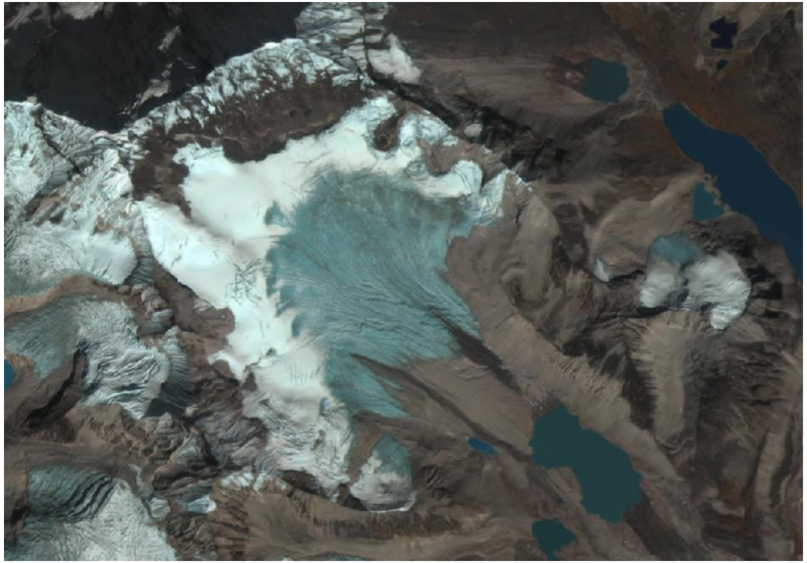
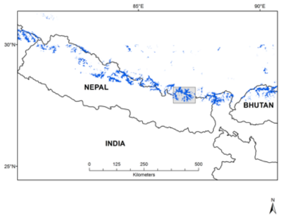
Spatio-temporal evolution of Glacier Facies in Himalaya using SAR Remote Sensing : examples from the Khumbu Himalaya



Adina Racoviteanu, A. Manimaran, B. Georjon, J.P Dedieu,
& contributions from P. Vinze, M. Kneib, F. Karbou

Context



Mera Glacier

Snow Line Altitude (SLA) : good proxy for monitoring climate-induced glacier changes

→ end of ablation season, **SLA_{max} ~ ELA**

Field – based monitoring

- limited in high mountain environments
- ~ 36 glaciers monitored in the Himalaya-Karakoram

Optical remote sensing methods

- difficult to automate fully (Rabatel et al. 2012 , Racoviteanu et al. 2019, Rastner et al. 2019, Davaze et al. 2020)

Context

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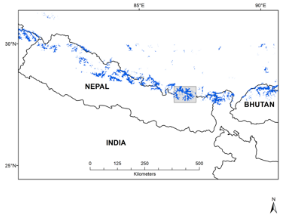
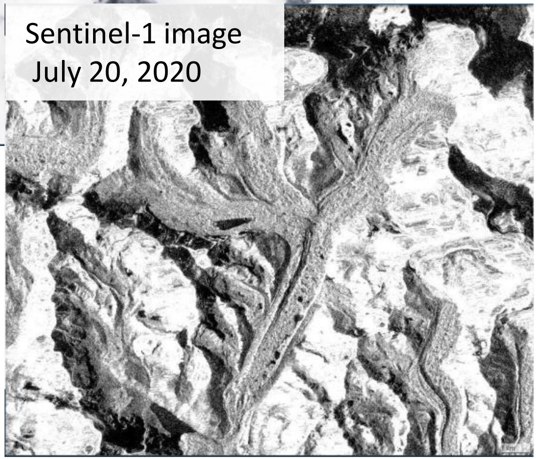
Optical remote sensing methods

- difficult to automate fully (Rabatel et al. 2012 , Racoviteanu et al. 2019, Rastner et al. 2019, Davaze et al. 2020)
- surfaces obstructed by snow and clouds (ie. Monsoon-dominated regions)



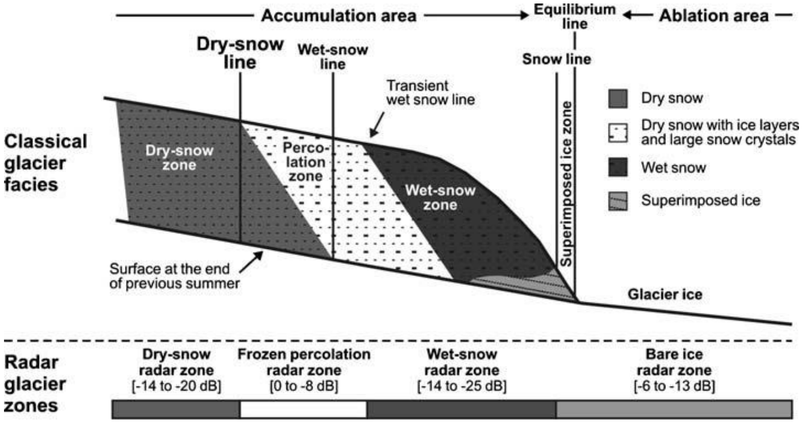
Khumbu Glacier



Main questions

- How can we **combine SAR + optical data** to track *glacier zones?*
- Can we **automate the method** to apply it to regional scales?

SAR: Glacier "radar zones"



After Rau et al, 2011

Optical: snowlines

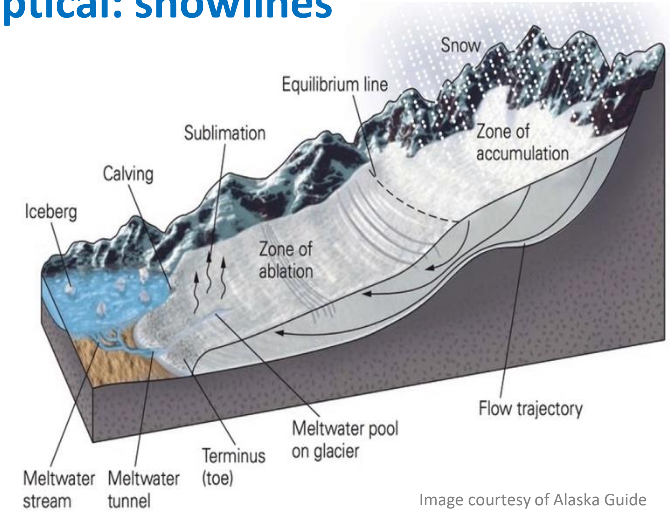


Image courtesy of Alaska Guide

Study area

Two climatically-distinct areas

Khumbu region (Nepal) :

