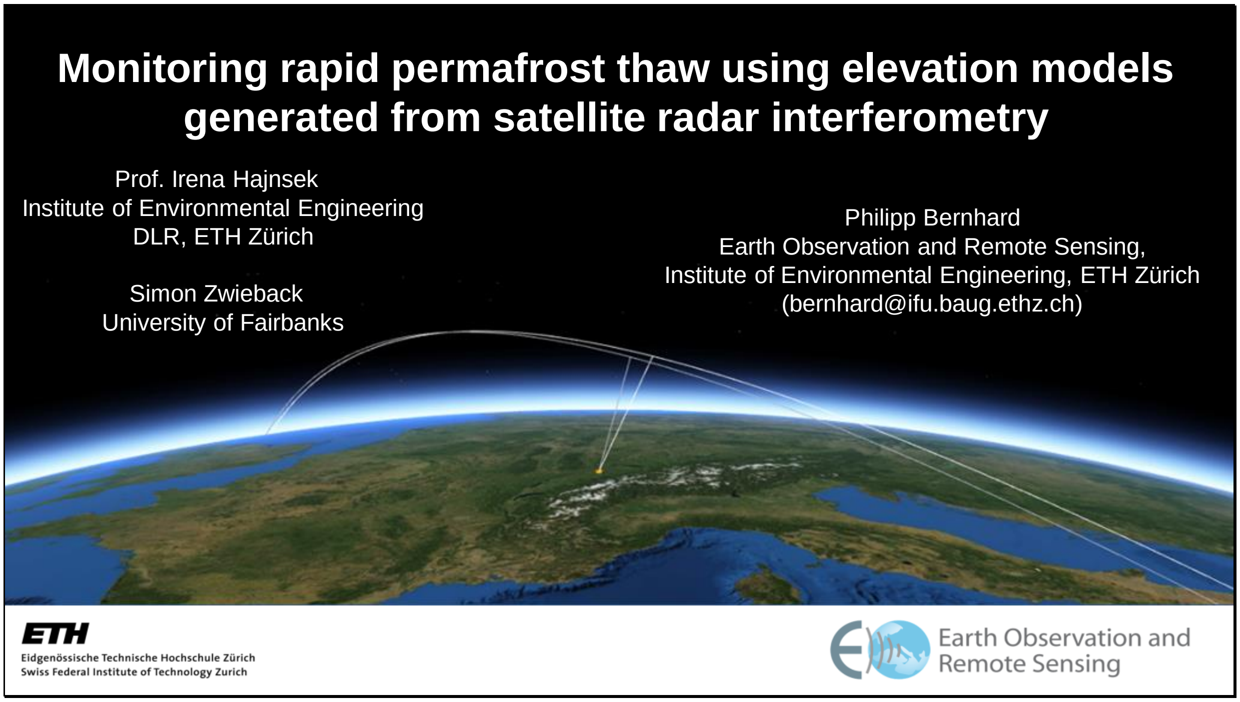
Slide 1

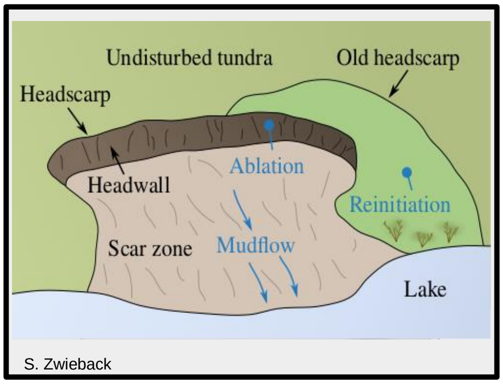


Welcome to the presentation about "Monitoring rapid permafrost thaw using elevation models generated from satellite radar interferometry".
The presentation is kept in the original style but we added additional explanations below each slide.

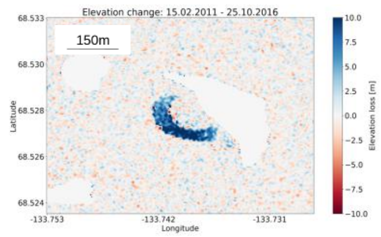
The presentation is separated in two parts:
First, we will talk about retrogressive thaw slump (RTS) detection using elevation models generated from single-pass bistatic TanDEM-X observations. We will present our processing chain showing results from two study areas in Northern Canada. We will comment on the data availability and particularities that have to be considered.
In the second part, we will show some preliminary results of the RTS property extraction (e.g. volume, average elevation) in 3 study areas located in Northern Canada, Alaska and Siberia and talk about first validation efforts.

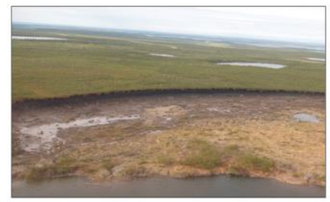
Slide 2

Retrogressive Thaw Slumps (RTS)



Initiation: Exposure of ground ice
Growth: Melting of ice in the headwall, sediment transport downstream
Stabilization: change in conditions (e.g. topography, ground ice content)





Active RTS: Headwall retreats → detectable by DEM differencing

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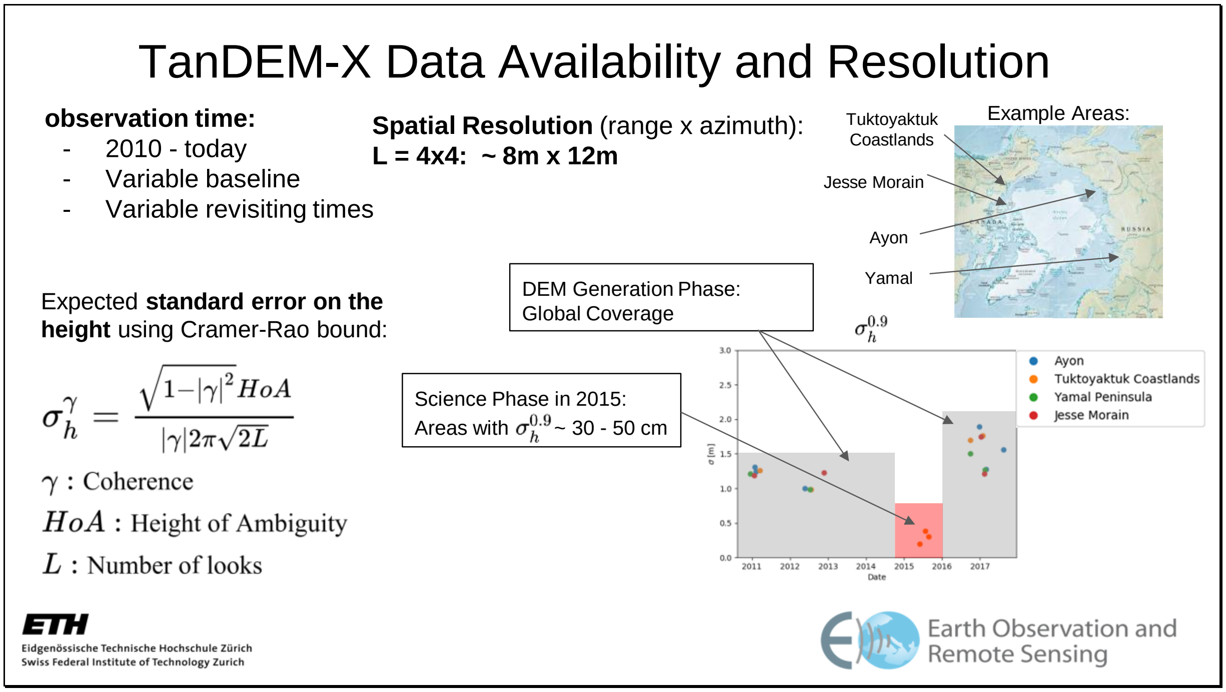
General overview slide of RTSs
RTSs are characterized by a steep headwall, that can reach several tens of meters in height. During the summer, the ice in the headwall melts and sediments get transported downslope, leading to a continuous retreat of the headwall. In the context of recent warming an increase in the rates and size of RTSs in permafrost regions of Northern Canada and Alaska has been found. On the pan-arctic scale the prevalence and rates of thaw slumping remain poorly constrained, and so does their contribution to climate change. This is mainly due to the remote landscape and the severe climate conditions in the Arctic, making remote sensing techniques highly important for studying RTSs in these areas.
One approach to investigate RTSs using remote sensing data is with Digital Elevation Models (DEM) by computing DEM difference images over time.
Here we use DEMs generated from InSAR single-pass bistatic TanDEM-X observations.

