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Mapping The Unseen: A Quantitative Analysis of Avalanche Cycle Using Sentinel-1 and Google Earth Engine

Figure 1 Avalanche at Reinøya, photo is from NRK article
(Amundsen, To personer skal være døde etter skred på Reinøya i Troms, 2023)

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Contents

Summary

This thesis explores the use of Sentinel-1 satellite data through Google Earth Engine (GEE) for detecting avalanche cycles in Lyngen, Northern Troms. By integrating data from various sources, including the Regobs database and weather conditions, the study aims to enhance understanding of these data sources. The analysis focuses on an avalanche event from March 31, 2023, evaluating the effectiveness of using GEE with simple coding and open-source tools for detecting avalanches using Sentinel-1 data.

Introduction

This thesis applies advanced remote sensing techniques, focusing on Sentinel-1 satellite imagery, to understand avalanche cycles in Lyngen, Northern Troms—a region known for its steep mountains and high avalanche-related fatalities.

A primary objective is to evaluate the effectiveness of open-source tools and simple coding, specifically Sentinel-1 data in Google Earth Engine (GEE), for conducting detailed avalanche detection. Sentinel-1 data has been used in mapping snow avalanches in past studies, it has not been utilized through open-source functions like this study.

This study analyses an avalanche cycle from March 31, 2023, by integrating data from the various sources such as the Regobs database, weather conditions, and Sentinel-1 imagery. This multifaceted approach aims to understand factors contributing to avalanches and assesses the strengths and limitations of various data sources. Through this analysis, this thesis seeks to provide insights into the avalanche cycle of March 31, 2023, in Northern Norway, combining traditional observations with remote sensing technologies to enhance our understanding of avalanche cycles. This thesis will attempt to answer the research question:

How effective is Google Earth Engine (GEE) in detecting avalanche events in Lyngen using simple coding techniques and open-source data, and how can it contribute to traditional forecasting?

Area of interest

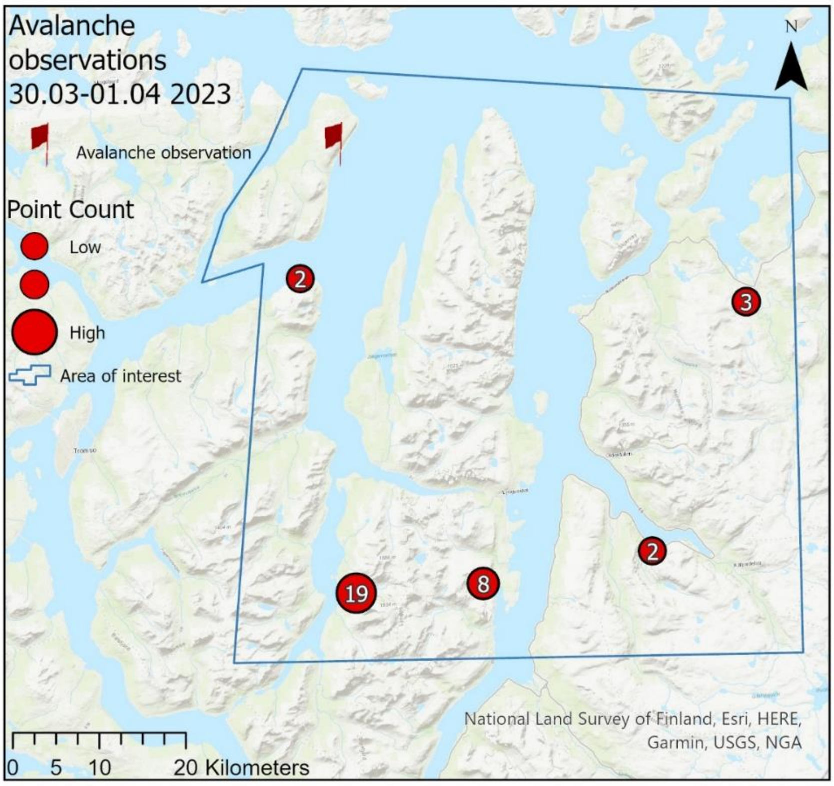


Figure 3 Overview map of area of interest

On March 31, 2023, a series of devastating avalanche incidents occurred within hours, impacting human lives, residences, and livestock. This study focuses on analysing the events through different data sources, including observations in Regobs, Sentinel-1 images and weather data. The study area selected is chosen based on the accidents that occurred and avalanche observations available from Regobs.

Timeline of Snow Avalanche accidents on March 31. 2023

- **14:30** A group of 5 skiers was taken by an avalanche in Kvalvikdalen, Lyngen. Where one died and another got heavily injured.
- **15:10** A house was taken out on the ocean close to Grøtnesdalen on Reinsøya in Karlsøy, where 2 persons was killed and the 140 goats in the farmhouse.
- **17:11** A farm was hit with 100 animals, the couple got out. (Amundsen, Fem utenlandske skiturister tatt av snøskred: en person omkommet, 2023).
- Additional reports include an incident at 17:57 near Tverrelva on Storslett, initially reported as an avalanche fatality but later clarified by Nordlys newspaper as a fatal fall, not related to this study (Aamo Holte, 2024).

Theory

Snow Avalanches

A snow avalanche, hereafter referred to simply as an avalanche, is snow situated on sloping terrain that has been set in motion (NVE, n.d.). For an avalanche to happened, three main factors need to be present: slope angel, some sort of structure and a trigger.

Contributory Factors to Avalanches

Avalanche Problems

The European Avalanche Warning Services (EAWS) categorize avalanche problems into five main types: new snow, wind slab, persistent weak layers, wet snow, and gliding snow. The five reflects different mechanics and causes of instability in the snow, providing crucial information for evaluation of avalanche hazards (EAWS, n.d.). The assessment processes involve addressing four key questions: What type of avalanche problem(s) exists? Where are these problems located in the terrain? How likely is it that an avalanche will occur? And how big will the avalanche be? (Statham, 2018)

This process provides a standard method for assessing hazards, helping to predict avalanches based on a thorough understanding of the risks. Different factors effect if an avalanche will happen, the size of it and how sensitive it is to triggers. Factors such as Avalanche terrain, temperature, wind, and snow accumulation.

Avalanche Terrain

Snow avalanches occur most in slopes between 30-45 degrees, although they can also occur on slopes all the way down to 25 degrees and all the way up to 60 degrees (Avalanche Canada, n.d.). The “sweet spot” between 30-45 degrees is when the slope is steep enough to give the snow a lot of potential energy as it’s steep and at the same time as snow can gather in a large scale.

Slope Angle (Degrees)	Avalanche Characteristics
60 to 90	Avalanches are rare; frequent small sluffs of snow.
50 to 60	Frequent loose snow avalanches.
45 to 55	Frequent small slab avalanches.
30 to 45	Slab avalanches of all sizes.
25 to 30	Infrequent but often large slab avalanches; wet loose avalanches.
10 to 25	Infrequent wet snow avalanches and slush flows.

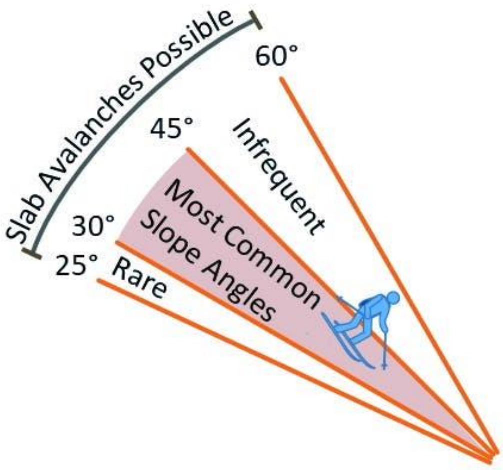


Figure 4 Slope angels for which avalanches occur (Avalanche Canada, n.d.)

Temperature

Temperature significantly impacts the stability of the snowpack in various ways. For example, an increase in temperature can quickly destabilize the snowpack by weakening the surface layers, thereby increasing the load on underlying layers (Schweizer, Jamieson, & Schneebeli, 2003). The mechanical properties of snow, such as hardness, toughness, and strength, are particularly sensitive to temperature changes. As temperatures rise, the hardness and strength of a weak layer tend to decrease rapidly, leading to instability. Additionally, the process of creep—where snow gradually settles and densifies under its own weight—can accelerate with higher temperatures, though this effect often stabilizes the snowpack after a delay (Schweizer, Jamieson, & Schneebeli, 2003).

Wind

Wind is often considered the second-most contributing factor after new snow. Wind moves snow and deposits it rapidly, creating layers with varying density and hardness. The irregular layering can cause stress within the snowpack and potentially lead to an avalanche (Schweizer, Jamieson, & Schneebeli, 2003). The deposition pattern is especially variable on the lee side of a ridge, where snow accumulates more than on even ground due to eddies that form under certain conditions (Schweizer, Jamieson, & Schneebeli, 2003). Since wind can change and move the snow in almost any direction, it is very hard to predict in a forecast as it is highly localized.

Snow Accumulation

In avalanche forecasting, the accumulation of new snow is a critical factor, particularly in larger and catastrophic avalanches. Around one meter of snowfall within a storm may trigger extreme avalanches, while 30-50cm could instigate naturally released ones (Schweizer, Jamieson, & Schneebeli, 2003). However, the probability of avalanche releases does not proportionally increase with snow depth, indicating other influencing factors. One such factor is the accumulation rate; a high rate (2,5cm/hour) may not give layers underneath time to adapt and stabilize from the extra load. The race between the rate of the load and the rate of strengthening provides the foundation for forecasting (Schweizer, Jamieson, & Schneebeli, 2003).

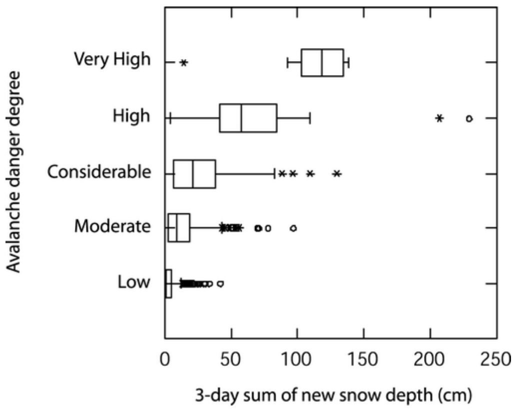


Figure 5 The probability of avalanche release based on snow depth (Schweizer, Jamieson, & Schneebeli, 2003)

Regobs in Norway

The Norwegian avalanche warning service produces warnings for large regions such as Trollheimen, Jotunheimen and Sunnmøre that give general knowledge about the conditions. In addition to producing warnings, they also have an interactive map that shows all registered observations (NVE, n.d.).

How the warnings are made

The warnings are produced daily based on analysis of the present situation using snow observations registered in Regobs. Both unvalidated reports and professional avalanche observers' reports are considered. Then weather data is collected using xgeo in addition to webcams, field observations and the status on roads and other relevant factors. Taking in all this data, they try to make a warning based on how they think the current conditions will affect the snow for the next couple of days (NVE, n.d.).

