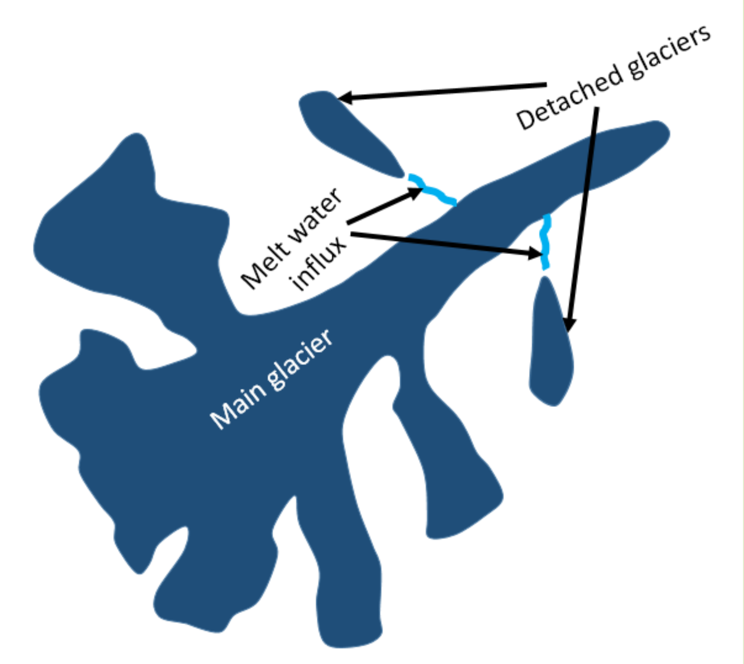
  Offset tracking (uses amplitude/intensity information)

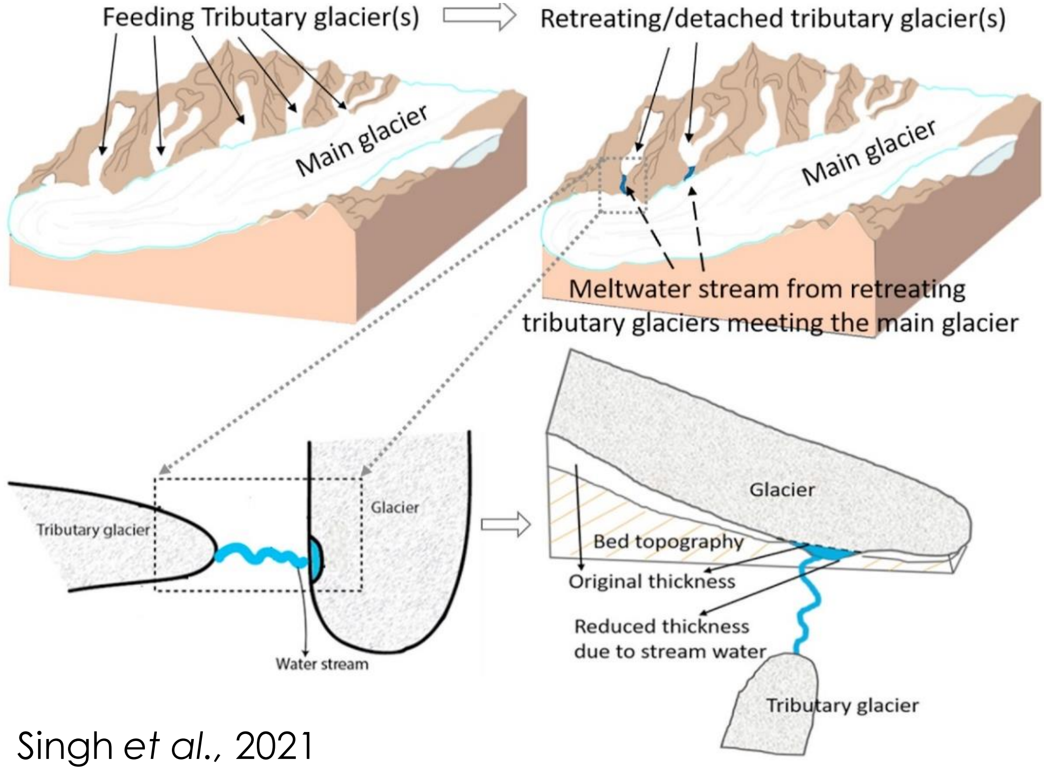
Motivation

- The glacier system behaviour in the Himalaya is sparsely studied using the DInSAR technique (Yellala et al. 2019)
- The complex, heterogeneous behaviours and unclear trends in glacier movement studies using DInSAR have not yet been performed in the large scale
- Retreat/detached tributaries of glacier and influences of their discharged water were not yet considered to explain and understand the acceleration of glacier flow and collapsing of glaciers
- **It is therefore necessary to understand the role of water discharge from adjacent tributary glacier in glacier dynamics**

Melt water discharge from tributary glaciers

- Water discharge from the tributary glacier effects the main glacier
- Influx of melting water from adjacent glaciers is major cause for anomalous dynamics of glaciers
- The melt water influx can play an important role in changing the glacier velocity and ice thickness





Singh *et al.*, 2021

3-Pass DInSAR

- The absence of any external DEM improves the accuracy of surface movement (Bishop et al. 2011)
- The uncertainties present in the interferometric phase measurement may prevent the identification of displacements smaller than 2 cm (Hoffmann and Zebker, 2003)
- Significant glaciers/ice caps/ice sheets surface elevation changes are reported worldwide (Moholdt et al. 2012)
- Glacier surface changes are not accounted for the topographic phase removal steps of the 2-pass DInSAR

Research Questions

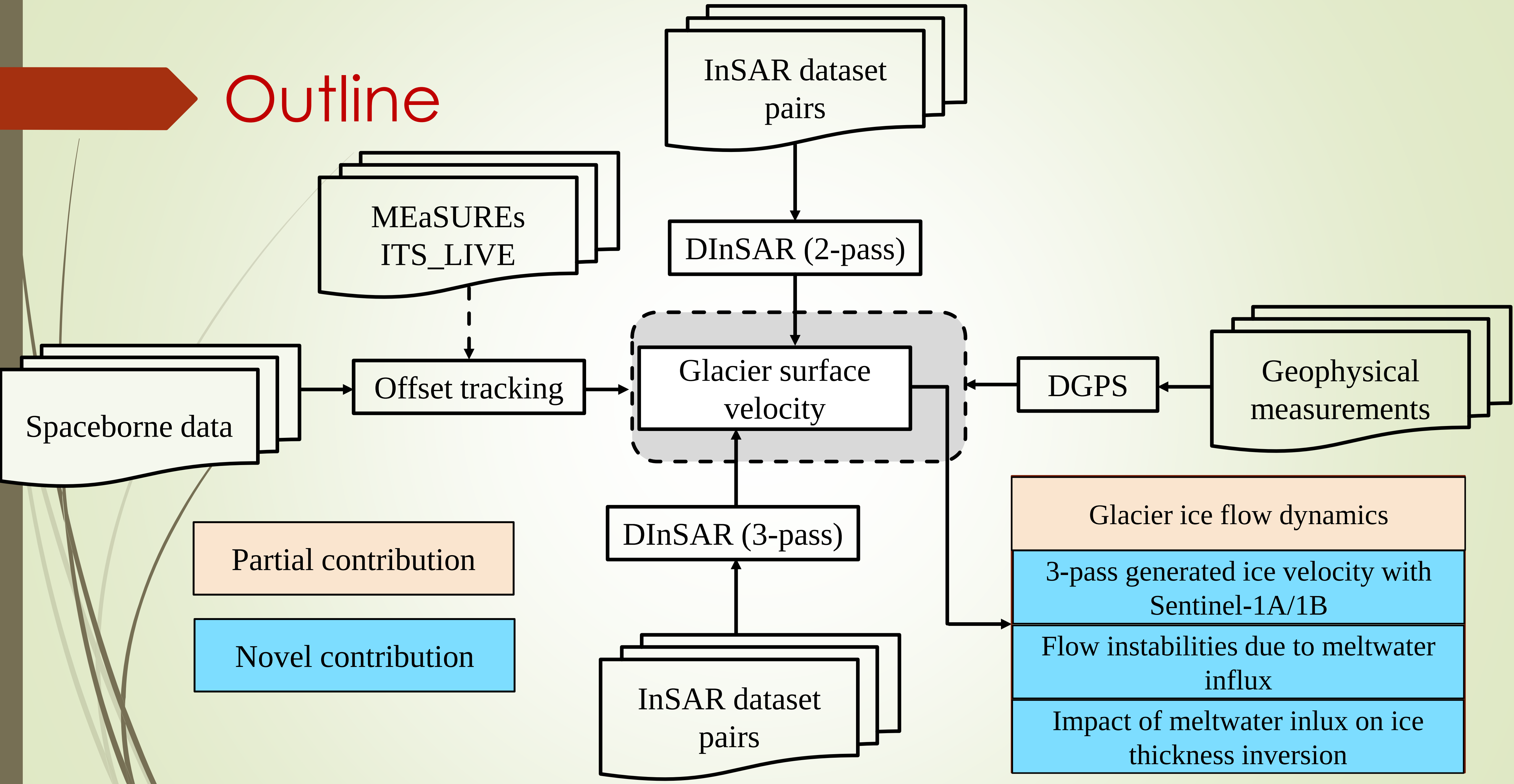
The research done under the scope of this thesis seeks to answer the following questions:

- How does the 2-pass DInSAR technique help to understand the heterogeneous glacier dynamics?
- How does the meltwater influx from adjacent tributary glaciers affect the ice flow velocity and retrieval of glacier parameters using SAR remote sensing?
- Can the 3-pass DInSAR technique be applied operationally to map glacier flow and spatial distribution of irregular behaviour of glacier dynamics?

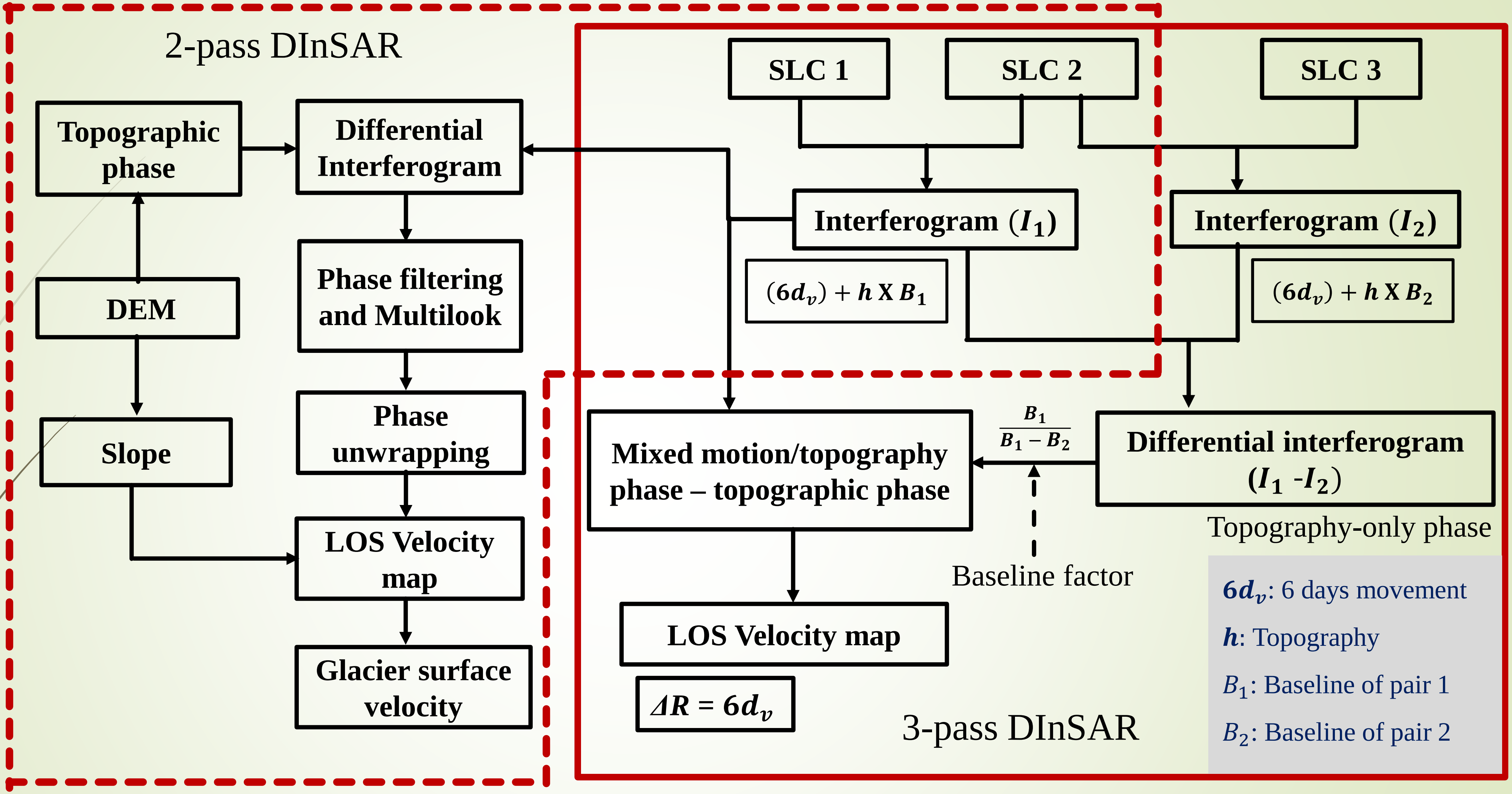
Research Objectives

- Study the heterogeneous pattern of glacier ice flow dynamics and disintegration behaviour in glaciers using the 2-pass Differential SAR Interferometry (DInSAR) technique
- Study the impact of meltwater influx on glacier flow dynamics using DInSAR
- Retrieval of glacier ice velocity using 3-pass DInSAR
- Monitoring the effect of glacier surface elevation change on retrieval of glacier movements using 2-Pass DInSAR
- Assessment of the influence of tributaries glacier meltwater influx on glacier ice thickness inversion

Outline


InSAR dataset pairs
DInSAR (2-pass)
MEaSUREs ITS_LIVE
Spaceborne data
Offset tracking
Glacier surface velocity
DGPS
Geophysical measurements
DInSAR (3-pass)
InSAR dataset pairs
Partial contribution
Novel contribution
Glacier ice flow dynamics
3-pass generated ice velocity with Sentinel-1A/1B
Flow instabilities due to meltwater influx
Impact of meltwater inlux on ice thickness inversion

Methods



Copland *et al.*, 1997

$$\text{LOS } (\Delta r) = \frac{\lambda}{4\pi}\,\Delta\phi_{unw}\ ;\ \text{Glacier surface velocity} = \frac{\Delta r}{\cos\alpha\cos\Psi\sin\theta + \cos\theta\sin\alpha}$$

Data sets

- ALOS-2/PALSAR-2: **L-band**
  - **2-pass DInSAR**
  - Minimum temporal baseline: **14 days**
  - Chandra and Bhaga sub-basins
  - Severnaya Zemlya archipelago
- Sentinel-1A/1B: **C-band**
  - **3-pass DInSAR**
  - Minimum temporal baseline: **6/12 days**
  - Svalbard archipelago
- DGPS: Validation purpose
  - **Hamtah glacier**
  - July 2019
- TanDEM-X DEM
  - Topo-phase removal in **2-pass**
  - Chandra and Bhaga sub-basins
- ASTER DEM
  - Topo-phase removal in **2-pass**
  - Severnaya Zemlya archipelago
- ArcticDEM
  - Topo-phase removal in **2-pass**
  - Svalbard archipelago

Chapter 1

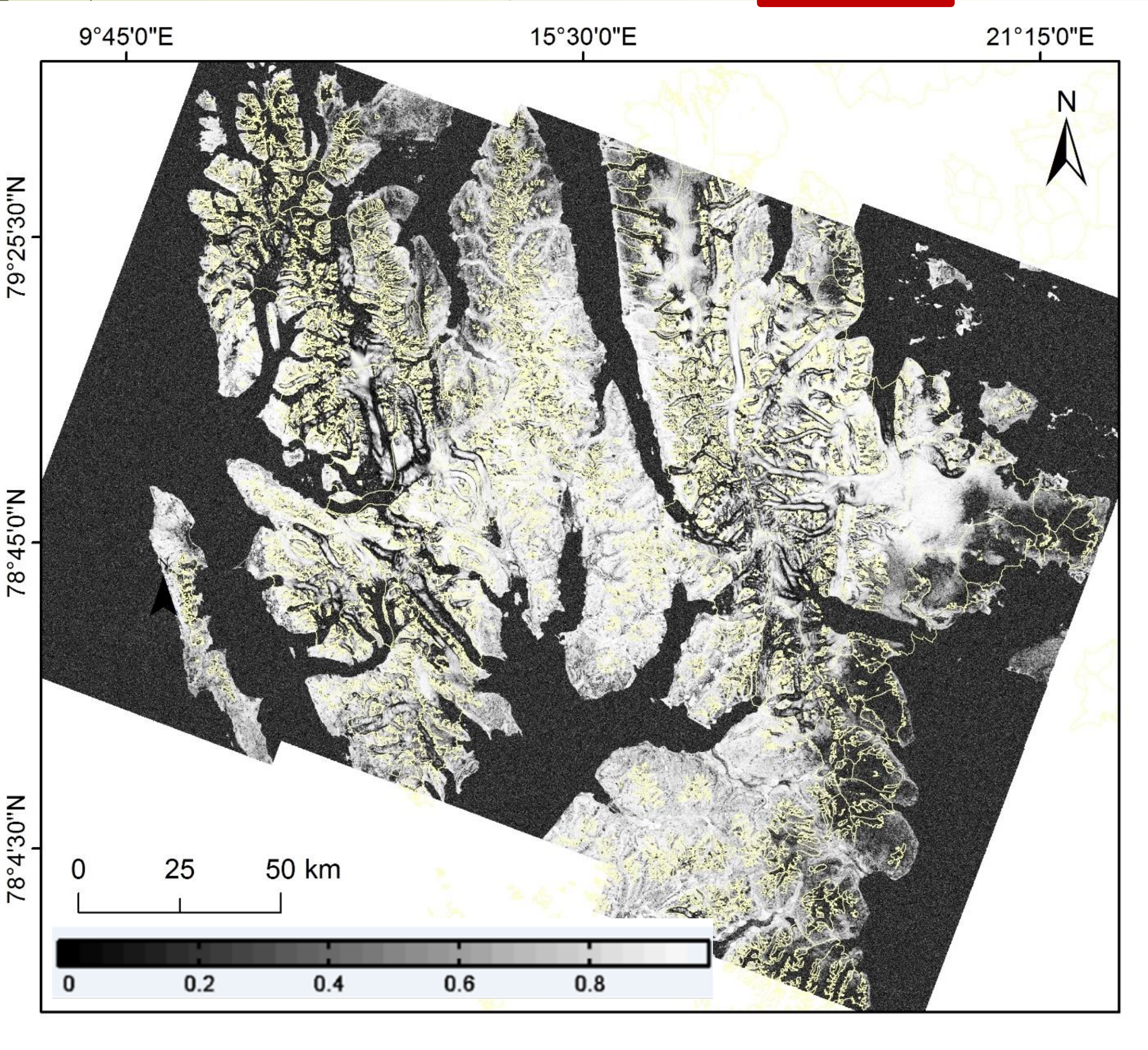
Optimum conditions to measure glacier velocity using Differential SAR Interferometry (DInSAR)

- Temporal Baseline
- Wavelength
- Polarization

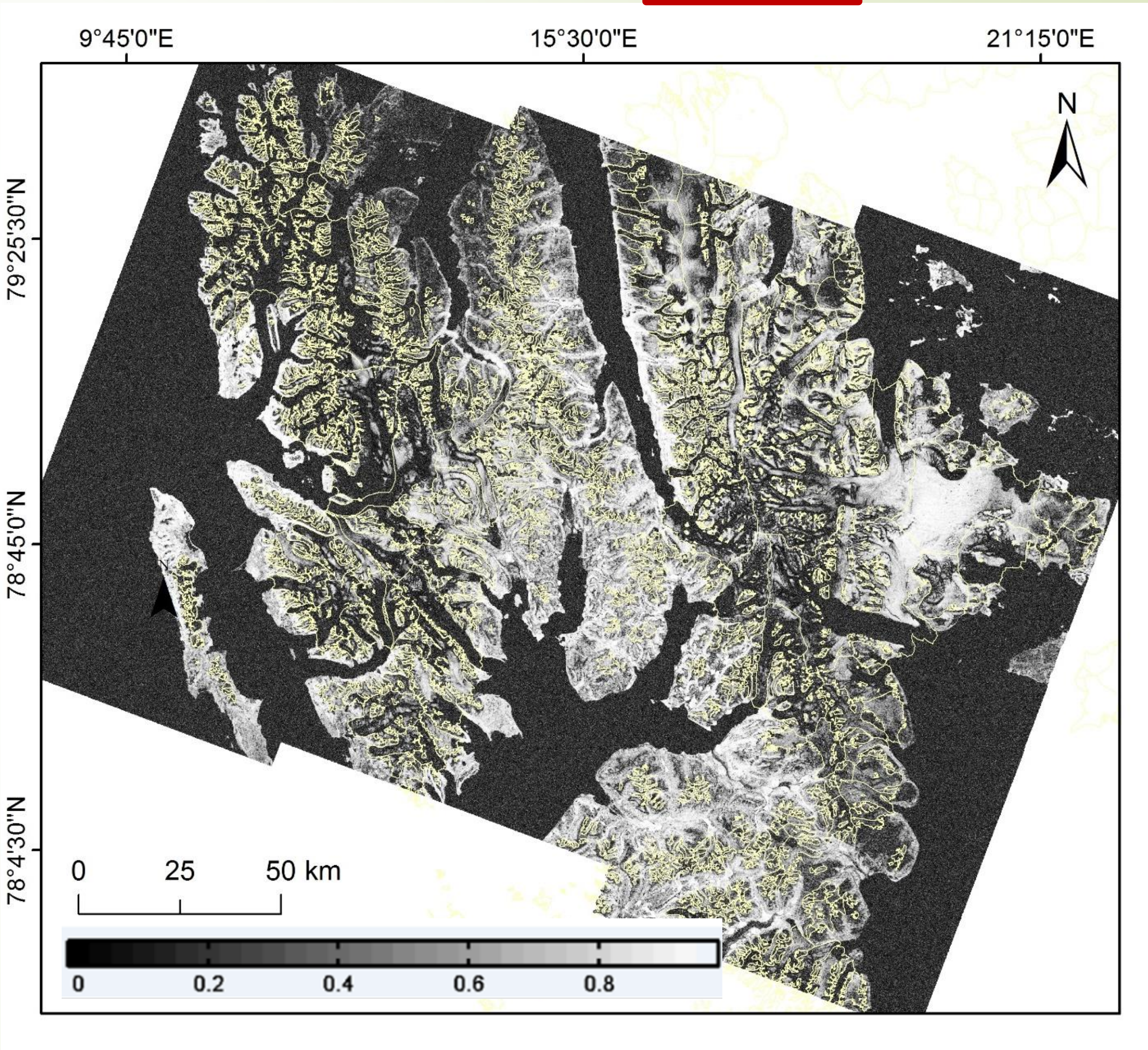
Spitsbergen region, Svalbard (Sentinel-1A C-band)