→ <u>monsoon-influenced</u>

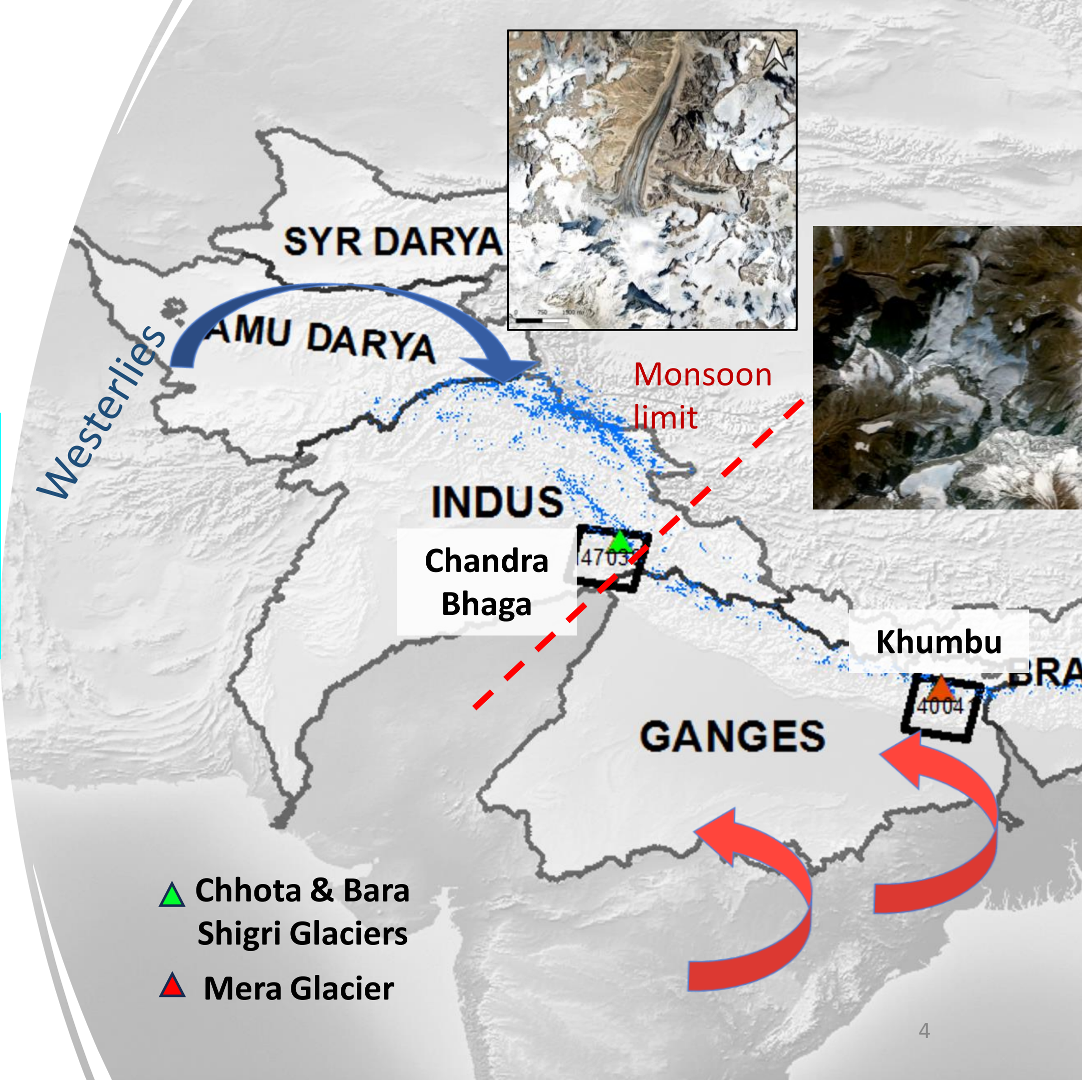
→ Mera Glacier (Nepal): field monitored since 2007; clean glacier

Chandra Bhaga basin (India):

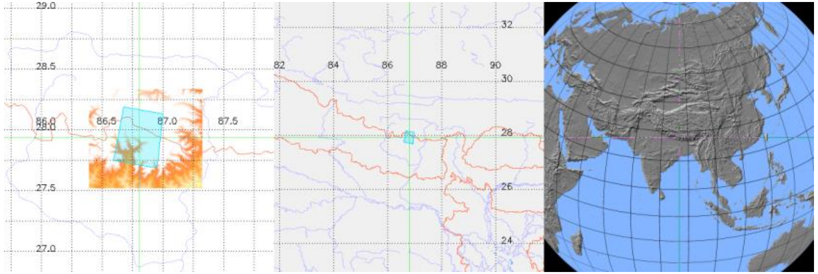
→ <u>monsoon transition</u>

→ Chhota Shigri (India): field monitored since 2002, almost clean

→Bara Shigri (debris-covered)



Data acquired



SAR images:

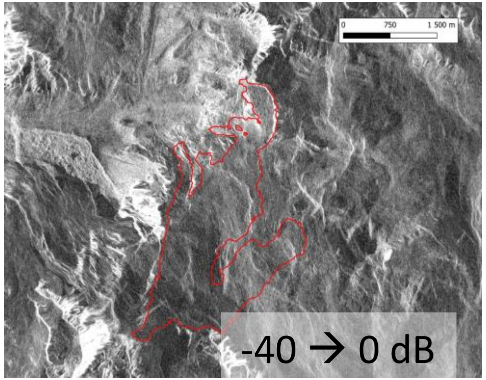
Sentinel-1A images (Alaska Facility Center)

- C-band (wavelength: 5.5 cm), every 12 days, 10 m
- GRD, Interferometric Wide Swath (IW) beam mode, dual pol
- 318 tiles **2017 – 2021,** ASC/DESC

PAZ (Hisdesat)

- X-band (3.75–2.5 cm), every 11 days, 5 m, dual pol
- current acquisitions: June – Nov 2024, ASC/DESC

ESA SNAP



PAZ scene VH
Mera Glacier, June 2024

Optical images:

VENµS images (CNES-ISA) franco-israelian

- VM1 phase (2017-2020), Khumbu region
- Every 2 days, 5 m, 12 spectral bands (423.9 - 908.7 nm)

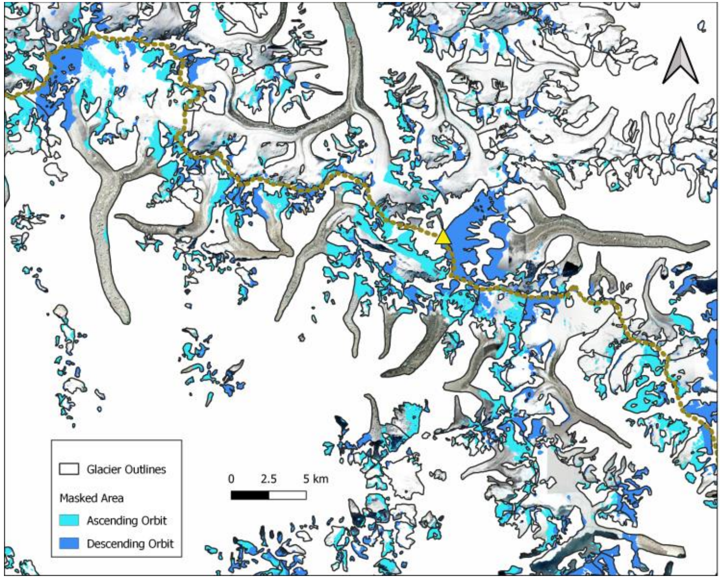
Field data:

- Ablation stake measurements (→ mass balance, snow heights, 2007 - 2023)
- AWS, ground camera

SAR methodology : progress and challenges

SAR geometric distortion, data loss!

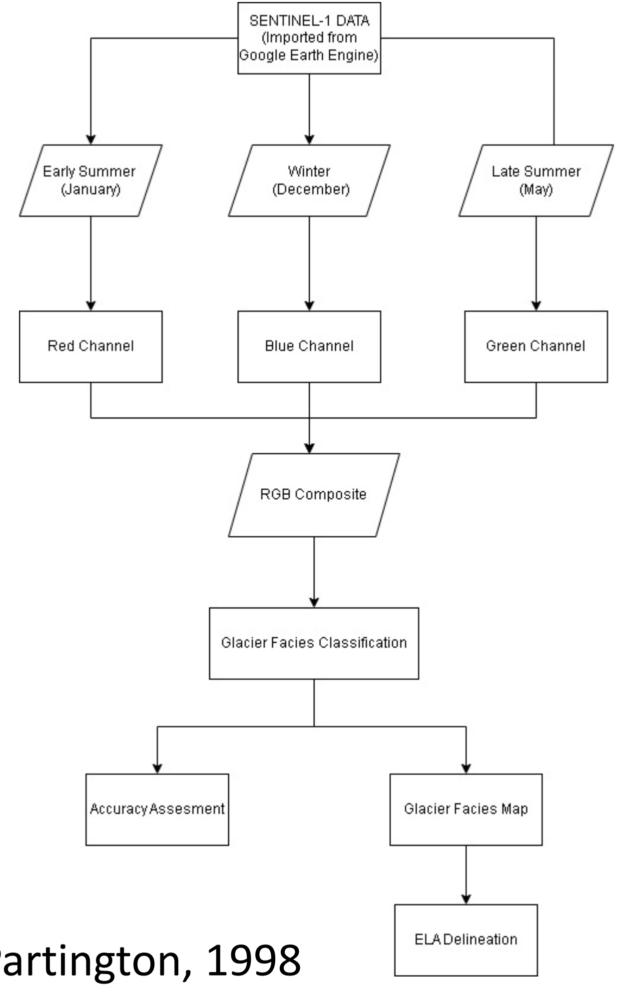
Raw backscatter from Sentinel-1 (ascending orbit)
(Rongbuk Glacier) November, 2017