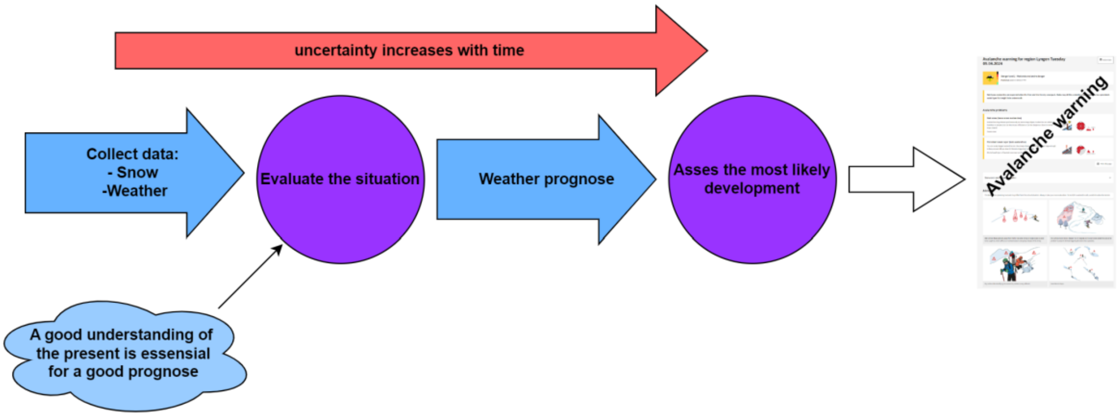


Figure 6 Visualization on how forecast is made (NVE, n.d.)

How the danger level is calculated

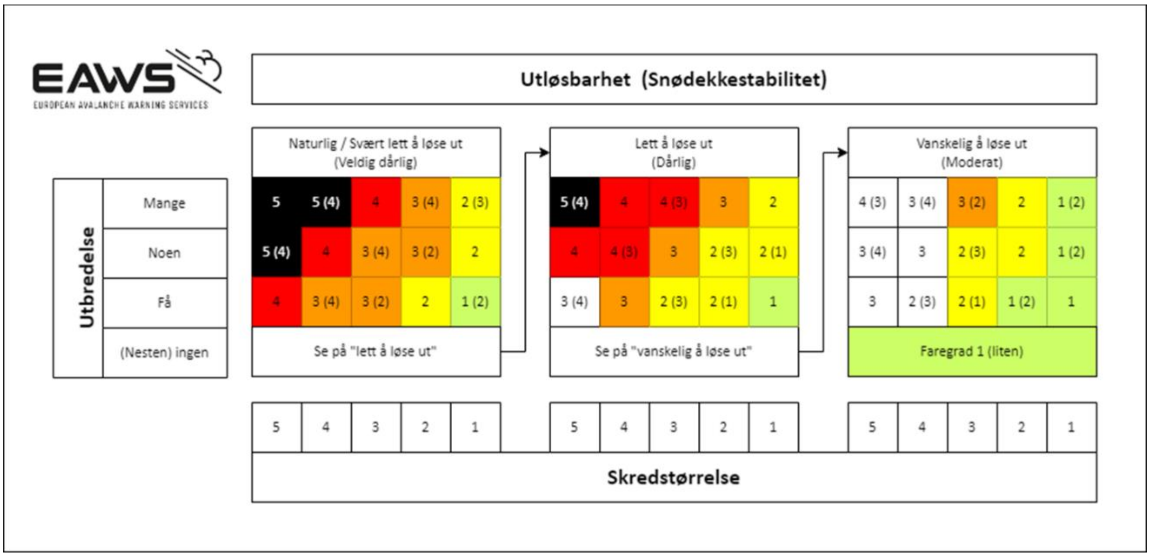


Figure 7 How the danger level is calculated using ADAM matrix (NVE, n.d.)

In the warning they present the danger level, advice for travel, avalanche problems, most exposed terrain, and different summaries (NVE, n.d.). All of this is based on the interpretation of the specialists at NVE. The danger level is calculated using the ADAM matrix seen in the figure above. This calculation incorporates the frequency of the avalanches, their size, and how easily they can be triggered.

Limitations and Challenges for Avalanche Forecasting in Norway

As mentioned, the avalanche forecast is based on the present conditions and an interpretation from experts on how the forecasted weather will affect the current conditions. The amount and the quality of the data are therefore central for a good forecast.

Regobs generates forecasts for large regions using data collected by various sources. The reliance on non-professional reports introduces uncertainty, especially if the observer lacks formal training. Recognizing the uncertainty in these reports is a key part of the data sorting process (NVE, n.d.). To improve data quality and quantitatively, NVE invests in training and employs professionals to perform regular and specific observations, such as detailed snow profiles in certain areas (NVE, n.d.).

One significant challenge in avalanche forecasting is the danger of going into avalanche-prone terrain. While accurate forecasts rely on real-time data from the field, collecting this data can put observers at risk, particularly during or after storms. These storms often lead to avalanche cycles, making it difficult to gain a clear visual due to heavy snowfall and strong winds. This complicates the process of gathering reliable information, potentially leaving regions under-monitored and increasing the risk of inaccuracies in avalanche forecasts (NVE, n.d.).

Another challenge in Norwegian avalanche forecasting is the country's diverse local environments, characterized by varying temperatures and winds due to fjords, valleys, and a long coastline. This diversity makes it difficult to provide a detailed forecast for a large region, as conditions can vary significantly within the same area.

Autodetection station

In frequently exposed areas it has been conducted projects using automatic detection of snow avalanches with radar, web cameras and thermal cameras. The purpose of these stations is to increase safety on exposed roads and to decrease the number of days they need to be closed due to avalanche danger. Since the station provides both images and radar data 24/7, it offers crucial information for understanding the avalanche hazard in the area (Geo Prevent, 2021).

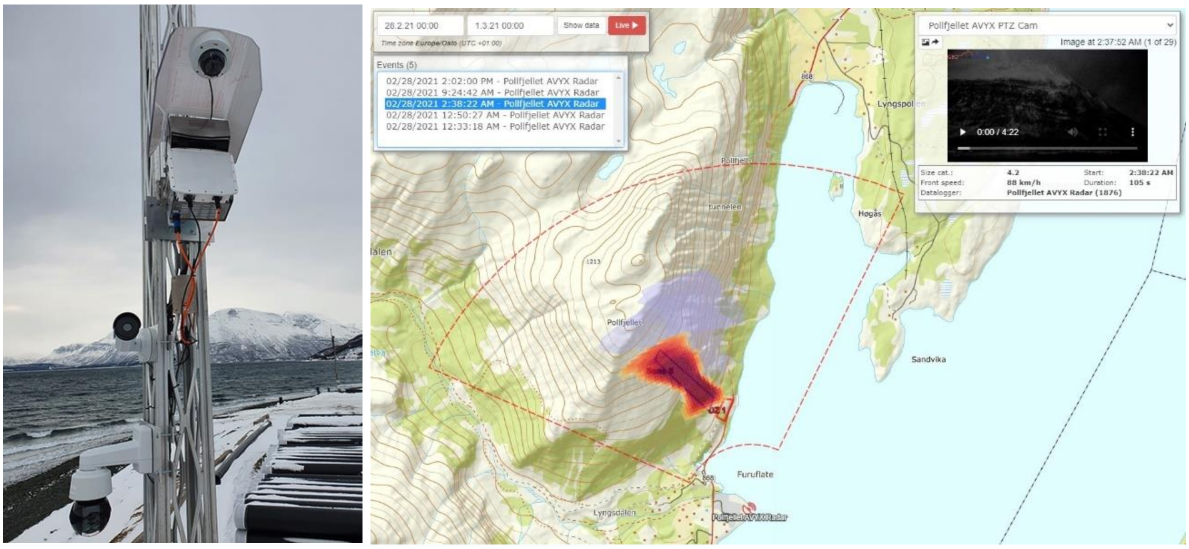


Figure 8 Radar for avalanche detection and geopraevent data portal (Geo Prevent, 2021)

Sentinel-1 and Google earth Engine (GEE)

Sentinel-1 is part of the Copernicus program managed by the European Space Agency (ESA). The program includes sentinel-1A and B, which have a C-band synthetic Aperture radar (SAR) (Copernicus, n.d.).

Instruments

The radar on the satellite supports operation in dual polarization which means it can transmit and receive signals simultaneously using combinations like HH+HV and VV + VH (Copernicus Program, n.d.). This allows it to use single look complex (SLC) which helps to preserve both the amplitude and phase of the received signal. Polarimetric techniques including eigenvector-based and model-based methods help distinguish between different types of scattering targets (Copernicus Program, n.d.). These methods can provide detailed insights into how radar signals interact with various surfaces. The use of specialized techniques for analysing dual-polarization SAR data enhances the accuracy in identifying and classifying both specific objects and broader areas based on how they scatter the radar signals (Copernicus Program, n.d.).

Polarization

The first letter stands for the transmission signal and the second letter stands for the signal that it receives. These configurations are critical for understanding how the signal from the radar interacts with the surface.

We have three main types of scattering:

- Rough surface scattering, caused by flat surfaces like water or bare fields.
- Volume scattering, caused by trees, etc.
- Double bounce, caused by buildings, cliffs, etc.
  (NASA, n.d.)

HH (Horizontal transmit, horizontal receive): Sensitive to surfaces with double bounce, so mainly used in urban environments.

VV (vertical transmit, vertical receive): Sensitive to flat surfaces like water, and is mainly used for flood events, sea ice etc.

HV (Horizontal transmit, vertical receive) and VH (Vertical Transmit, horizontal receive): Are sensitive to volume scattering and is therefore used a lot for vegetation studies etc.

(Copernicus Program, n.d.)

Acquisition mode

Sentinel-1 can operate with 4 different acquisition modes, each designed for specific types of observation and data collection.

Mode	Resolution	Swath Width	Usage
Stripmap (SM)	High resolution (~5m x 5m)	Narrow (40-60 km)	Ideal for detailed observation of smaller areas. • Used for mapping features such as infrastructure, urban development, and detailed terrain.
Interferometric Wide Swath (IW)	Moderate resolution (~5m x 20m)	Wide (around 250 km)	Most used for interferometry. • Monitoring Earth surface movements and changes over time. • Environmental monitoring, disaster management, and land deformation studies.
Extra-Wide Swath (EW)	Lower resolution (~20m x 40m)	Very wide (over 400 km)	Designed for capturing large areas. • Maritime and polar ice monitoring, tracking large-scale environmental phenomena such as sea ice movements, oil spills, and climatic changes.
Wave (WV)	High resolution (similar to SM)	Very narrow (5-20 km in burst mode)	Optimized for capturing images of the ocean and sea waves. • Predominantly used for meteorological studies, oceanography, and marine forecasting.