Temporal

8 and 14 October 2020 (6 days)



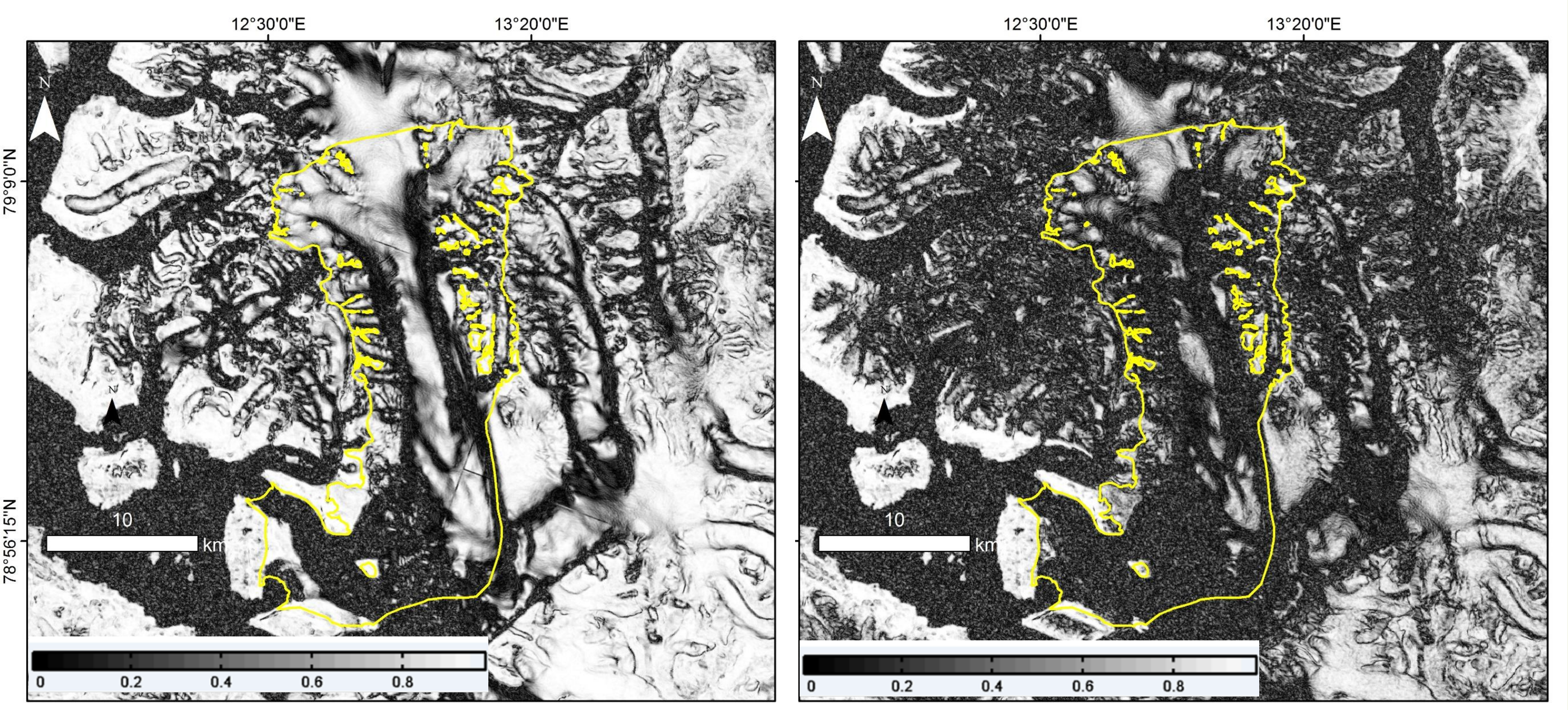
2 and 14 October 2020 (12 days)



Kongsbreen glacier, Svalbard (Sentinel-1A C-band)

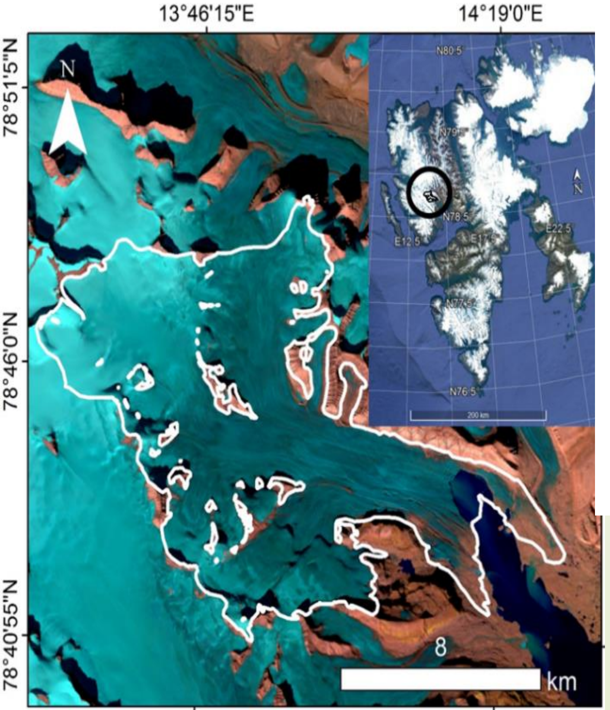
Temporal

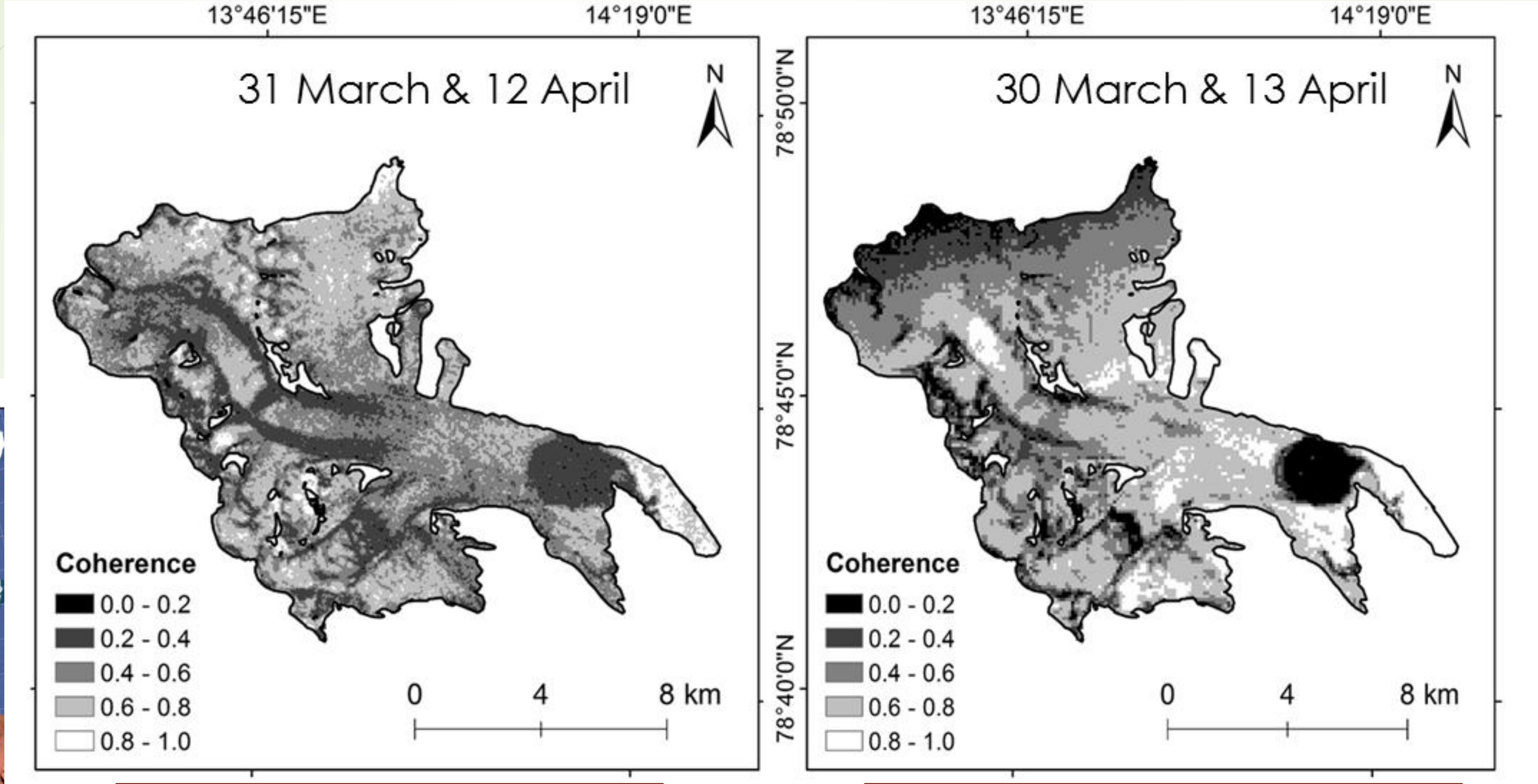
8 and 14 October 2020 (6 days) | 2 and 14 October 2020 (12 days)



Sefströmbreen glacier, Svalbard

Wavelength



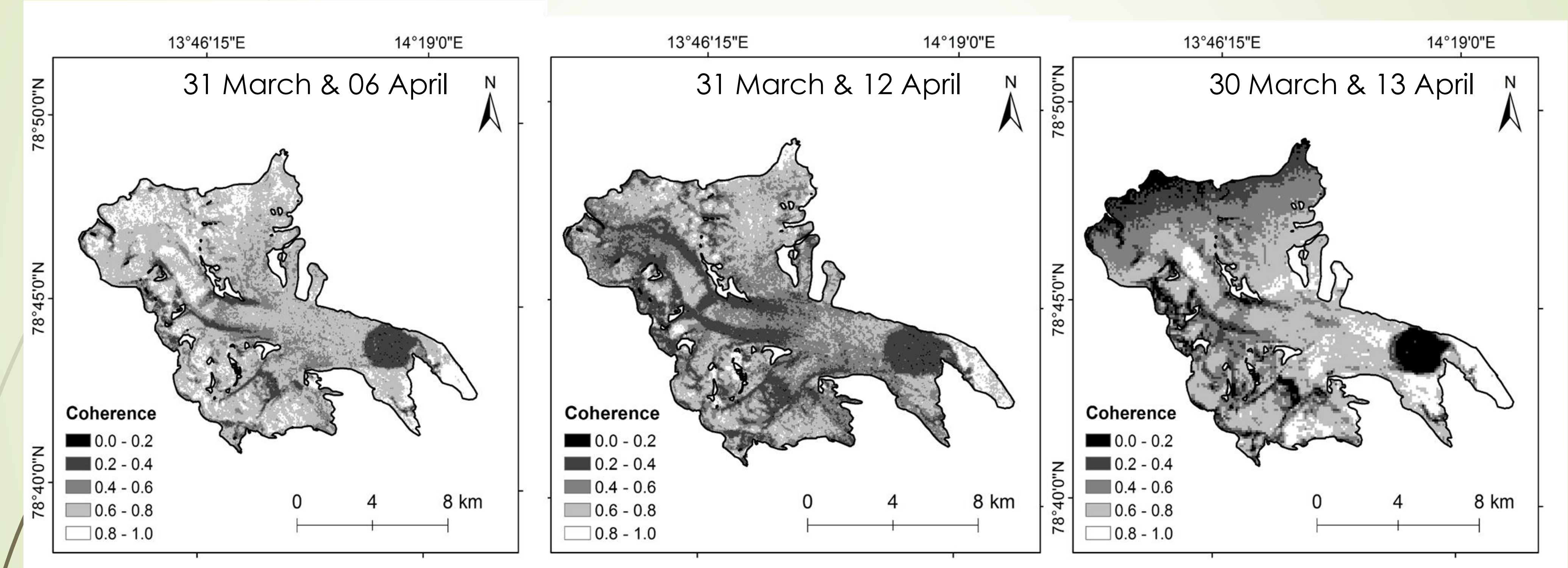


Sentinel-1A (12 days)

ALOS-2/PALSAR-2 (14 days)

Coherence

Sefströmbreen glacier, Svalbard



Sentinel-1A/1B (6 days) Sentinel-1 (12 days) ALOS-2/PALSAR-2 (14-days)

Polarization

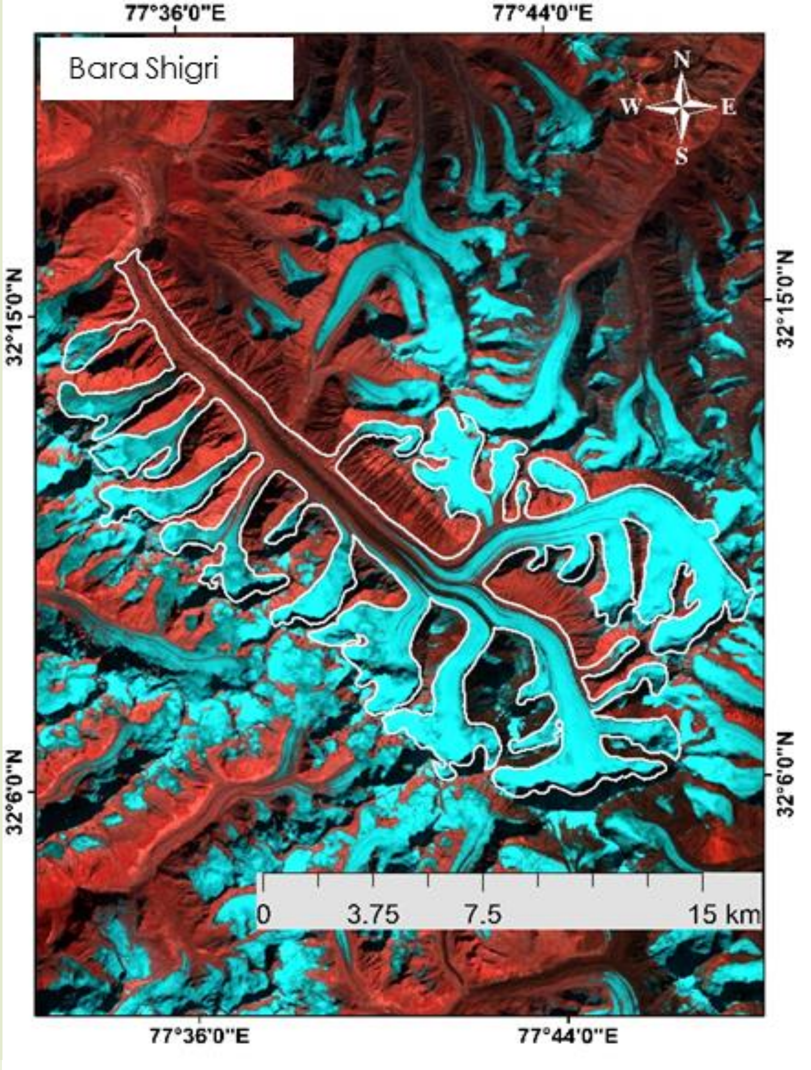
Data used

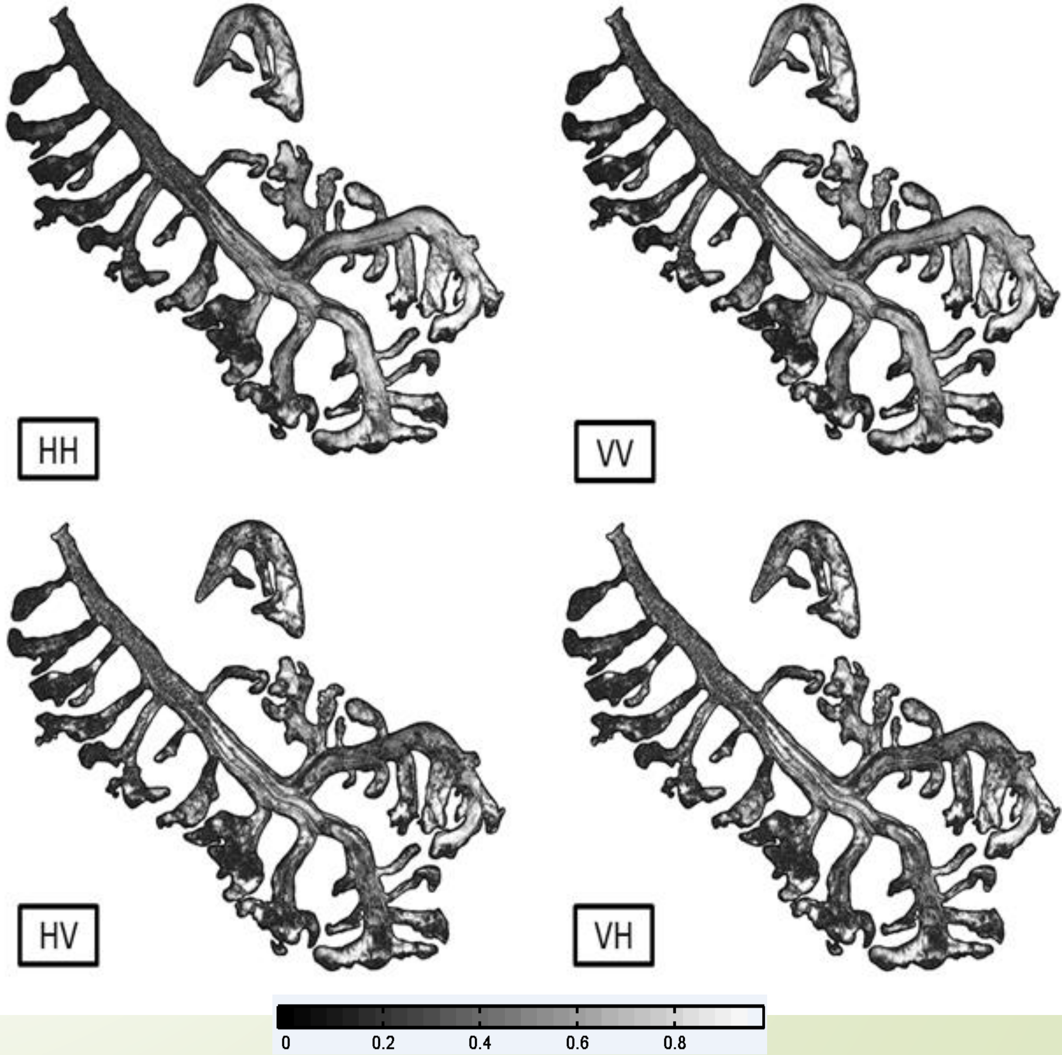
Data	Dates	Look angle	Perpendicular Baseline (m)	Pass	Temporal Baseline (Days)	Polarization
ALOS-2 (L band)	25th Mar 2016	32.7	0	ASC	0	Quad Pol
	08th Apr 2016	32.7	178.8	ASC	14	Quad Pol