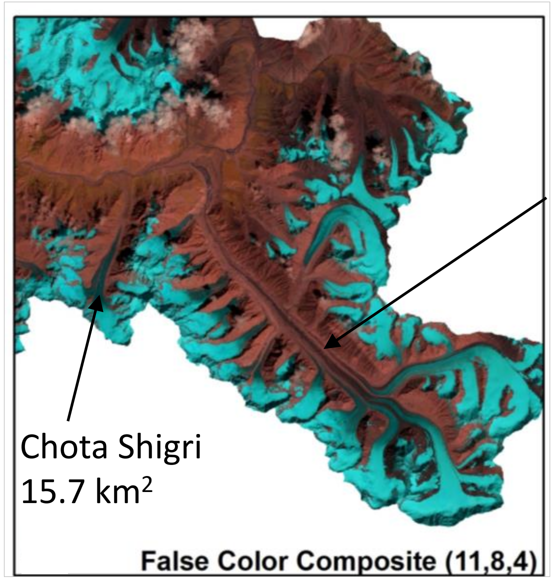
Rugged terrain → geometric distortions

~ 15 – 20 % data losses in Khumbu

Previous work : GEE

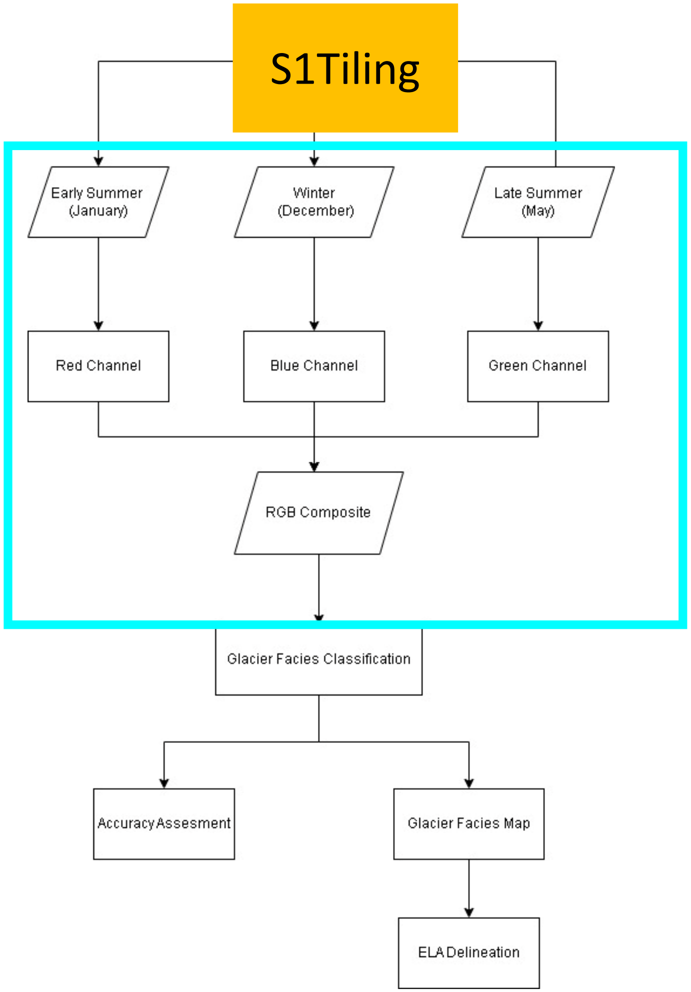


Partington, 1998



Bara Shigri
136 km²
Sentinel-2 image

- Period 2019 – 2022
- Focus on classification and ELA detection



From GEE / SNAP to S1Tiling

- **CNES + CESBIO tool**

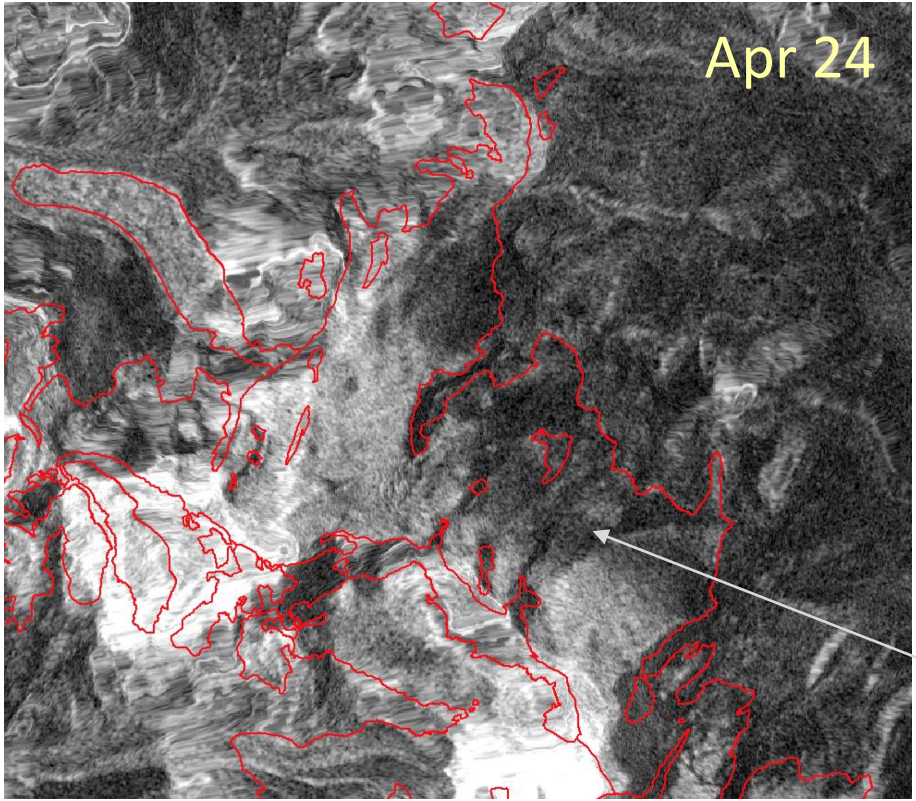
- generate calibrated and ortho-rectified Sentinel-1 data on the Sentinel-2 grid
- python-based

- Now installed on the UGA cluster ☺
- Yet to test σ^0RTC NORMLIM calibration

D. Small, 2011 "Flattening Gamma: Radiometric Terrain Correction for SAR Imagery," IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 8, pp. 3081-3093

https://s1-tiling.pages.orfeo-toolbox.org/s1tiling/develop/intro.html

Seasonal variability in backscatter intensity



Mera and Naulek Glaciers, Khumbu

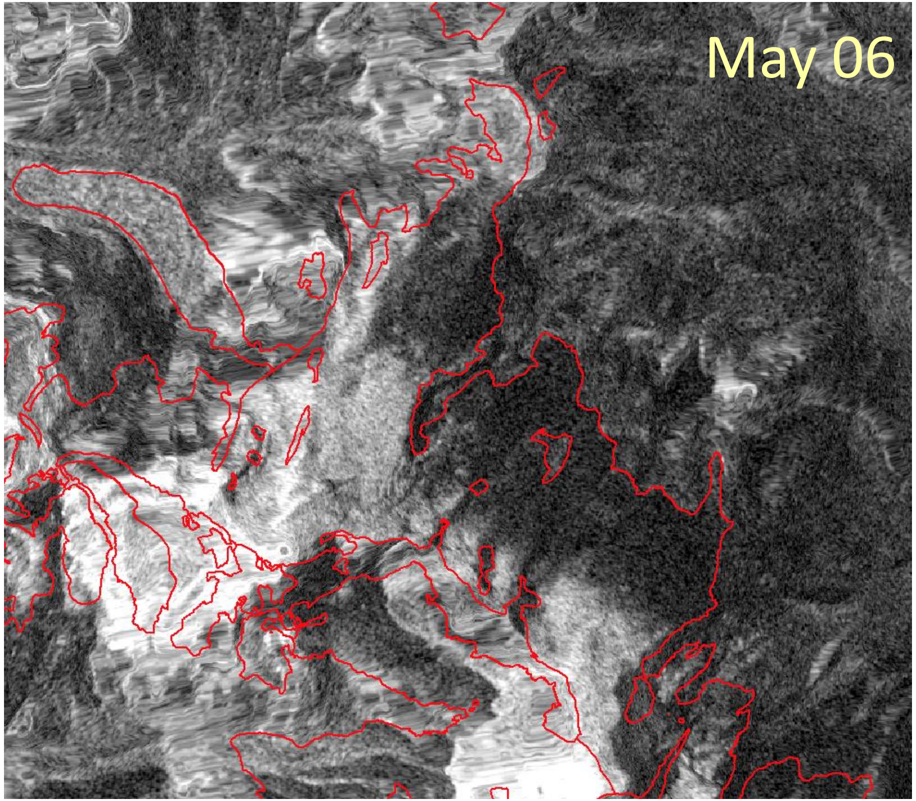
Sentinel-1 images

Pre-monsoon

Glacier outline

Dark = wet snow/ice (ablation areas)