(Copernicus, n.d)

In-depth Interferometric wide swath

The IW mode is the most used acquisition mode used over land because it satisfies most service requirements (Copernicus Program, n.d.). As we can see in the overview table is uses a 250km swath at 5m with a spatial resolution of 20m, which produces an image with a 20m x 5m resolution. The Sentienl-1 uses a technique called terrain observation with progressive scans (TOPSAR), which means it adjusts the radar side-to-side and front-to-back which secure the uniform quality of the images by avoiding issues like unevenness. TOPSAR has two main improvements from past techniques: it has consistent signal strength and produces images with clarity across the whole image regardless of the position in the image (Copernicus Program, n.d.). By using these techniques, the IW mode produces consistent detailed images with high quality over a large area making it a good tool for monitoring and studies of land surfaces.

Sentinel-1 Geographic Coverage

The sentinel-1A was launched 3. April 2014 and Sentinel-1B on 25. April 2016 orbiting in a near-polar, sun-synchronous orbit with a 12-day cycle on the same orbit plane with 180 degrees difference (Copernicus Program, n.d.). Using the IW acquisition mode one satellite can then cover the whole planet in 12 days from either descending or ascending orbit. Normally images would be available every 6th day, but since sentinel-1 B has been retired due to a fault in the power supply, the revisit time is now doubled until sentinel-1 C is ready (The European Space Agency, 2022).

Because the satellites orbit varies with latitude, the repeat sequence is a lot greater on higher latitudes, with the most frequent being the Arctic with coverage daily (Copernicus, n.d).

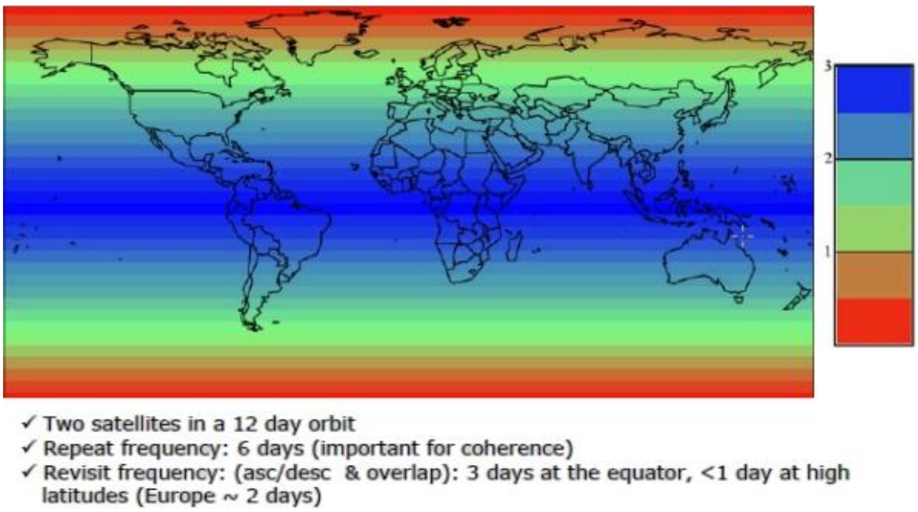


Figure 9 Illustration of global coverage, Revisit time for Sentinel-1 A and B (Copernicus, n.d.)

How to use Sentinel-1 for Avalanche Detection

The principle of detecting avalanches using Setninel-1 involves using the backscatter from the debris surface to detect avalanches, a process that is relatively straightforward as the surfaces become rugged and easily distinguishable (Eckerstorfer M. &., 2015). However, the challenge lies in the varying physical properties of snow, such as crystal size and water content, which complicate the creation of a fixed model. As mentioned Abermann and Eckerstorfer addressed this issue by using a dynamic threshold model to accommodate the changing conditions. Figure 9 shows how different surfaces and snow conditions effect the backscatter.

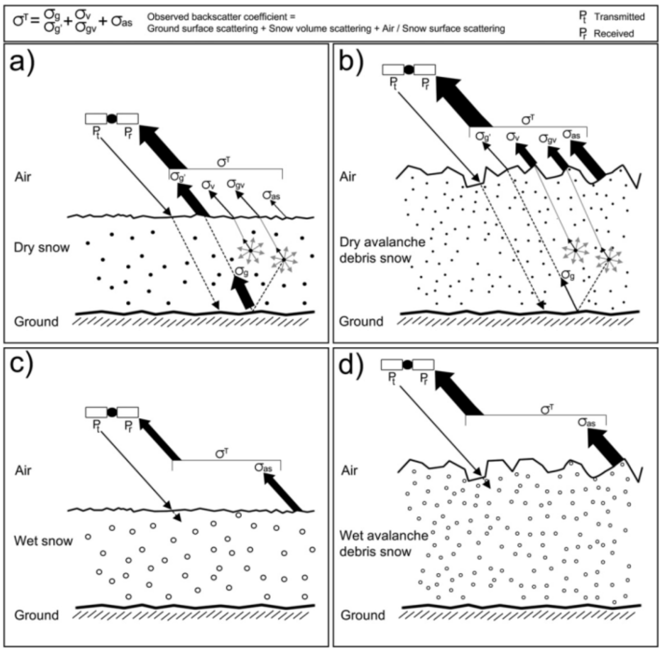


Figure 10 Visualizing how backscatter transmits when hitting different surfaces (Eckerstorfer M. &., 2015).

Previous studies for avalanche detection using Sentinel-1

The utility of Sentinel-1 for avalanche detection has been demonstrated in northern Norway earlier by M. Eckerstorfer in 2016 using data from 2 winters (M. Eckerstorfer A, 2017). The study suggested the potential to distinguish between dry and wet snow avalanches based on backscatter signal differences. Also highlighted the challenges of detecting smaller avalanches due to the sensor's resolution and noted the transitional snow climate of Tamokdalen, which affects avalanche behaviour. The research pointed out the frequent underestimation of avalanche activity, underscoring the need for enhanced monitoring techniques. (M. Eckerstorfer A, 2017).

M. Eckerstorfer has also done a similar study in West Greenland in 2019 with J. Abermann focusing on wet avalanche cycle. This study aimed to apply similar principles of utilizing Sentinel-1 satellite data for avalanche detection and using Sentinel-2 and ground observations to quality check the results. In the study area they had an automated meteorological station, several hydrometric stations and six time-lapse cameras to overlook the area and compare it to Sentinel-1 and Sentinel-2 images (Jakob Abermann, 2019). The study revealed that nearly 800 avalanches were triggered during a specific cycle, mainly due to wetting of the snow induced by rain and a significant rise in air temperature.

In the study they highlighted several limitations of using Sentinel-1 data for avalanche detection. The spatial resolution may not effectively capture smaller avalanches. Errors in distinguishing avalanche debris from similar geomorphological features could lead to misinterpretations. The side-looking nature of SAR sensors also creates radar shadows and layover effects in mountainous areas, potentially leading to underestimation of avalanche activity. They also found it challenging to use fixed backscatter and used a dynamic threshold instead to adjusted for the snow conditions (Jakob Abermann, 2019).

A third study was done in Langtang Nepal by Markus Eckerstorfer and Jakob Grahn, with the goal to establish a multi-year inventory of snow avalanche activity, but also to show the results of Sentinel-1 snow avalanche detection and discuss the strengths and weaknesses of the used method (Eckerstorfer M. &., 2021). They used a highly advanced method based on three modules; initiation module and avalanche detection modules which is ran separately in consecutive order and then processed in the output model.

The initiation module sets up the study by defining the area and timeframe, downloading Sentinel-1 data, and utilizing a digital elevation model to create avalanche runout masks and geocode the data. In the avalanche detection module, Sentinel-1 GRD images are precisely geocoded using proprietary SAR software, which adjusts and resamples data to accurate ground positions and exports radar backscatter data along with masks for radar shadows and layovers. The output module then presents detailed vector data for each avalanche detected, including temporal and topographical information, alongside RGB change detection images for visual assessments (Eckerstorfer M. &., 2021). However, the effectiveness of their snow avalanche detector, which uses dynamic thresholds based on backscatter changes, was limited by the inability of C-band SAR to detect dry snow, potentially leading to false positives within designated avalanche runout zones (Eckerstorfer M. &., 2021).

Pre-processing done by GEE

Google Earth Engine is an ideal platform for handling and analysing SAR data like Sentinel-1 imagery, one of the reasons is because of the already built in pre-processing. It's important to know what type of pre-processing is done to be able to understand and make a correct analysis.

In this thesis 'COPERNICUS/S1_GRD' will be used from the Sentinel-1 image collection which is providing data from a dual-polarization C-band Synthetic Aperture Radar (SAR) instrument at 5.405GHz (C band) (Google earth engine, n.d.). Sentinel-1 satellites use level-1 ground range detected (GRD) scenes, processed to see the backscatter coefficient ($\sigma°$) in decibels (dB). Which means it takes the raw backscatter data from GRD and converts it to a logarithmic scale – decibels, which compresses the backscatter values and makes them easier to interpret visually (Google Earth Engine, n.d.). The reason why it's needed is that surfaces reflect radar waves differently for example, smooth surfaces like snow or water reflects radar waves away from the satellite, while buildings and other rough surfaces reflect them toward the satellite.

GEE uses the following pre-processing steps:

1. **Apply orbit file**
   Updates the satellite's metadata with precise orbit information to correct for any positional inaccuracies (Google Earth Engine, n.d.).
2. **GRD border noise removal**
   Removes low-intensity noise and invalid data at the scene edges, improving the clarity and quality of the data edges (Google Earth Engine, n.d.).
3. **Thermal noise removal**
   Improves the quality of the data by removing extra "noise" that comes from the satellite's sensors. This noise can interfere with the image, especially in images taken in modes where the satellite captures several overlapping sections at once. Removing this noise helps make the images clearer and more accurate (Google Earth Engine, n.d.).

4. **Application of radiometric calibration values**
   Adjusts the data using specific settings that come with the satellite's imagery data. It ensures that the measurements of how much radar signal is bounced back to the satellite are consistent and reliable, despite any differences in the satellite's sensors over time or across different images. It helps to standardize the readings, making it easier to compare images taken at different times or under different conditions (Google Earth Engine, n.d.).
5. **Terrain correction**
   Adjusts the imagery from the ground range geometry (which assumes a flat Earth) to account for terrain variations using Digital Elevation Models (DEMs). This correction is important for accurate geographical positioning and for applications requiring precise spatial analysis (Google Earth Engine, n.d.).

StatsSkred Project

In the Satskred project, Norwegian researchers developed an advanced automatic avalanche detection system using Sentinel-1 satellite data. The detection system identifies avalanches by comparing current images with those from previous days and highlights changes in the snowpack. While it performs well in identifying wet snow avalanches with about 75% detection probability, it is less effective for dry snow avalanches, detecting only about 20% of them (Eckerstorfer M. , 2024).
The project provides daily updates on avalanche activity presented in an interactive map showing information about the slope, size, registration, and trigger time when different avalanches are selected.