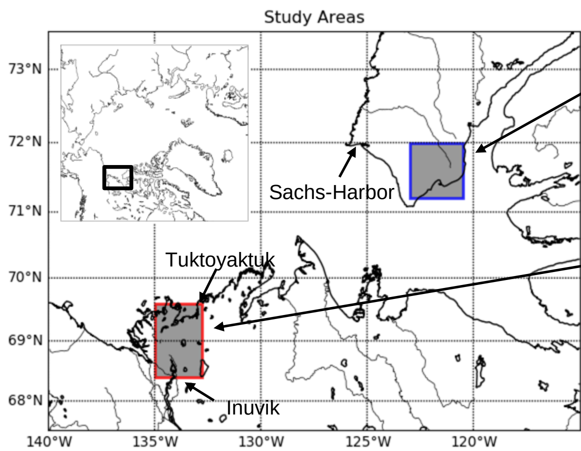
Slide 3



Pan-arctic repeated single-pass InSAR data have been acquired by the TanDEM-X pair since 2010. TanDEM-X is a high resolution single-pass interferometry satellite mission that was launched by the German Aerospace Center (DLR) with the purpose of generating a high resolution global DEM. The satellite pair started observations in 2010 and are still operational until today. From 2010 to 2018 the global land areas are observed at least three times. Both satellites carry an active synthetic radar (SAR) operating in the X-Band at a wavelength of 3.11 cm. A planimetric resolution after averaging of about 10-12m and, depending on the distance between the satellites, vertical height resolutions of the order of about 2m can be achieved.
In the right part of the slide you can see four example areas in the arctic. The plot shows the available TanDEM-X observations over time on the x-axis and the expected standard error assuming a coherence of 0.9 on the y-axis. All areas are covered with at least three observations and an expected standard error of less than 2 meters thus making it potentially possible to detection and monitor RTSs on a pan-arctic scale.

Slide 4

Study Areas for RTS detection



Banks Island (Banks):

- 8500 km^2
- Some topography
- Deep valleys and trenches
- Moss- and dwarf-shrub tundra
- RTS headwalls: ~10m

Mackenzie-River Delta (MRD):

- 7000 km^2
- Many thermokarst lakes
- Mostly flat
- Forested in south, shrub tundra north
- RTS headwalls ~5m

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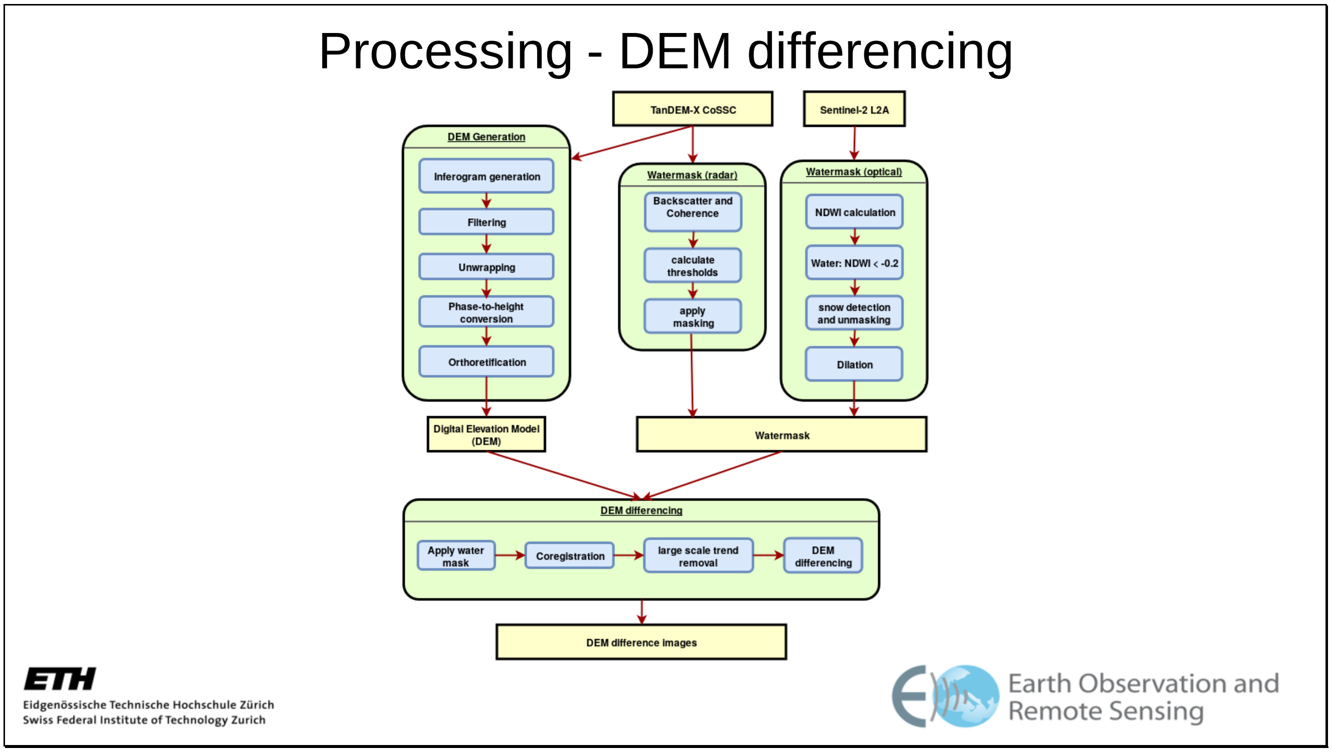
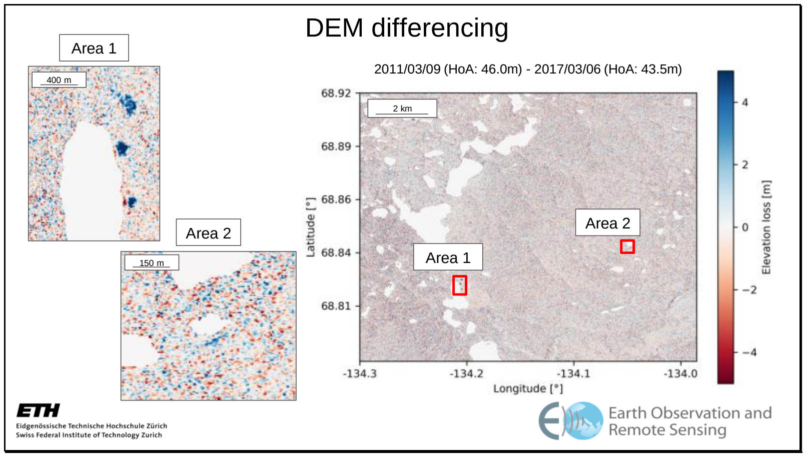
This slide shows a map of the two study areas in Northern Canada that we selected to test our RTS detection method. The two study areas show differences in climatic conditions, vegetation, topography as well as RTS characteristics.