Seasonal variability in backscatter intensity



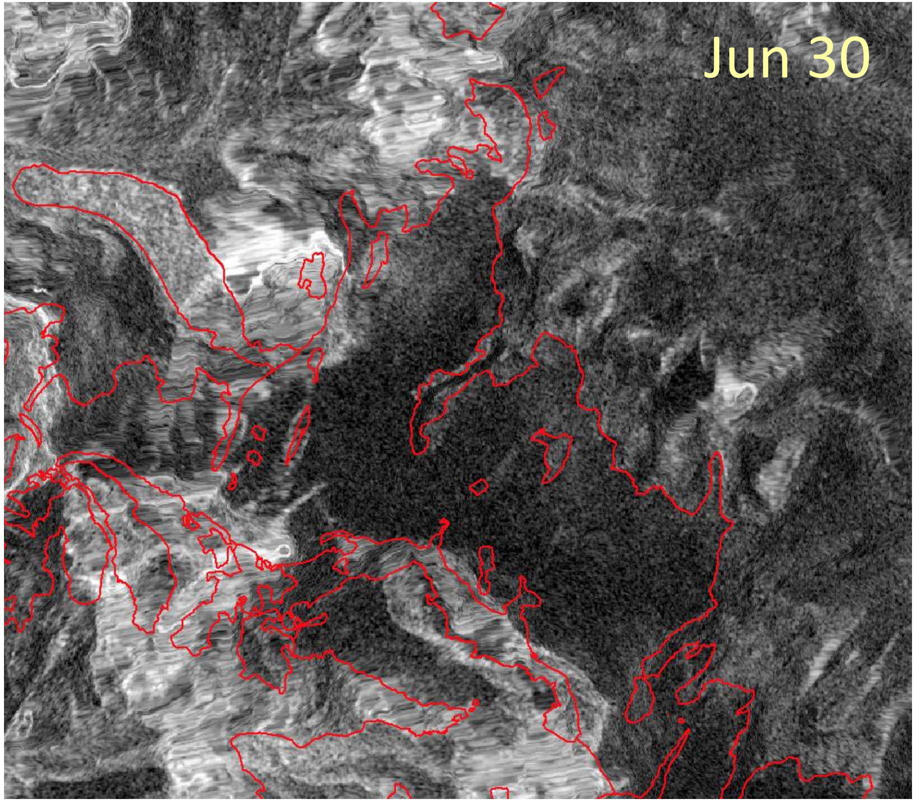
Mera and Naulek Glaciers, Khumbu

Sentinel-1 images

Monsoon starts

Glacier outline

Seasonal variability in backscatter intensity



Mera and Naulek Glaciers, Khumbu

Sentinel-1 images

Monsoon

—— Glacier outline

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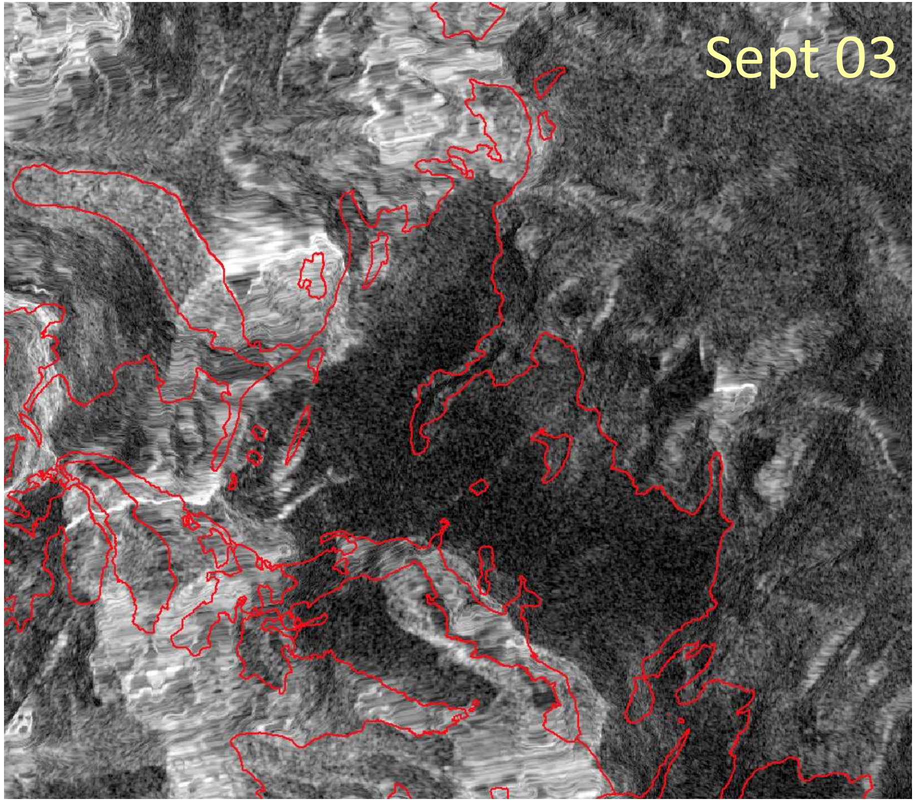

Mera and Naulek Glaciers, Khumbu

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Monsoon

Glacier outline

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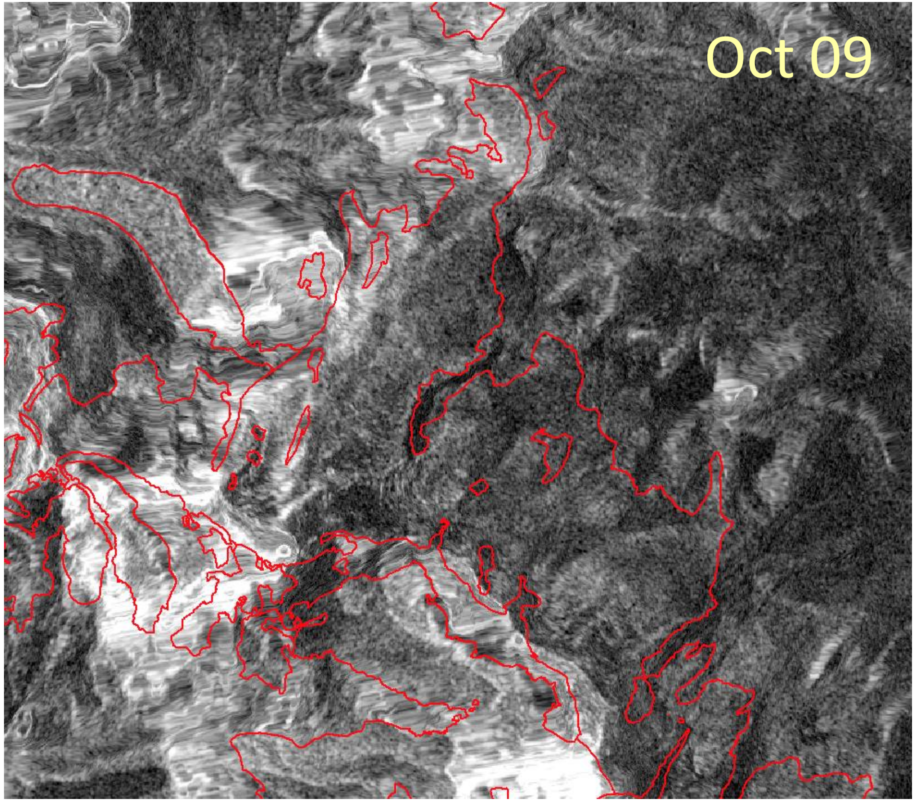