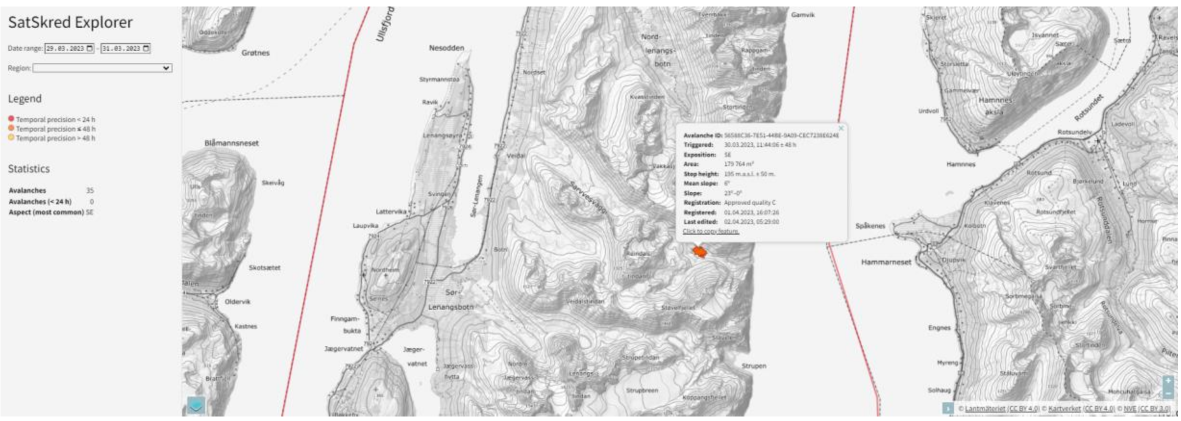


Figure 11 Shows an avalanche detection from 30.03.2023 in StatSkred Explorer (NVE, u.d.)

Figure 12 Avalanche timeline from 29.03 - 30.03.2023 presenting debris elevation and aspect (NVE, u.d.)

Resampling methods in GIS

Resampling in GIS is a key step to align raster datasets with varying pixel resolutions and projections for an accurate analysis. The process is particularly important when combining multiple datasets to make sure they share a common spatial grid, making integration and analysis seamless. Resampling redefines the values of pixels based on a new grid and can impact the quality of the data (Esri, n.d.).

Different techniques have been made for different types of raster data. Here is a short overview of the main types, how they work, their applicability and advantages.

Nearest Neighbour: This method is suitable for discrete data, like land-use classification, because it keeps pixel values without generating new ones. Although it is applicable to continuous data, it can maintain original reflectance values which are important for multispectral analysis. The technique is also the most efficient when it comes to process time but can cause offset by up to half a pixel (Esri, n.d.).

Bilinear Interpolation: The method uses a weighted average of the four nearest input pixels to calculate the output pixel value, smoothing transitions and producing visually appealing outputs. It's effective for showing gradual changes like elevation or pollution gradients (Esri, n.d.**).**

Cubic Convolution: The method uses a weighted average from the 16 closest input pixels, creating sharper images than bilinear interpolation. It enhances image clarity and resolution, making it suitable for detailed analysis where precision is critical (Esri, n.d.).

Methods

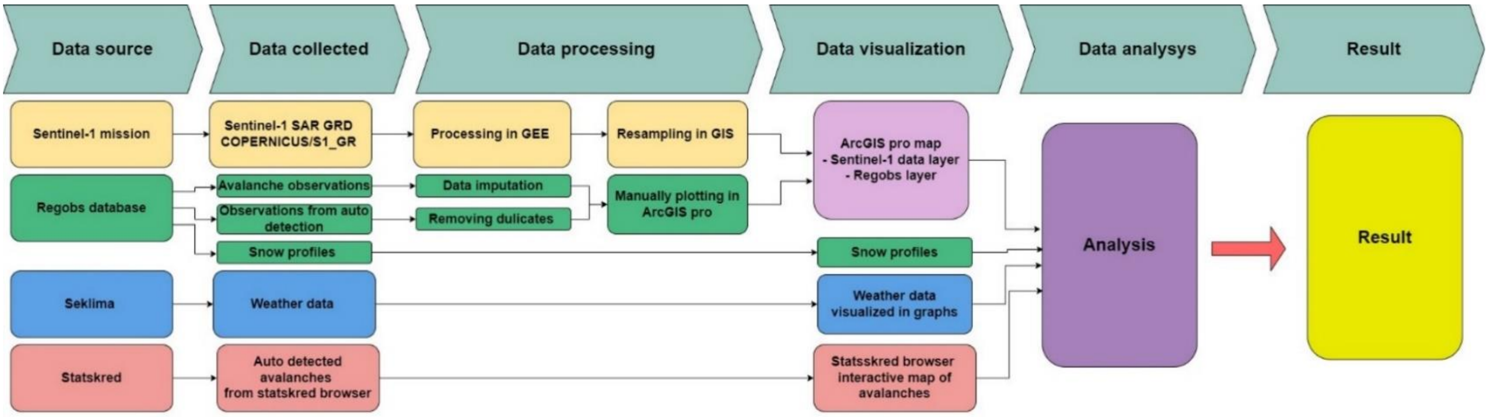


Figure 13 Overview of methods illustrated in draw.io

Sentinel-1 image collecting and processing using GEE

Choosing parameters

To use Sentinel-1 data for avalanche detection it's crucial to have high-quality images from pre- and post-event. By using EO Browser and selecting the preferred parameters the user can see day by day how the satellite moves in orbit.

The first step in the acquisition process is selecting the appropriate mode. This study requires frequent imagery, hence the choice between extra-wide swath (EW) and interferometric wide swath (IW). Due to EW's limited resolution of 20m x 40m, suitable only for very large avalanches, IW with a finer resolution of 5m x 20m is chosen for its superior deformation detection capabilities. For polarization VV and VH are selected in both descending and ascending orbit to assess and compare their effectiveness in capturing avalanche features.

GEE script Description

In this section, I will explain the code used for detecting avalanches using open-source data and tools provided by Google Earth Engine (GEE). The code is divided into two main workflows: one for creating a Digital Elevation Model (DEM) Avalanche Terrain Mask and another for detecting changes using Sentinel-1 radar data.

DEM Avalanche Terrain Mask Creation Workflow

In this thesis, the MERIT DEM was selected because of its high accuracy and comprehensive error corrections, in contrast to the Copernicus GLO30 DEM and NASA SRTM 30m DEM, which were unsuitable due to data gaps and lack of coverage in Lyngen (Google Earth Engine, n.d.). With a resolution of about 90 meters at the equator, MERIT DEM improves upon earlier models like NASA's SRTM3, JAXA's AW3D, and Viewfinder Panoramas DEM by eliminating absolute bias, stripe noise, speckle noise, and tree height bias (Google Earth Engine, n.d.). These enhancements improve the accuracy of land area mappings, making the MERIT DEM effective at representing complex terrain features.

Map Initialization: The map centres on the area of interest (AOI) at a specified zoom level to provide a focused view.

DEM Data Import: The MERIT DEM dataset is imported, and the elevation band is selected for processing.

Visualization Settings: Elevation data visualization properties are set to min: -3 and max: 1200 which specifying colour codes from low to high elevations. This means that elevations lower than -3 will be represented with the first colour in the palette, and elevations higher than 1200 will be shown with the last colour in the palette.

Layer Addition: The DEM data is added to the map as a base layer, and a hill shade layer of min: 0 and max: 255 also added for enhanced terrain visualization. Hill shading is a technique used to simulate shadows on terrain, giving the flat elevation data a three-dimensional appearance which makes the elevation data more understandable.

Slope Calculation: The terrain slope is calculated from the DEM to identify steep areas where avalanches are likely to occur.

Slope Masking: A mask is created for slopes between 20 to 45 degrees, which are the most typical avalanche slopes, and this mask is buffered by 200 meters to account for potential avalanche spread.

Sentinel-1 Change Detection Workflow

Sentinel-1 Data Filtering: Sentinel-1 images are filtered by the AOI, polarization (VH or VV), instrument mode (IW), and pass direction (Ascending/Descending).

Image Collection by Date: Images are collected for periods before and after the avalanche event to prepare for change detection.

Median Mosaic Creation: Median mosaics of the pre-event and post-event images are created to stabilize variation in radar backscatter. This technique involves taking multiple images captured before and after an event and computing the median value of the backscatter for each pixel across all these images.

Change Calculation: A change detection analysis is conducted by dividing the pre-event image by the post-event image to highlight areas of significant change. Using min: -1 and max: 5. Values close to 1 indicate little to no change, as the pre-event and post-event backscatter are similar. Values greater than 1 suggest an increase in backscatter, while values less than 1 indicate a decrease.

Binary Change Detection: A binary raster image is created using a threshold value of min: -25 and max: 5 to identify significant changes, which likely indicate avalanche activity.

Slope Mask Application: The binary change detection output is masked with the slope mask to ensure that changes are only considered within typical avalanche slopes.

This script enables the detection of avalanche activity by analysing changes in the radar backscatter, which may indicate disturbed snow surfaces typically seen in avalanche runouts. The use of slope masks helps focus the analysis on relevant geographic areas, increasing the accuracy and reliability of the detection results.

GIS Processing

When importing the binary layer over to ArcGIS pro the dataset needs to be resampled. For best possible analysis the closest neighbour interpolation method is used. This technique preserves the original values of the data points, ensuring that the characteristics of discrete data, such as land cover types or categorical data, remain unchanged. Unlike other interpolation methods that might introduce averaging or smoothing effects, closest neighbour interpolation maintains the integrity of the original data points. For visualizing the data, zero values are assigned no colour in the symbology to ensure they do not distract from significant data points.

Regobs data collecting and Processing

How data from Regobs database is collected and registered

Observations for this analysis were selected from March 29. to April 1. using the RegObs interactive map and manually inputted into an ArcGIS Pro map.
Data was registered directly from observer reports, which frequently lack details on avalanche size, trigger, and type. When reports are incomplete, but images clearly show distinct features like a crown fracture or a very small avalanche, specific sizes and types are assigned.

Object ID: Assign them a number	**Trigger:** Naturally or from human activity
Name of the area: Local name	**Type of avalanche:** wet/dry and slab/no slab
Date: Date of registration	**Size:** 1 – 4
Time of registration:	**Autodetected:** No or yes
Aspect: N,S,W,E	**Comments:** Short comment and link to the observation in Regobs

Figure 14 Example for when type of avalanche is not reported but is possible to see in the image (NVE, n.d.)

Collecting data from automatic detection stations

There are two stations placed in the area of interest, one is at Storura and one at Furuflaten. Both operative during the time of interest, providing many detections of avalanches from 30. March – 31. March, which was manually place in the ArcGIS pro map.