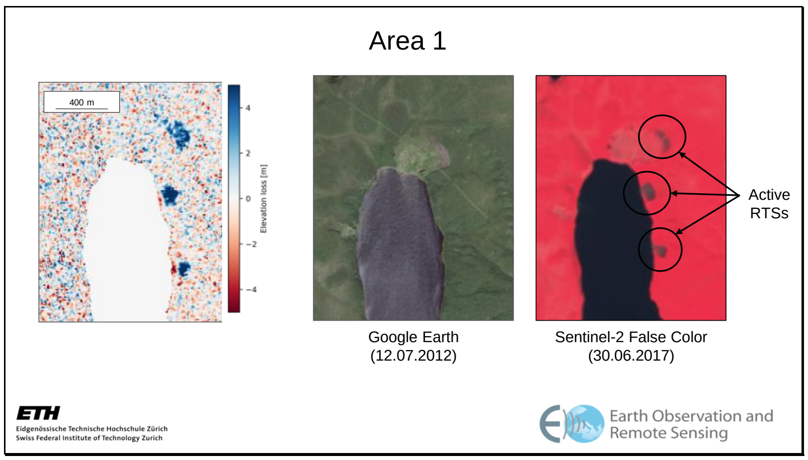
Slide 5

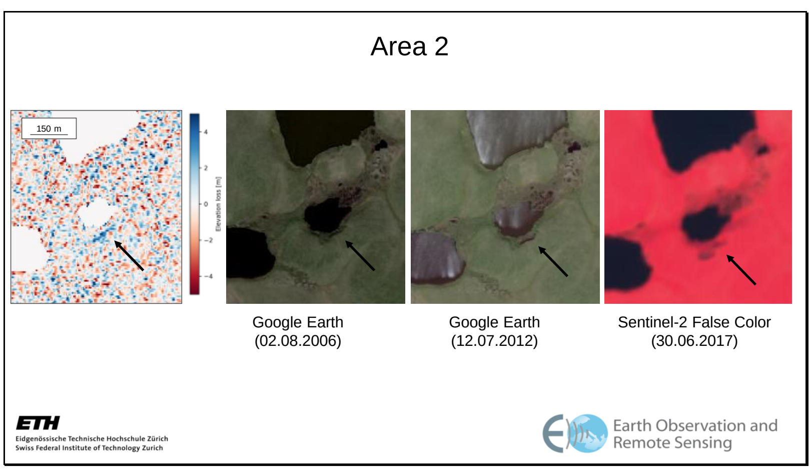


Overview of the processing chain. Additional to the DEM generation procedure we generate a watermask either based on TanDEM-X observations or, if no summer observations are available, on optical Sentinel-2 data. We apply a watermask on the generated DEMs and apply a coregistration and large scale trend removal before the DEM differencing. In the following slides we show an example DEM difference image from part of the MRD study area.