ALOS-2/PALSAR-2 L-band Quad polarization data

Polarization

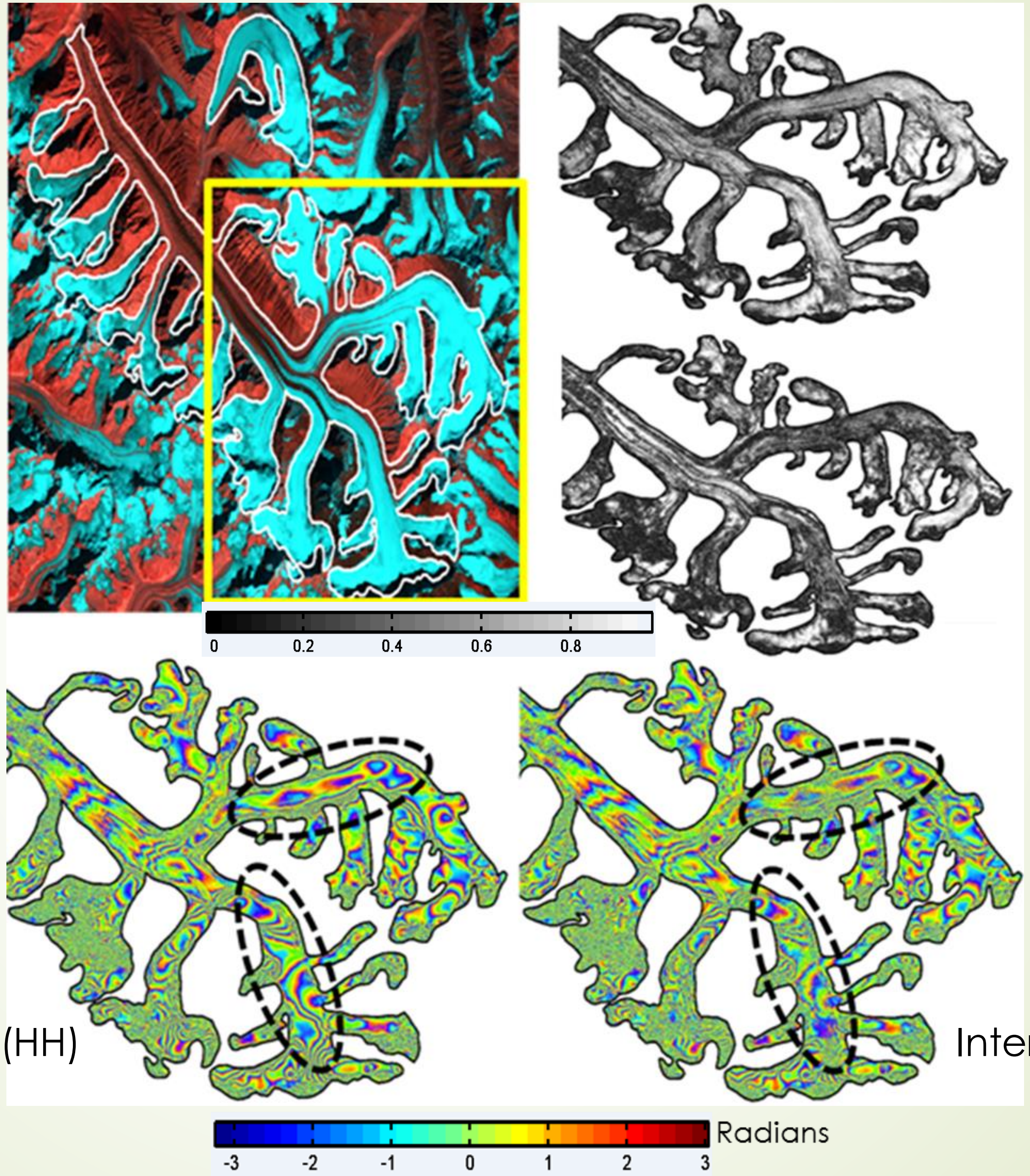
- Bara Shigri is the longest glacier in Chandra basin, Himachal Pradesh length nearly 28 km and area 126.5 km^2
- It Covered with snow, moraines, debris and sediments etc
- Therefore, it's perfectly suitable glacier to check the polarization effect





Polarization

HH polarization



Coherence (HH)

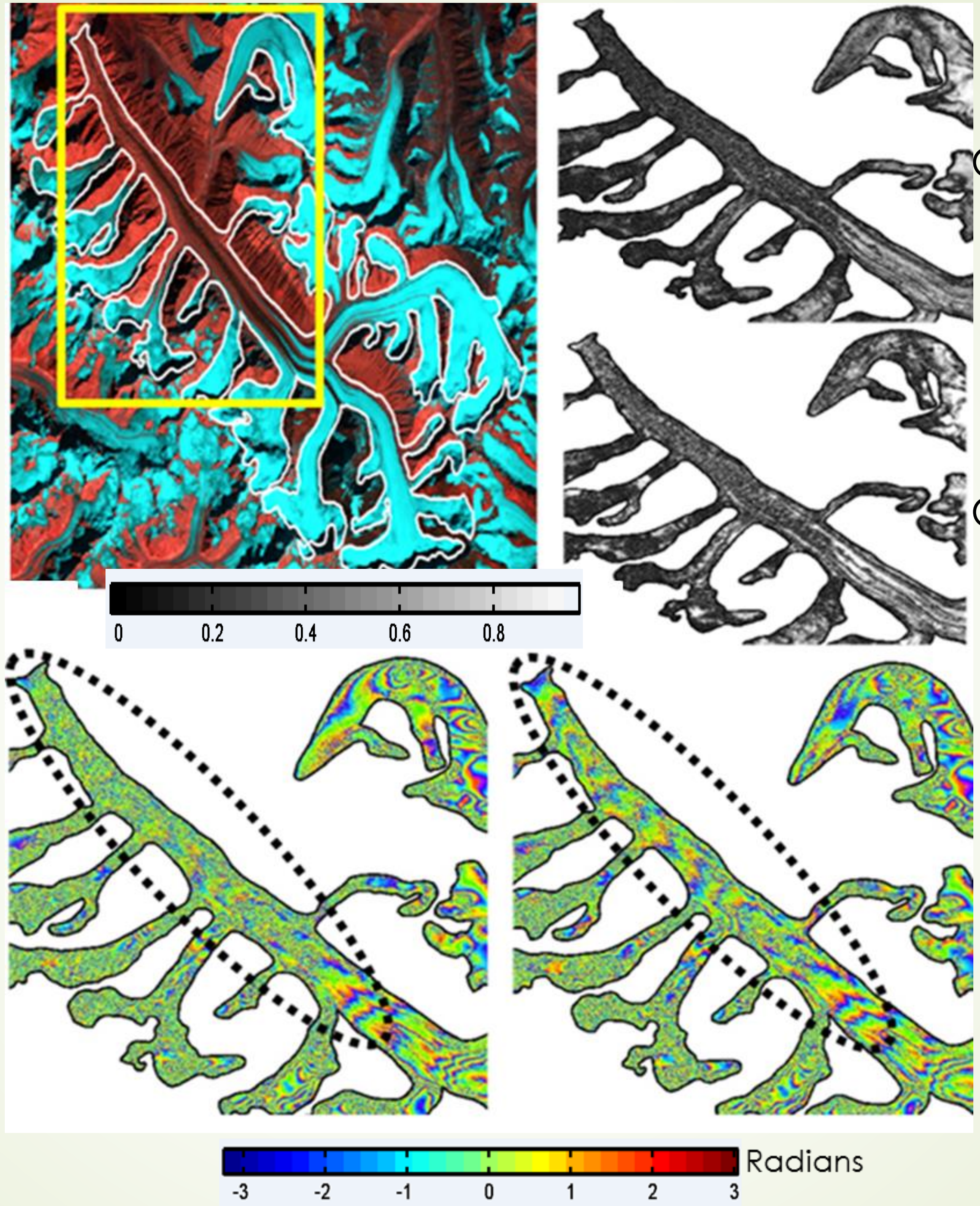
Coherence (HV)

Interferogram (HH)

Interferogram (HV)

Polarization

HV polarization



Coherence (HH)

Coherence (HV)

Interferogram (HH)

Interferogram (HV)

Summary

- The **L-band** is preferable for velocity mapping to avoid the temporal instabilities of the glacier ice over a long period to overcome the decorrelation problems
- But after launching the ESA **Sentinel-1A/1B** satellite, it is providing the data with minimum temporal baselines (**6-days**)
- Co-polarized (HH and VV) channels giving high coherences for the snow-covered area. While cross-polarized (HV and VH) channels giving high coherences for the debris-covered area

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OPTIMUM CONDITIONS FOR DIFFERENTIAL SAR INTERFEROMETRY TECHNIQUE TO ESTIMATE HIMALAYAN GLACIER VELOCITY

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Commission V, SS: Natural Resources Management

KEY WORDS: SAR, DInSAR, glacier zones, glacier movement and Coherence.

ABSTRACT

Differential SAR Interferometry (DInSAR) is the process of differencing two Interferograms for measuring surface movement with an accuracy of millimeter range. The DInSAR process can be applied to observe glacier movement, earthquake deformations, volcanic activities and rate of subsidence or uplift caused due to the extraction of groundwater or coal. By using single pass interferometry technique we can also generate accurate DEM. In this paper, we are presenting the movement of a Chhota Shigri glacier with the help two pass DInSAR technique and mainly we concentrated on the optimum conditions for estimating glacier movement using DInSAR. We got good coherence and Interferogram fringes for L-band sensor with less temporal baseline. Therefore, we generated glacier velocity using ALOS-2 data with 14 days temporal baseline. Initially, we generated Interferogram (defo-pair) by taking 10th March 2015 image as a master and 24 th March 2015 image as a slave. But this generated Interferogram also having topographic information and atmospheric errors with the displacement component. Therefore, we used SRTM DEM for removing topographic information from the Interferogram. Because we are using L-band data, results may not be affected by troposphere. Maximum glacier velocity we observed in the accumulation zone as 7.285 cm/day in the month of March and while it's moving towards ablation zone the glacier velocity is decreasing.

1. INTRODUCTION

Glacier is one of the important components in the cryosphere to check climate and temperature changes. The cryosphere is the surface on earth where the liquid is available in solid form. Glacier forms due to the compaction and recrystallization snow in accumulation zone. Due to it's own weight, pressure and slope it will move from accumulation to ablation zone (mountainous areas). Glacier movement is mainly dependent on a slope, ice thickness, surrounding climate temperatures and it's bed surface. Glacier velocity is the amount of glacier flow due to its own weight and gravity for a particular period of time. Monitoring of glacier velocity is important because it gives information about the health of a glacier, ice thickness and also information about glacier hazards. Glacier movement can be monitored either field based or remote sensing based techniques. Field based techniques are very difficult, spatially limited and cost efficient, but results are accurate if we use Differential Global Positioning System (DGPS). In remote sensing techniques, microwave data is more useful to monitor glaciers due to it's penetration capability. We used 2-pass Differential

2. DIFFERENTIAL SAR INTERFEROMETRY (DINSAR)

Massonnet *et al.*, (1993)[2] and Zebker *et al.*, (1994)[3] applied the two pass differential interferometry and three pass differential interferometry for the first time. DinSAR uses the phase information present in the SAR images to precisely estimate the movement or displacement of a particular target point between two SAR images. Coherence gives an information about the correlation between two SAR images in the DInSAR process and it's range is from 0 to 1. If the coherence value is 1, then there is no change in the target point between master and slave images. Glacier movement can be estimated by using Interferometry technique by using any one of these three techniques [4].

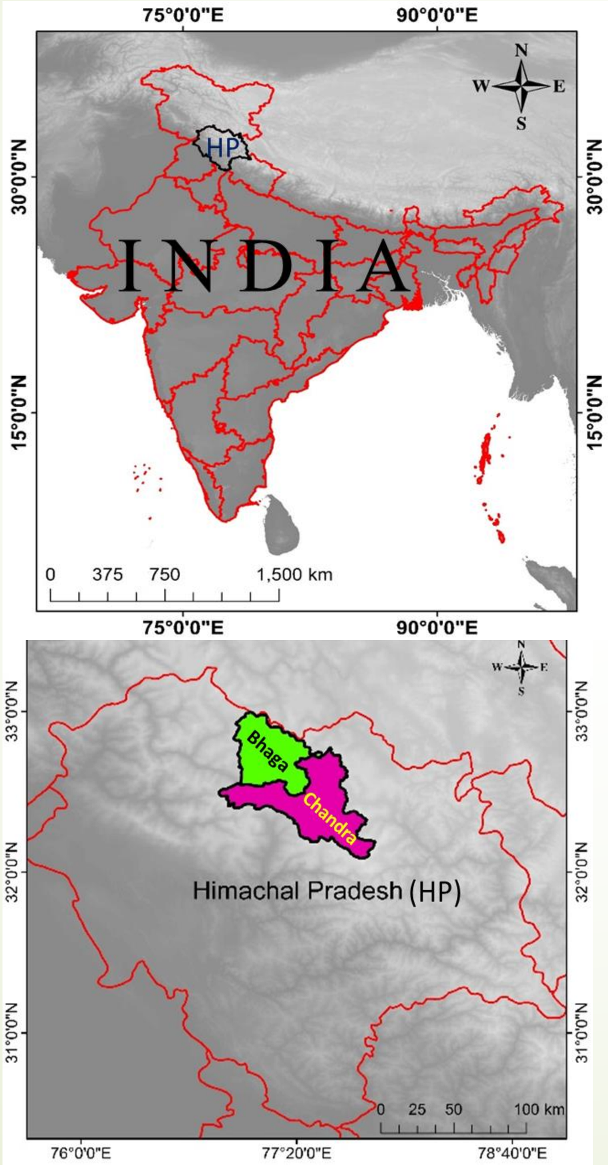
1. If the baseline between two sensors is zero, then we can directly get the glacier movement by generating a single interferogram. But no InSAR system is planned like this.
2. 2 Pass DInSAR is used to estimate glacier movement with the help of an external DEM to remove topographic phase from the generated interferogram by using two SAR

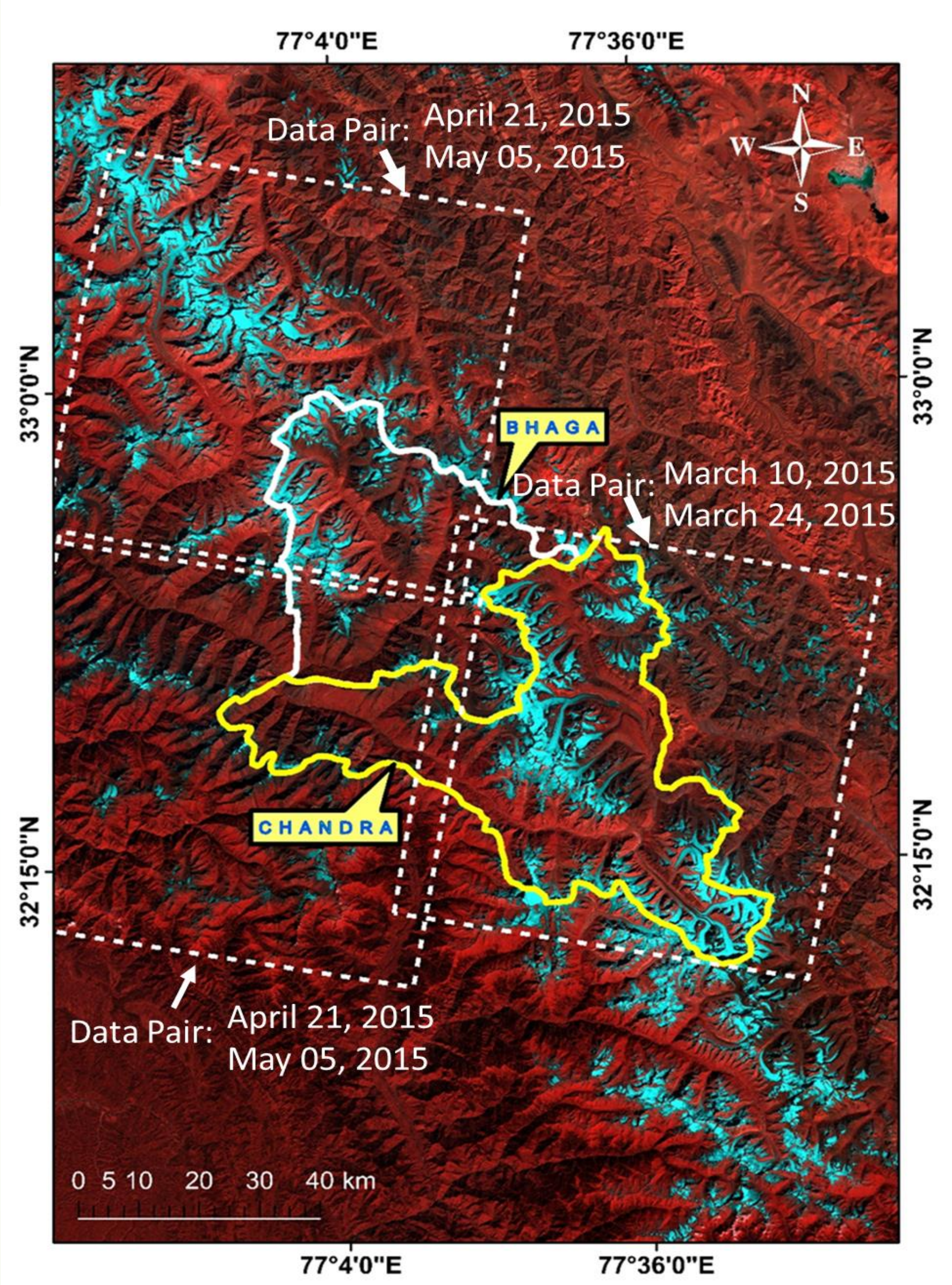
Nela *et al.*, 2018

Chapter 2

Glacier **ice flow dynamics** using 2-pass Differential SAR Interferometry (DInSAR)

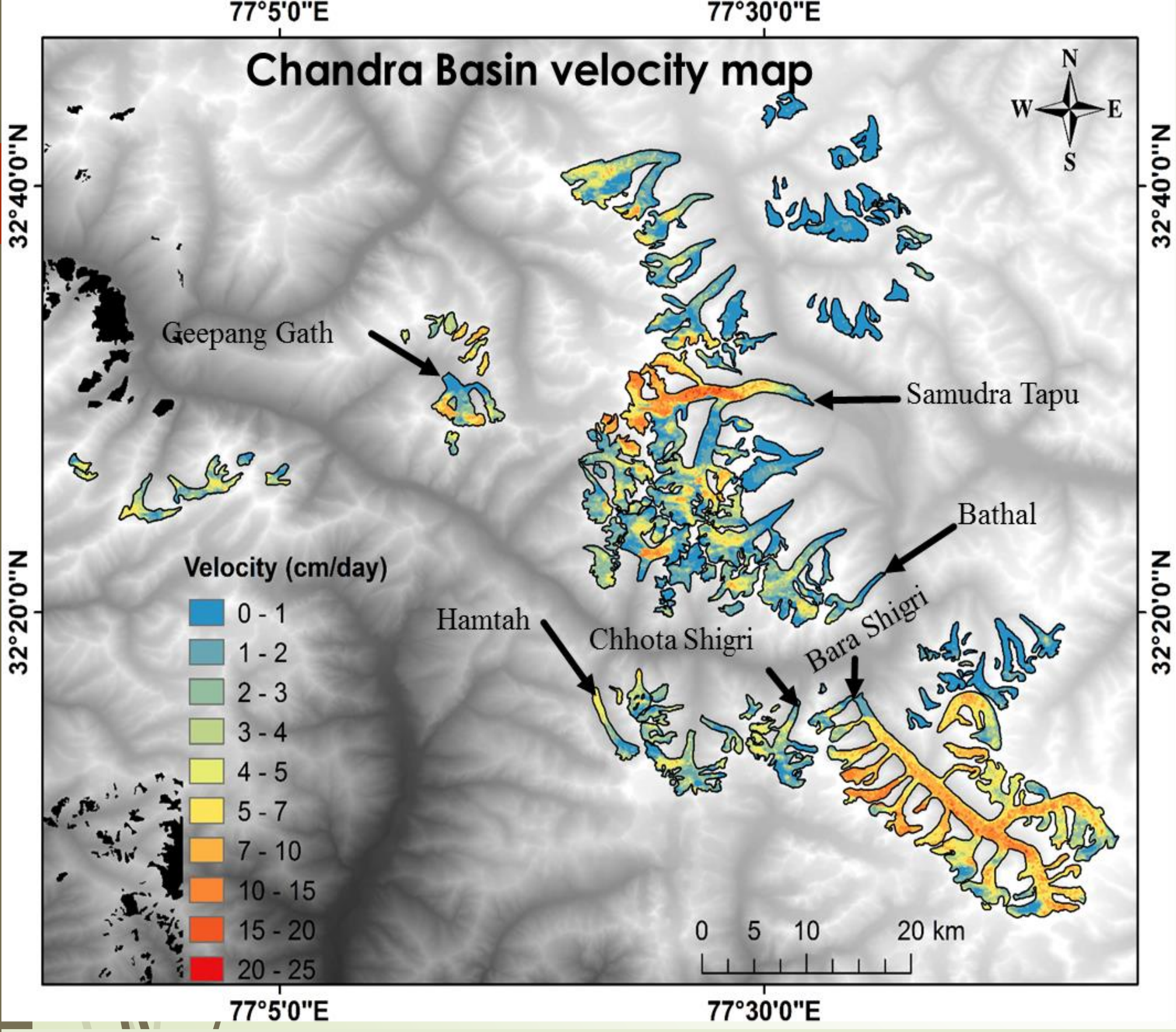
Study area

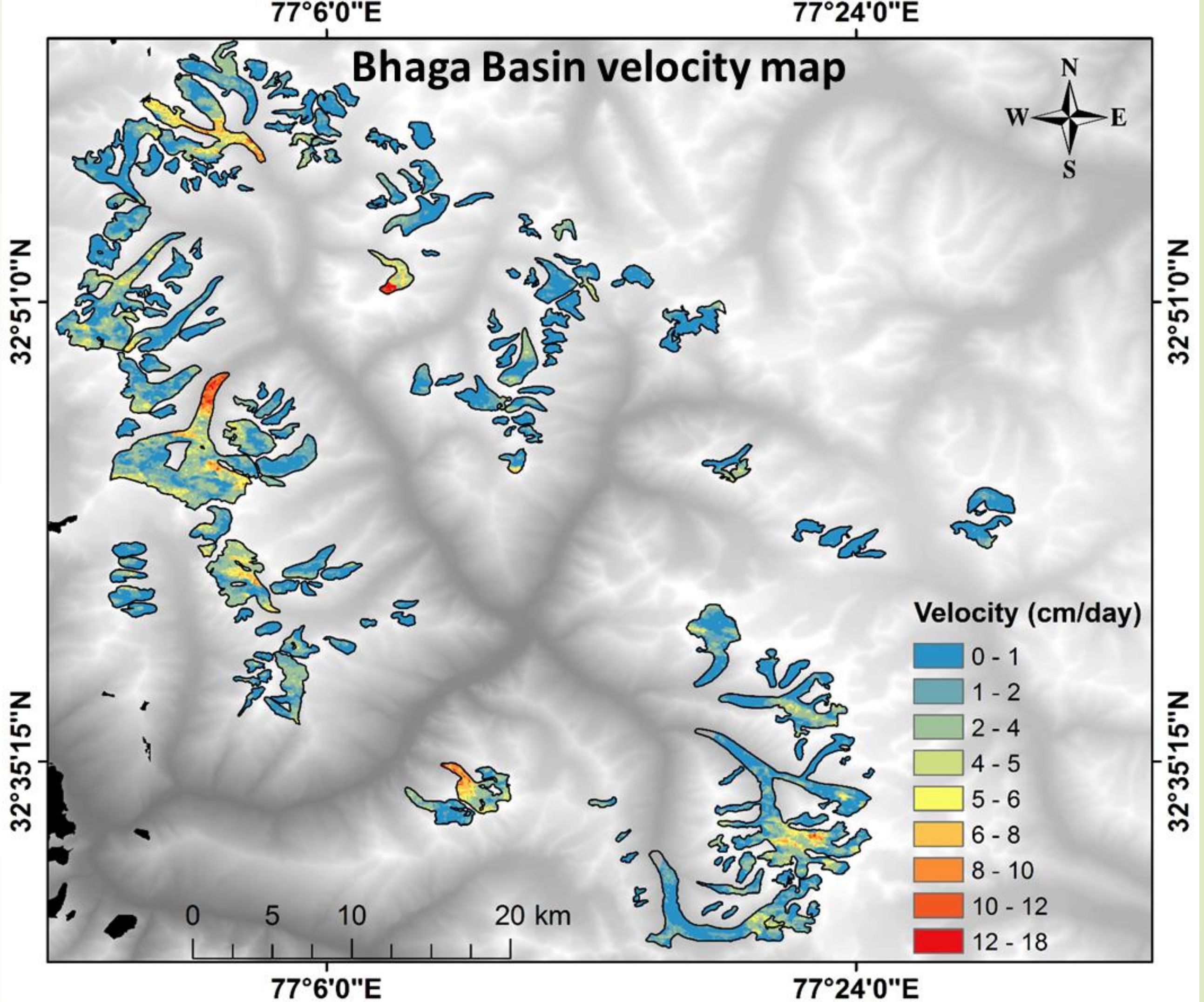

75°0'0"E
90°0'0"E
N
W
E
S
HP
INDIA
30°0'0"N
15°0'0"N
0 375 750 1,500 km
Bhaga
Chandra
Himachal Pradesh (HP)
33°0'0"N
32°0'0"N
31°0'0"N
76°0'0"E
77°20'0"E
78°40'0"E
0 25 50 100 km