Mera and Naulek Glaciers, Khumbu

Sentinel-1 images

Post-monsoon

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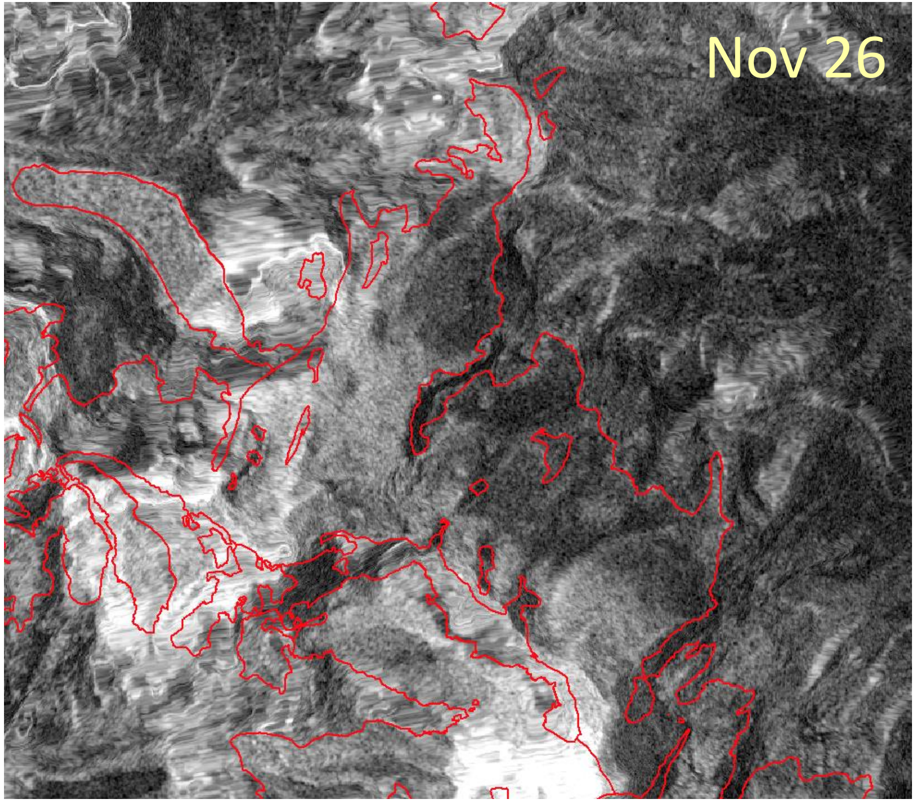


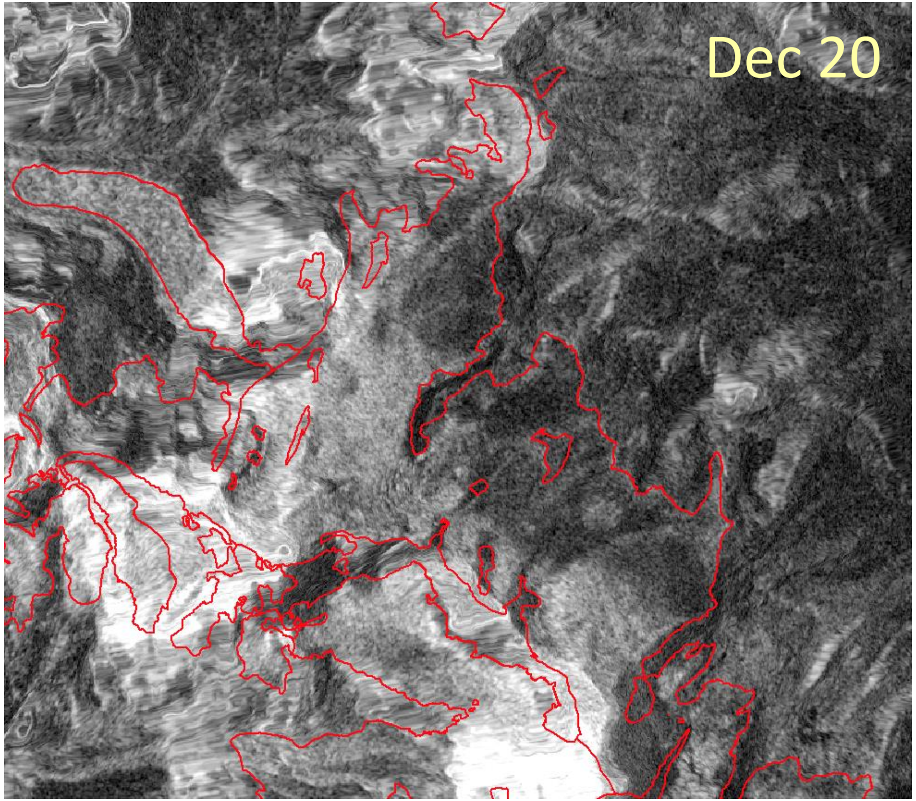
Mera and Naulek Glaciers, Khumbu

Sentinel-1 images

Post-monsoon

Glacier outline

Seasonal variability in backscatter intensity

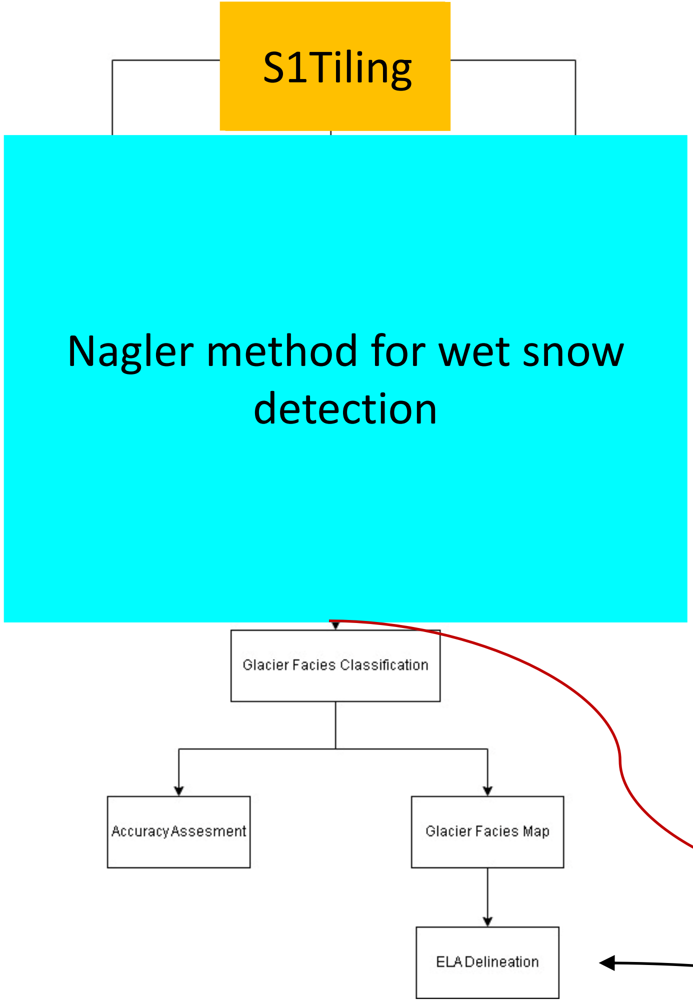


Mera and Naulek Glaciers, Khumbu

Post-monsoon, winter season

—— Glacier outline

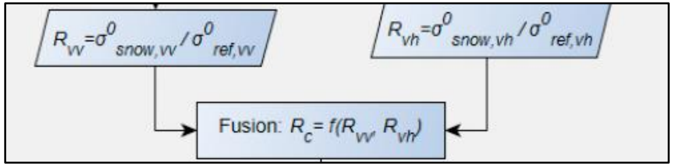
- How to quantify the backscatter to extract the wet snow?



From RGB to Nagler

Principle: *reduced backscattering coefficient (σ^0) of wet snow compared to snow-free / dry snow surfaces*
→ mapping of snowmelt areas (Nagler et al, 2000)

Nagler et al, 2016:



Weight (W) varies with the local incidence angle (ϕ);

Reduced separability of the classes for co-polarized backscatter at $\phi < 30^o$, and less for cross-polarized

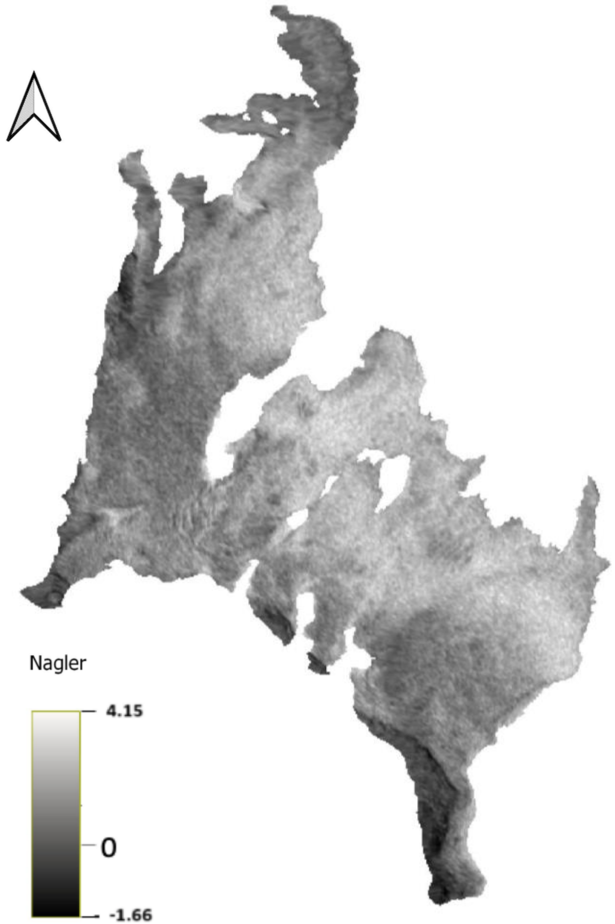
Output: combined single channel

$Rc \leq -2dB$ = wet snow (Nagler et al. 2016)