Slide 6 7 8

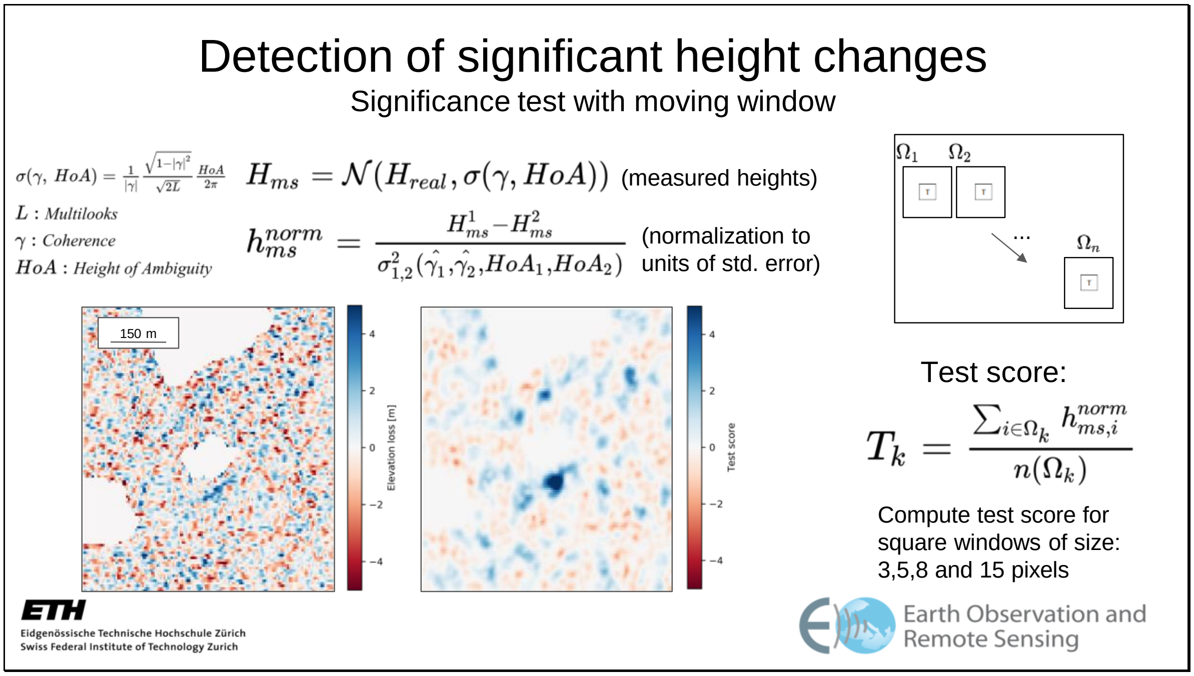






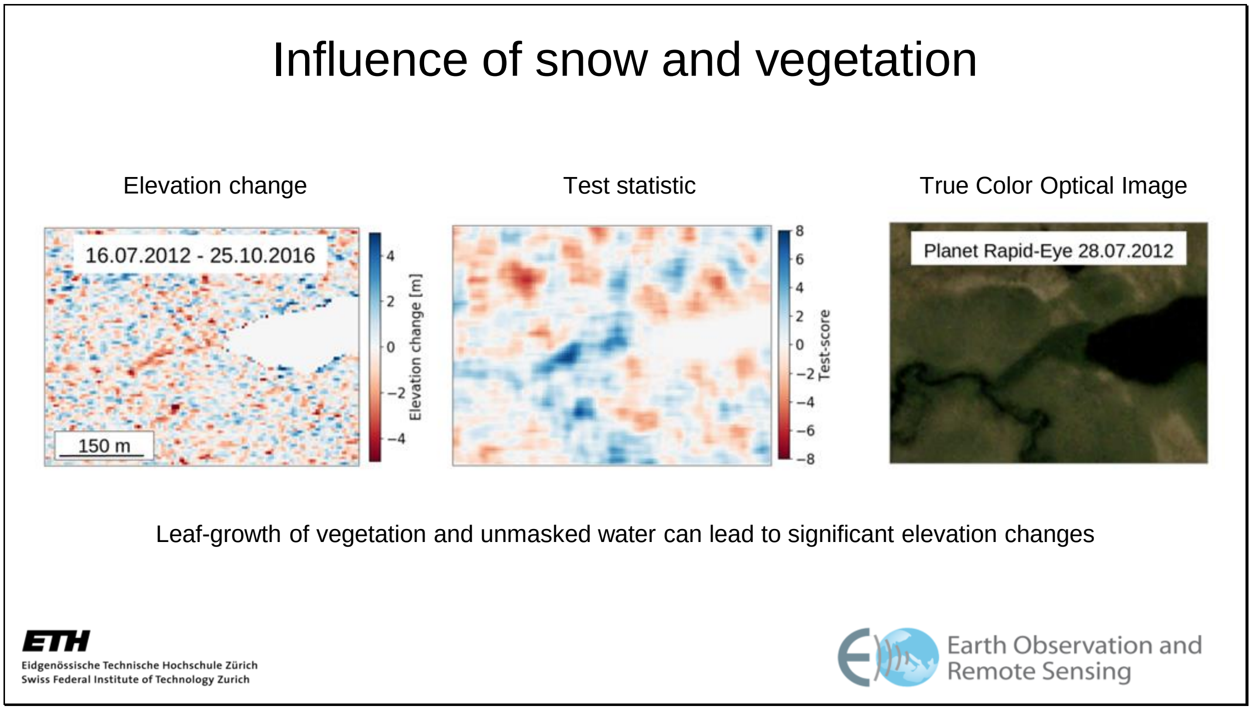
In a first step we apply differencing on the generated DEMs. One can see that on large scale no elevation loss is visible. When we zoom in on two areas that show signs of RTS activity, elevation losses are visible. On the two slides on the bottom we show the areas in a zoomed-in view with additional optical satellite imagery. In both cases a RTS retreat is visible between 2011 and 2017. It is to note that water bodies are masked since these generate large errors in the generated DEMs.

Slide 9



When comparing DEMs generated from single-pass interferometric observations, the elevation differences contains several error sources that have to be considered. These can arise due to errors in the DEM generation, like an inaccurate DEM registration and remaining large-scale trends, a random error in each DEM, related to phase inaccuracies in the individual observations as well as systematic elevation biases related to water, snow or vegetation. These effects can lead to apparent elevation changes in single-pass interferometric observations of several meters. To remove some of these error sources, we normalize the data using the estimated coherences (Cramer-Rao bound). A pixel by pixel thresholding approach yields many wrong detections since headwall heights can be only of the order of a few meters and thus only slightly above the expected standard error. Since typical thaw slumps are larger than a resolution cell we additionally use the spatial size of the slumps by computing a test score T over a moving window Omega of sizes 3, 5, 8, and 15 pixels.
The measured elevation changes for the RTS shown in “Area 2” on the previous slide can be seen on the image on the bottom left. The slump below the lake is only barely visible above the noise. In the computed test-statistic image (right) the slump much better distinguishable.

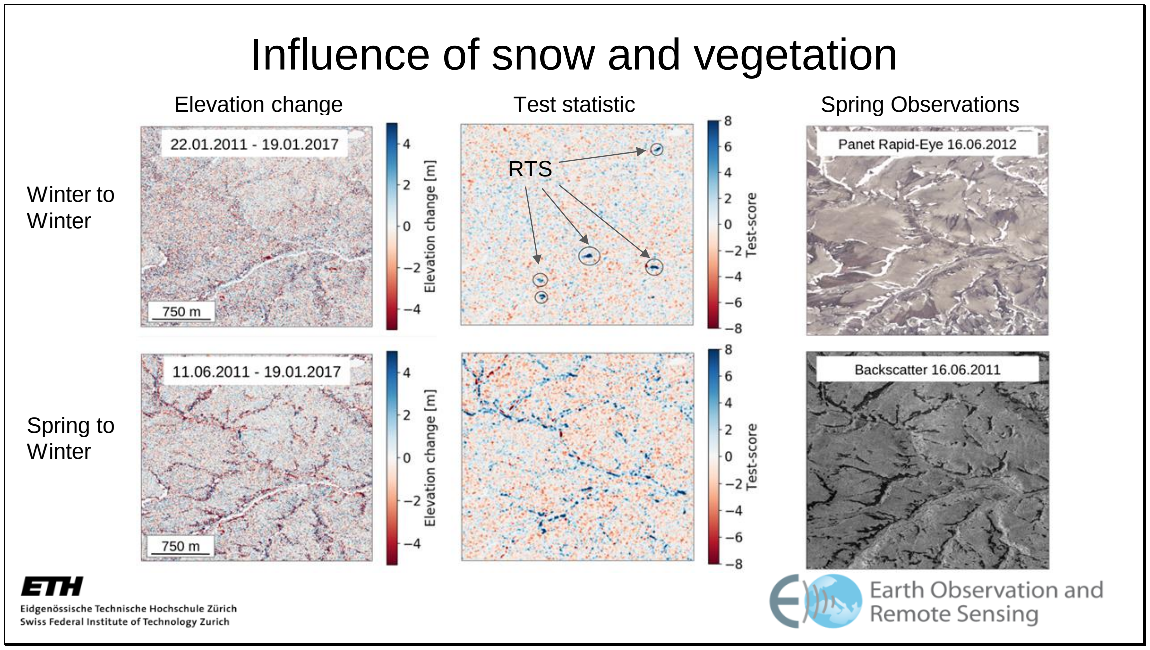
Slide 10



Spring and summer acquisitions are less suitable for thaw slump mapping due to seasonal vegetation and late-lying snow packs that persistent long into the summer. Here we show an example of how the influence of vegetation can induce spurious elevation changes.

The image on the left and in the middle show the measured elevation change respectively the calculated test statistic between DEMs generated from observation taken on the 16.07.2012 during the summer and on 25.10.2016 when the landscape was frozen. The image on the right side shows a Rapid-Eye observation taken on 28.07.2012 of the same area, indicating that area that shows signs of an elevation change is covered by vegetation.