77°4'0"E
77°36'0"E
Data Pair: April 21, 2015
May 05, 2015
N
W
E
S
BHAGA
Data Pair: March 10, 2015
March 24, 2015
CHANDRA
Data Pair: April 21, 2015
May 05, 2015
33°0'0"N
32°15'0"N
0 5 10 20 30 40 km

Data used

Data Pair	Dates	Look angle	Perpendicular Baseline (m)	Parallel Baseline (m)	Temporal Baseline (days)	Polarization
InSAR Pair -1	March 10, 2015	28.2	0	0	0	HH
	March 24, 2015	28.2	127.6	80.6	14	HH
InSAR Pair- 2	April 21, 2015	32.5	0	0	0	HH
	May 05, 2015	32.5	113.3	26.6	14	HH

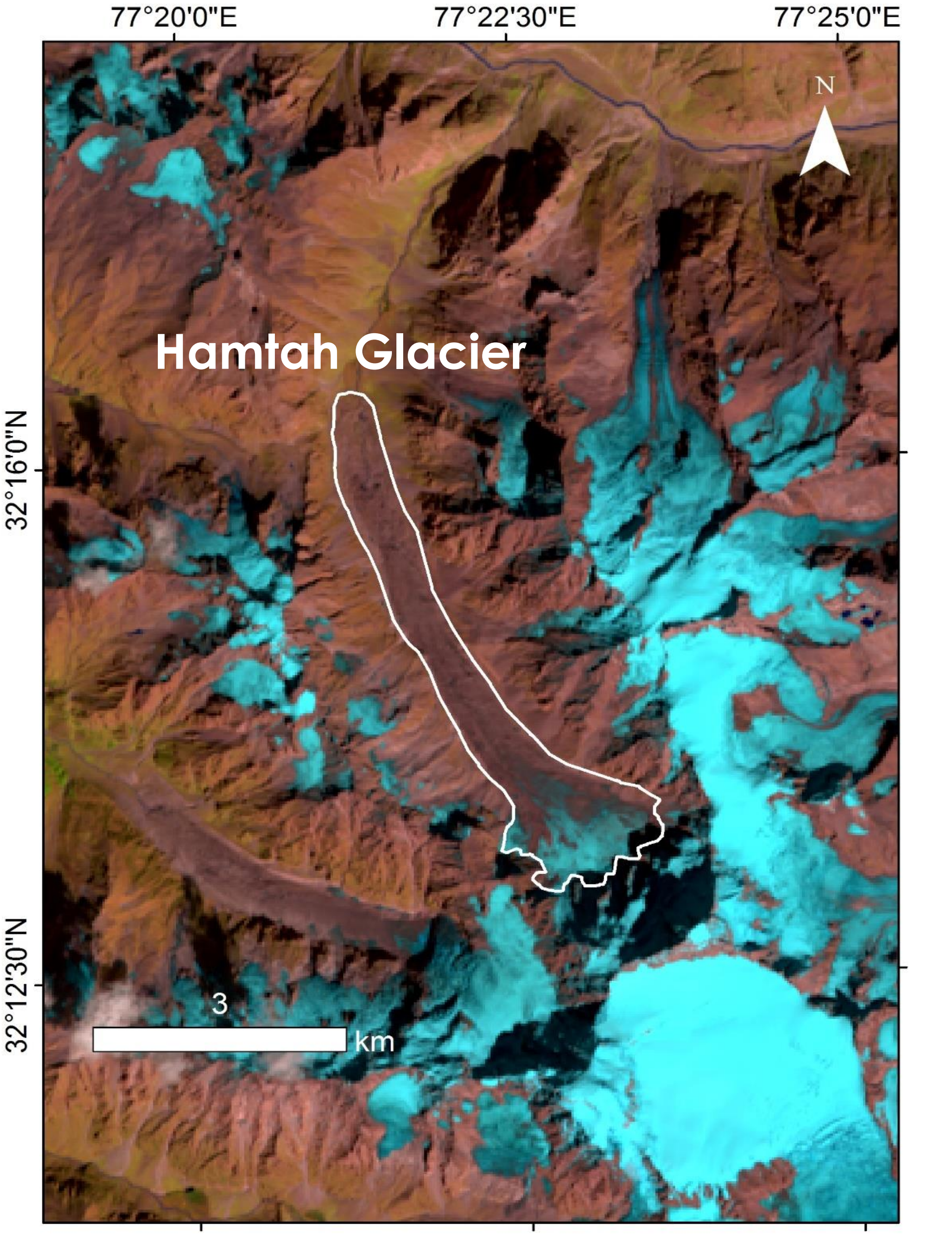




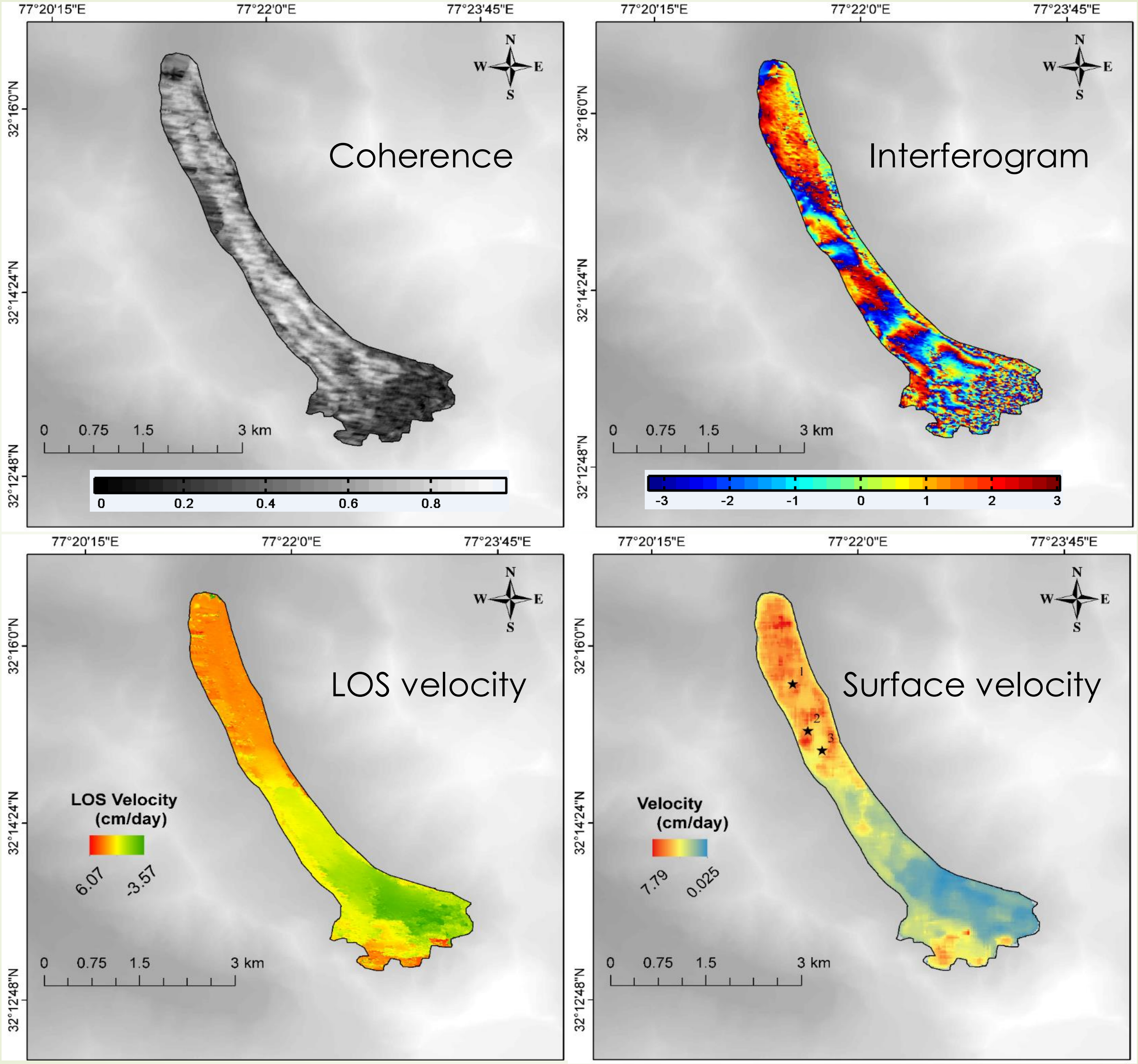
- The glaciers in Chandra sub-basin are found to have a high flow rate as compared to the glaciers in Bhaga sub-basin
- Local slope and ice thickness, which decrease towards the terminus in general, control the movement of valley glaciers, and lower movement rate is observed for most of glaciers towards the terminus/frontal area
- The retrieved errors in velocity measurements are 0.75 and 0.42 cm/day for Bhaga and Chandra sub-basins, respectively

Field

Collected field points on July 2019



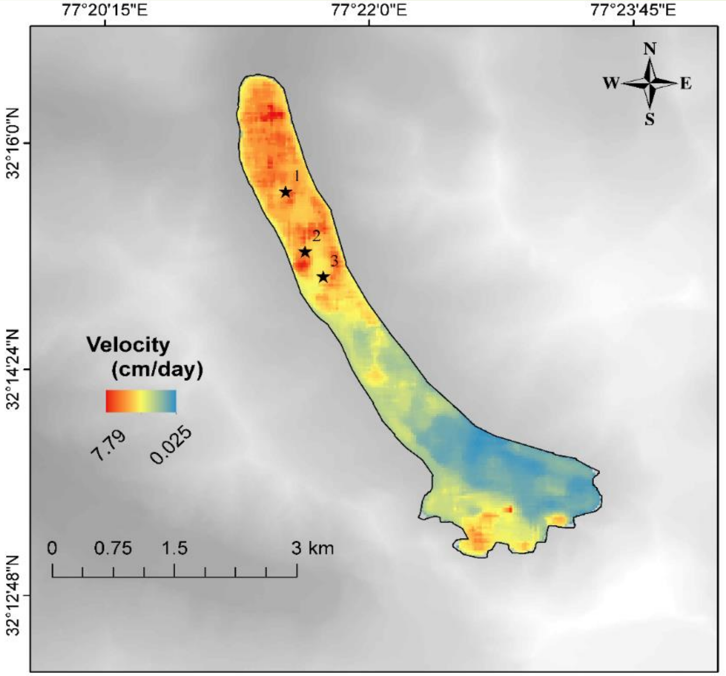
Hamtah



77°20'15"E
77°22'0"E
77°23'45"E
32°16'0"N
32°14'24"N
32°12'48"N
N
W
E
S
Coherence
0 0.75 1.5 3 km
0 0.2 0.4 0.6 0.8
Interferogram
-3 -2 -1 0 1 2 3
LOS velocity
LOS Velocity (cm/day)
6.07
-3.57
Surface velocity
1
2
3
Velocity (cm/day)
7.79
0.025

Validation

Latitude/Longitude (Decimal Degrees)	DInSAR technique (cm/day)	Corresponding DGPS survey (cm/day)
32.2614N/77.3575E	5.30	6.08
32.2538N/77.3596E	5.54	6.87
32.2509N/77.3616E	6.07	7.75



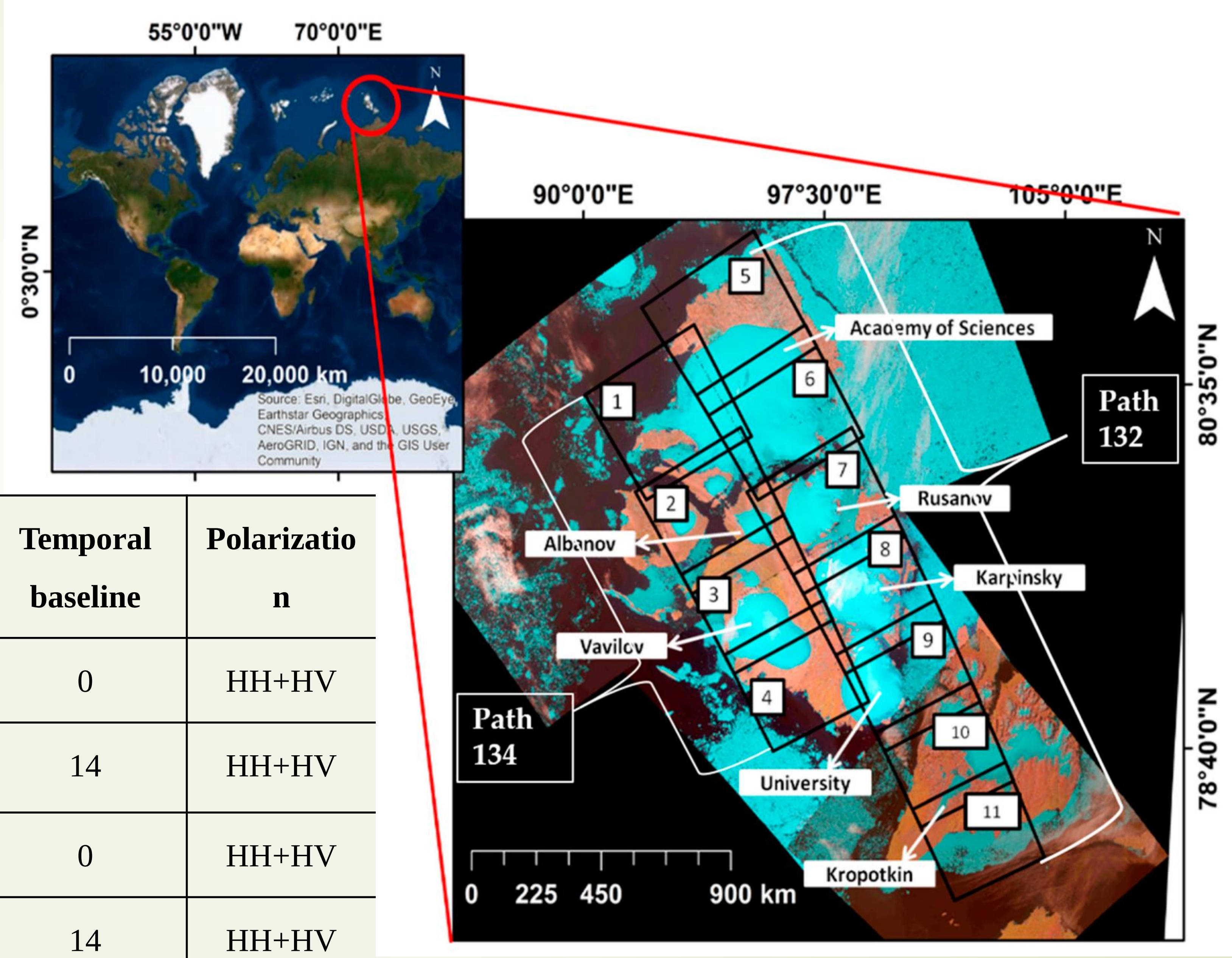
Validation of DInSAR velocity results using field-surveyed (DGPS) points for Hamtah glacier

Summary

- Most of the smaller glaciers in both Chandra and Bhaga sub-basins have movement **less than 2 cm/ day**
- Lower movement rates are observed for most of glaciers towards the terminus/frontal area
- Furthermore, it is observed that the flow velocity is high for large area glaciers, like, **Samudra Tapu (24.63 ± 0.42 cm/day) and Bara Shigri (20.32 ± 0.42 cm/day)** with maximum surface flow velocities