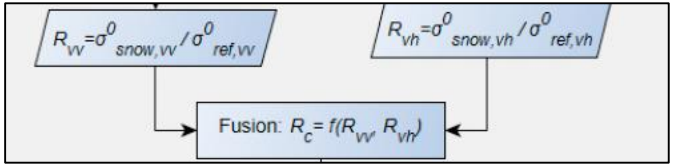
Nagler output

Mera / Naulek Glaciers, Khumbu

Sept 09, 2018



Nagler et al, 2016:



Weight (W) varies with the local incidence angle (ϕ);

Reduced separability of the classes for co-polarized backscatter at ϕ < 30°, and less for cross-polarized

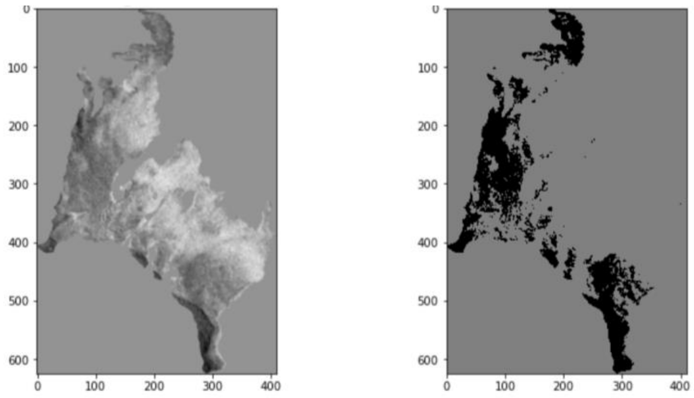
Output: combined single channel

***$Rc \leq -2dB$ = wet snow (Nagler et al. 2016)

Work in progress

1. How to threshold the SAR Nagler output?.... σ = −2.5 to −3.0 dB not applicable everywhere! → need a flexible threshold

Otsu thresholding (Otsu, 1979)

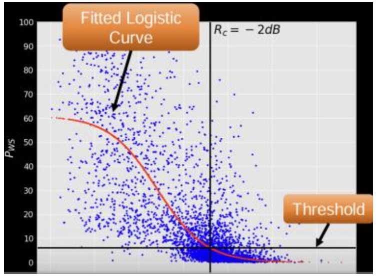


→ optimal threshold by maximizing the between-class variance of gray levels of object and background

Issues and improvements needed:

- Does not capture class distribution
- Need statistical thresholding (i.e based on Std Dev)

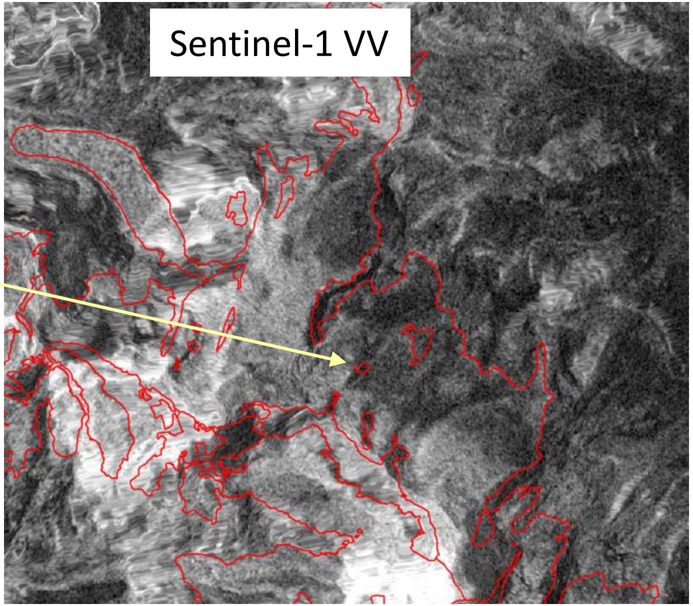
Longépé 2008
Guiot et al 2024
James et al 2024
Li et al 2024

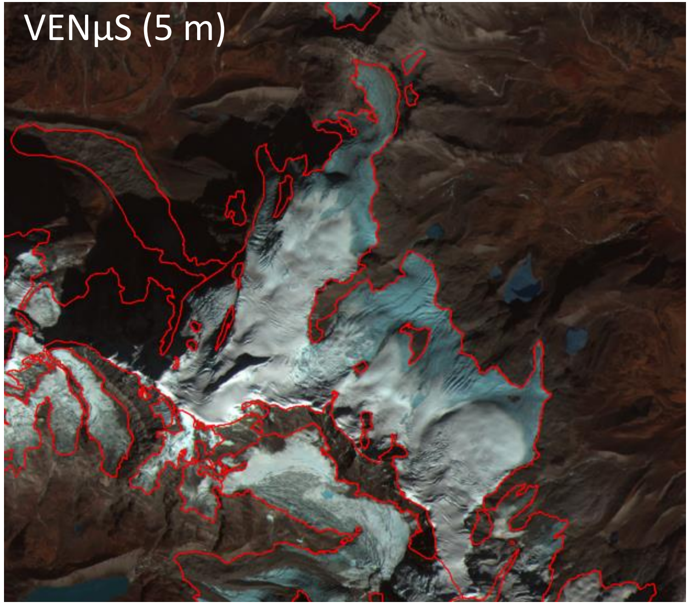


2. Compare optical and SAR outputs

Mera and Naulek Glaciers (Nov. 26, 2018)

Transition zone?