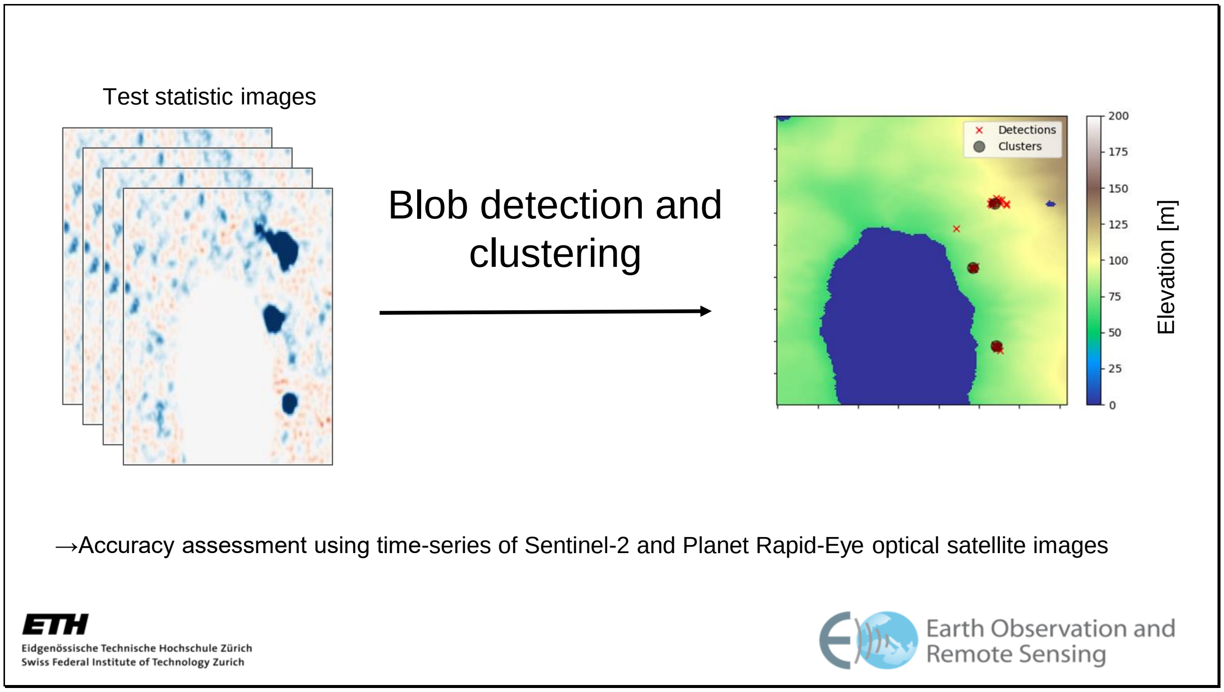
Slide 11



Influence of snow on elevation measurements on Banks. Top left and Top middle show the elevation change respectively the computed test score for DEMs generated between 22.01.2011 and 19.01.2017. Several significant elevation changes are visible corresponding to active RTSs. The circles show the locations of active RTSs that were detected. Bottom left and bottom middle show the elevation change respectively the computed test score for DEMs generated between 11.06.2012 and 19.01.2017. The measurements show many disturbances especially at locations in trenches. A true-color Rapid-Eye observation taken on the 16.06.2012 can be seen on the top right. Several late-lying snow packs at similar location than the elevation changes in the TanDEM-X difference image are visible. The influence of wet snow is also visible in the backscatter intensity image for the TanDEM-X observation taken on 11.06.2012 (bottom left). The darker areas corresponding to lower backscatter values and are in similar areas then the snow areas in the optical Rapid-Eye true-color image.

We deal with these errors by removing DEMs generated in times when the landscape was not frozen and thus only use winter observations. (Note: The winter temperatures in the arctic fall to average monthly temperature values of below -20 Celsius resulting in a dry snow-pack and radar waves can propagate through without being strongly affected, measuring the elevation at the ground.)

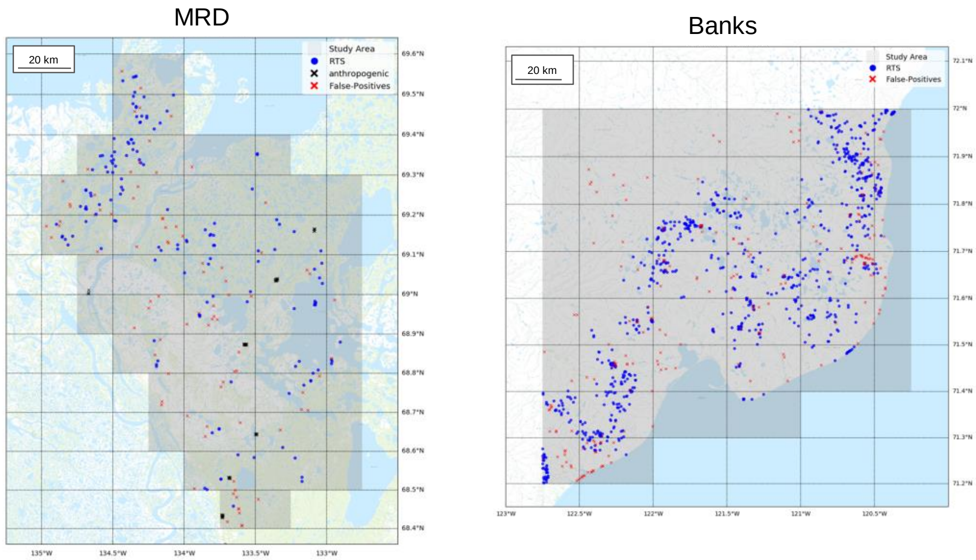
Slide 12



After the computation of the test statistic we detect significant elevation changes using a blob detection method followed by a clustering algorithm to merge detections in the same locations over time.

Slide 13

Detection results



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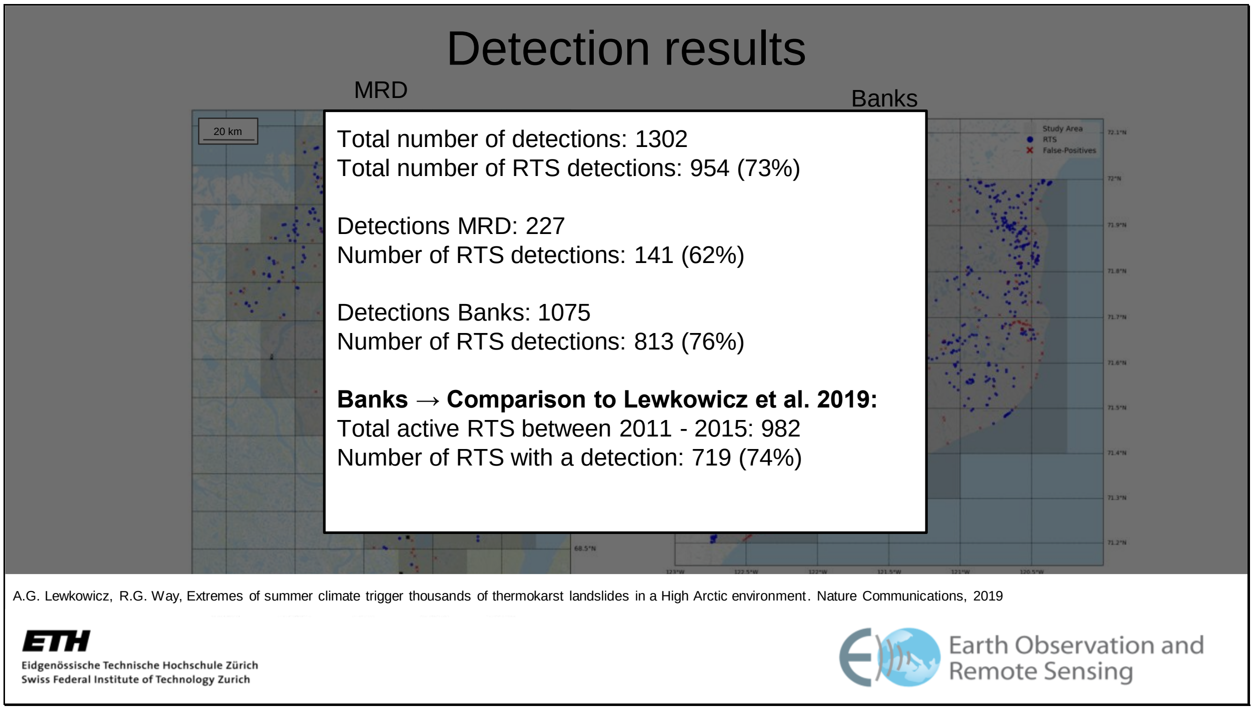
Detection results for the two study areas on MRD and Banks. On MRD several detections could be attributed to anthropogenic causes, mainly due to gravel pits for road construction.