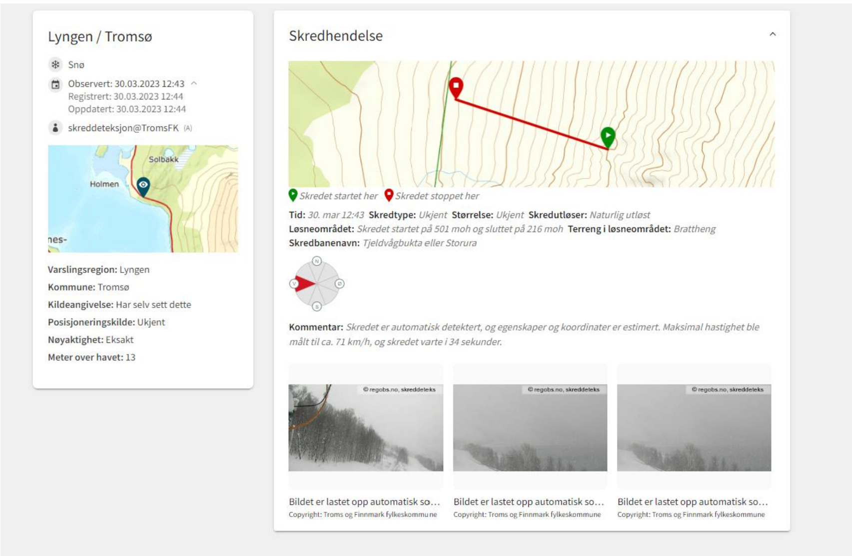


Figure 15 Example of observation done by automatic detection station (NVE, n.d.)

Weather

In the theory section, it is noted that temperature, wind, and accumulation are key factors affecting snow conditions. To gain insights into the conditions leading up to the avalanche cycle, Seklima was used to collect and graphically represent the data.

It is crucial to choose stations that offer the most relevant and comprehensive data for the specific area of interest. Not all-weather stations in Seklima record all types of data, so different stations were selected for each type, prioritizing stations close to the avalanche-prone areas. Stations closer to these areas typically provide more accurate and relevant readings for the specific terrain and climate conditions where avalanches might occur. Wind, temperature and accumulation can be presented in different time caps, such as per hour or over 24-hour periods, and with various parameters. Choosing a 24-hour period ensures data availability, improves visualization, and an hourly selection can be implemented if more detailed results are needed.

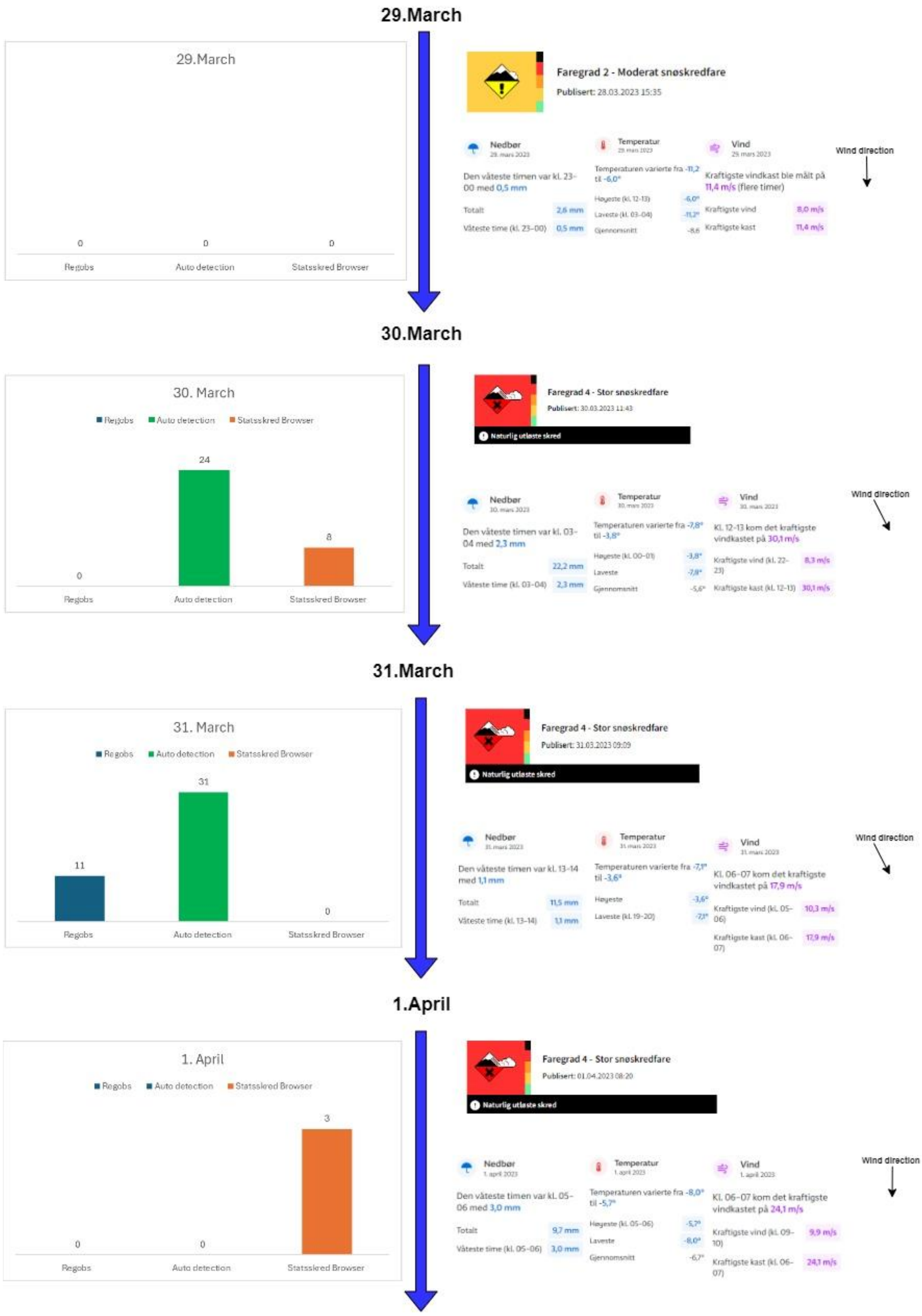
To best understand temperature variations, the middle, maximum, and minimum temperatures were utilized. The middle temperature provides a comprehensive overview, while the maximum and minimum temperatures reflect conditions during the day and night respectively.
For wind analysis, the middle value of the highest gusts was chosen to represent extreme weather conditions, which might indicate storms. Additionally, the middle value of the highest average wind speed per hour was selected to provide a general representation of wind conditions. The average wind speed was also used to compare with the highest average wind speed to gain further insights into wind stability.
For accumulation the initial plan was to differentiate between snow, wet snow, and rain; however, this was not feasible due to data limitations, and average accumulation was used instead.

The following stations were used for temp, accumulation, and wind.

Figure 16 Overview maps taken from Seklima for overview of temp(right), temp (middle) and wind (right)

Results

Timeline 29. March – 1. April



Avalanches observations from Regobs

Few avalanches have been registered. The size of the avalanches is documented in 80% of the data, while the remaining 20% is taken from interpretations of photographs and descriptions. The recorded time is based on when the avalanche was observed, not when it occurred.

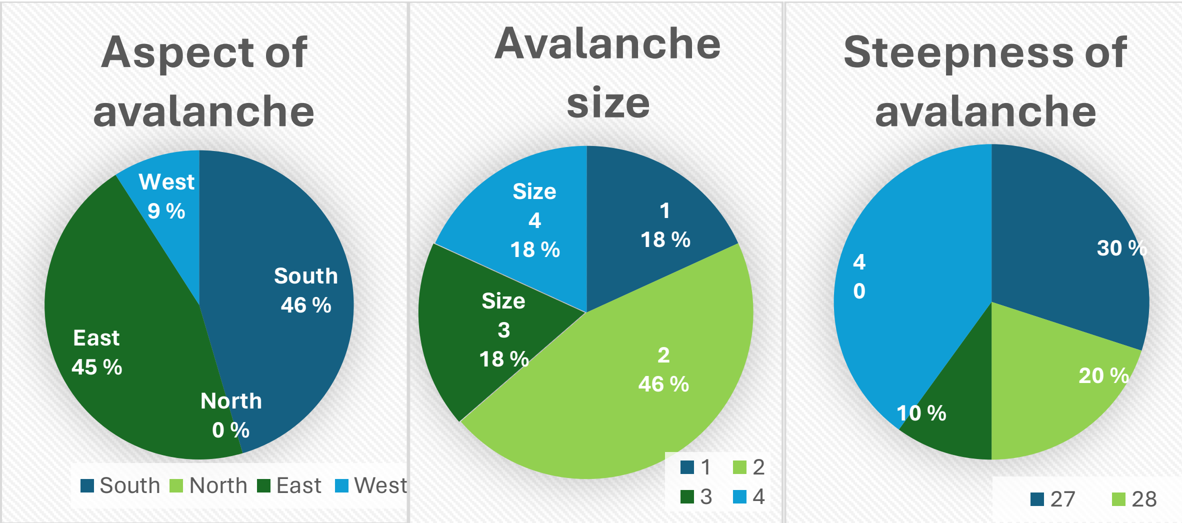


Figure 17 Charts displaying the distribution of aspect, size, and steepness.

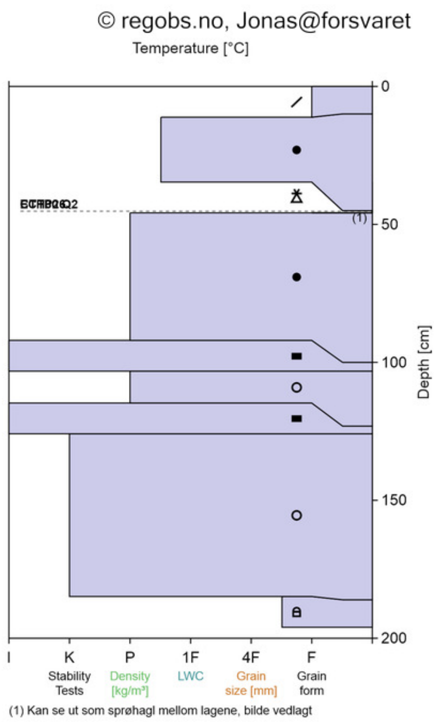
Most avalanches detected were size 2, with other sizes less frequently observed. All avalanches started on slopes between 27 to 31 degrees and the majority faced south and east.

Result from snow profiles

Pre avalanche cycle

Two snow profiles and compression test from March 26th give some information about the snow conditions before the avalanche cycle.

- In Lyngen's northern area at Storgalten's northwest face (857 AMSL), dry loose snow (10-30cm) and light wind slabs were observed. An extended compression test (ECPT26@45cm, Q2) indicated a stable snowpack as it fractured after 26 taps without propagation (NVE, 2023).
- At Leangstindan's southeast face in central Lyngen (1197 AMSL), contrasting conditions of dry shadowed snow and wet sun-exposed snow were reported. The initial Extended Column Test (ECTN11@25cm, Q3) showed no propagation. After removing a 25cm layer, a second test still showed no propagation, marking the snow as stable despite uneven fractures (NVE, 2023).