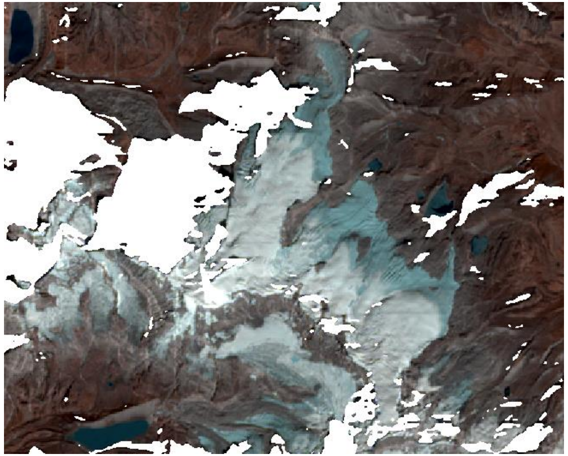


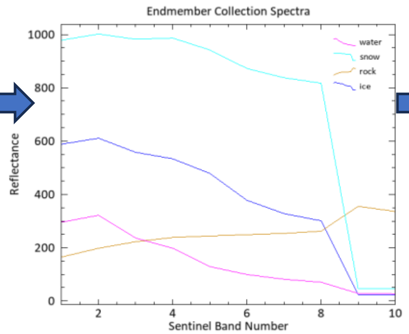


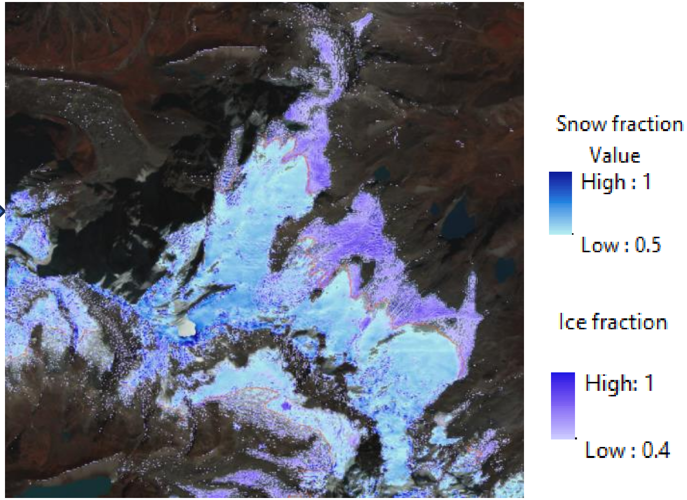
— Glacier outline

2. Compare optical and SAR outputs : Sentinel-2 spectral unmixing

Mera / Naulek Glacier







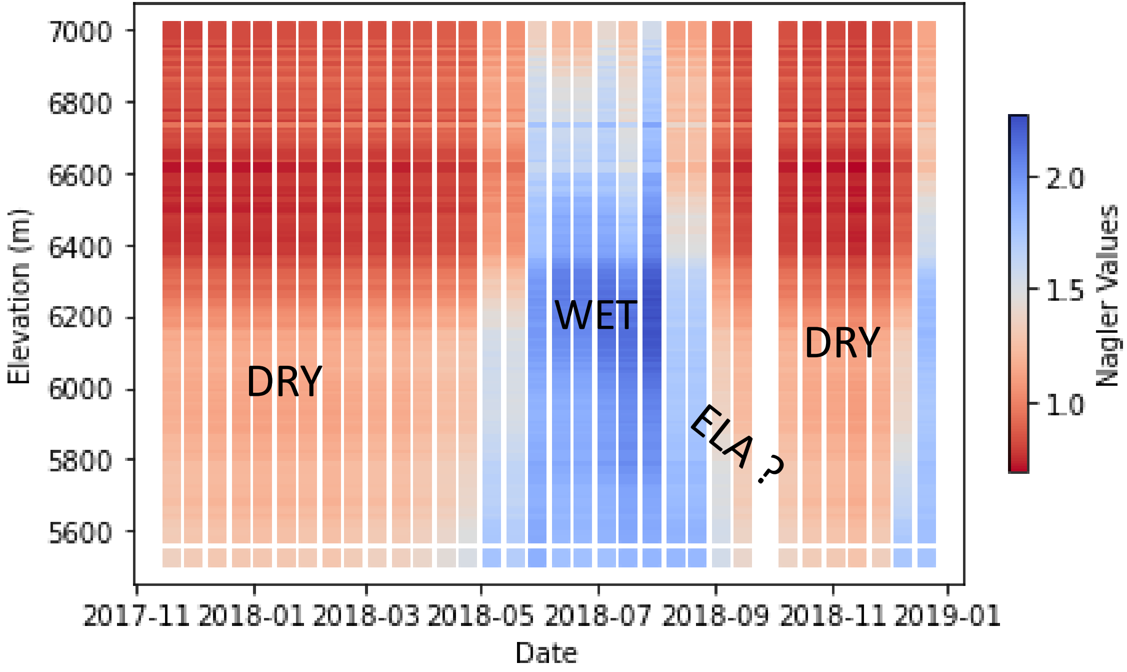
Sentinel-2, 2018-11-24

topographically corrected

Next step: extract snow grain size from spectral unmixing

3. Compare optical and SAR outputs : extract SLAs

Heat plots



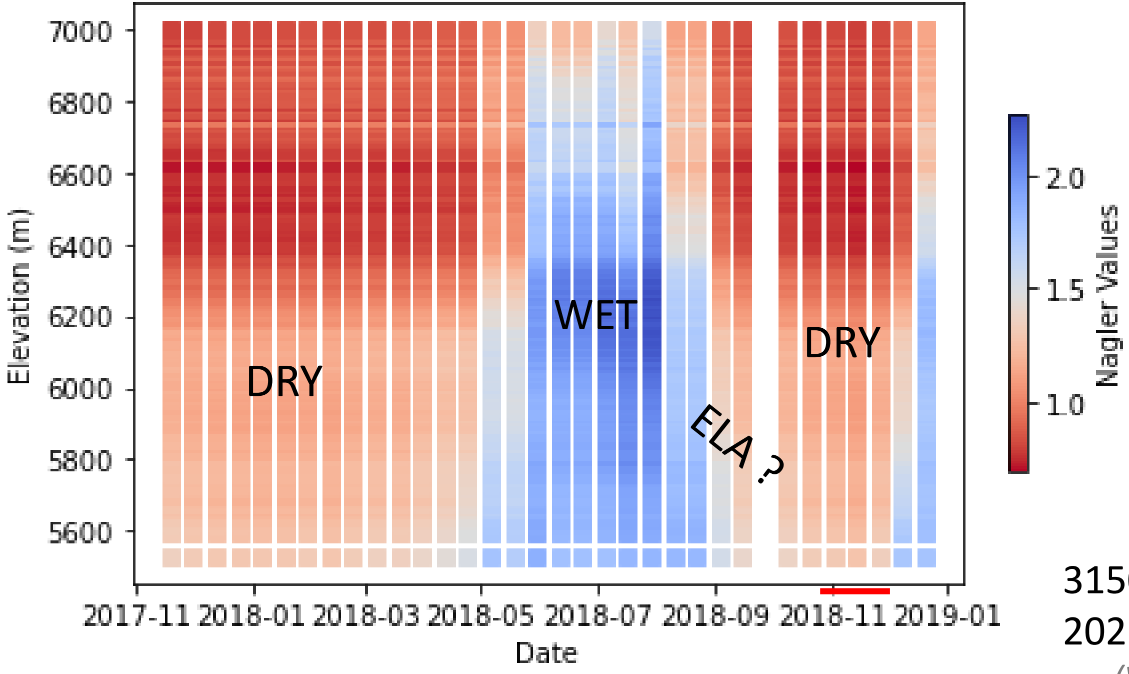
SLA from VENµS Nov 28, 2018

(Vinze, Racoviteanu et al, JOG, submitted)

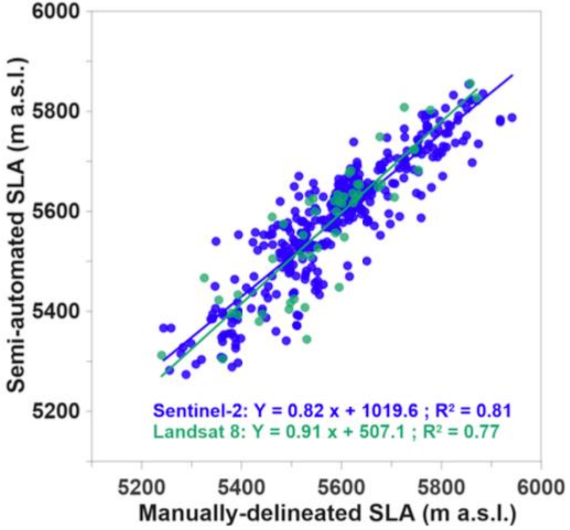
Winsvold et al. 2018

3. Compare optical and SAR outputs : extract SLAs

Heat plots



Winsvold et al. 2018

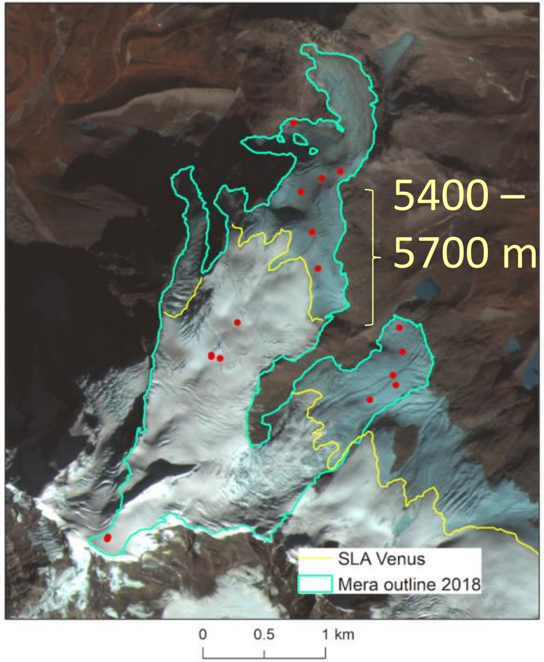


3150 SLA from Landsat/Sentinel 2 1980-2022 validated with VENµS/Planet

(Vinze, Racoviteanu et al, JOG, submitted)