Slide 14

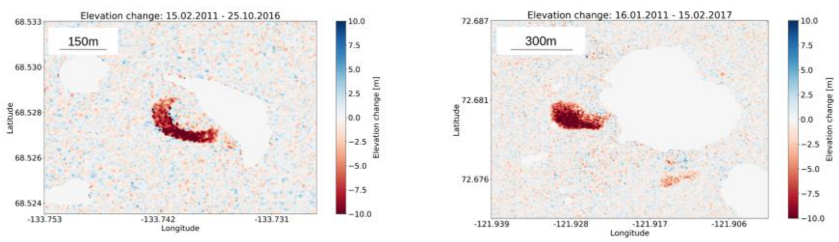


Overview of the number of detections and corresponding RTS detections.
To get an estimate on the false negative rate we use reference data from a study by Lewkowicz (Lewkowicz, A.G., Way, R.G. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. *Nat Commun* **10,** 1329 (2019). https://doi.org/10.1038) for the Banks study area. The google earth engine Landsat time-laps dataset was used to identify active slumps by their change over time (1985 to 2015). We include all RTSs that show signs of movement after the year 2011 (”Lewkowicz sample”). It is to note that due to the use of optical data not every year is guaranteed to contain usable observations and that the cut-off between active and non-active RTSs is governed by the relatively coarse resolution. The exact year of stabilization and activation of RTSs in the Lewkowicz sample can thus be erroneous. Additionally, no information about RTS headwall heights are available, which are an important parameter of RTSs to be detectable by our method. 719 of the 982 RTSs in the Lewkowicz sample had a matching detection in our sample (false negative rate: 26%).

Slide 15

Summary and Conclusion

- Implementation of a processing chain using TanDEM-X generated DEMs for the detection of retrogressive thaw slumps using the volumetric change as an indicator
- We found a detection true positive rate of 73% and an estimated false negative rate of 27%
- Waterbodies and DEMs generated in the spring and summer lead to large errors
- First step towards a RTS detection and monitoring method on the pan-Arctic scale
- More information with an additional implementaion and evaluation of machine learning methods for the classification of the detections into RTSs and non-RTSs detection can be found in: *Bernhard et al. 2020 "Mapping retrogressive thaw slumps using single-pass TanDEM-X observations" JSTARS (in review)*



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We presented and assessed a method to detect active RTSs, using for the first time the volumetric change as an RTS indicator by applying DEM differencing. Our suggested approach is applicable on flat and medium mountainous terrain and provides an important step towards a RTS detection and monitoring method on the pan-arctic scale. We isolated significant height changes using a statistical multi-scale approach that is intended to discard spurious changes induced by measurement noise. In total 1302 significant height changes were detected but reference data showed that 27% are due to processes other than thaw slumps.
Since the TanDEM-X observations cover the whole pan-arctic landscape the availability of a RTS detection method makes it possible to generate large-scale inventories of RTSs. Such inventories have the potential to be used as a starting point to measure RTS induced volumetric changes and estimate the amount of mobilized materials including organic carbon, nutrients and sediments.
In the following slides we will present some preliminary results of the extension of our study areas and first estimation of the property extraction at each detection location.

Slide 16

Preliminary Results – RTS Property extraction and extension of study areas

Location	Study-Area (km^2)	No. TanDEM-X Obs.	Time-Frame
Noatak Basin	15.700	147	winter 2010/11 – winter 2016/17
Peel Plateau, Richardson Mountains	19.000	237	winter 2010/11 – winter 2016/17
Siberia (Gyda Peninsula)	14.600	91	winter 2010/11 – winter 2016/17

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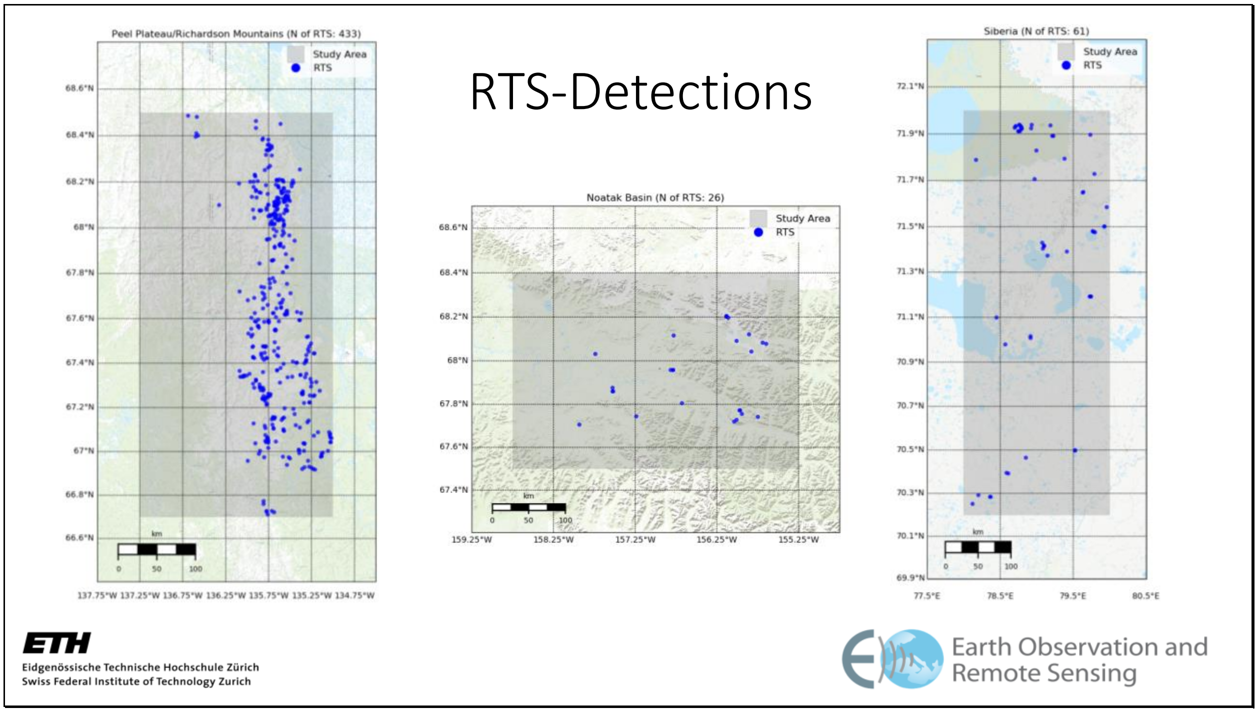
For the further analysis, we choose three study areas, located in Alaska (Noatak Basin), Nothern Canada (Peel Plateau/Richardson Mountains) and in Siberia (Gyda Pensinsula).