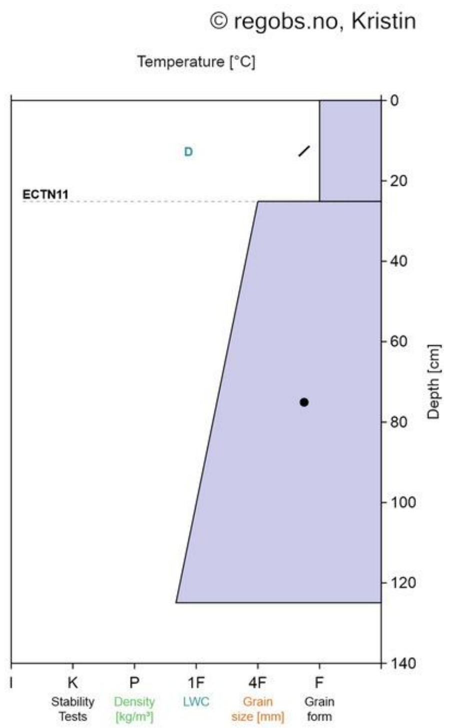


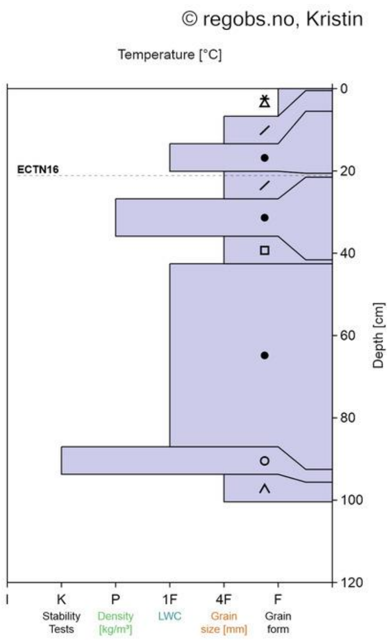
Figure 18 Snow profile from 26th March (NVE, 2023)

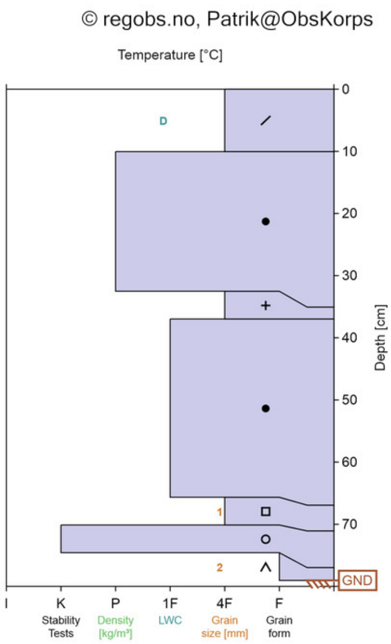
Figure 19 Snow profile from 26th March (NVE, 2023)

Post avalanche cycle

After the avalanche cycle we have three snow profiles and compressions test that gives insight in the snow conditions.

- In Rottenvika, central Lyngen (556 AMSL), a simple compression test (CTE2@10cm, Q3) revealed a weak layer breaking smoothly under soft snow, suggesting instability due to dry, wind-transported snow (NVE, 2023).
- In Gjerdedalen (656 AMSL), a south-facing slope test showed dry snow and a potential for large slab avalanches as indicated by a Low-Quality Block Test (LBT@30cm, Q1) (NVE, 2023).
- Nearby, another test (ECTN16@21cm, Q2) confirmed a hard-to-disturb snowpack with a weak layer prone to triggering avalanches, underscoring the complex snow stability post-event. (NVE, 2023)





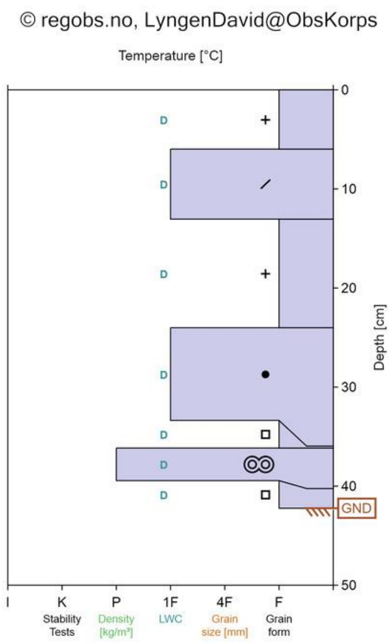


Figure 20 Snow profile 2. April (NVE, 2023)

Figure 21 Snow profile 2. April (NVE, 2023)

Figure 22 Snow profile 3. April (NVE, 2023)

Result from weather

Temperature

Looking at the result from temperature in the area we can clearly see an increase in temperature from the 29. March – 31. March. The stations visualize data from sea level up to 700 AMSL. Looking at the minimum temperature we can see an increase of 10 degrees in many areas and a middle temperature close to the freezing point.

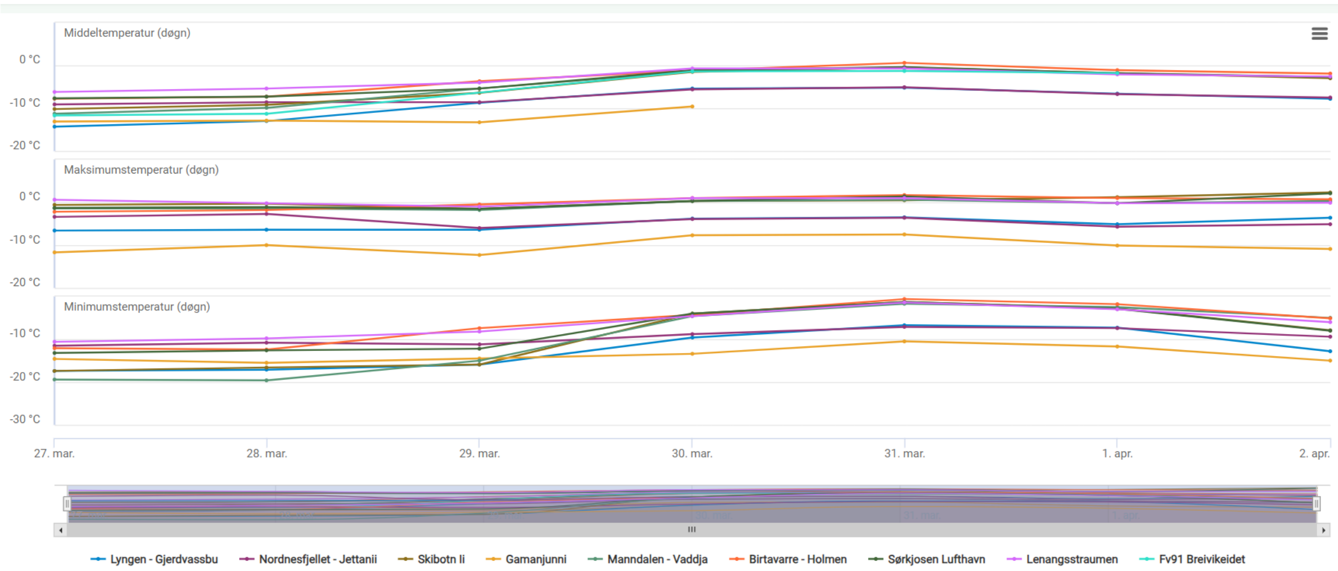


Figure 23 Graph of middle, max and min temp from 27. March - 2. April (Norwegian Meteorological Institute, u.d.)

Accumulation

Looking at the average accumulation we can see a sudden spike on 31. mars with areas receiving huge amount of snow in a short time span. We can interpret it as snow or wet snow because of the temperature in the area.

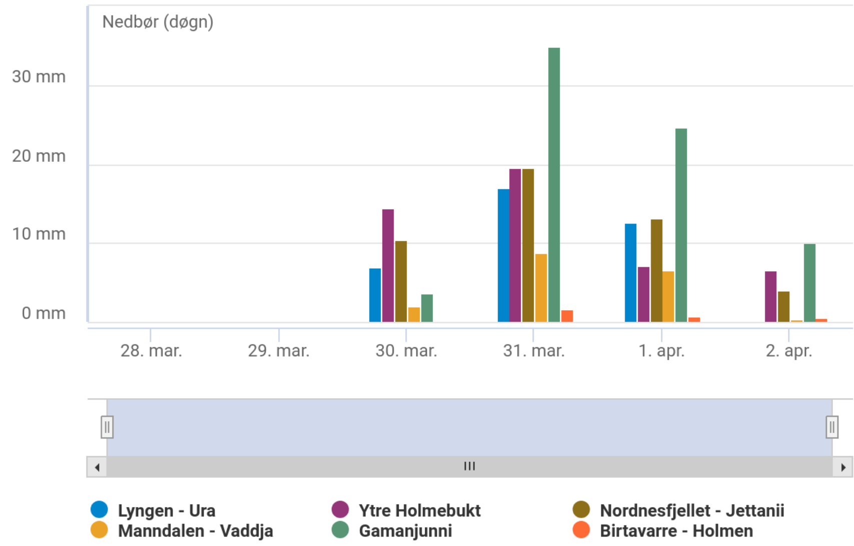


Figure 24 Accumulation timeline (Norwegian Meteorological Institute, u.d.)

Wind

Looking at the wind it steadily increases from 29. – 31. March with the most extreme conditions at Fakken which is located exposed in the north. The wind direction is constant from the north to south.

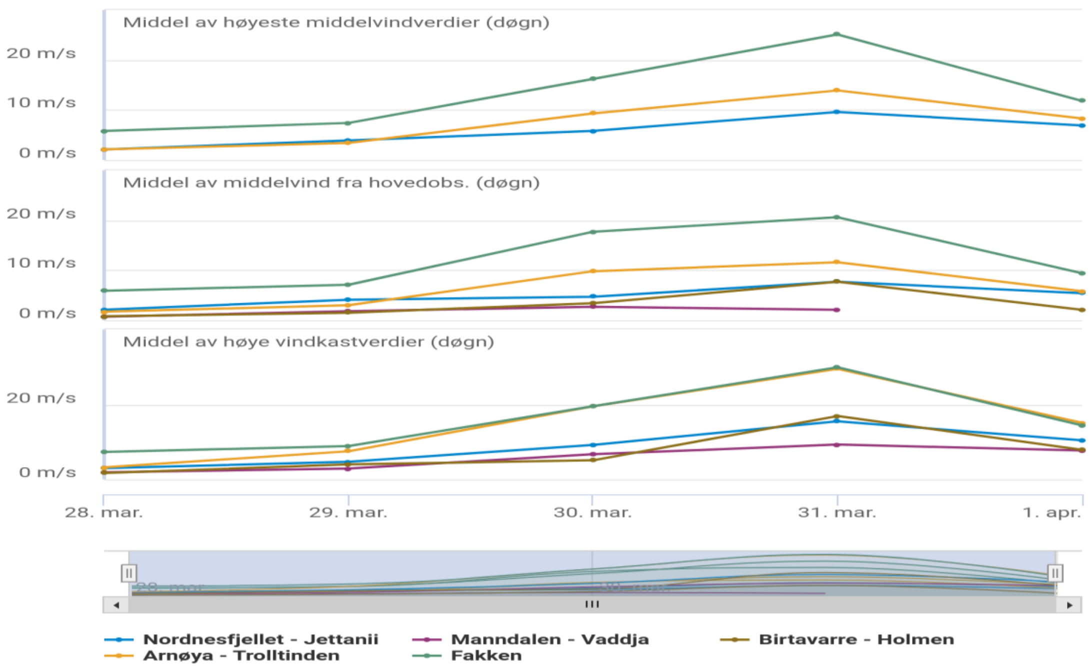


Figure 25 Wind data from 28. March - 1. April (Norwegian Meteorological Institute, u.d.)