4. Investigate field data to link SAR signal with field processes

Mera / Naulek Glacier 2017/18 hydrologic year

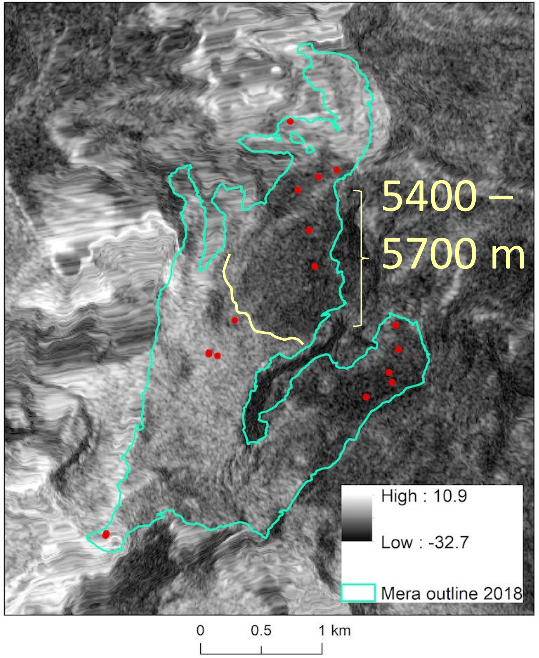


Measurement date	Field ELA	Sentinel-2 Image date	Rem. sens SLA
17—25 Nov. 2018	5796	24 Nov. 2018	5546

- 250 m mismatch between field and optical SLA!!!
- Optical SLA below the field ELA, <u>why?</u>

5. Investigate field data to link SAR signal with field processes

Mera / Naulek Glacier 2017/18 hydrologic year



Measurement date	Field ELA	Sentinel-2 Image date	Rem. sens SLA
17—25 Nov. 2018	5796	24 Nov. 2018	5546

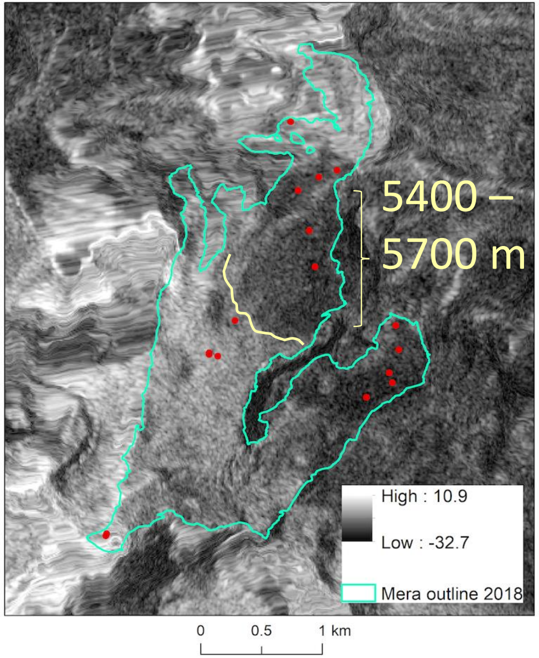
- 250 m mismatch!!!
- RS SLA below the field ELA, **<u>why?</u>**

Year	2017/18	
Elev. (m)	H	Ba
5400-5500	0	-1.3
5500-5600	5.4	-1
5600-5700		-0.2
5700-5800		-0.1

- Glacier areas in ablation
- Dry year, high ELA
- SAR SLA ˜ 5670 – 5700 m

5. Investigate field data to link SAR signal with field processes

Mera / Naulek Glacier 2017/18 hydrologic year



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17—25 Nov. 2018	5796	24 Nov. 2018	5546

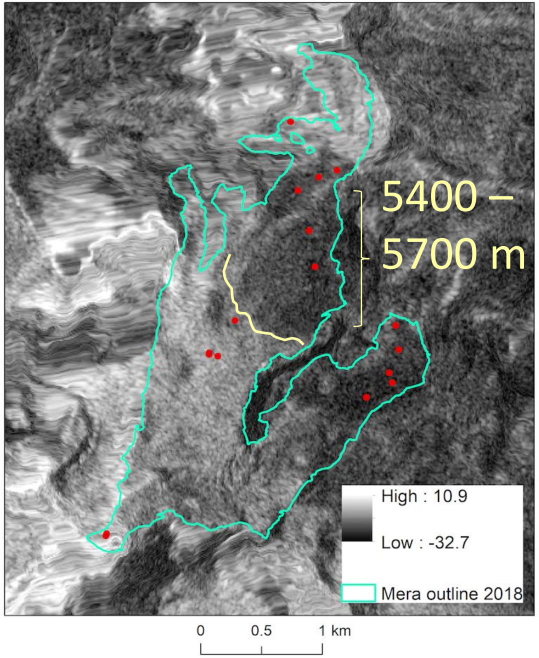
- 250 m mismatch!!!
- RS SLA below the field ELA, **why?**

Year	2017/18		2018/19		2019/20		2020/21		2021/22	
Elev. (m)	H	Ba	H	Ba	H	Ba	H	Ba	H	Ba
5400-5500	0	-1.3	48.5	-1.2	17.0	-1.3	72	0.3	62.5	-1.4
5500-5600	5.4	-1	57.7	-1.1	12.5	-0.4			70.5	
5600-5700		-0.2				0.3		0.4		-0.2
5700-5800		-0.1		0.1		0.3		0.8		-0.2

SNOW!

5. Investigate field data to link SAR signal with field processes

Mera / Naulek Glacier 2017/18 hydrologic year



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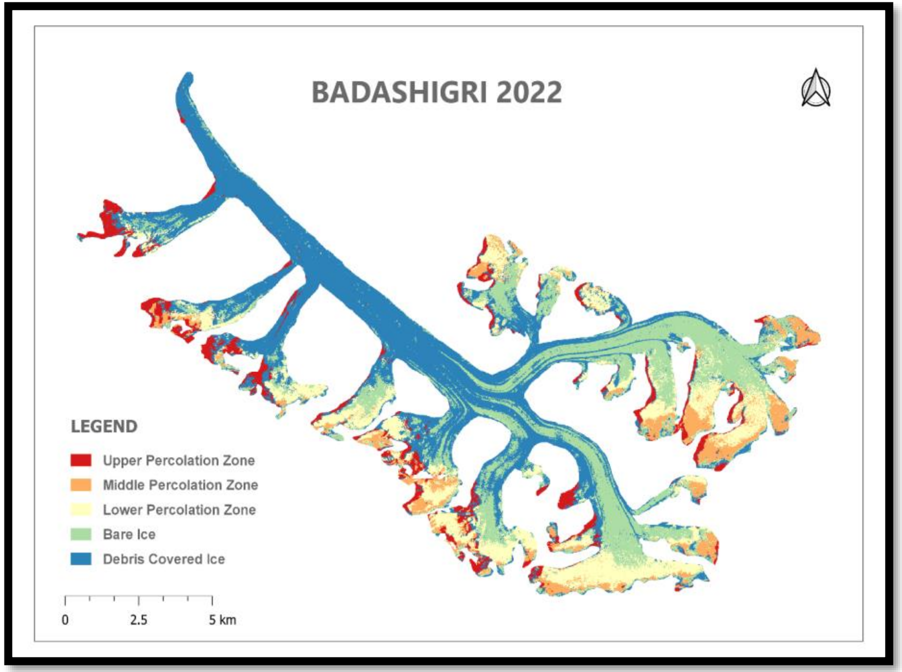
5500-5600	5.4	-1	57.7	-1.1	12.5	-0.4			70.5	
5600-5700		-0.2								
5700-5800		-0.1								

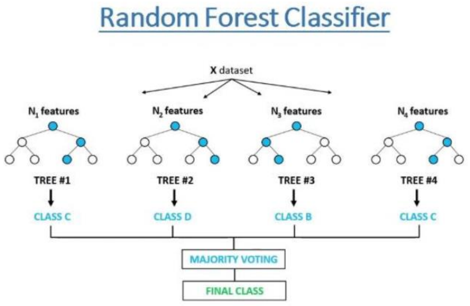
Better match with field ELA!!

so, <u>SAR line ~ true ELA !??</u>

5. Use of machine learning to automate threshold selection → requires good training data → lots of manual digitization?



Previous work (MSc)



..work to be continued!

Challenges & further work

- **Difficulties with masks** (layover, foreshortening, shadow) → loss of data
- **SAR data more difficult to process** and **time consuming**

Current work :

- How to threshold the output?..nominal threshold backscatter value $\sigma = -2.5$ to -3.0 dB not applicable to glacier areas! ☹ → <u>need flexible threshold</u>
- Use of ML to automate threshold selection → requires good training data
- Further investigate field data (snow profiles etc.) to confirm that SAR SLA = ELA
- So far, good match between SAR (wet) snowline and field ELA

Thank you!

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