Slide 17

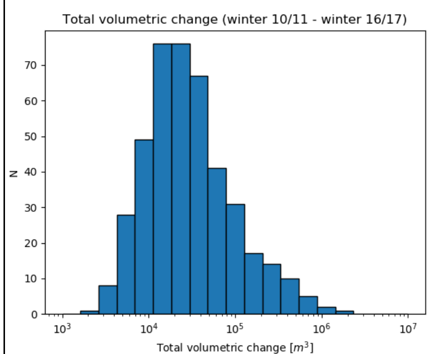


Result of the RTS detection procedure. We checked each detection manually and kept the detections that show signs of RTS activity. The RTS in the Noatak Basin and in the Siberia study area occur at a lower density than the RTS on the Peel Plateau. In the next few slides we show historgrams of some of the generated properties. The total volumetric change is computed from winter 2010/2011 to winter 2016/2017. Aspect and Slope were calculated from the earliest DEM available. These result have to be taken with caution and further validation steps are needed to assess the accuracy of our method.

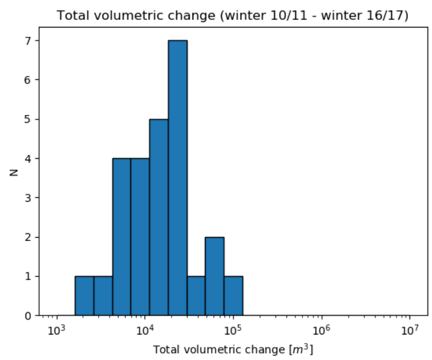
Slide 17 18 19

Total volumetric change (winter 10/11 – winter 16/17)

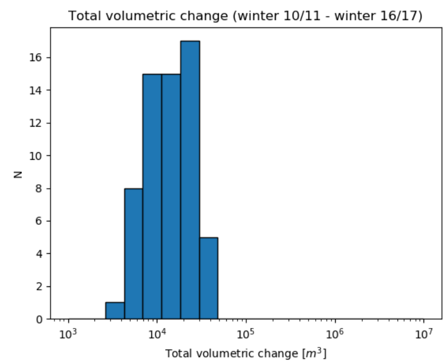
Peel Plateau/ Richardson Mountains, Canada (RTS: 433)



Noatak Basin, Alaska (RTS: 26)



Gyda Peninsula, Siberia (RTS: 61)



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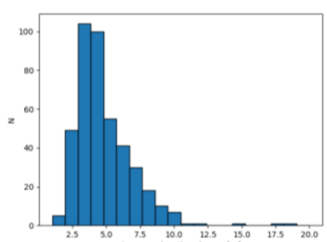
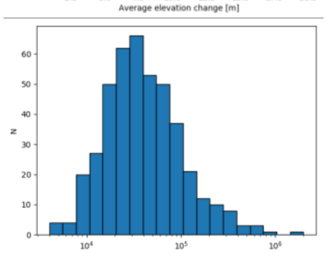
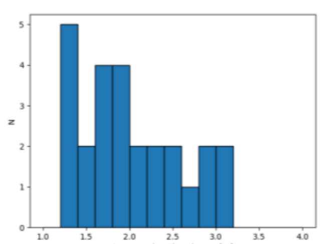
Average elevation change and affected area

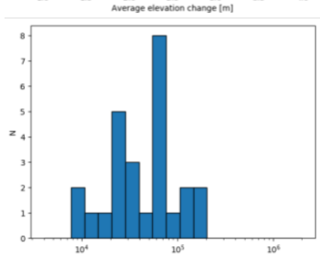
Peel Plateau/ Richardson Mountains, NWT Canada



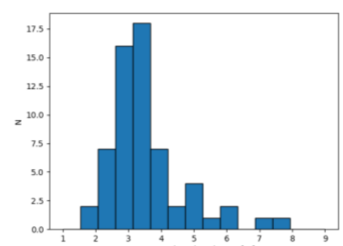


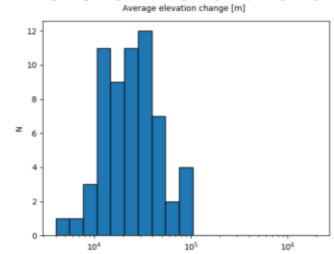
Noatak Basin, Alaska





Gyda Peninsula, Siberia





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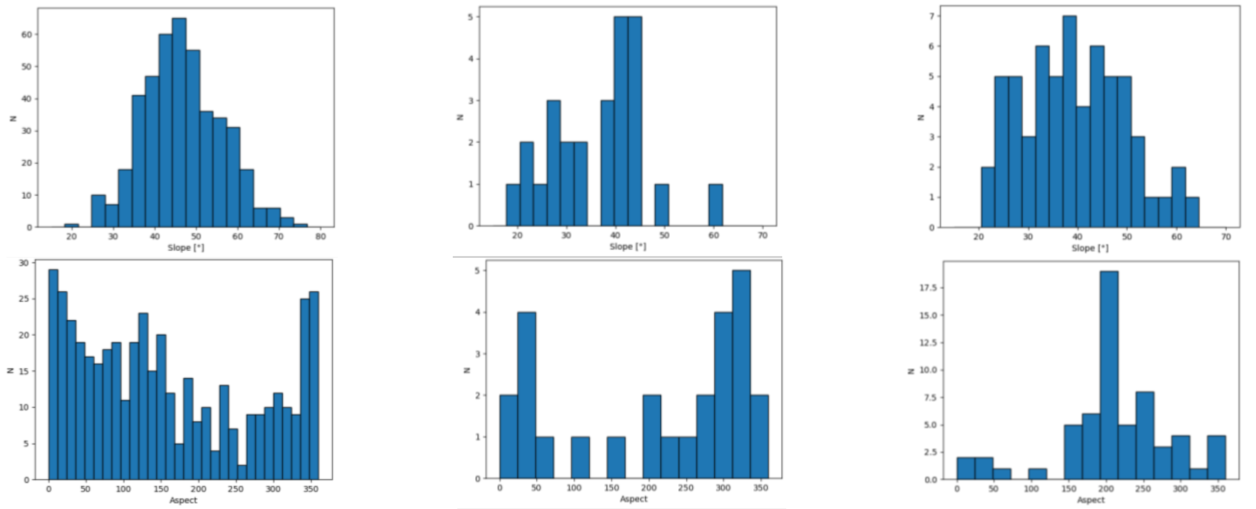
DEM properties