Result from StatSkred Explorer

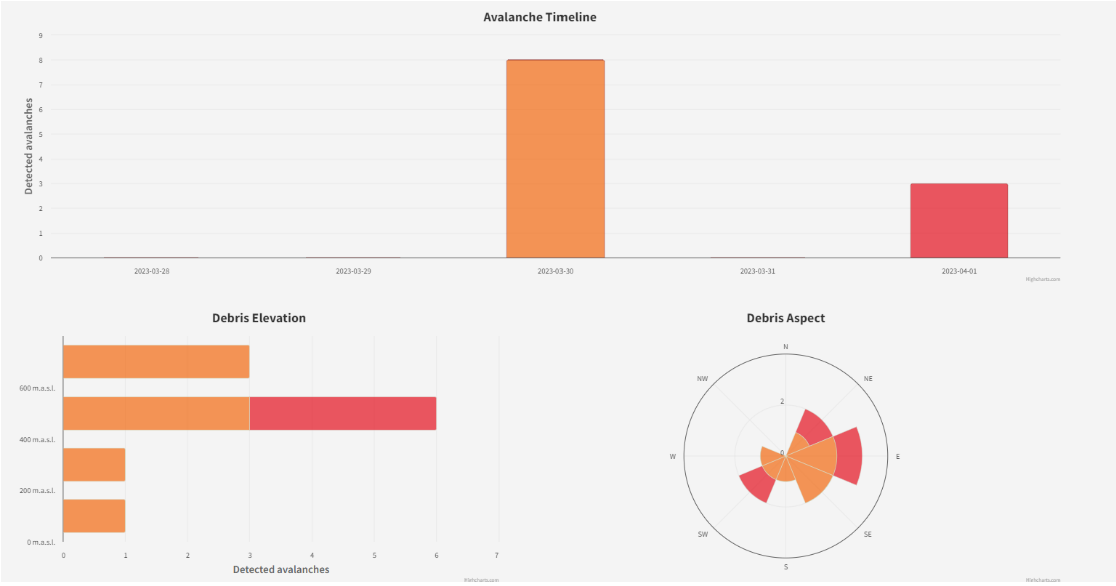


Figure 26 Avalanche timeline 28. March - 01. April (NVE, u.d.)

The StatSkred Explorer recorded eight avalanches on March 30, and none on March 31. However, it's important to note that these events have a reporting precision of 48 hours, so it's possible that some of these avalanches occurred on March 31. They were all registered on April 1. It is also noteworthy that none of the significant avalanches, which destroyed houses and were large in size, were registered by the browser. This highlights potential limitations in the detection capabilities or reporting criteria of the system.

Result from Sentinel-1

Distribution of binary data

Distribution of the binary layers was extracted directly from the four different layers and presented in a histogram.

- VV Descending has the highest count of detections, indicating it's the most sensitive to surface changes.
- VV Ascending shows fewer than the descending, but still significant. This can indicate more change on one of the aspects of the mountains than the other, which can be explained by the snow transported with wind from the north to south.
- HV descending and ascending shows significantly fewer detections compared to the VV polarizations. This indicates that the HV polarization is less sensitive. We can see the same pattern that ascending has a lot more detections than descending which supports the theory that one aspect has more activity than the other.

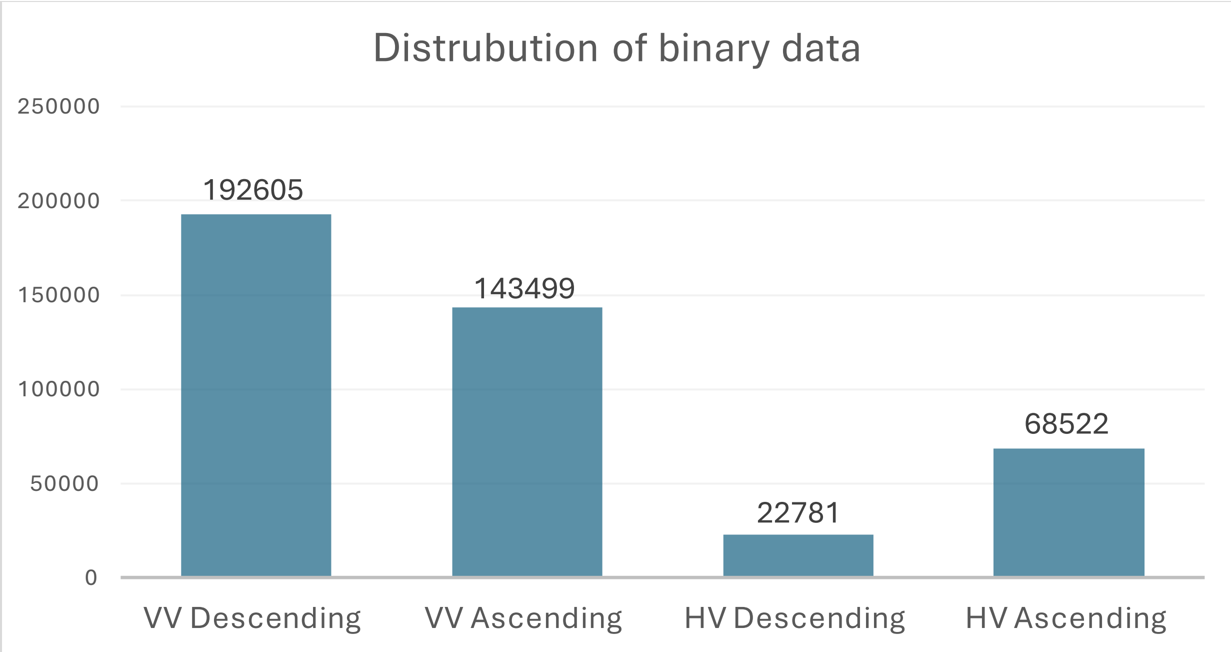


Figure 27 Distribution of the binary data

To visually present the result I have chosen 2 areas which is facing east and west for representation of the data.

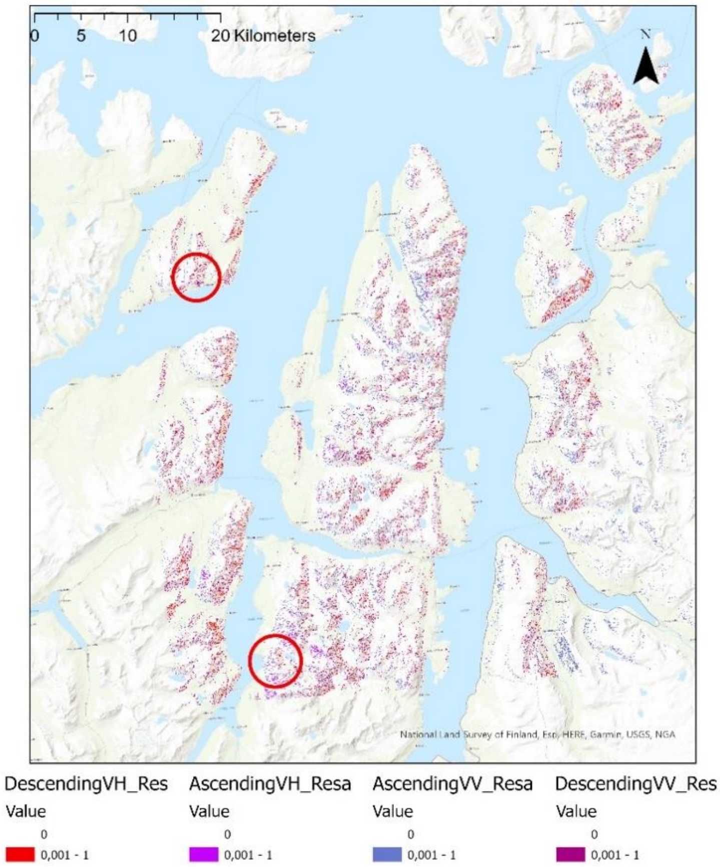


Figure 28 Figure 29 Overview map of AOI with marked areas for analysis

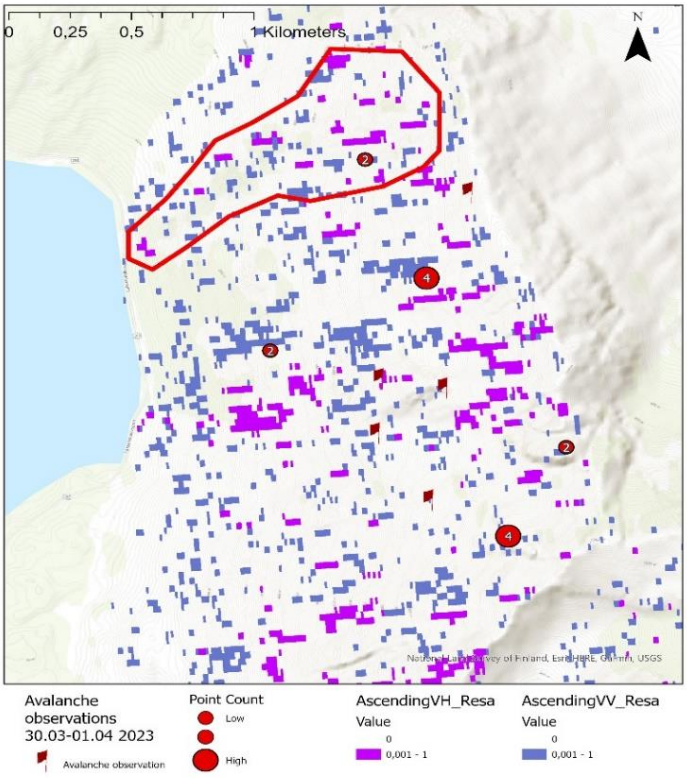


Figure 29 West side of mountain side close to Solbakk

Here presenting the west facing side close to Solbakk using both VV and VH polarization in an ascending orbit to visualize the data from the binary layer which has been resampled.
The area is marked with the autodetected station using radar for reference of activity.

VV in blue shows lots of output, indicating a lot of change. But from the data it's not possible to identify avalanches.

VH in pink shows less output in more confined areas, and there seems to be patterns from wide to slim going down the hill. An area in the north is marked with a red polygon to show the pattern.
Looking at the elevation and steepness of the curves, VH here can be used to identify avalanche activity, but doesn't have the resolution to identify individual avalanches.