SA & Data

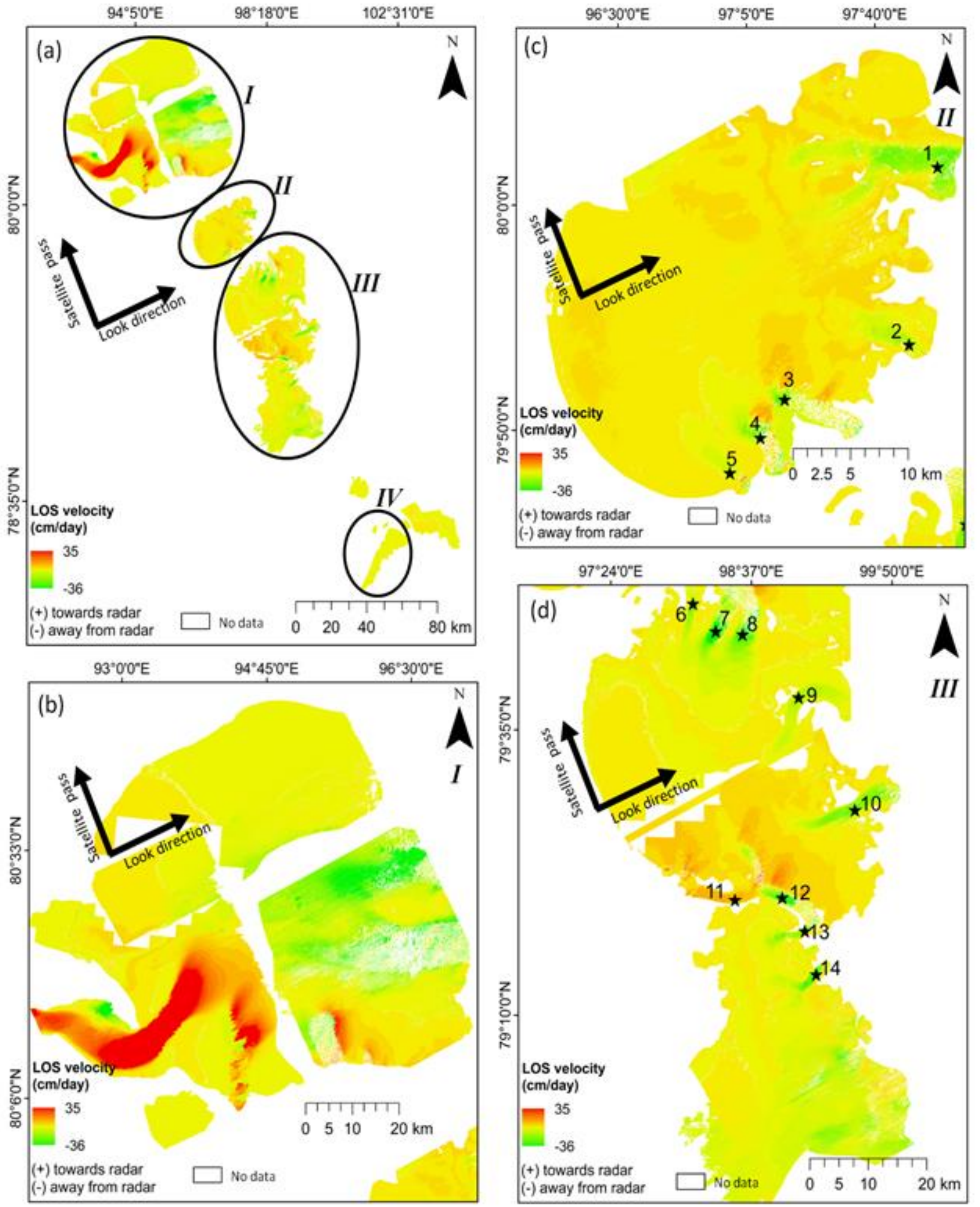
Severnaya Zemlya archipelago

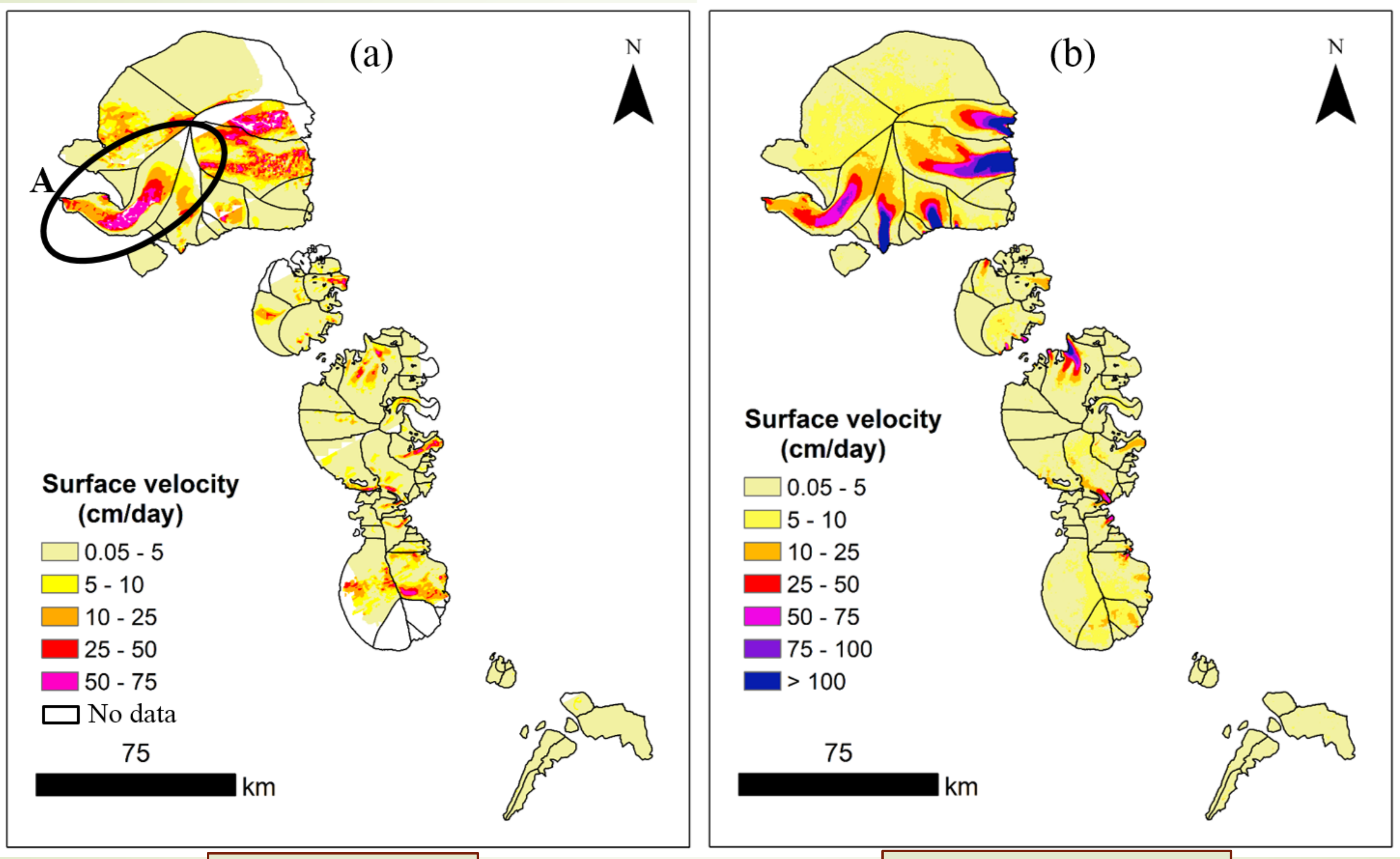


Pair	Dates	Path number	Temporal baseline	Polarization
Pair 1-4	28/03/2018	134	0	HH+HV
	11/04/2018	134	14	HH+HV
Pair 5-11	01/04/2018	132	0	HH+HV
	15/04/2018	132	14	HH+HV

LOS

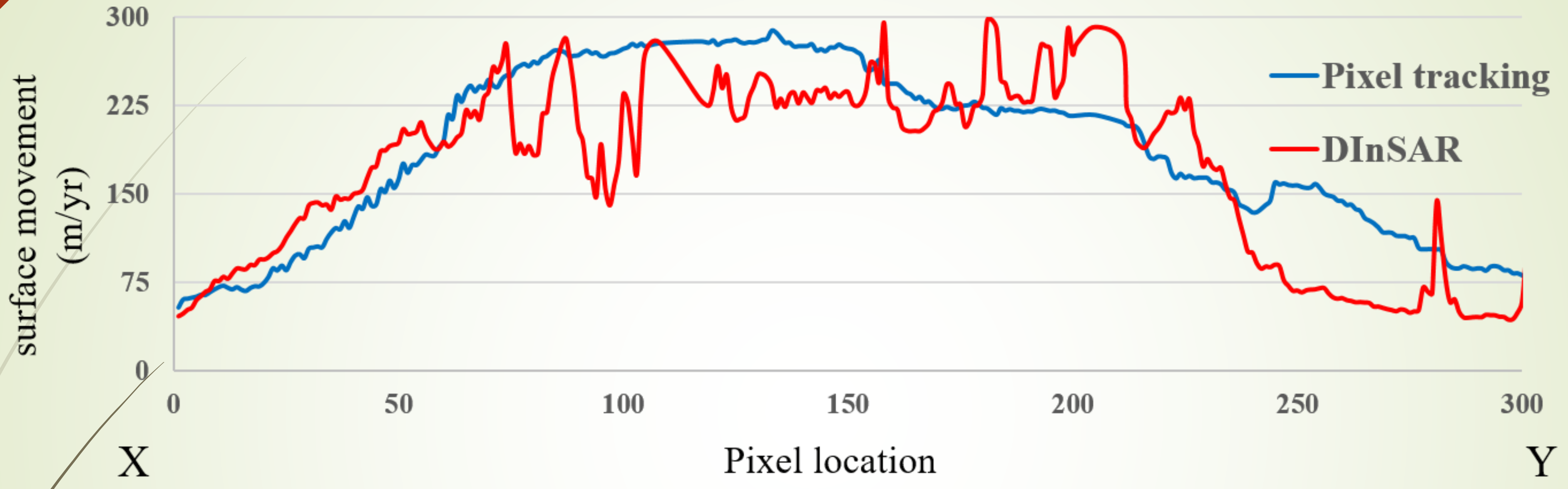
- Ice velocities of - Academy of Sciences, Rusanov, Karpinsky, University ice caps
- Annual flow velocity is the highest for one of the outlet glaciers in the Academy of Sciences
- Rusanov ice cap (5): Ice velocity is ranging from 11.49 to 21.93 cm/day
- Karpinsky (8): 7.43 cm/day to 32.12 cm/day
- University ice cap (Glacier no.14) has a max surface velocity of 27.81 cm/day
- Kropotkin (Zone IV): The ice flow rate is considerably low (6.62 cm/day).





DInSAR

Offset tracking



- Both pixel tracking and DInSAR technique show a similar trend and pattern
- From previous studies, for ice caps, it has been observed that basal motion is a dominant component of surface motion (Doyle et al., 2018)
- Around 50% of the glacier bed is below sea level (Dowdeswell and Williams, 1997)

Summary

- Spatial distribution of complete Chandra and Bhaga sub basin velocities and Severnaya Zemlya archipelago ice flow velocities are mapped using 2-pass DInSAR
- It is observed that marine-terminating glaciers have a higher velocity than land-terminating glaciers
- The glaciers in Chandra sub-basin are found to have a high flow rate as compared to the glaciers in Bhaga sub-basin
- A few glaciers of Bhaga sub-basin demonstrate an **accelerated movement in their frontal areas**

water MDPI

Nela *et al.*, 2019

Article

Glacier Flow Dynamics of the Severnaya Zemlya Archipelago in Russian High Arctic Using the Differential SAR Interferometry (DInSAR) Technique

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Abstract: Glacier velocity is one of the most important parameters to understand glacier dynamics. The Severnaya Zemlya archipelago is host to many glaciers of which four major ice caps encompassing these glaciers are studied, namely, Academy of Sciences, Rusanov, Karpinsky, and University. In this study, we adopted the differential interferometric synthetic aperture radar (DInSAR) method utilizing ALOS-2/PALSAR-2 datasets, with a temporal resolution of 14 days. The observed maximum velocity for one of the marine-terminating glaciers in the Academy of Sciences Ice Cap was 72.24 cm/day (≈263 m/a). For the same glacier, an increment of 3.75 times the flow rate was observed in 23 years, compared to a previous study. This has been attributed to deformation in the bed topography of the glacier. Glaciers in other ice caps showed a comparatively lower surface velocity, ranging from 7.43 to 32.12 cm/day. For estimating the error value in velocity, we selected three ice-free regions and calculated the average value of their observed movement rates by considering the fact that there is zero movement for ice-free areas. The average value observed for the ice-free area was 0.09 cm/day, and we added this value in our uncertainty analysis. Further, it was observed that marine-terminating glaciers have a higher velocity than land-terminating glaciers. Such important observations were identified in this research, which are expected to facilitate future glacier velocity studies.

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Discovering anomalous dynamics and disintegrating behaviour in glaciers of Chandra-Bhaga sub-basins, part of Western Himalaya using DInSAR

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ARTICLE INFO

Keywords:
Glacier dynamics
Collapse
Disintegration
Interferometry
Elevation change
Melt water

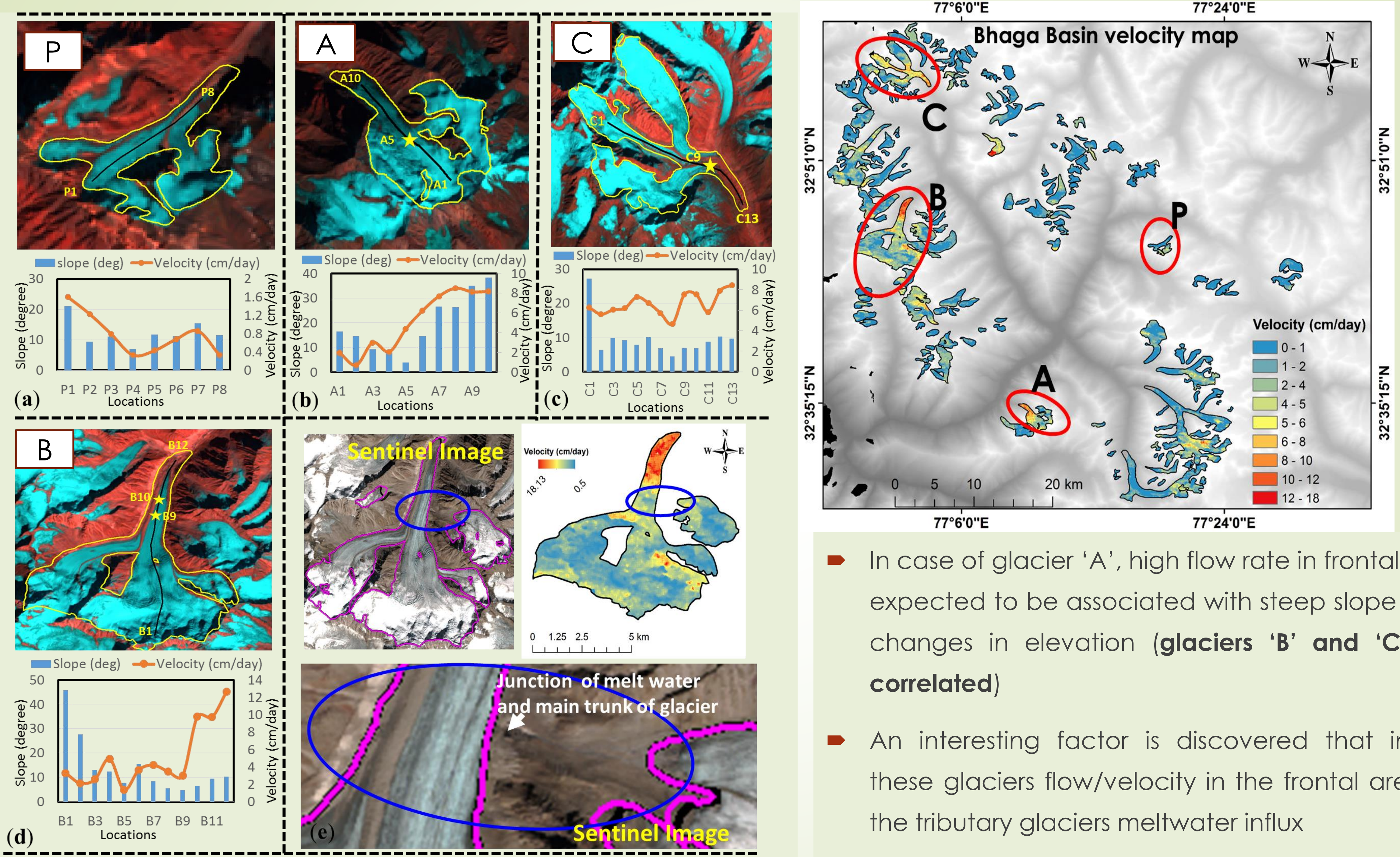
ABSTRACT

Glacier velocity is one of the important parameters to know about glacier dynamics, its mass and health. Understanding glacier velocity also assists in the analysis of ice thickness, ice flux and mass balance. Furthermore, basin/sub-basin wise studies are helpful to understand the climate change over that region instead of monitoring individual glaciers. In the current study, the spatial distribution of glacier velocity is generated for the entire Chandra and Bhaga sub-basins, in the Lahaul-Spiti district of Himachal Pradesh, India, using Advanced Land Observing Satellite-2/Phased Array type L-band Synthetic Aperture Radar-2 (ALOS-2/PALSAR-2) differential interferometry pair images with a 14-days temporal gap. The glaciers in Chandra sub-basin are found to have a high flow rate as compared to the glaciers in Bhaga sub-basin. Local slope and ice thickness, which decrease towards the terminus in general, control the movement of valley glaciers, and lower movement rate is observed for most of glaciers towards the terminus/frontal area. However, a few glaciers of Bhaga sub-basin demonstrate an accelerated movement in their frontal areas. This irregular behaviour is also studied in this work and it is discovered that terrain slope and influx of melting water from adjacent glaciers are the major causes for such behaviour of these glaciers. They are, therefore, prone to accelerated mass loss compared to other glaciers in the sub-basin. Another key finding of the anomalous glacier dynamics study is the disintegrating behaviour of glaciers, which is also identified by interpreting the responses of physical scattering mechanisms retrieved from glaciers using fully polarimetric ALOS-2/PALSAR-2. Warming temperatures are expected to cause glacier retreat and separation of tributary glaciers from the main glacier body. Melt water from tributary glaciers can further accelerate glacier flow and ice melt in lower part of glacier trunk. This can lead to formation of dead ice zones and disintegration of Himalayan glaciers, which are supported by numerous tributary glaciers. Therefore, we expect that the loss in glacier area due to warming will be larger than the present prediction, where mass loss is considered from conventional way.

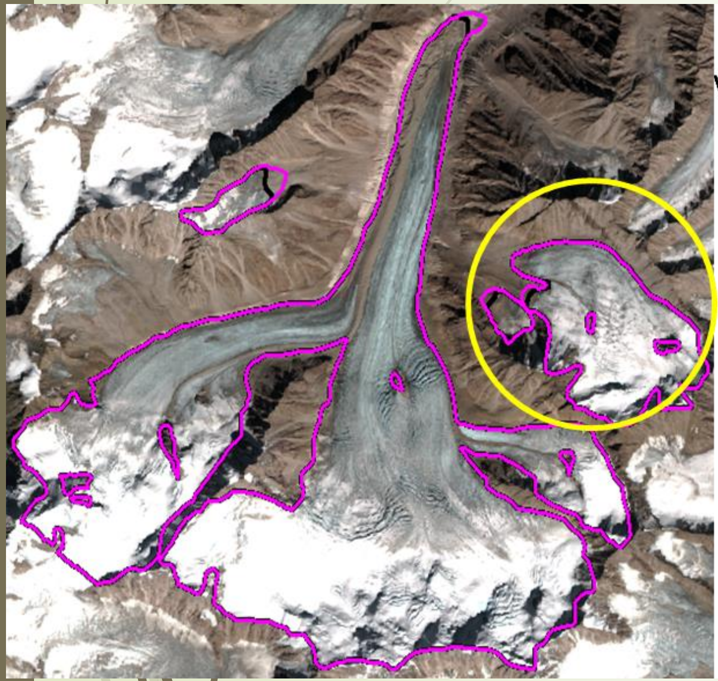
Singh *et al.*, 2020

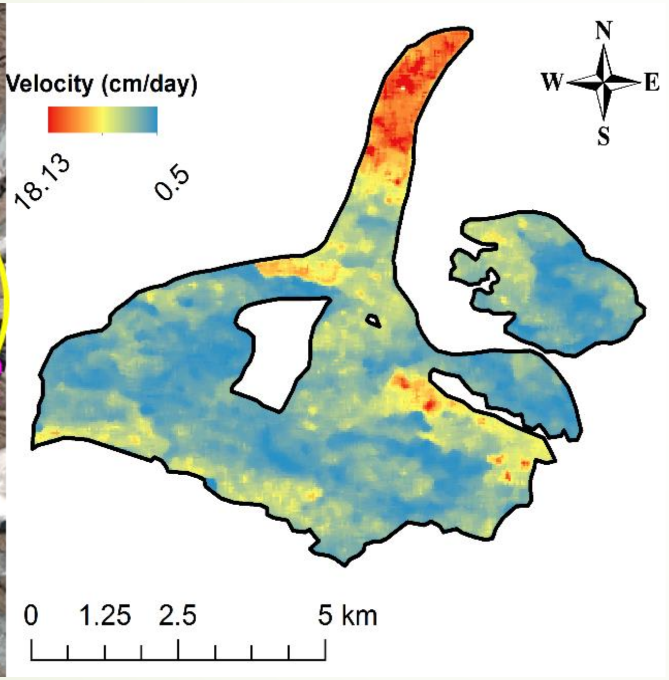
Chapter 3

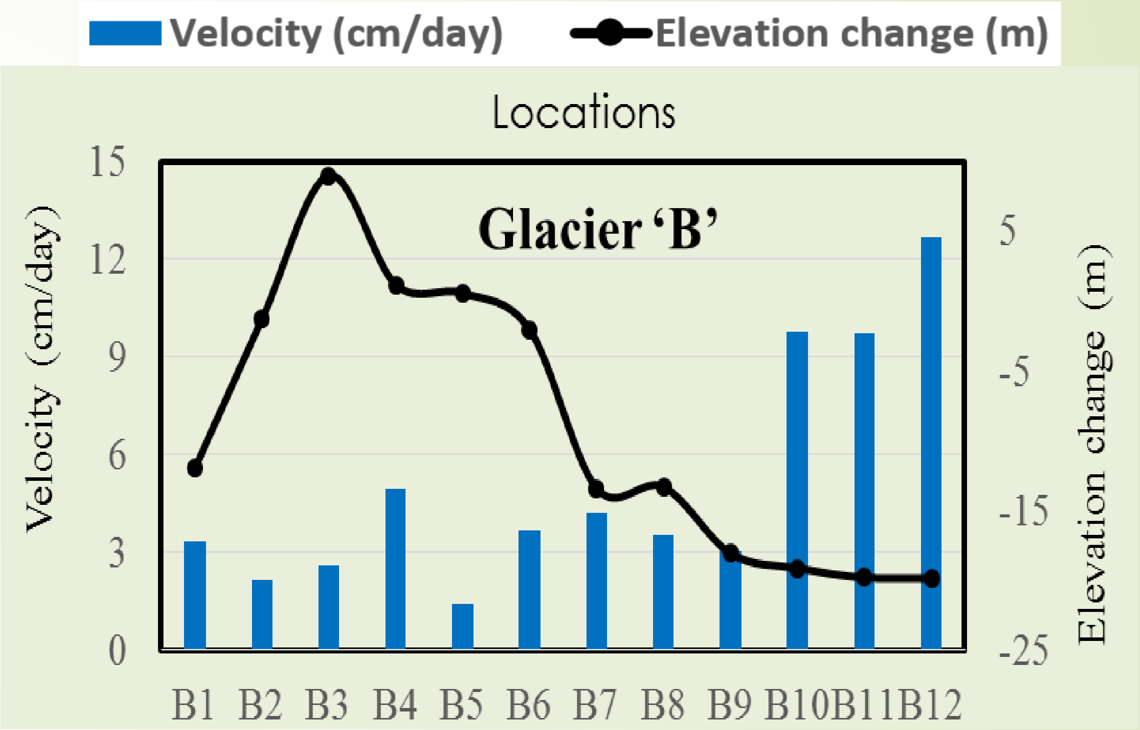
Influence of **meltwater influx** on glacier dynamics using Differential SAR Interferometry (DInSAR)



- In case of glacier ‘A’, high flow rate in frontal area was expected to be associated with steep slope or abrupt changes in elevation (**glaciers ‘B’ and ‘C’ are not correlated**)
- An interesting factor is discovered that influenced these glaciers flow/velocity in the frontal area due to the tributary glaciers meltwater influx