Peel Plateau/ Richardson Mountains, NWT Canada

Noatak Basin, Alaska

Gyda Peninsula, Siberia



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Slide 20

Next step: Validation

Validation by comparison to previous studies:

- Volumetric changes estimations for RTSs are rare in the literature
- Based on field data – high precision (e.g. by LiDAR, UAV measurements)
- Only available for a small number of RTS
- Variable time periods

Validation by comparison to ArcticDEM data:

- Pan-arctic coverage and high resolution (spatial/vertical)
- Variable data availability depending on area
- Contain many artefacts - no quality assessment

Noatak Basin

RTS	Avg. elev. change [m]	Affected area [m²]	Volume (10/11-16/17) [m³]	Volume Swanson [1] (09.2013 – 07.2016) [m³]
RTS 14 (NOAT068)	1.6	21 136	34 009	19 216
RTS 13 (NOAT069)	1.2	11 167	13 987	7 759
RTS 12 (NOAT070)	1.9	25 230	49 228	15 062
RTS 18 (NOAT148)	2.9	9 217	26 789	6 529
RTS 16 (NOAT151)	2.3	11 863	27 285	12 732

factor 2-3
time period?

Peel Plateau/Richardson Mountains: RTS 378 (Slump FM2)

	Time	Vol. scare zone [10^6 m³]	Vol. debris zone [10^6 m³]
This study	Winter 11/12 – 16/17	1.66	-0.32
van der Sluijs [2]	08.2011 – 07.2017	1.8	-0.4

[1] David K. Swanson and Matt Nolan, *Growth of Retrogressive Thaw Slumps in the Noatak Valley, Alaska, 2010–2016, Measured by Airborne Photogrammetry*, Remote Sens. 2018, 10, 983; doi:10.3390/rs10070983
[2] Jurjen van der Sluijs, Steven V. Kokelj, Robert H. Fraser, Jon Tunnicliffe and Denis Lacelle *Permafrost Terrain Dynamics and Infrastructure Impacts Revealed by UAV Photogrammetry and Thermal Imaging*, Remote Sens. 2018, 10, 1734

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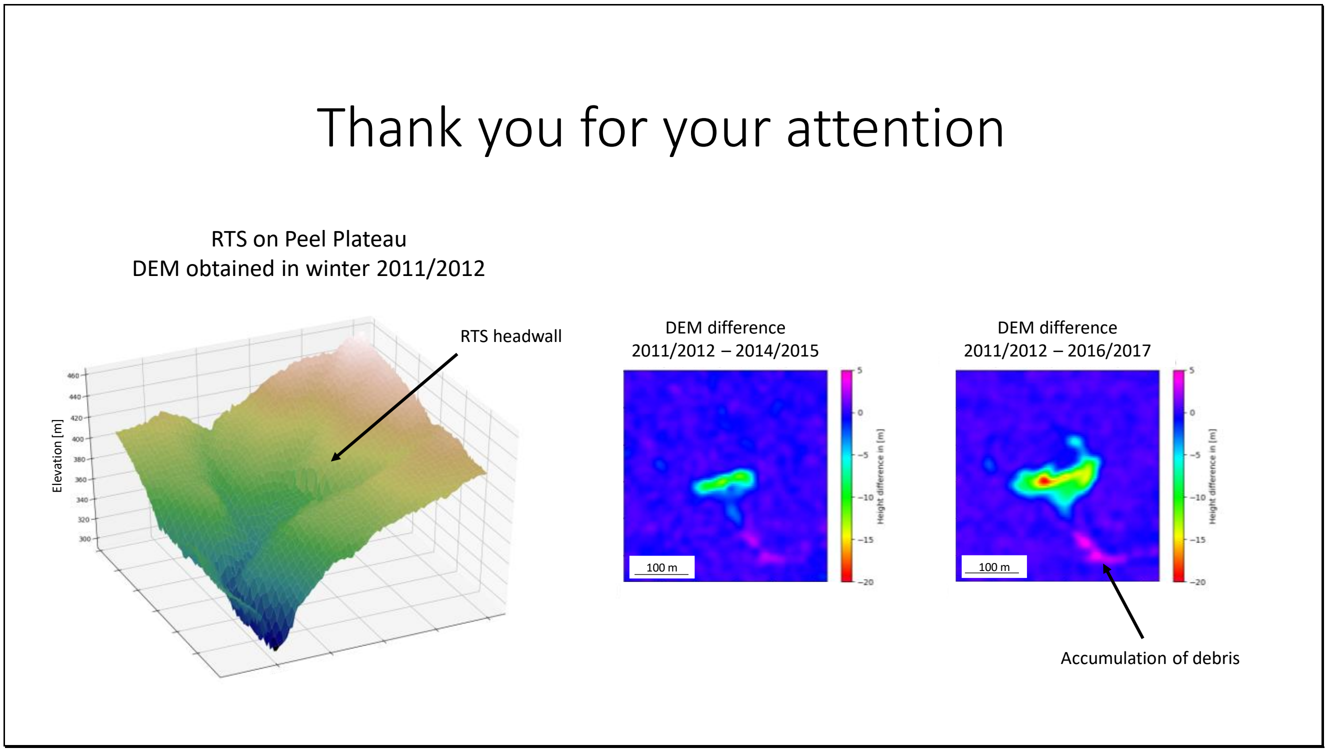
We are currently working on two approaches to validate our RTS property estimation: Validation by comparison to previous field studies and by comparison to the ArcticDEM. Both approach have their advantages and disadvantages (see Slide).

On the bottom left we show the comparison of five detected RTS to [1]. In this study the growth of 22 RTSs in the Noatak Basin were monitored using high resolution photographs taken from airplanes and helicopters and with DEM accuracies in the range of 10-15 cm. The timeframe of the reported volume changes are from September 2013 to July 2016, approximately corresponding to two summers of RTS activity. In our study the data availability spans from winter 2010/2011 to winter 2016/2017, corresponding to six summers. Our volume estimates are about 2 to 3 times higher which could be related to the longer timeframe of our study, assuming a constant RTS growth.

On the bottom right we compare the volumetric estimate of a Mega Slump on the Peel Plateau to the study [2], were they used UAV to generate high resolution DEMs. The study time period is approximately the same (late start in summer 2011 and early ending in summer 2017) as in our study. For the volumetric change in the scare zone as well as in the deposition zone we get similar volume estimates

[1] David K. Swanson and Matt Nolan, *Growth of Retrogressive Thaw Slumps in the Noatak Valley, Alaska, 2010–2016, Measured by Airborne Photogrammetry,* Remote Sens. 2018, 10, 983; doi:10.3390/rs10070983
[2] Jurjen van der Sluijs, Steven V. Kokelj, Robert H. Fraser, Jon Tunnicliffe and Denis Lacelle *Permafrost Terrain Dynamics and Infrastructure Impacts Revealed by UAV Photogrammetry and Thermal Imaging*, Remote Sens. 2018, 10, 1734

Slide 21



We thank you for reading our presentation. We are currently looking for additional data on RTSs that can be used to validate our method and are happy to collaborate. We are looking forward to share our data and help in the generation of a pan-arctic RTS inventory that can be used to better understand RTS activity.