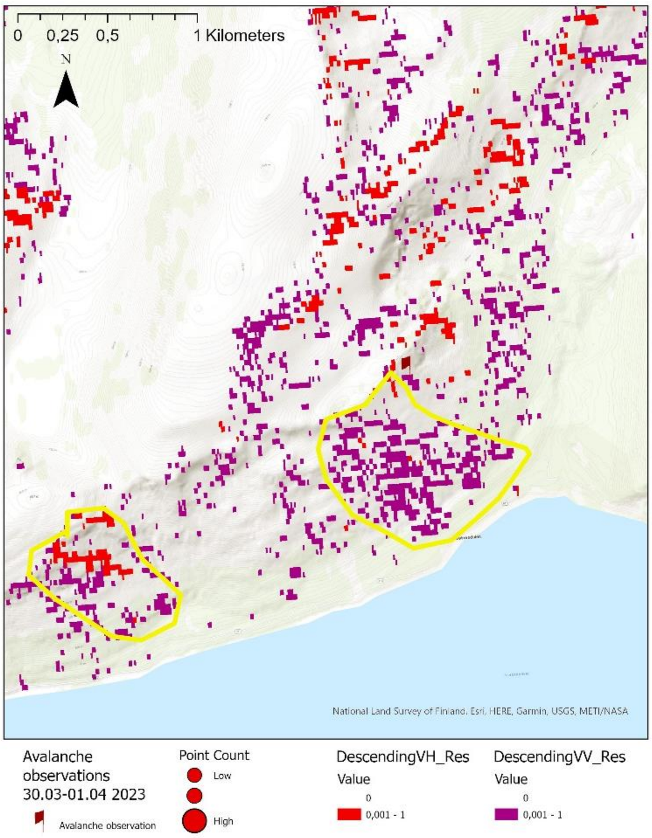


Figure 30 Mountain side at Reinøya for visualization

Here presenting the east facing side at Reinøya using both VV and VH polarization in descending orbit to visualize the data from the binary layer.

VV in purple here shows a lot of output, but here in a more structured way. The marked area is where a big avalanche happened that crushed buildings and took them out to sea.

The VH here also shows less output and is easier to interpret. In both yellow polygons the VH is present in the upper part of the avalanche and the VV is detecting the debris underneath.

Discussion

The use of GEE for processing Sentinel-1 data

DEM selection

As mentioned, the MERIT DEM was chosen because other higher resolution DEMs had data gaps. However, there are limitations in using MERIT DEM due to its resolution constraints. The 90-meter resolution of MERIT DEM may not capture fine-scale topographical features that are critical for identifying potential avalanche initiation zones accurately. This limitation can also affect the precision of slope calculations and subsequently, the effectiveness of the slope mask which is designed to isolate slopes between 20 to 45 degrees. The lack of precision can lead to avalanches not being detected because they're outside of the slope range. It is also worth noting that the slope range of 20 to 45 degrees might be too conservative for detection. For instance, Eckerstorfer and Grahn use a broader range of 28 to 68 degrees for their slope mask (Eckerstorfer M. &., 2021), which could potentially capture a wider variety of avalanche-prone areas, potentially leading to more accurate detection outcomes.

Filter by orbit number

In the analysis, an attempt was made to filter Sentinel-1 data by orbit number to maintain consistency in imaging angles, which is crucial for reliable radar backscatter analysis. Unfortunately, it was not possible to successfully implement this filtering within the constraints of the available tools, resulting in images having different orbital passes. This could lead to inconsistencies in the satellite imagery due to variations in viewing angles, potentially affecting the interpretation of avalanche-related changes in the backscatter and compromising the reliability of the results.

Detection sensitivity

The use of pre-event to post-event images to detect changes primarily assumes that notable differences in radar backscatter signify avalanche activities. This might lead to false positives if the surface and the condition of the snow are changed in another way. For the data from 31. March 2023 strong wind transported a lot of snow, which can create wind dunes in the snow or other deformation which might lead to false positives. In addition, heavy accumulation with wind can lead to the same thing. It's important to underline that fresh snow doesn't have the density to cover avalanche debris from being detected. A third factor is the sun affecting the snow after the cycle before the post images was taken, which can deform the snow and can also create false positives.

Data coverage

Data coverage limitations significantly impact the effectiveness of monitoring and analysing rapid environmental changes using Sentinel-1A. With only Sentinel-1A operational, the revisit frequency is restricted to approximately every 12 days. Which is insufficient for tracking rapid environmental changes accurately. The more time between images and the event, the more time the environmental factors have to affect the snow, making analysis and detecting challenging because of the uncertainties around false positives as mentioned in the detection sensitivity.

Results of using GEE

As we could see from the results, it was hard to distinguish avalanches and get an exact picture of the conditions. What we could see was avalanche activity without a doubt, which can be a good indicator alone and help with forecasting. The method shows that it is possible to use GEE for detection, but without implementing crucial steps such as an orbit filter, it will be hard to know in what extent it will work, and how it would look like in comparison to the more comprehensive methods used in past studies.

Contributions and limitations for each data source

After discussing the capabilities and limitations of GEE in processing Sentinel-1 data for avalanche detection, it becomes essential to consider how this technology integrates with other data sources. In this next section, we will explore the specific contributions and limitations of each data source used in this study, shedding light on their collective impact on our understanding of the avalanche cycle on March 31, 2023.

Regobs observations

Regobs offers in-depth observations that significantly enhance our understanding of snow conditions and avalanche risks. These observations, detailed through comprehensive snow profiles and photographs, provide clear insights into the current conditions. The detailed information is very important for correctly assessing avalanche risks and helps create dependable forecasts. Essentially, it serves as a reliable source of truth, provided that observations have been conducted in the region.

While Regobs is valuable, it does have limitations. The level of detail concerning the type, size and other crucial information is often lacking, which can hinder comprehensive analysis.

There is a shortage of observations from qualified personnel, making it difficult to double-check and verify the results. Additionally, the coverage provided by Regobs is notably low, especially in adverse weather conditions, which further complicates data collection and reliability in critical times.

Autodetection stations

Autodetection stations provide highly detailed information about specific mountainsides. They can be used as a definitive source and verify the accuracy of other methods such as Sentinel-1 imagery. A significant limitation of autodetection stations is that they only cover small areas, which restricts the breadth of the data they can provide.

StatsSkred Explorer:

The StatSkred Explorer is an example of a project that uses Sentinel-1 images and autonomously detects, marks, and provides information on avalanches. This project is useful as a point of comparison for this study. The browser offers a wealth of information and is very user-friendly. However, it currently under detects the number of avalanches in the region. This assessment is based on comparisons with avalanche data from Regobs, which is provided by observers. One example is that it didn't register the avalanche in figure 1, which was massive in size.

Weather

Weather data provides crucial insights that explain why conditions in avalanche-prone areas change, enhancing our understanding of the environmental factors involved. By Correlating weather conditions with avalanche events, it's possible to identify a relationship and predict potential future avalanches under similar conditions.

Weather data sometimes lacks the spatial resolution required for detailed avalanche forecasting, which can miss localized weather changes that are critical for accurate predictions. Additionally, integrating local weather data into avalanche forecasting models is time-consuming and requires significant effort to ensure accuracy and relevance when such data is available.

Sentinel-1:

Sentinel-1 covers large regions, providing valuable data about areas that lack ground information. Operating autonomously, it collects data without human intervention and can be presented without any interpretation. The feature proves especially valuable in conditions of poor visibility, such as under cloud cover or fog, where traditional methods of visual observation are ineffective.

Despite its capabilities, Sentinel-1 has some limitations. The resolution of the satellite is too coarse for capturing fine details and smaller avalanches, which are needed for detailed analysis. Currently, with only Sentinel-1A operational, data collection is limited to approximately every 12th day, which is not sufficient for monitoring rapid environmental changes. The data's accuracy frequently requires additional validation, as it typically provides approximations rather than precise depictions, partly due to possibility of false positives. The sensors also struggle to identify dry avalanches as the C-band goes straight through, making it ineffective for predicting dry avalanches. Furthermore, the requirement for comprehensive Radiometric Terrain Correction and preprocessing introduces a level of complexity that may affect the usability and precision of the data.

Summary of Data Sources

Regobs provides reliable observations that act as a source of truth, yet its geographical coverage is limited and can be affected by human bias. Autodetection stations offer constant monitoring of specific mountainsides, providing accurate data around the clock but only for very localized areas. Sentinel-1 offers broad coverage across the entire region but suffers from infrequent imaging and lacks the resolution necessary for detailed analysis of smaller avalanches, making data interpretation challenging. The StatsSkred browser demonstrates an autonomous use of Sentinel-1 imagery for avalanche detection; however, it tends to underreport the number of avalanches. Finally, weather data are crucial for explaining why avalanches occur but providing detailed insights for extensive regions is challenging due to variability in data resolution and collection.

Enhancements and Future Perspective

To refine the methodology and results of this study, introducing an orbit number filter would greatly enhance the consistency and reliability of the data, which is crucial for accurate change detection. Further improvements could involve adjusting parameters for the slope mask, the change threshold between pre- and post-event layers, and the criteria for binary change detection to optimize results. Additionally, evaluating and potentially enhancing the pre-processing conducted by Google Earth Engine might lead to better detection of avalanches.

Looking forward, the upcoming launch of the Sentinel-1C satellite is expected to substantially improve data availability and frequency, thereby enhancing the quality of studies like this one. In future studies, integrating autodetection stations on mountainsides could provide a robust means to validate Sentinel-1 imagery, as these stations offer continuous data. This continuous stream of data presents an opportunity to experiment with various processing techniques for monitoring and analysing avalanche activities. Furthermore, expanding the study to include data from other satellites, such as Sentinel-2, could validate the results from Sentinel-1, providing a more comprehensive dataset.

Lastly looking into combination of Sentinel-1 imagery with machine learning algorithms could be explored to improve avalanche detection accuracy. Machine learning models trained on large datasets could identify subtle patterns and correlations that might be missed by traditional analysis methods.

Conclusion:

How effective is Google Earth Engine (GEE) in detecting avalanche events in Lyngen using simple coding techniques and open-source data, and how can it contribute to traditional forecasting?

This study has systematically shown the capabilities of GEE to detect avalanche events in Lyngen using simple coding methods and open-source available data. The findings highlight GEE's potential to enhance traditional avalanche forecasting methods by providing rapid, accessible, and cost-effective analysis. Despite some limitations in data resolution and frequency, the integration of GEE with traditional data sources offers a promising prospect for detection of avalanches in regions like Northern Norway. This research underscores the significant role that open-source technologies can play in environmental monitoring and disaster management.

Acknowledgements

I would like to thank my advisor, Ursula Enzenhofer, for her guidance and support throughout this project, especially in aspects of coding which were crucial to my analysis.

I am thankful to the teams behind the Sentinel-1 mission for their invaluable satellite data, which was essential for my remote sensing analysis. I also appreciate the efforts of the team at Varsom and the contributors to the Regobs database for providing crucial avalanche data.

This thesis could not have been accomplished without the tools and data generously made available by these organizations.

Appendix

The code incorporates contributions from Ursula Enzenhofer and Ronja Lappe, along with inspiration from various online tech articles, including those by Eckersdorfer and other sources discussing S1 and GEE.

The code is available on GitHub (Bjerke, n.d.)

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