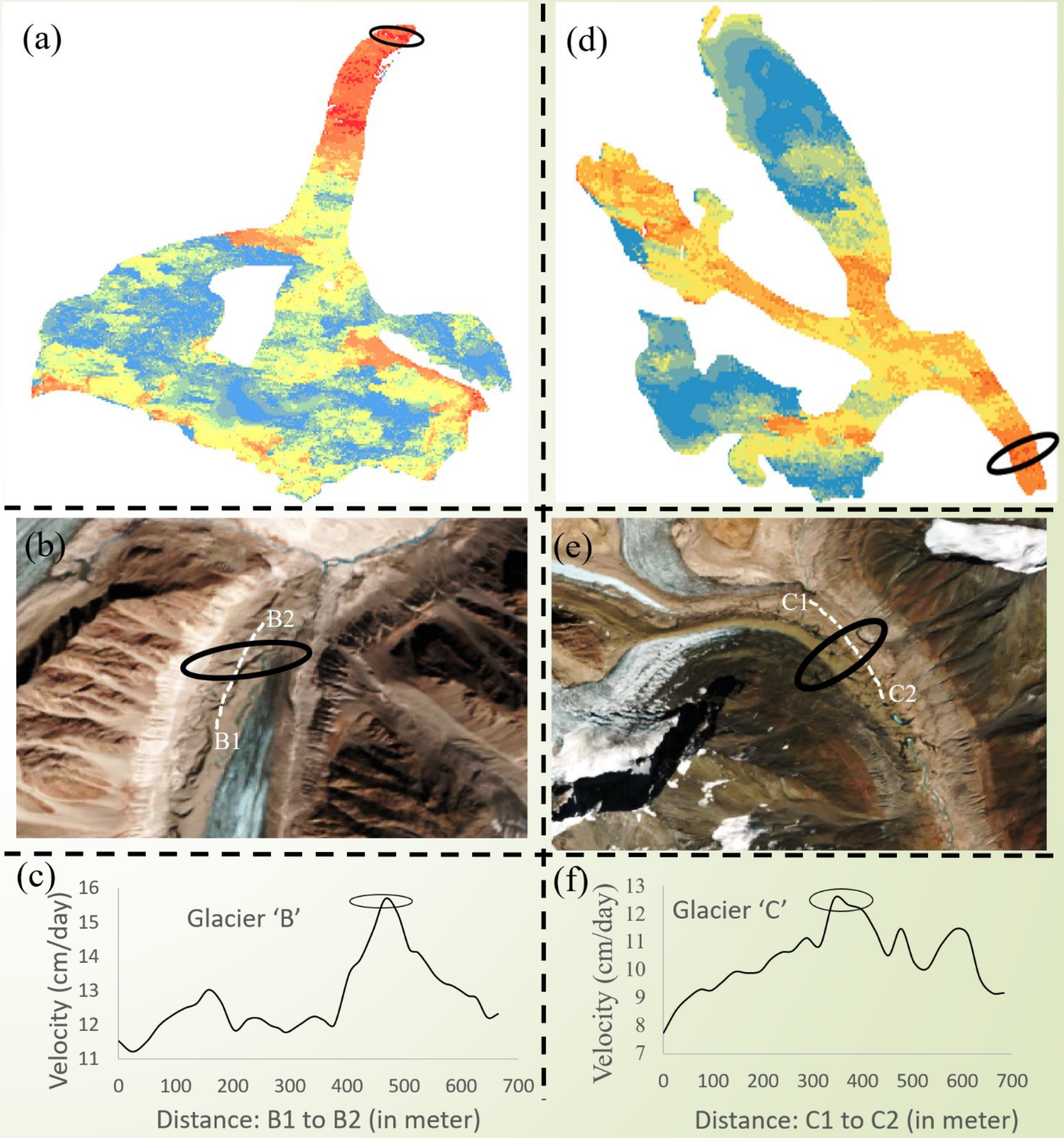



Velocity (cm/day)
18.13
0.5
N
W
E
S
0
1.25
2.5
5 km


Velocity (cm/day)
Elevation change (m)
Locations
Glacier 'B'
15
12
9
6
3
0
5
-5
-15
-25
Velocity (cm/day)
Elevation change (m)
B1
B2
B3
B4
B5
B6
B7
B8
B9
B10
B11
B12

Disintegration line

- The additional input of melt water on glacier bed increases basal sliding and thaw conditions; thus modifies/destroys sub glacial drainage and cavity systems
- When mass loss and movement exceeds the ice feed from accumulation zone, the glacier ablation zone deforms/collapses
- This mechanism develops crevasses/ disintegration line, which are visible on both glaciers ‘B’ and ‘C’ surfaces in the frontal zone

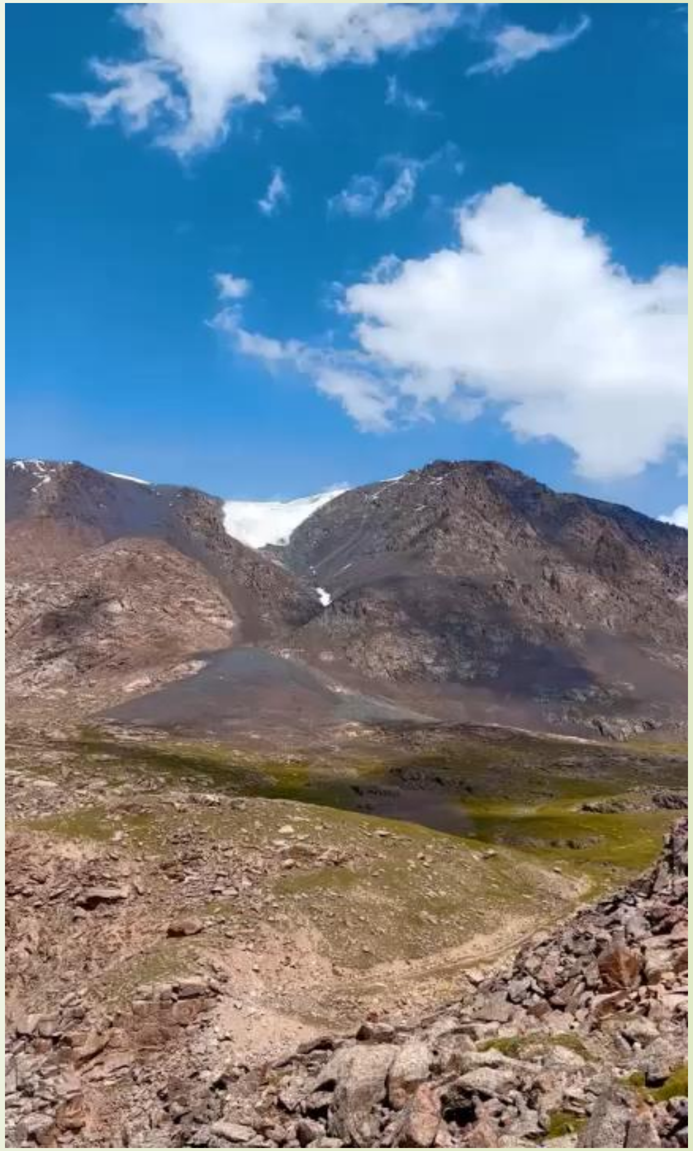


Glacier collapsed events

- Italian Alps glacier collapse
- A **glacier collapsed** on the mountain of Marmolada
- 7 people were dead

3 July 2022

A **glacier collapsed** in the mountains of the Issyk-Kul region of Kyrgyzstan, triggering an avalanche



8 July 2022

Image/Video credits

Summary

- Anomalous glacier dynamics information is discovered using DInSAR
- The melting water helps to increase the glacier movement, which results in faster glacier ice melting and increased thinning rate (negative mass balance).
- This is one of the major effect as well as disadvantage in the glacier detaching process.
- Disintegrating behaviour in glaciers is also observed due to influx of melting water
- Our findings suggests that mass wastage of Himalayan glaciers will be increased further in future (due to the meltwater influx).

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ABSTRACT

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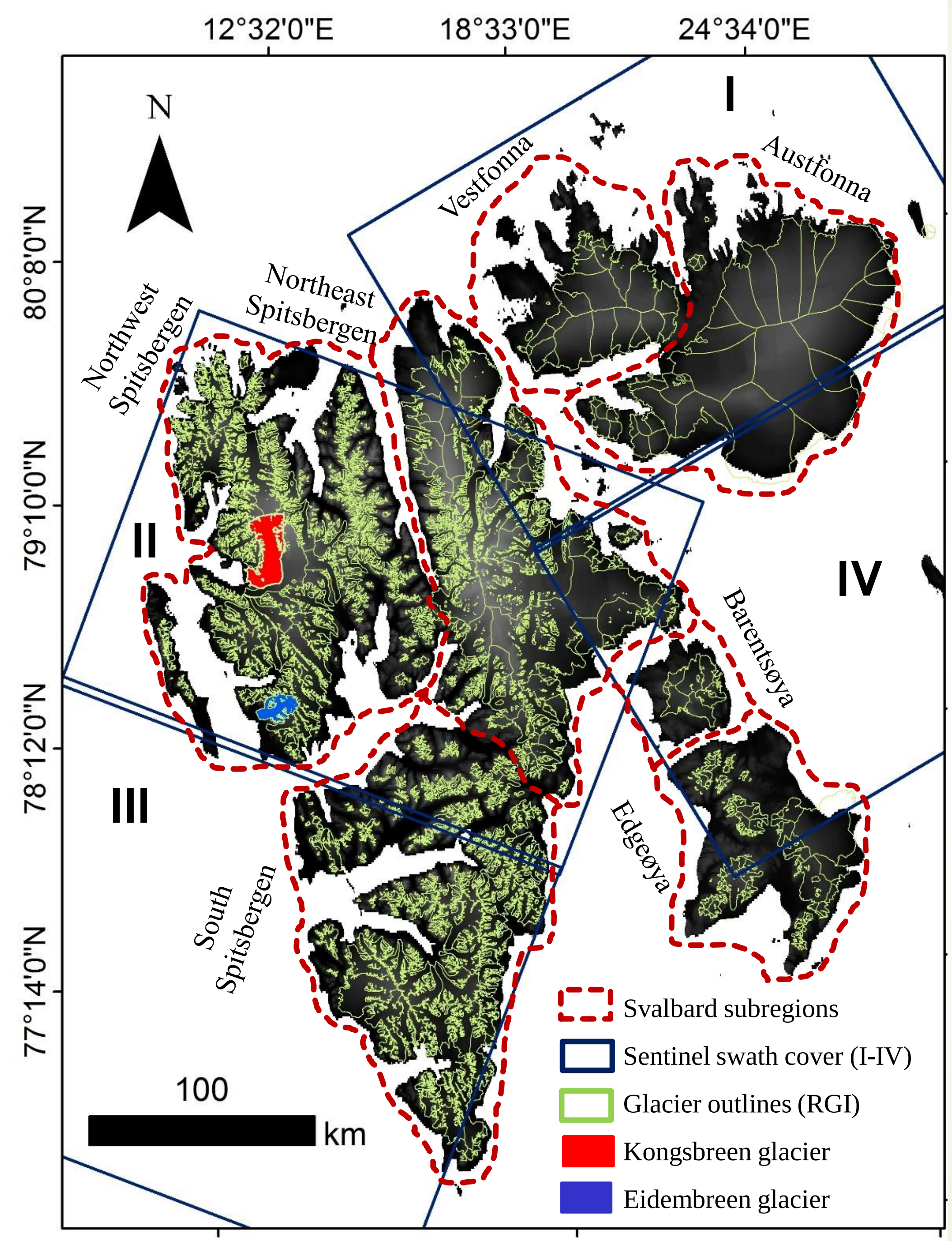
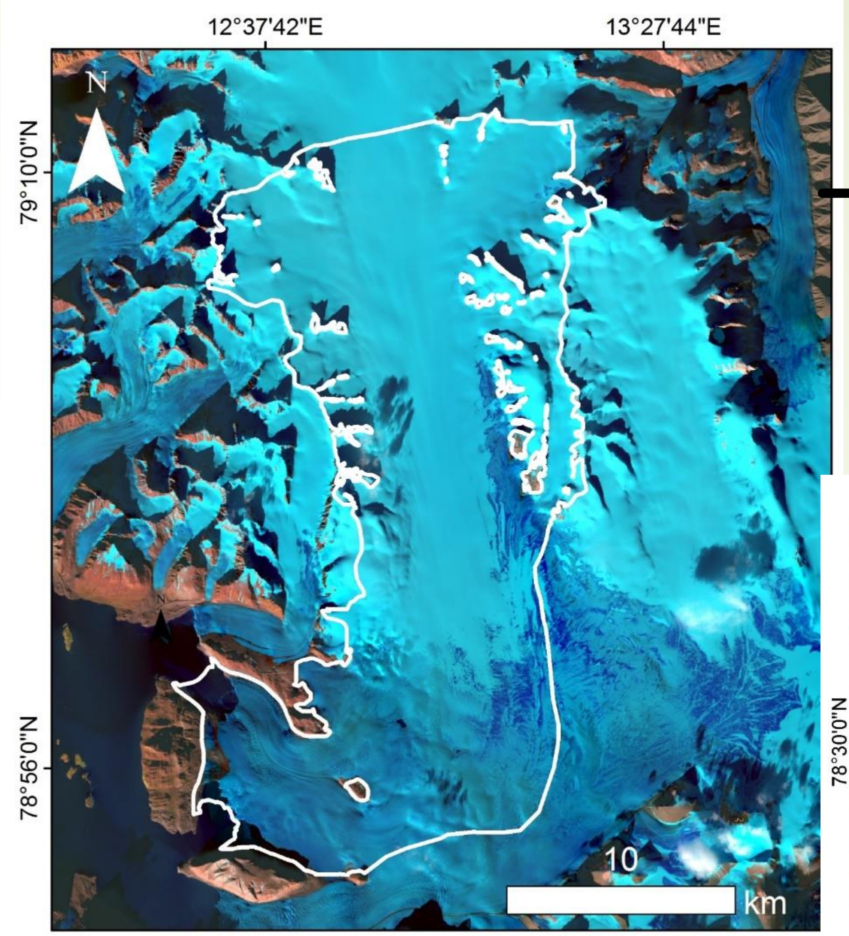
Singh *et al.*, 2020

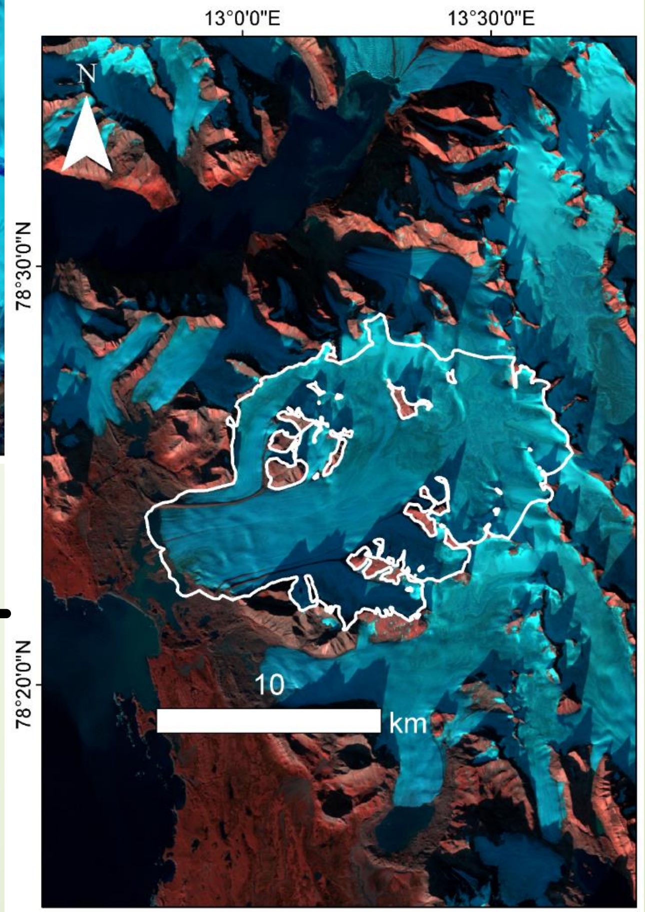
Chapter 4

Glacier ice velocity using **3-pass DInSAR** and compare it with the 2-pass DInSAR



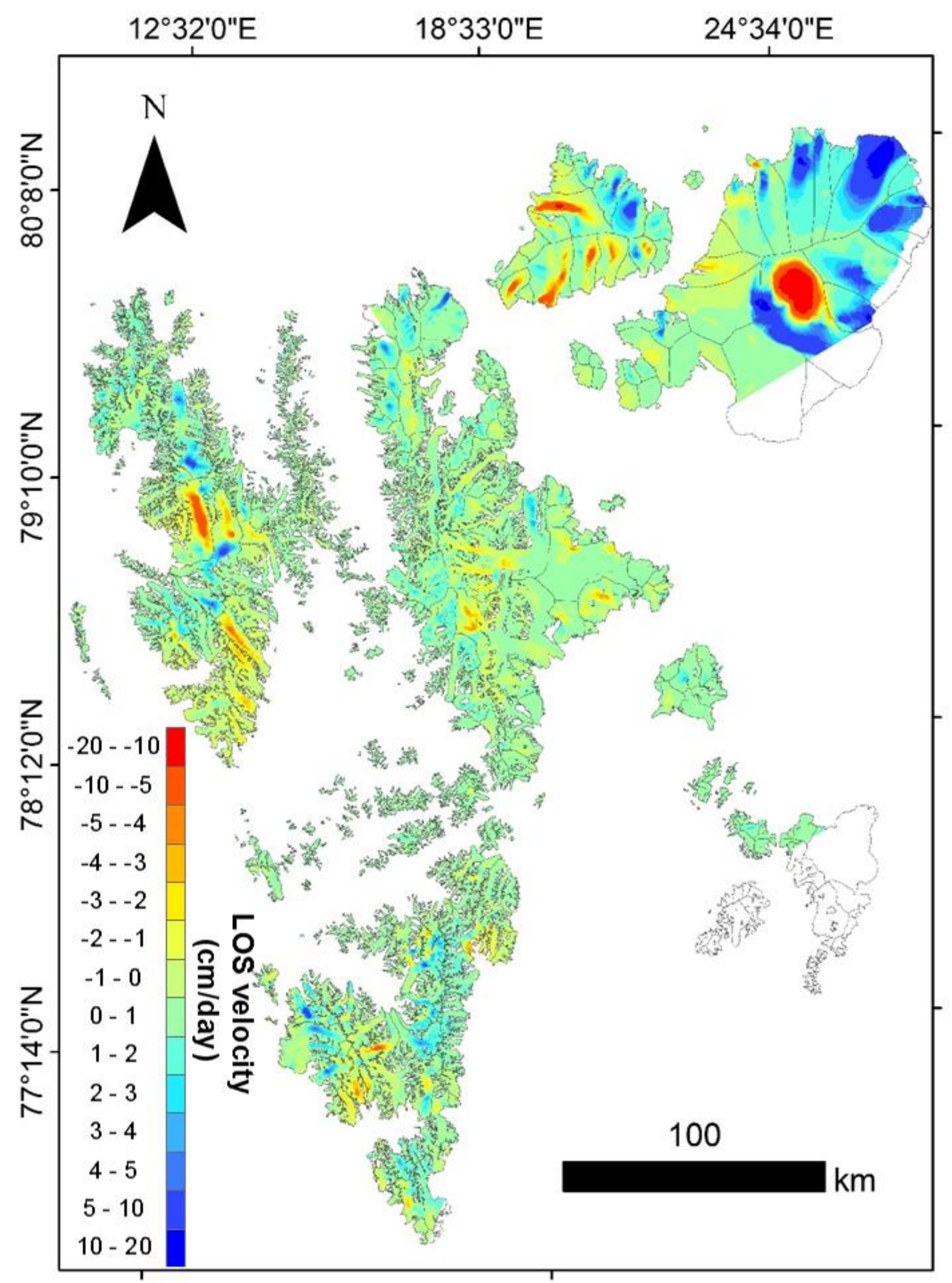


Kongsbreen



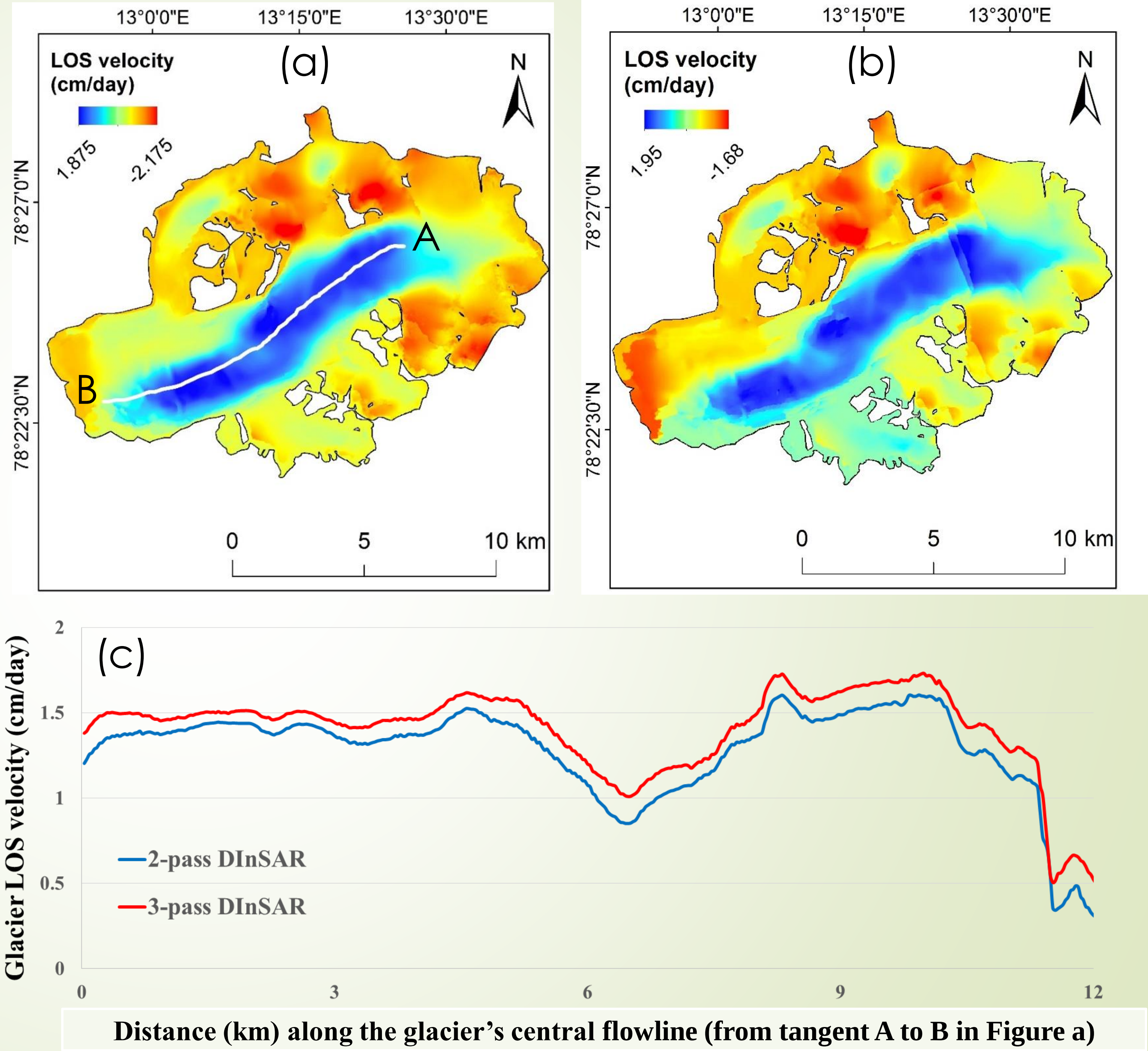
Eidembreen

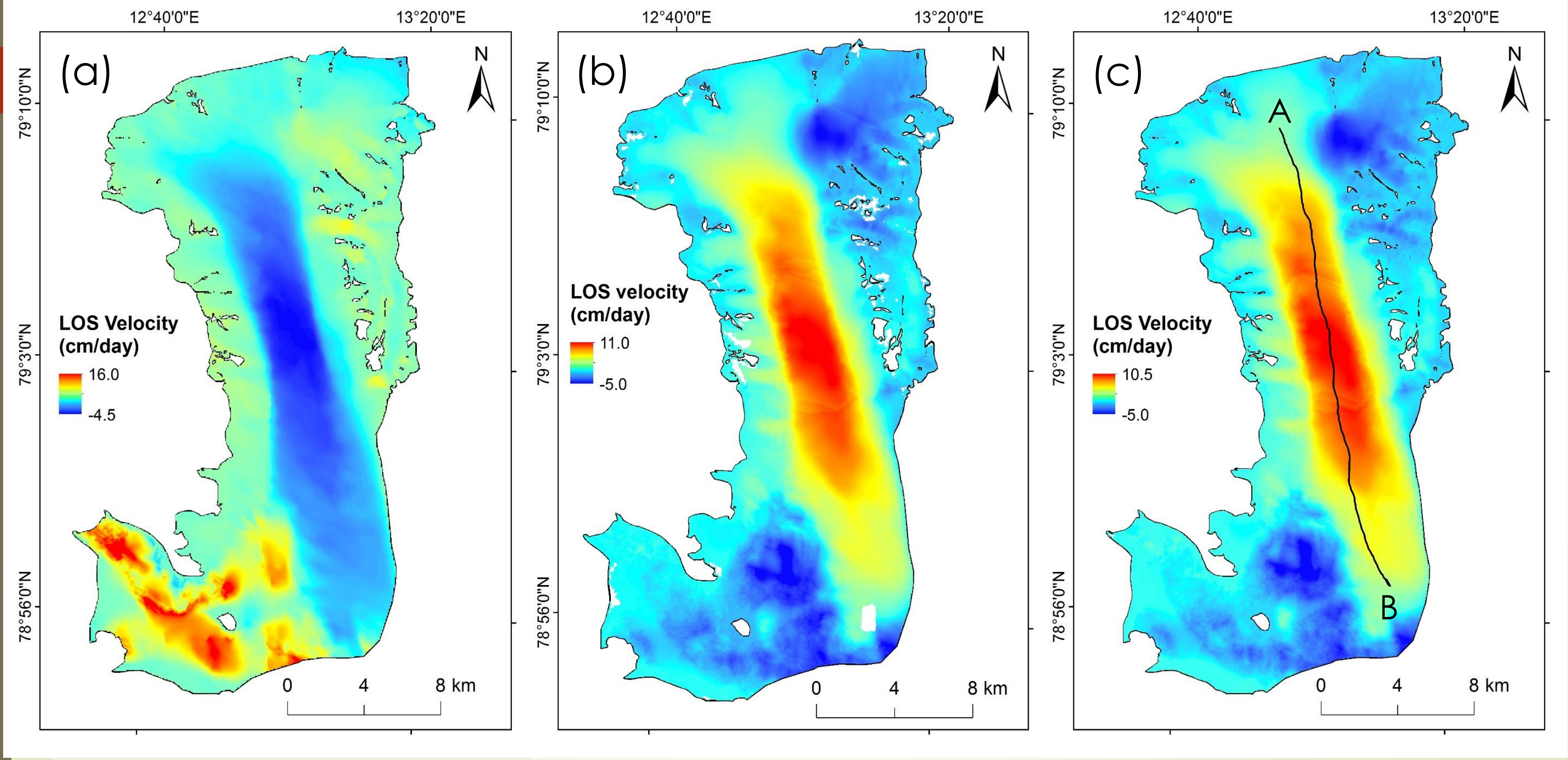
- It is observed that C-band InSAR measurements from space with a 6-days gap are found to be suitable
- **Kongsbreen glacier** is observed as the fast-moving glacier among all other glaciers in the entire Spitsbergen region with a **maximum LOS velocity of 9 cm/day**
- Indeed, Negribreen and Monacobreen are examples of fast-moving glaciers located in Spitsbergen (Schuler et al. 2020). Fast-moving/rapid flow increases the decorrelation effect in the coherence image and adds inaccuracies to the LOS velocities
- The glaciers/ice caps located in the **Vestfonna and Austfonna** sub-regions are showing maximum glacier velocity (**more than 10 cm/day**) among others in the entire archipelago



LOS

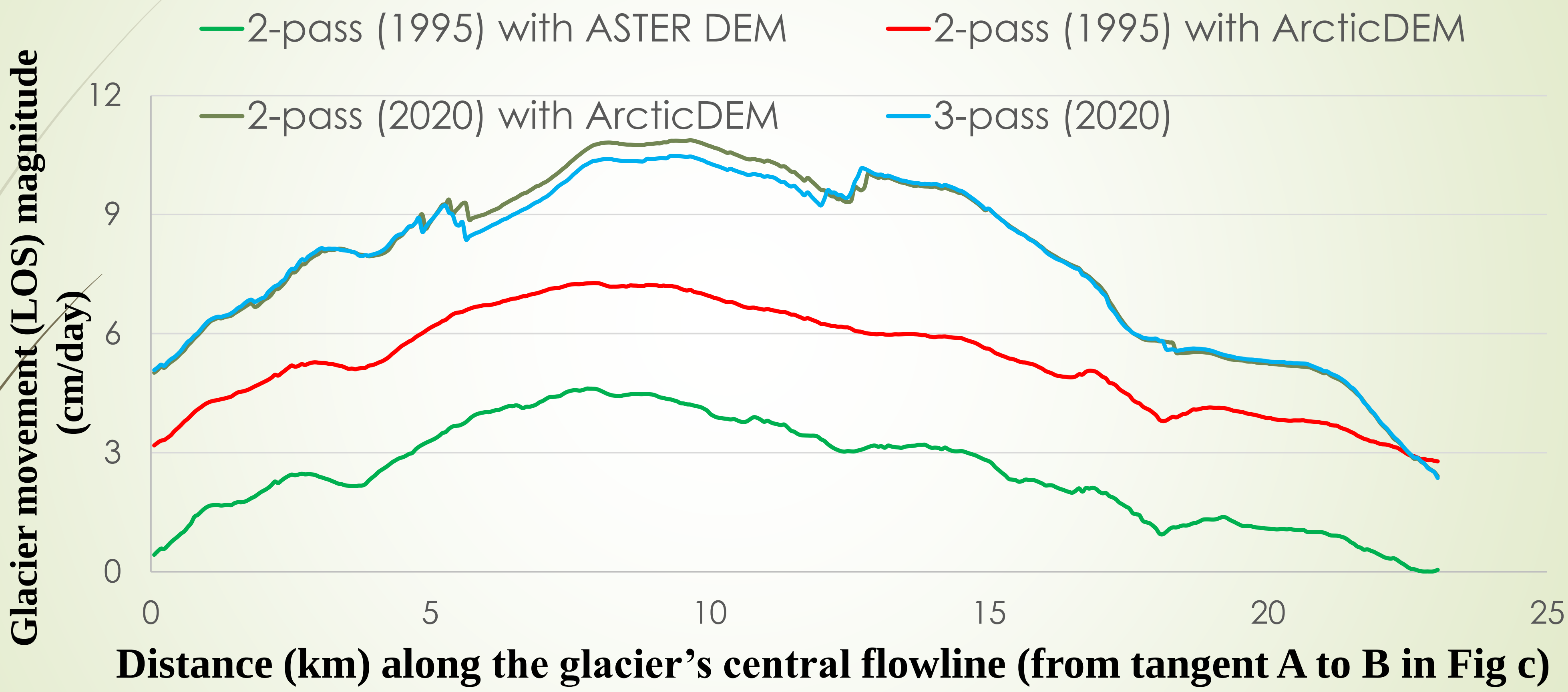
- The glacier movement is high in the central portion of the trunks and reduces along the lateral edges
- The results of 3-pass DInSAR are found to be very close to the results of 2-pass DInSAR (if the DEM is high accurate and insignificant glacier surface elevation change)
- To reduce topographic induced error in 2-pass DInSAR results, ArcticDEM with the near time of the 2017 InSAR pair acquired over Edimbreen glacier was used to infer velocity (Figure: b)
- It is noticed that the results of the two techniques follow the similar variation and trend with a deviation value of around 0.12 cm/day (Figure: c)





2-pass LOS velocity (cm/day) 1995 **2-pass LOS velocity (cm/day) 2020** **3-pass LOS velocity (cm/day) 2020**

Comparison



2-pass (1995) with ASTER DEM
2-pass (1995) with ArcticDEM
2-pass (2020) with ArcticDEM
3-pass (2020)
Glacier movement (LOS) magnitude (cm/day)
0
3
6
9
12
0
5
10
15
20
25
Distance (km) along the glacier's central flowline (from tangent A to B in Fig c)

Summary

- The study reveals that the **Sentinel 1A/1B has great potential** and capability to estimates the glacier ice flow velocities using the 3-pass DInSAR technique
- The 3-pass DInSAR based movement studies are more suitable over the region of **surge-type glacier** as compared to 2-pass DinSAR
- However, the availability of DEMs with more accuracy and the near time of the acquired interferometry pair gives an insignificant change in 2-pass DInSAR velocity results with the 3-pass
- Additionally, a DDI also gives information to find the **grounding line** of ice sheets (i.e., a boundary line between grounded and floating ice).

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Retrieval of Svalbard ice flow velocities using Sentinel 1A/1B three-pass Differential SAR Interferometry

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[a]Centre of Studies in Resources Engineering, IIT Bombay, Mumbai, India; [b]Department of Remote Sensing, Birla Institute of Technology Mesra, Ranchi, India; [c]Instituto de Oceanografia, Universidade Federal do Rio Grande (FURG), Rio Grande, Brazil; [d]Institute of Geography, Russian Academy of Sciences, Moscow, Russia

ABSTRACT
Glacier velocity is an important parameter to characterize glacier dynamics and to derive ice thickness and mass balance. The 2-pass/3-pass Differential Synthetic Aperture Radar Interferometry (DInSAR) techniques are advantageous in estimating glacier movements. However, the 2-pass DInSAR requires an external Digital Elevation Model (DEM), whereas the 3-pass DInSAR does not. The 3-pass DInSAR technique is adopted with Sentinel-1A/1B to map the Svalbard glacier flow velocities. Furthermore, the effect of glacier surface elevation change on the 2-pass DInSAR results were revealed by comparing glacier velocity with the two time period topographic information. The coherence indicates that Sentinel-1A/1B has a high potential to infer operational glacier velocity using the 3-pass DInSAR method with an average atmospheric uncertainty of 0.24 cm/day over the studied region. The precision of the 3-pass DInSAR is analyzed by comparing 2-pass derived line-of-sight (LOS) velocity on the same dates. The 3-pass DInSAR achieves high-resolution and detailed information.

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KEYWORDS
Glacier movement; Differential SAR Interferometry; 2-pass and 3-pass interferometry; DEM; coherence and interferogram

Nela *et al., 2022* Geocarto Int.

Chapter 5

Glacier thickness and Influence of meltwater influx to retrieve ice thickness using glacier flow models

Glacier Ice Thickness

- The glacier ice thickness distribution is a fundamental parameter for both glaciological, hydrological, and disaster management applications
- The inter-annual glacier ice thickness observations (more than 5 years) exploit the glacier mass changes
- Ice thickness is one of the important parameters to predict the future sea-level rise
- Without adequate knowledge and precise information of glacier ice thickness distribution, future sea-level changes cannot be accurately assessed
- The accurate assessment of glacier ice thickness is essential for projecting sea-level rise and understanding glacier dynamics.

Glacier flow models

- One of the major uncertainty in predicting the future sea-level rise or mass loss originates from the **incomplete understanding of the meltwater influx effect on flow models**. Hence, it is important to understand the effect of surface meltwater and basal water on the flow models
- These models have to be refined according to the glacier conditions in the current scenario. For example, the prescribed value of the flow law exponent was observed as 3 (in most cases) in Glen's flow law. But the recent study by **Millstein et al., (2022),** Observed the value of '**n**' as **4.1 ± 0.4** for fast-flowing areas Antarctic ice shelves
- However, the prescribed values in the flow models differ according to the glacier condition and its hydrology system. Hence, the ice flow models are very important and need to be correct in order to reduce the uncertainties in the flow models

Thickness

- The complete glacier ice thickness distribution is mapped for the Indian state of Himachal Pradesh using the physical-based model of a laminar Flow law
- In this study, most of the glaciers are showing the maximum ice thickness along the flow line of glaciers
- In some of the benchmark glaciers in Himachal Pradesh namely, Bara Shigri, Samudra Tapu, and Miyar high ice thickness are observed
- The ice thickness of these glaciers is observed in the range of 300 to 400 m
- However, the estimated mean ice thickness of Himachal Pradesh glaciers is 92 m.

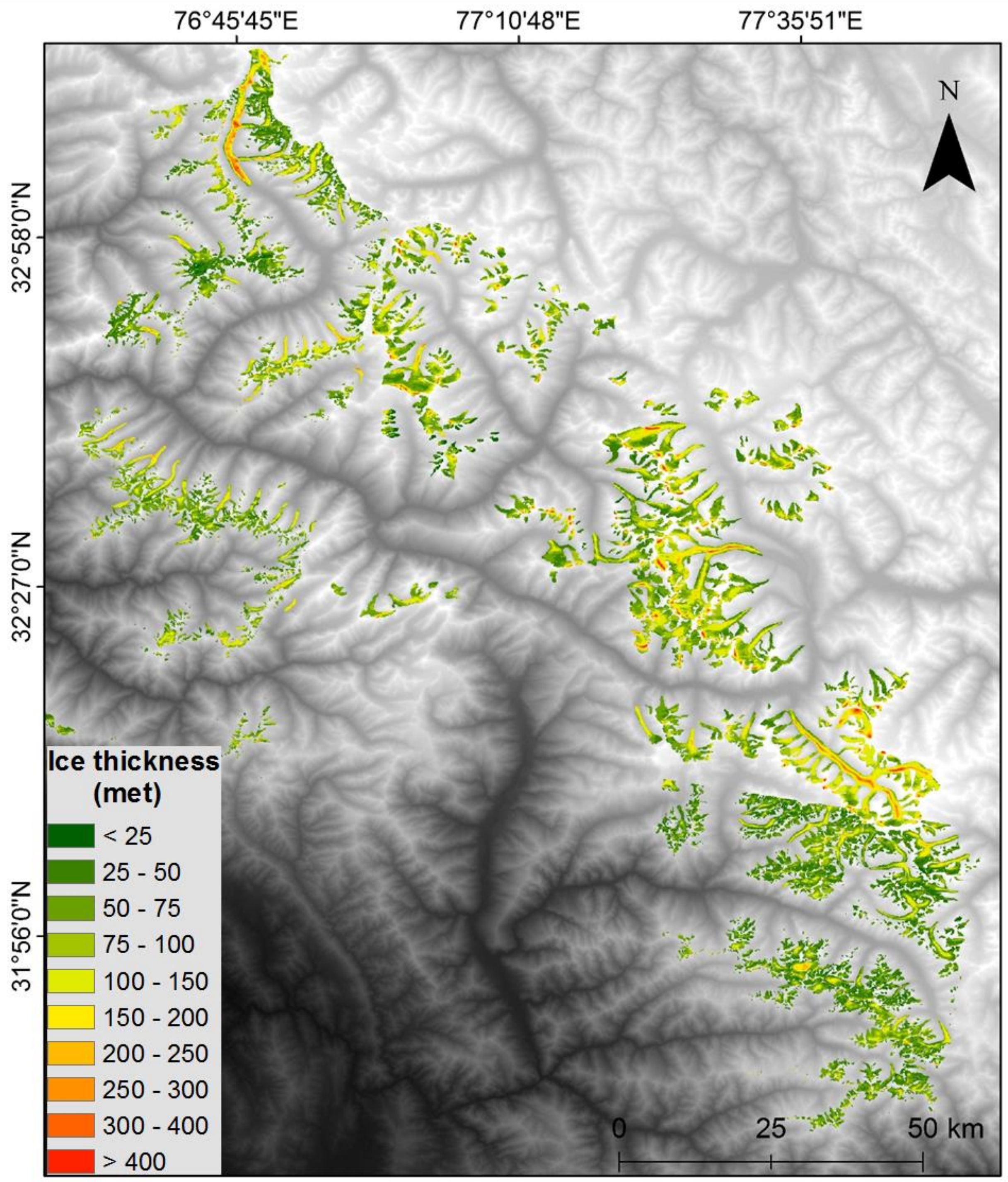


Figure: Complete Himachal Pradesh region glaciers ice thickness derived from DInSAR based glacier velocity

Validation

- Comparison with *Farinotti et al., 2019* estimates
- Farinotti et al., (2019) estimated the modeled-based ice thickness distribution
- Ice thickness maps are available online https://www.research-collection.ethz.ch/handle/20.500.11850/315707
- Benchmark glaciers (well-investigated glaciers in previous studies) are selected for validation purposes namely, Samudra Tapu, Bara Shigri, Sakchum, and Gangotri glaciers.

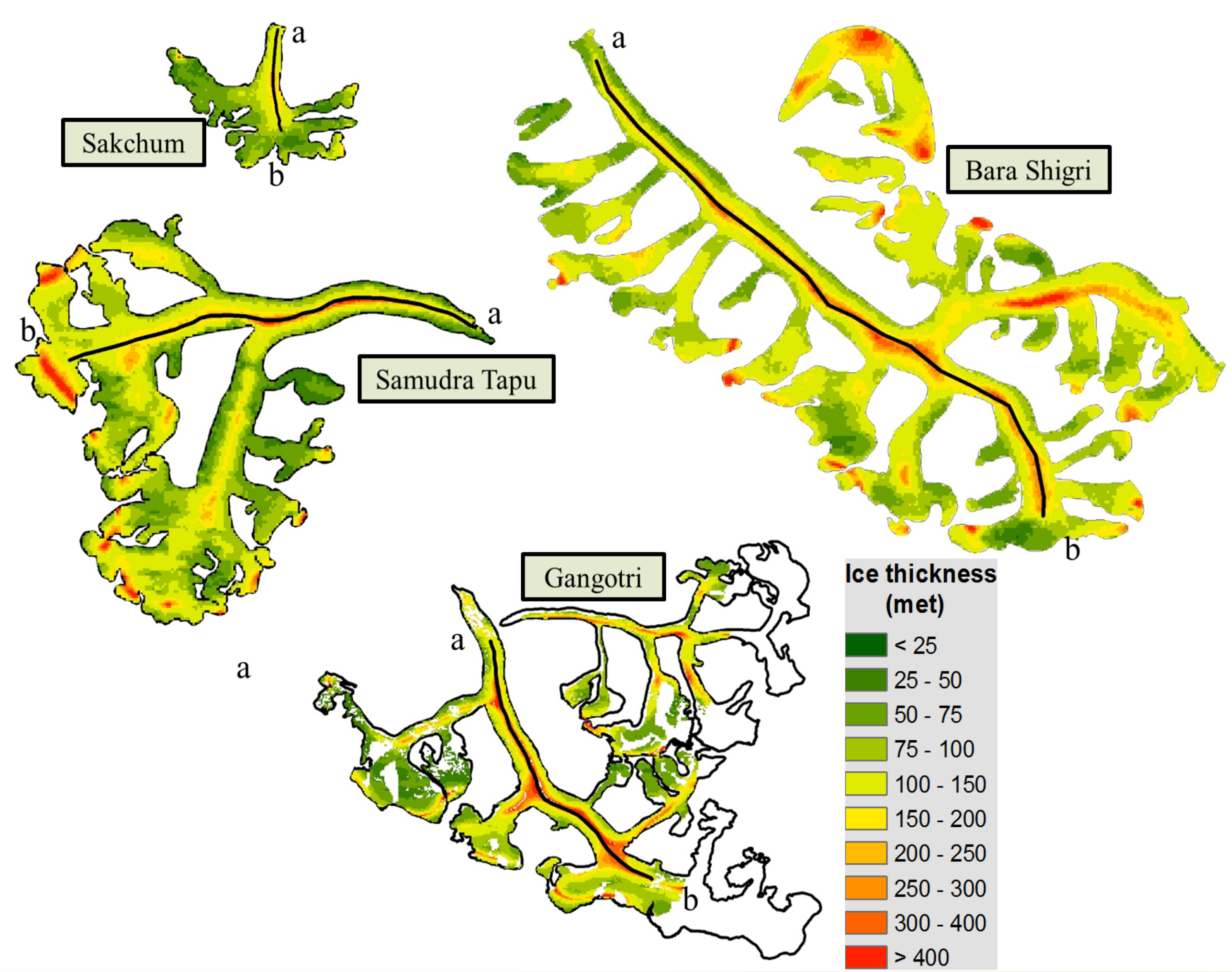
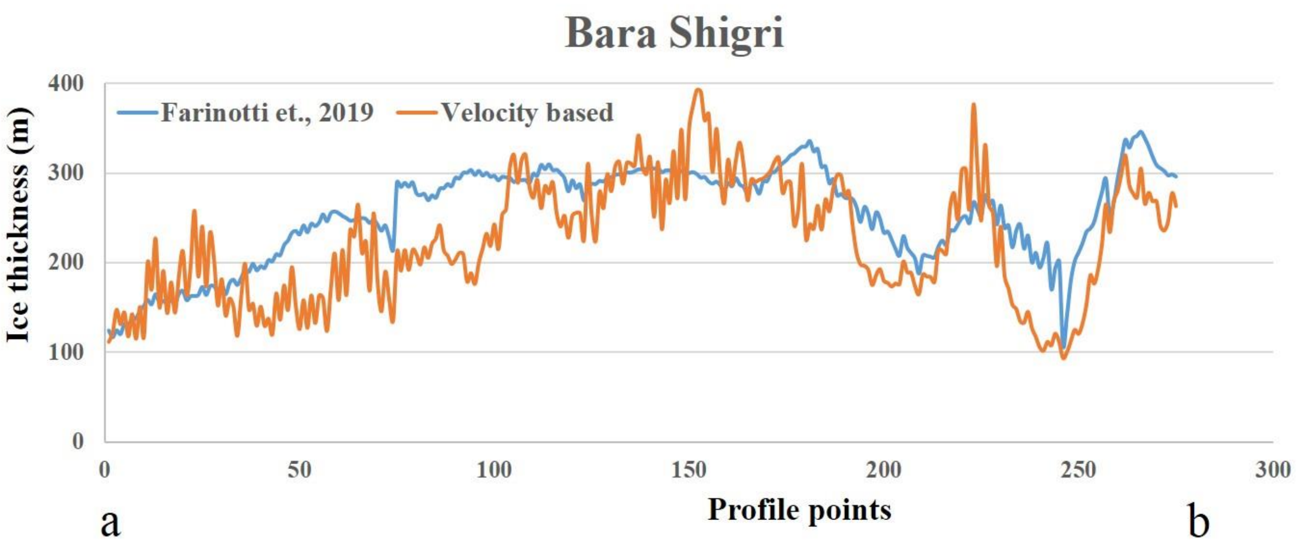
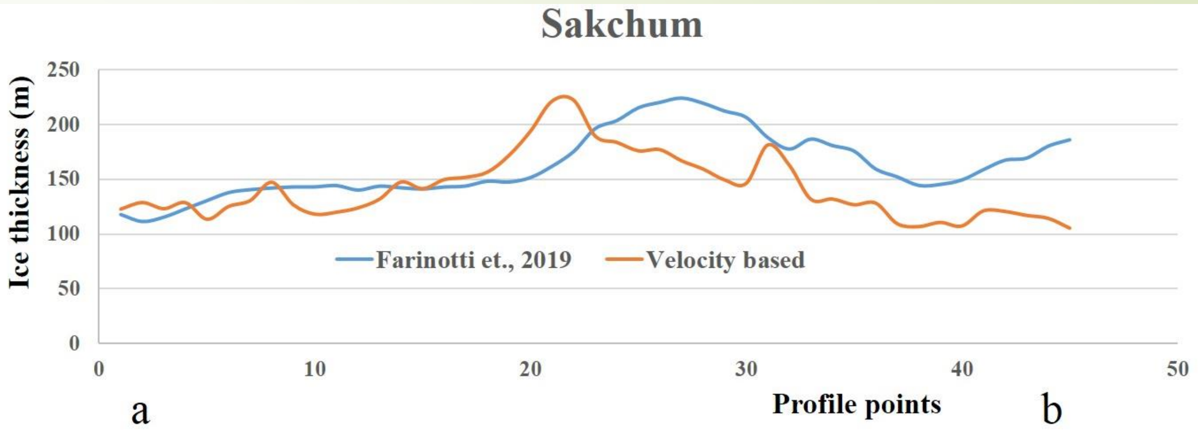
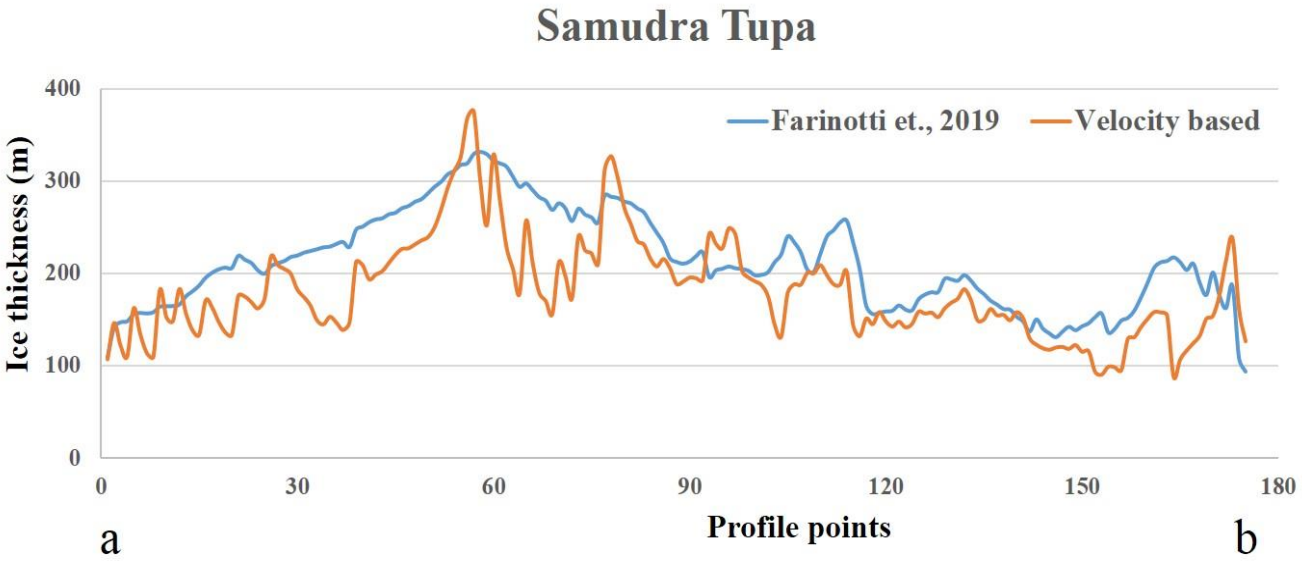


Figure: Selected benchmark glaciers in HP region to validate the velocity derived glacier ice thickness with Ferenotti et al., 2019

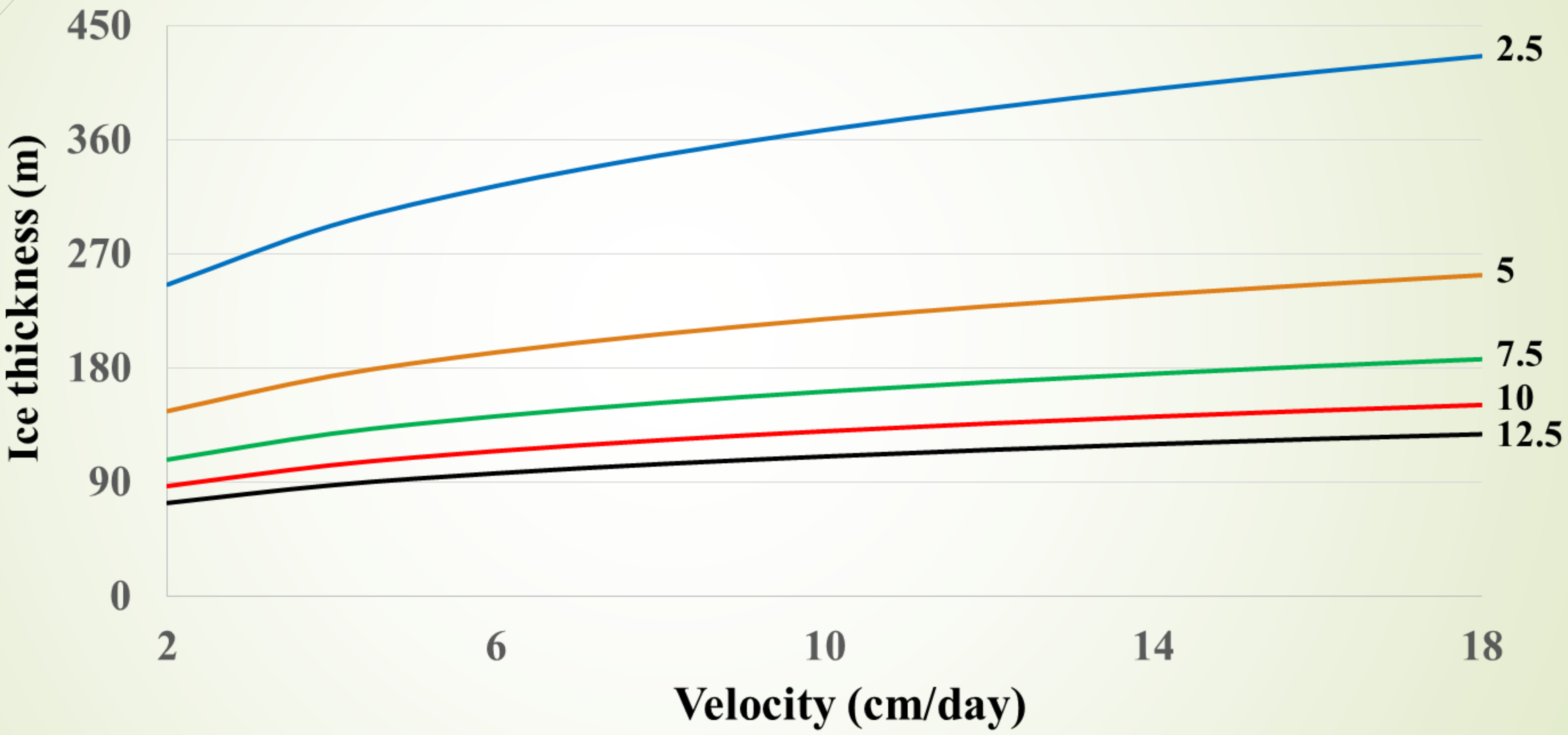
Validation







- Validation of velocity derived glacier ice thickness with Ferenotti et al., 2019
- The comparison profiles along the glacier flowline from the ablation to the accumulation zone
- The patterns are almost similar


450
360
270
180
90
0
Ice thickness (m)
2
6
10
14
18
Velocity (cm/day)
2.5
5
7.5
10
12.5

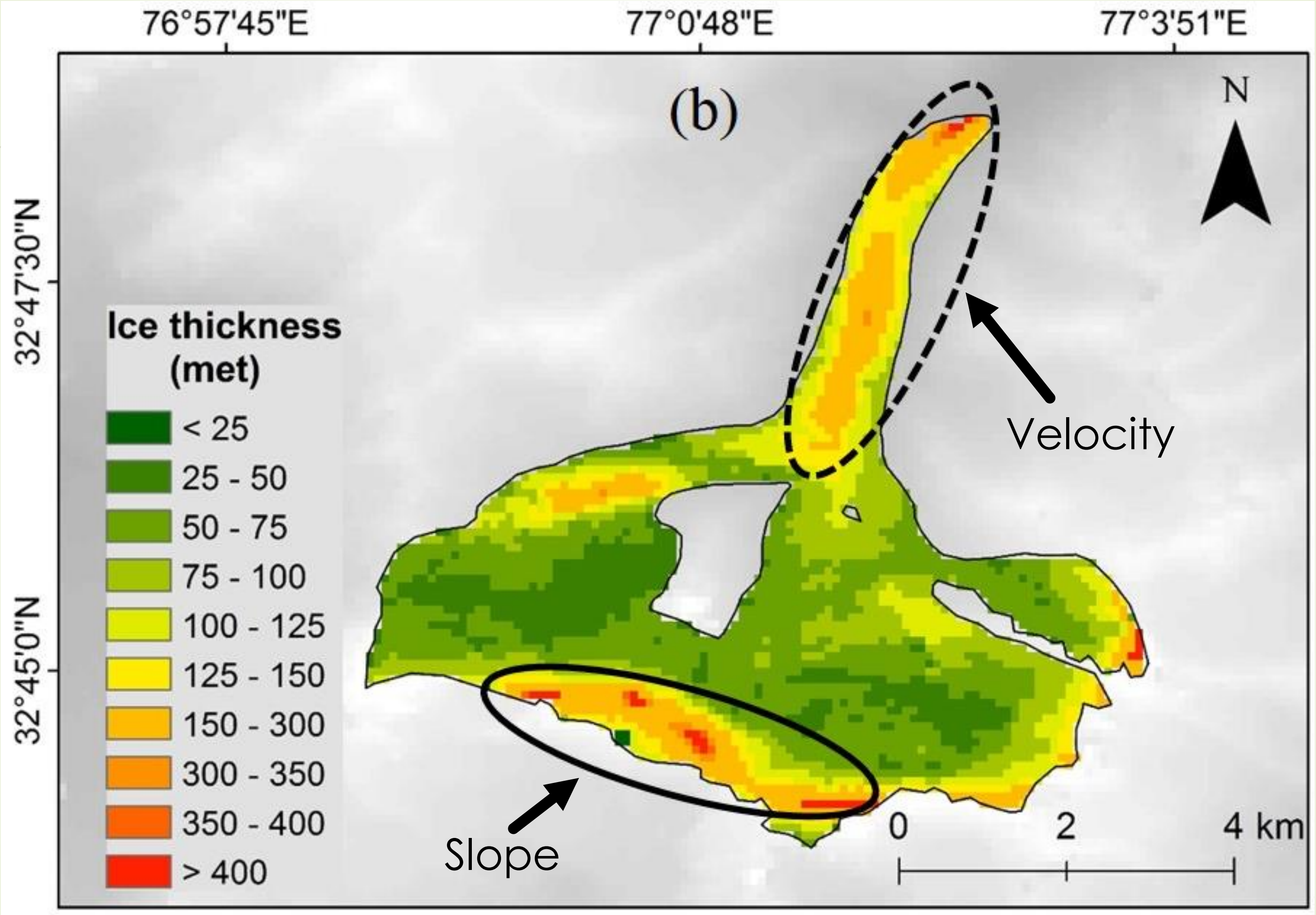
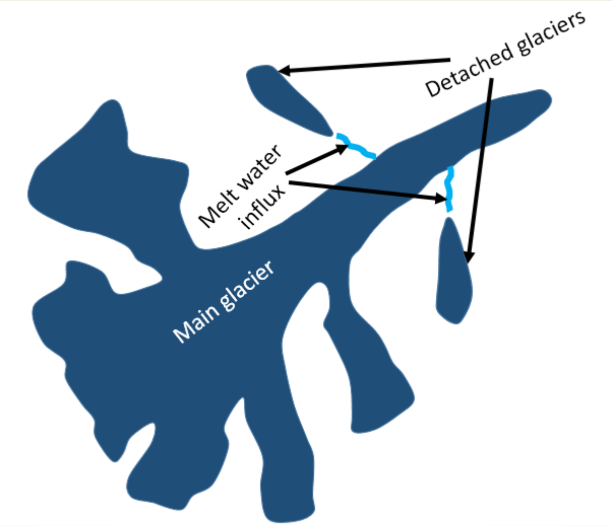


Figure: Glacier ice thickness changes due to velocity and glacier slope



Theory

Melt water influx

Velocity ↑

Ice thickness ↓

Model

$$U_s = U_b + \frac{2A}{n+1} {\tau_b}^n H$$

$$\tau_b = f \rho g \mathrm{H} \sin \alpha$$

$U_s \; \alpha \; H$

Velocity ↑

Ice thickness ↑

* The velocity influencing parameters due to melt water influx should be included in the physical-based models for estimating accurate ice thickness inversion

Summary

- Melt water from tributary glaciers accelerates glacier flow and it further effects the glacier ice thickness (thinning)
- The existing physical models to be modified with inclusion of melt water influx parameters

Nela, B. R., Singh, G., Kulkarni, A.V., Ice thickness distribution of Himalayan glaciers inferred from surface velocity. Environmental Monitoring and Assessment (Under review)

Conclusions

- Influx of melting water from adjacent glaciers are the major causes of anomalous behaviour of the glaciers in HP region
- The velocity influencing parameters due to melt water influx should be included in the physical-based models for estimating accurate ice thickness inversion
- Sentinel 1A/1B has great potential and capability to estimates the glacier ice flow velocities using the 3-pass DInSAR technique.
- The 3-pass DInSAR based movement studies are more suitable over the region of surge-type glacier as compared to 2-pass DinSAR
- Our findings provide direct evidence that the meltwater influx from tributary glaciers can cause large and rapid changes in glacier dynamics.

Thesis major findings

- Meltwater influx on glacier dynamics — (Glaciology)
- Retrieval of ice velocity using S-1A/B SAR —(RS technique)
- Flow models in ice thickness inversion —(Modelling approach)

Future scope/ Recommendations

- Understanding the effect of basal sliding for comprehensive analysis of glacier dynamic studies
- Fusion of DInSAR and Offset tracking
- The velocity influencing parameters due to melt water influx should be included in the Laminar flow model for estimating accurate ice thickness inversion

Publications (Journal papers)

1. **Nela, B. R.**, Singh, G., Mohanty, S., Rajat., Arigony-Neto, J., and Glazovsky, A.F., (2022). Retrieval of Svalbard ice flow velocities using Sentinel 1A/1B three-pass Differential SAR Interferometry. Geocarto International, 1-19. https://doi.org/10.1080/10106049.2022.2032391
2. Singh, G., Bandyopadhyay, D., **Nela B. R.**, Mohanty, S., Malik, R. and Kulkarni, A.V., (2021). Anomalous glacier thinning due to climate feedback mechanism in the Himalaya and evidences in other mountain ranges. Remote Sensing Applications: Society and Environment, 22, p.100512. https://doi.org/10.1016/j.rsase.2021.100512
3. Singh, G., **Nela, B.R.**, Bandyopadhyay, D., Mohanty, S. and Kulkarni, A.V., (2020). Discovering anomalous dynamics and disintegrating behaviour in glaciers of Chandra-Bhaga sub-basins, part of Western Himalaya using DInSAR. Remote Sensing of Environment, 246, p.111885. https://doi.org/10.1016/j.rse.2020.111885
4. **Nela, B.R.**, Bandyopadhyay, D., Singh, G., Glazovsky, A.F., Lavrentiev, I.I., Kromova, T.E. and Arigony-Neto, J., (2019). Glacier flow dynamics of the Severnaya Zemlya archipelago in Russian high arctic using the differential SAR interferometry (DInSAR) technique. Water, 11(12), p.2466. https://doi.org/10.3390/w11122466
5. **Nela, B. R.**, Singh, G., Kulkarni, A.V., Ice thickness distribution of Himalayan glaciers inferred from surface velocity. Environmental Monitoring and Assessment, 2022 (Revised, and waiting for the decision)

Publications (Conference proceedings)

- **Nela B. R.,** Singh, G., Kulkarni, A. V., Malik, K., "Optimum conditions for Differential SAR Interferometry technique to estimate Himalayan glacier velocity," ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., IV-5, 137-140, https://doi.org/10.5194/isprs-annals-IV-5-137-2018, 2018.
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- **Nela B. R.,** Singh, G., "Glacier movement estimation of benchmark glaciers in Chandra basin using Differential SAR Interferometry (DInSAR) technique," presented at the IGARSS 2019, Yokohama, Japan, 2019.
- **Nela B. R.,** Singh, G., Patil, A., "Estimation of velocity for benchmark glaciers in North-Eastern Himalayas," Waterfuture 2019, Bengaluru, India, 2019.
- **Nela B. R.,** Singh, G., "Estimating dynamic parameters of Bara Shigri glacier and derivation of mass balance from velocity," presented at the IGARSS 2020, Virtual Symposium.
- **Nela B. R.,** Singh, G., "Evaluating the TanDEM-X Digital Elevation Model in Differential Interferometric topographic phase removal process for glacier velocity estimation," presented at the ACRS 2020, Virtual Symposium.
- **Nela, B.R.**, Bandyopadhyay, D., and Singh, G., 'Observing Bara Shigri glacier velocity changes in 15 years using radar Interferometry technique', presented at the International Conference on Himalayan Cryosphere (ICHC-2020), Oct 19-23, 2020 organized by IISc Bangalore, India (Virtual conference).
- Bandyopadhyay, D., Singh, G., Dasaundhi, G., **Nela B. R.**, Patil, A. and Mohanty, S., 2020. Surging Glacier Dynamics in Tarim Basin Using SAR Data. In *IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium* (pp. 2999-3001). IEEE.

Publications (Conference proceedings)

- Patil, A., Singh, G., Kumar, S., Mani, S., Bandyopadhyay, D., **Nela, B.R.,** Musthafa, M. and Mohanty, S., 2020. Snow Characterization and Avalanche Detection in the Indian Himalaya. In *IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium* (pp. 2005-2008). IEEE.
- Bandyopadhyay, D., Dasaundhi, G., **Nela, B.R.**, and Singh, G., 'Surging glacier dynamics in the Indus Basin', presented at the International Conference on Himalayan Cryosphere (ICHC-2020), Oct 19-23, 2020 organized by IISc Bangalore, India (Virtual conference).
- **Nela, B.R.**, Singh, G., and, Patil, A., 'Velocity estimation of Eidembreen glacier in Svalbard using Sentinel 1A/1B Three pass Differential Interferometry technique', presented at FRINGE-2021, May 31-June 04, 2021 (Virtual conference).
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